



**Università Politecnica Delle Marche**  
**Environmental Engineering**  
**Gaseous Emissions and Treatment Plants**

**Final Report**

**NO<sub>2</sub> Concentration Analysis over Ancona Municipality-Italy  
through Remote Sensing and Machine Learning Technics, and  
SCR & SNCR Systems for NOx Removal**

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## **Introduction:**

One of the biggest and the most challenging issues facing all nations especially in developing countries is air pollution. Rapid increase in population and demand for energy have resulted in emission of toxic air pollutants that affect the surrounding environment as well as human health. (*Naik, 2018*)

At the national, regional, and worldwide levels, pollution and environmental degradation have emerged as major issues in recent decades. When significant amounts of dangerous chemicals, particulate matter, and biological molecules enter the Earth's atmosphere, air pollution results. Additionally, it may exacerbate the effects of global warming or diseases that affect people, including heart attacks, pneumonia, asthma, and a variety of respiratory allergies. The most dangerous air pollutants in global urban areas are among the gases that pollute the air. (*Program, 2021*)

The most critical and hardness pollutant all over the world and metropolitan areas are ozone (O<sub>3</sub>), sulphur dioxide (SO<sub>2</sub>), carbon monoxide (CO), nitrogen dioxide (NO<sub>2</sub>), Particulate Matters (PM2.5 and PM10). All these pollutants typically emitted form a variety of stationary and mobile resources. Stationary sources encompass domestic, residential, and industrial activities. (*European Environment Agency*) (*WHO, September 2021*)

Air pollution from mobile sources stems from vehicles and transport, emitting these with exhaust fumes and particulate matter. Except SO<sub>2</sub> that emitted from residential and industrial sources and the other pollutants are generally emitted generally by the vehicles. (*Roy M. Harrison et al, October 2021*)

For the purpose of this study, in the first part I tried to explain how we can remove or mitigate NO<sub>x</sub> from sources using Selective Catalytic Reduction (**SCR**) and Selective Non-Catalytic Reduction (**SNCR**). But in the second part I used remote sensing and machine learning technology or satellite based remote sensing technology which provides a valuable approach to continuous monitoring air quality in different periods and diverse scales to analyse NO<sub>2</sub> emission over Ancona province in difference years.

Some satellites which use for air quality analysis are, European Remote sensing satellite-2(ERS-2), Environmental Satellite (ENVISAT), Meteorological Operational Satellite (MetOP), and Sentinel-5 (Sentinel-5P) which use for analyzing air quality.

The Sentinel- 5 precursor mission is the first Copernicus mission dedicated to monitoring our atmosphere. Copernicus sentinel-5 is the result of close collaboration between ESA and the European commission, the Netherlands space office, data users and scientists(Copernicus sentinel-5 Precursor). (*agency, 2017*) Nitrogen Dioxide and How We Can Control it.

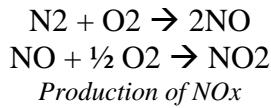
# Nitrogen Oxide (NOx) and How We Can Control It

## NOx production

Diatomeric molecular nitrogen ( $N_2$ ) is an inert gas that makes up about 80% of the air we breathe. However, the chemical element nitrogen (N), when it exists as a single atom, can be quite reactive. At room temperature, nitrogen is generally inactive, but it can form various compounds, some of which are harmful to both the environment and human health. Specifically, NOx can transform into different forms when:

- It is hit with a photon of UV or a shorter wavelength light
- is hit with photons that together transfer energy to change its ionization level
- It is catalyzed
- It is stimulated sufficiently by thermal (IR) energy
- It reacts with a chemically oxidizing or reducing radical
- It reacts with an oxidizing or reducing chemical

Most of NOx are produced during the combustion processes (thermal NOx) by the oxidation of the atmospheric nitrogen at very high temperatures, according to the following formulas:



NOx typically consists of a mixture of 95% nitric oxide NO and 5% nitrogen dioxide  $NO_2$ . In table 1 all the possible NOx forms are schematized.

Formula	Name	Nitrogen Valence	Properties
$N_2O$	nitrous oxide	1	colorless gas water soluble
$NO$ $N_2O_2$	nitric oxide dinitrogen dioxide	2	colorless gas slightly water soluble
$N_2O_3$	dinitrogen trioxide	3	black solid water soluble, decomposes in water
$NO_2$ $N_2O_4$	nitrogen dioxide dinitrogen tetroxide	4	red-brown gas very water soluble, decomposes in water
$N_2O_5$	dinitrogen pentoxide	5	white solid very water soluble, decomposes in water

Table 1 Nitrogen Oxides (NOx)

First of all, it is necessary to clarify that even short-term exposure of NOx can lead to respiratory problems, i.e. impaired host defense system, lung inflammation diseases and decreased lung function and growth. In fact, also small particles coming from NOx pollution and acid rain can infiltrate into the lungs and cause bronchitis, emphysema and heart disease problems.

$N_2O$ , NO, and  $NO_2$  are the most abundant nitrogen oxides in the air.

$N_2O$  is produced abundantly by biogenic sources such as plants and yeasts. It is only mildly reactive but it has a long life time (up to 150 years). It is an ozone depleting substance which reacts with  $O_3$  in both the troposphere and in the stratosphere.

This compound is in fact a Greenhouse Gas, which absorbs long wavelength infrared radiation to keep heat radiating from Earth, for this reason it is contributing to global warming. The greenhouse impact on a per molecule basis is 300 times higher than that of CO<sub>2</sub>. Furthermore, N<sub>2</sub>O concentration of 300 ppb leads to the warming of the Earth by 0.1 Watts per square meter.

Emissions of NOx from combustion are primarily in the form of NO. NO is originated from anthropogenic sources. It is just partially soluble in water and it can spread to the respiratory system. For this reason, it is considered dangerous especially for children and sensitive people. More in particular, it diffuses through the alveolar-cells and the capillary vessels of the lungs disrupting the alveolar structures and, consequently, the lungs. Moreover, it is rapidly converted into NO<sub>2</sub>.

$\text{NO}_2$  is present in the atmosphere and in acid rain. When it comes in contact with water, it produces nitric acid  $\text{HNO}_3$ .  $\text{NO}_2$  can be formed from the oxidation of  $\text{NO}$  caused by radicals from the photo reaction of VOC. For this reason, our present ozone concentration (in the troposphere) is the product of both  $\text{NOx}$  and VOC pollution.

EPA regulates only nitrogen dioxide ( $\text{NO}_2$ ) as a surrogate for this family of NOx because it is the most prevalent form in the atmosphere that is generated by human activities.

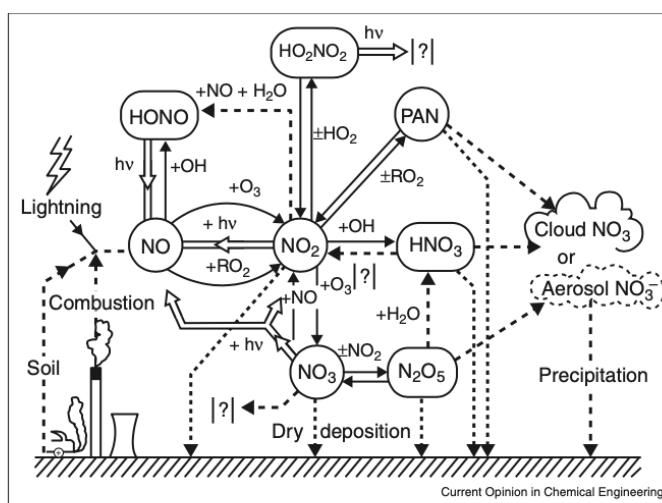


Figure 1 NOx reactions

From the figure 1, it is possible to sketch the different chemical reactions that NOx compounds and derivates might undergo in the environment. Nitrate radicals  $\text{NO}_3$  are the most active oxidants, which are unstable and leads to several reactions. Between the main processes and transformations that this compound can experience in the atmosphere it is possible to find photochemical processes (a chemical reaction initiated by the absorption of energy in the form of light, that allows  $\text{NO}_3$  to become  $\text{NO}_2$  and  $\text{NO}$ ), thermal gas phase processes, heterogeneous reactions that can lead to uncertain compounds and dry deposition.

## Sources of NOx

In figure 2 from EPA it is possible to observe the main sources of NOx.

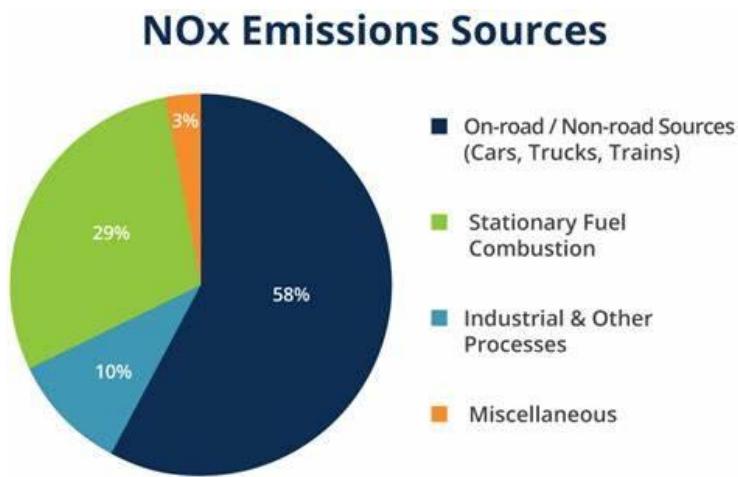


Figure 2 main sources of NOx

Cars and mobile sources (trucks, buses, and motorcycles) contribute about half of the NOx that is emitted in the atmosphere. NOx are created during the combustion of fuel in motors, particularly in gasoline and diesel engines.

Countries with higher transportation, energy, and industry activity, and hence NOx emissions, generally offer enhanced standard of living for citizens. As a result, the total magnitude of NOx emissions can indicate the social status of a country and normalizing it on a per capita basis can then give a baseline for comparison with other countries.

Additionally, other sources of emission include anthropogenic sources as industrial boilers, incinerators, gas turbines. In general, these gases form when fuel is burned at high temperatures. Indeed, burning fossil fuels including coal, oil, and natural gas in power plants results in significant NOx emissions into the atmosphere. The combustion methods utilized to produce power are responsible for these pollutants.

NOx emissions may be also influenced by the usage of fuel-burning equipment for cooking, heating, and other functions in both residential and commercial structures. Examples include gas-powered water heaters, kitchen stoves, and home heating systems.

# Nitrogen Dioxide NO<sub>2</sub> Analysis of Ancona Municipality-Italy Via Remote Sensing - Google Earth Engine (GEE) and Machine Learning Techniques.

## Sentinel-5Ps TROPOMI data.

The sentinel-5 initiative is an integral part of the European Earth Observation Program known as ‘Copernicus’, overseen by the European Commission (EC).

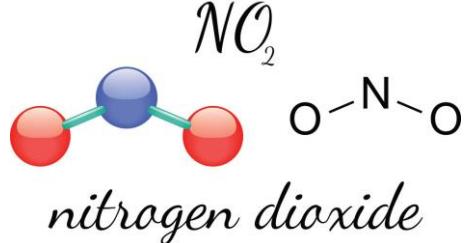
The sentinel-5 precursor mission dedicated to monitoring our atmosphere, consist of one satellite carrying the TROPOspheric Monitoring Instrument (TROPOMI) instrument. The main purpose of this sentinel are to provide daily global observations at a spatial resolution of  $3.5 \times 7$  km of key atmospheric constituents related to air quality, climate change monitoring and ozone layer. Level 2 data provide total columns of ozone, sulphur dioxide, carbon monoxide, **nitrogen dioxide**, vertical profile of ozone and cloud information. This level data are available since the end of 2018. The TROPOMI instrument has four separate spectrometer, which cover spectral range in the ultraviolet and near-infrared ( $0.27\text{--}0.5 \mu\text{m}$  and  $0.675\text{--}0.775 \mu\text{m}$ ) and the shortwave infra-red ( $2.305\text{--}2.385 \mu\text{m}$ ).

## NO<sub>2</sub> (Nitrogen dioxide)

Toxic gas that is formed in high-temperature combustion temperature. Its main sources are internal combustion engines, thermal plants, thermoelectric power plants. This pollutant is a chemical compound with the formula NO<sub>2</sub>, one of several nitrogen oxides. NO<sub>2</sub> is an intermediate in the synthesis of nitric acid, millions of tones of which are produced each year.

Limit value for the protection of human health: 200  $\mu\text{g}/\text{m}^3$

Alarm Threshold: 400  $\mu\text{g}/\text{m}^3$



As shown in the **Fig.9**, NO<sub>2</sub> concentration across different years have changed. The highest concentrations are observed in months of February and January of any year. In January and February 2020 the concentration in Ancona province between 15-17 of January reached around 0.0004 mole/ m<sup>2</sup>, but the average of concentration is around 0.0001mole/m<sup>2</sup>. in January and February 2021 it decreased to around 0.0002 mole/ m<sup>2</sup>, but by in January and February 2022 it still decreased to 0.00016, and in January and February 2023 it is almost the same, and in February and January 2024 in the end of January the concentration is too high and reached to 0.00017 mole/m<sup>2</sup>, but the average of concentration across those two months is around 0.00006 mole/ m<sup>2</sup>. In conclusion comparing in these 5 years we understand that **the concentration of NO<sub>2</sub> from 2020 to 2024 decreased from 0.0001mole/m<sup>2</sup> to 0.00006 mole/m<sup>2</sup>**. In addition, the satellite images shows the same result.

## Google Earth Engine (GEE)

I analysed NO<sub>2</sub> concentration that includes the resource Sentinel-5P TROPOMI-based NO<sub>2</sub> products. So for the analysis I used the Google Earth Engine (GEE) platform. GEE is one of the open source geospatial analysis platform which is possible for users globally or locally analyse changes, visualization, quantity differences and map trends on the earth surface. In this platform JavaScript program was developed to analyse, correct and visualize the data from imaged collections.

## Study Area: Ancona Municipality

A city and seaport in the Marche region of central Italy, with population around 100,000 as 2015. Ancona is the capital of the province of Marche of the region. The city is located 280 km northeast of Rome, on the Adriatic sea. Ancona is one of the main ports on the Adriatic sea, especially for passenger traffic, and is the main economic and demographic centro of region.



Figure 8. geographical location of Ancona Municipality

## 1- Upload the Shapefile of Comune di Ancona.

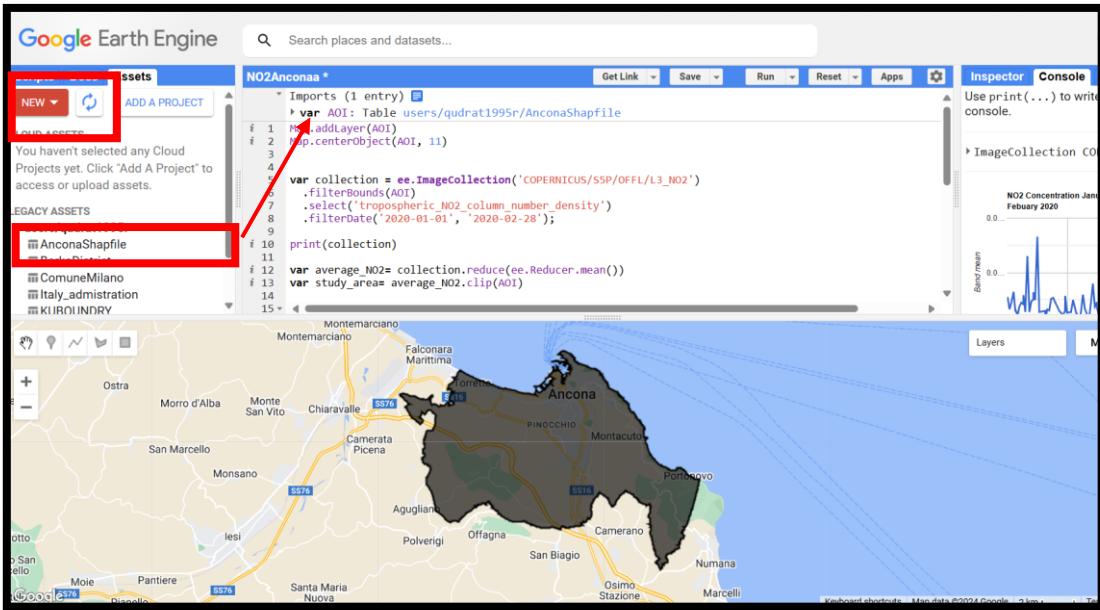


Figure 9. Upload the shapefile of Ancona Municipality

## 2- Collect the Image

Second step is to add the satellite image to google earth engine platform. Here we collect the data from the Copernicus program which is the European Union's Earth observation program.

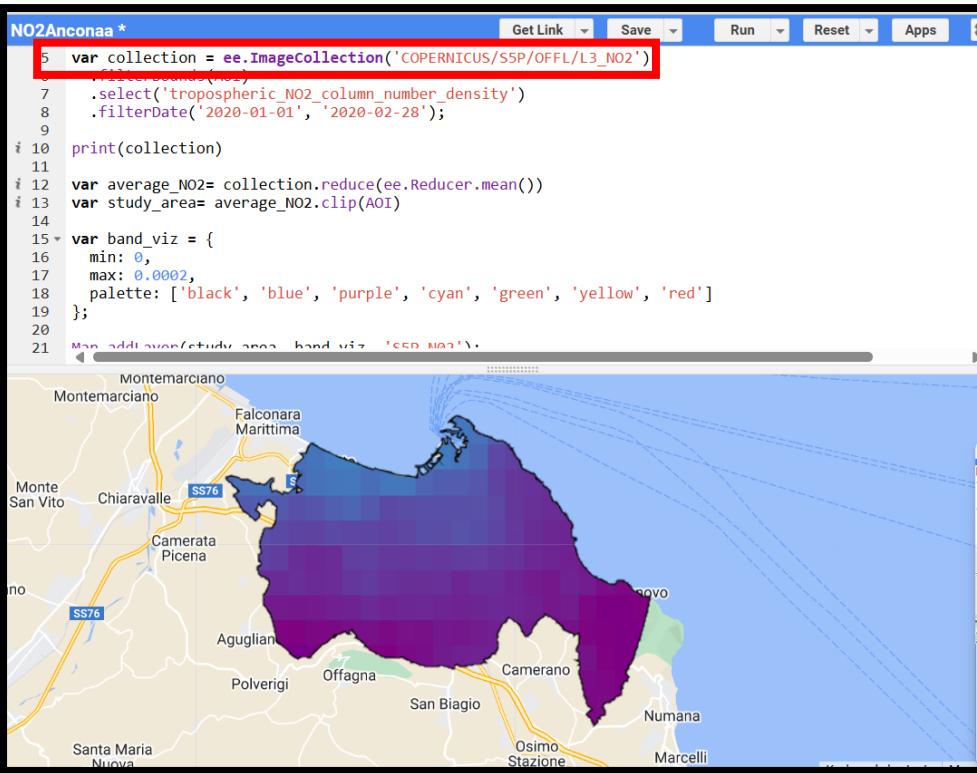


Figure 9. Image collection

### 3- Filter the Collected Images and Set the Date

In this part we filter the image collection and based on our specified area as uploaded the geographical boundary, and set the specific date range and time, so for example here we captured the images from 2020-01-01 to 2020-02-28.

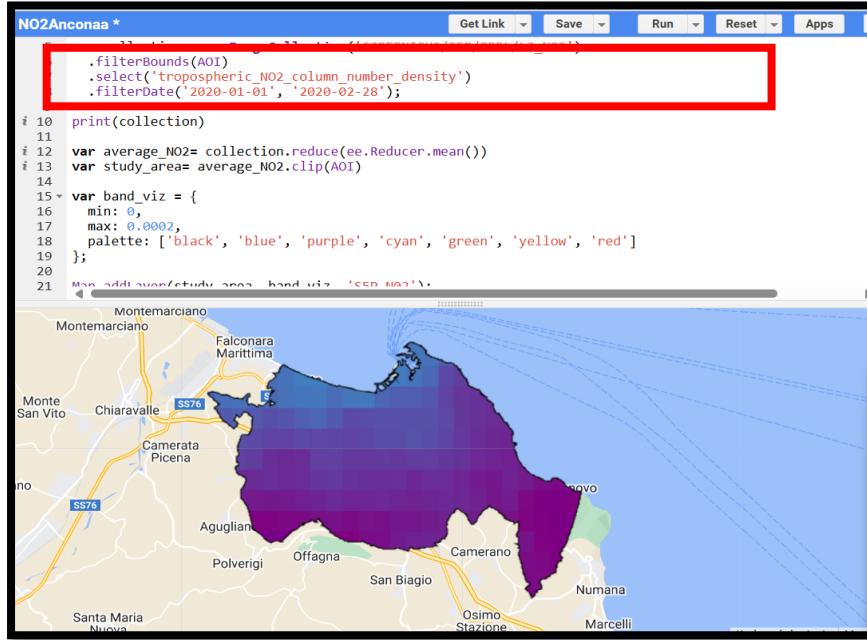


Figure.9. filter the Images and date

### 4- Visualization and Average Concentration.

In this step we compute the mean value of concentration of pixels in each band of the image across all the image collection. And then we used colour palate range from black to read, and other intermediate colour like, blue, cyan, green and yellow. And the data values started from 0 to 0.0002 that will be mapped in this colour palette

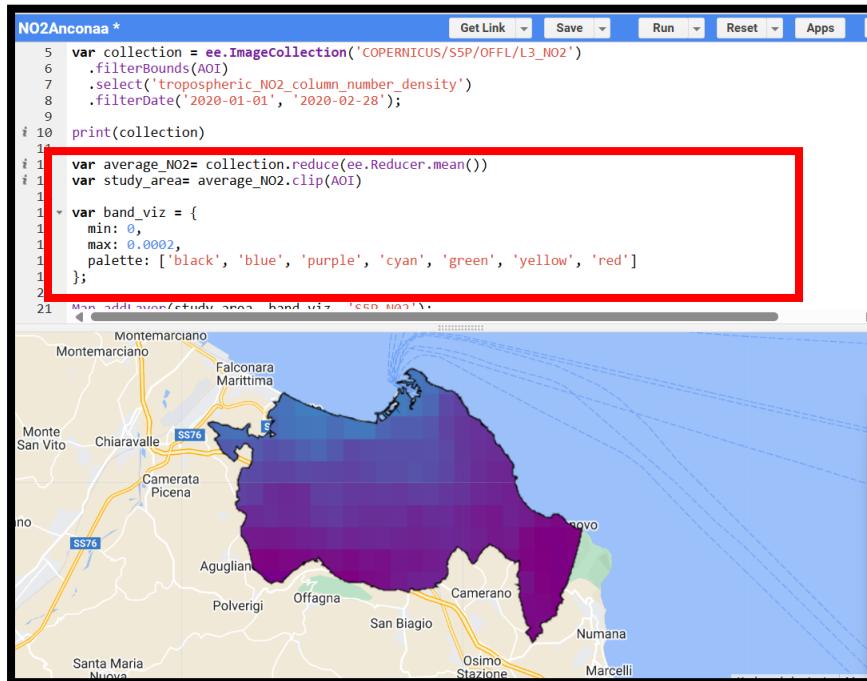


Figure.9. calculation of the average and visualize it

## 5- Time Series and print the results.

We generated a time series chart showing the mean NO<sub>2</sub> concentration over time for the area of Comune di Ancona.

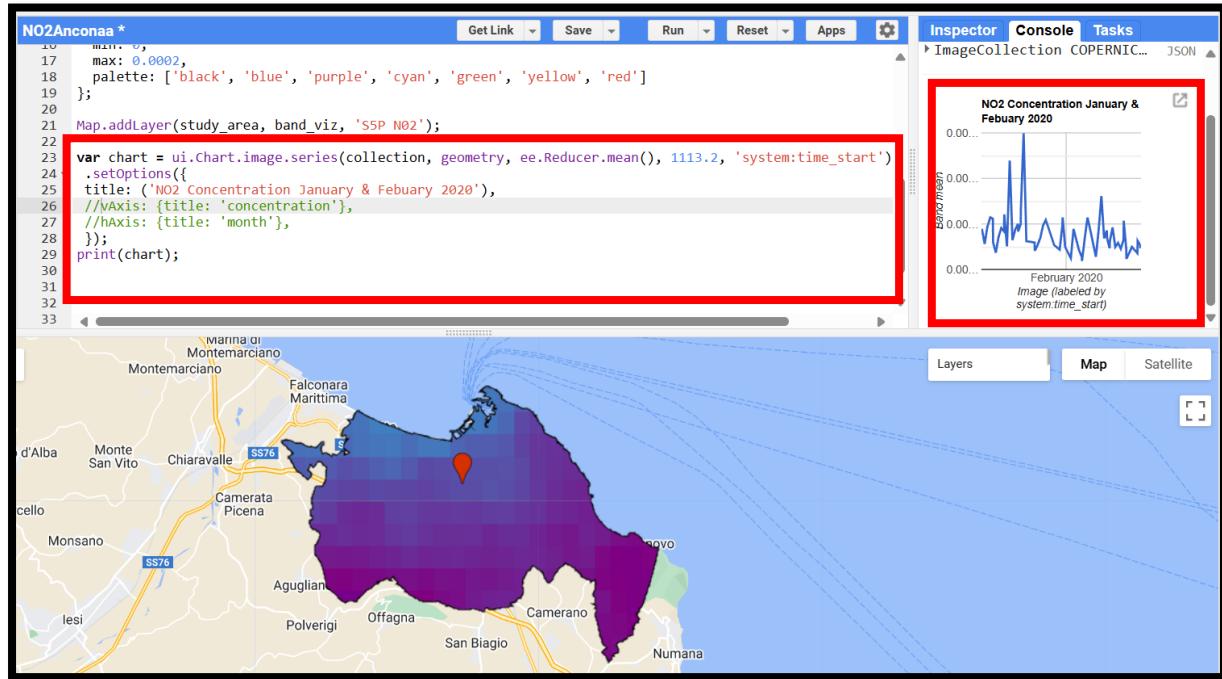


Figure.9. Time series and print the results

## 6- Analyse NO<sub>2</sub> concentration in five different years

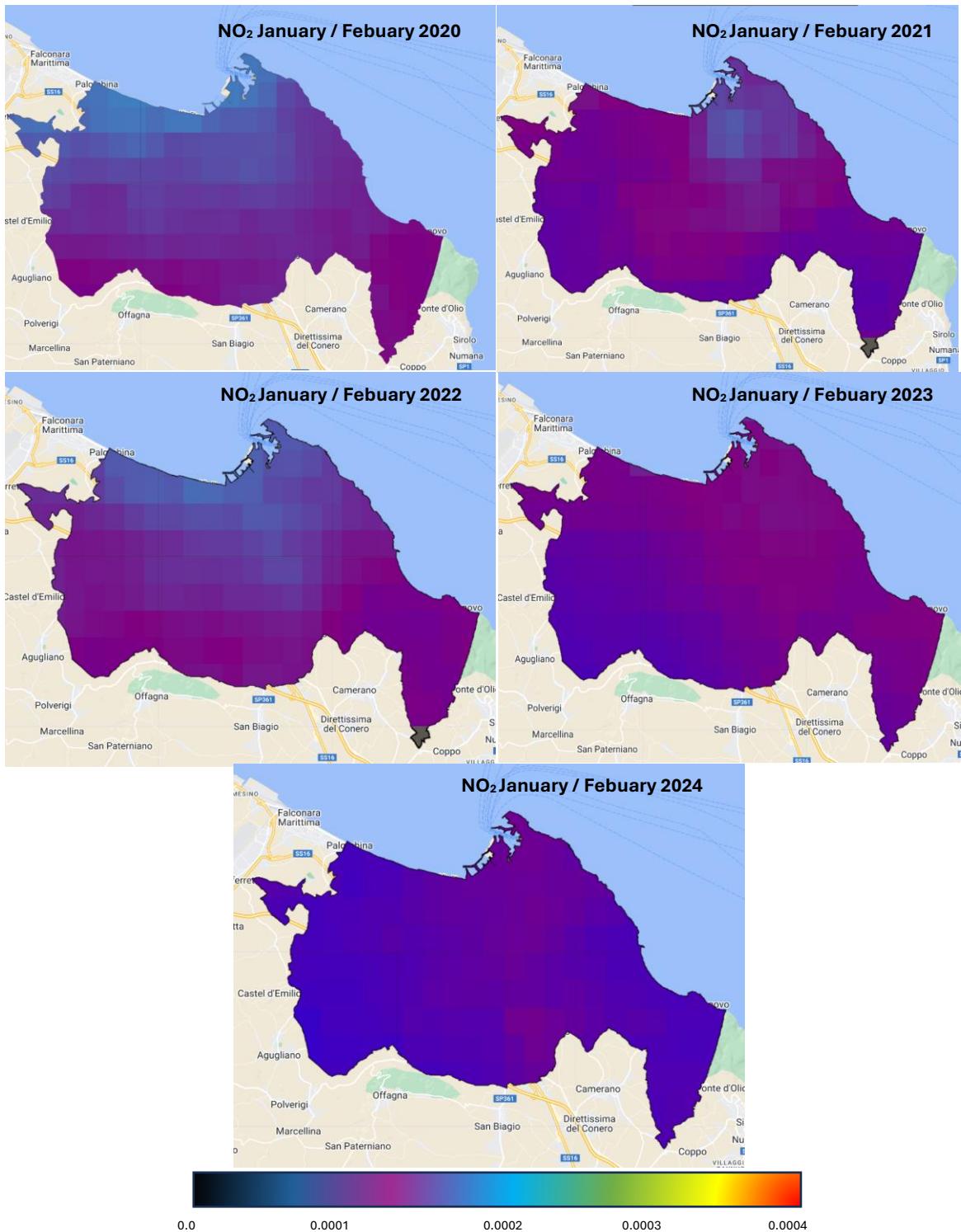


Figure.9. The monthly images of NO<sub>2</sub> column density (mole/ m<sup>2</sup>) over Ancona province, January and February of (2020, 2021, 2022, 2023 and 2024).

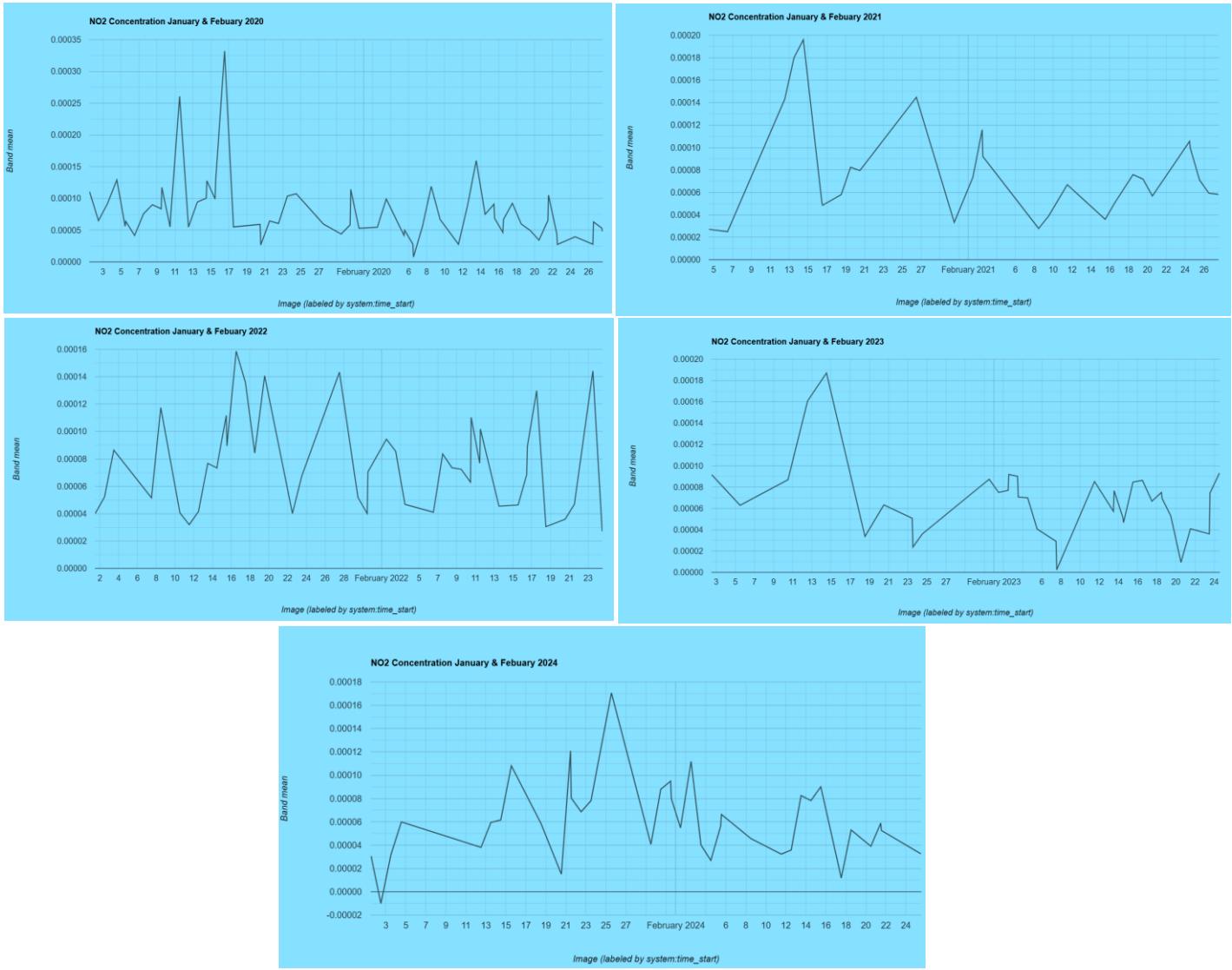


Figure.10. NO<sub>2</sub> concentration time series (mole/ m<sup>2</sup>) over Ancona province, January and February of (2020, 2021, 2022, 2023 and 2024) shows how changed the amount of NO<sub>2</sub> over different time periods.

## NO<sub>2</sub> Concentration, June and July of (2020, 2021, 2022, 2023), Over Ancona Province

In previous Analysis I have just analysed the winter months in cold weather, to be clear how the concentration change during the warm weather, I considered months of June and July in all four years (2020, 2021, 2022 and 2023), after processing As shown in the **Fig.11**, and time series, NO<sub>2</sub> concentration across different years in months June and July are almost the same and didn't changed a lot. So we can see that NO<sub>2</sub> release in the air more January and February than July and June.

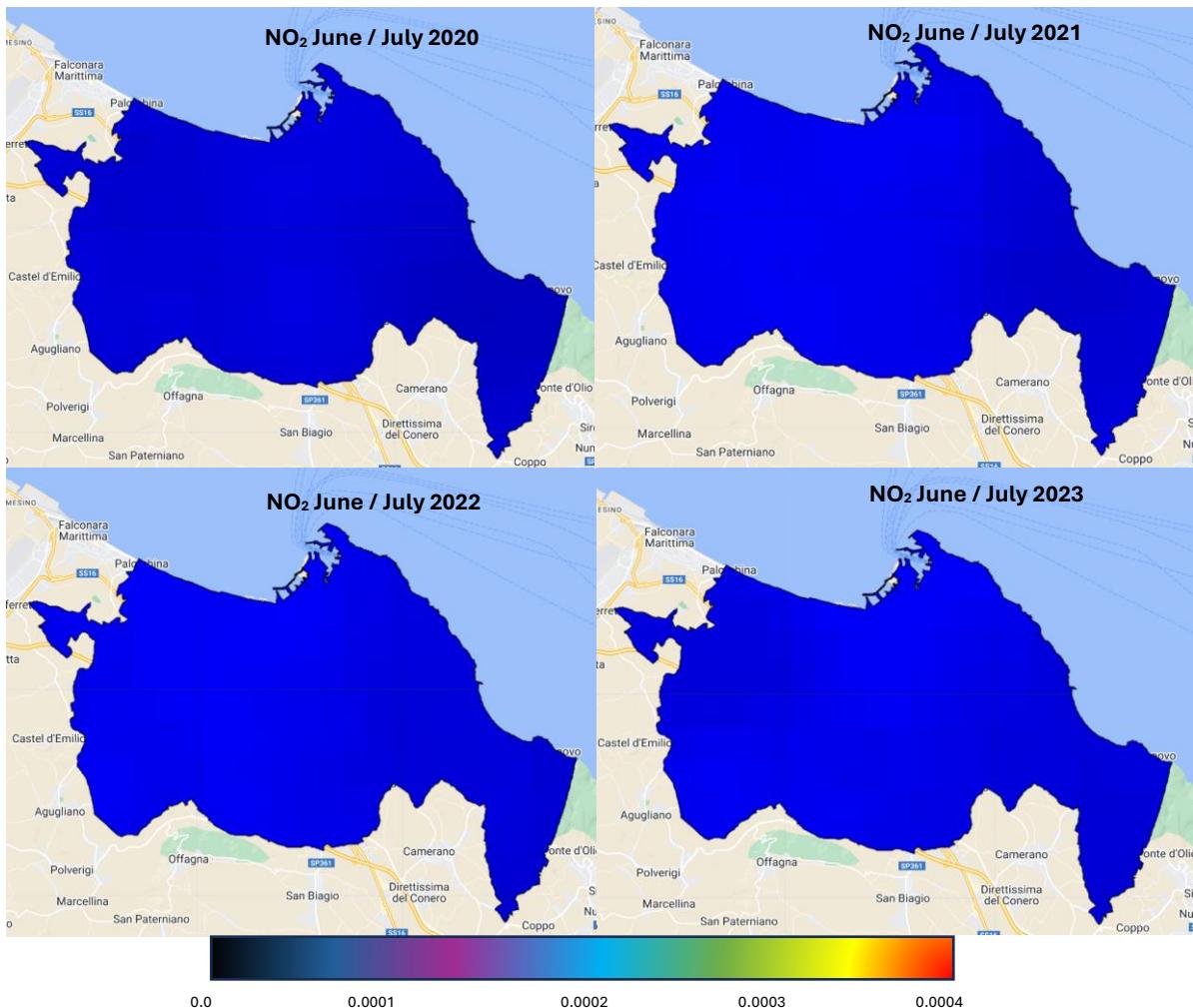


Figure.12. The monthly images of NO<sub>2</sub> column density (mole/ m<sup>2</sup>) over Ancona province, June and July of (2020, 2021, 2022, 2023).

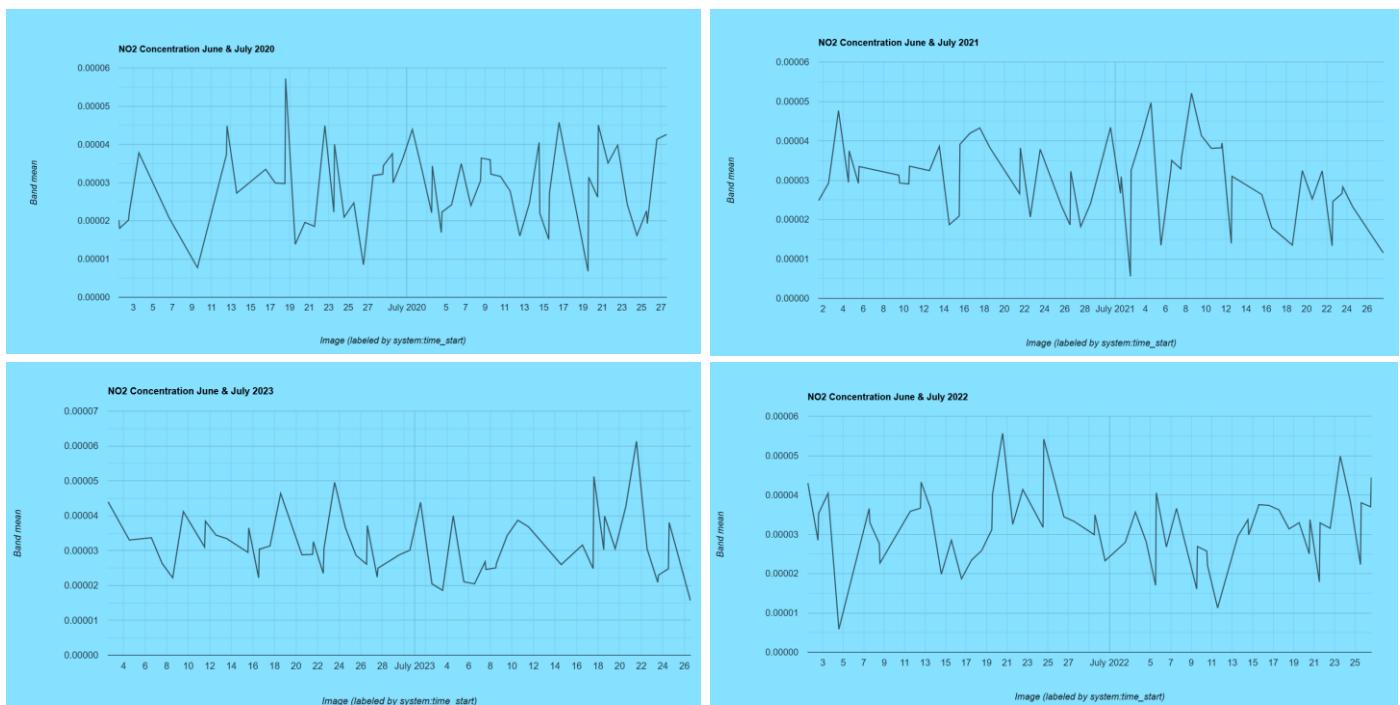


Figure.13. NO<sub>2</sub> concentration time series (mole/ m<sup>2</sup>) over Ancona province, June/ July of (2020, 2021, 2022, 2023)

## Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR)

The removal of NOx from the flue gases produced by the combustion of waste can take place through various techniques, including selective catalytic reduction (SCR) systems or non-catalytic reduction systems (SNCR). **The final goal is to convert NOx into harmless gases N<sub>2</sub>.**

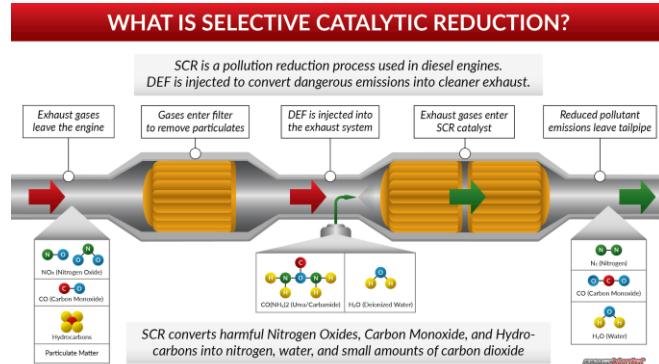


Figure 3 sketch of SCR system

### Selective Non-Catalytic Reduction (SNCR)

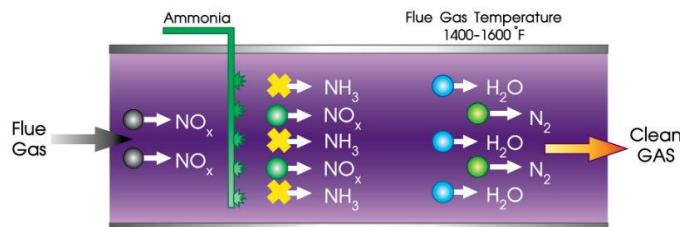


Figure 4 sketch of SNCR

### SNCR

In SNCR de-NOx technology, NH<sub>3</sub> or urea are injected directly into the flue gases at elevated temperatures, creating a reaction zone where NOx and NH<sub>3</sub> or urea can react to form nitrogen (N) and water (H<sub>2</sub>O).

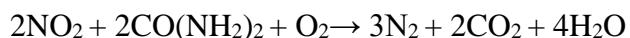
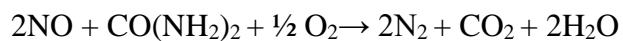
This process takes place at higher temperatures than SCR technology and without the aid of a catalyst, it produces a less effective reduction of NOx and can be influenced by the temperature distribution and the amount of NH<sub>3</sub> or urea used.



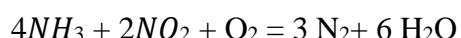
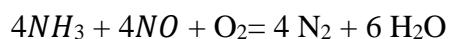
Figure 5 SNCR system, BCE (burners & combustion equipment)

SNCR has been regarded as a practical and affordable method for treating post-combustion flue gases.

More and more combustion sources, such as industrial boilers, electric utility steam generators, thermal incinerators, cement kilns, pulp and paper power boilers, steel industry process units, refinery process units, and municipal solid waste energy recovery facilities, are using SNCR to reduce NOx emissions. In this process NO and N<sub>2</sub>O from flue gases react with amines that are released by the reagent. Depending on the type of reagent, the reactions occur in a combustion chamber under specific oxygen conditions. End products of the reactions include carbon dioxide (CO<sub>2</sub>), nitrogen (N<sub>2</sub>), and water (H<sub>2</sub>O).



*Reaction with urea*



*Reaction with ammonia*

The SNCR reduction efficiency ranges widely, but usually is around 30-50% [1]. The reduction efficiency of the SNCR is mainly influenced by:

- Temperature of reaction
- residence time
- ammonia slip
- normalized stoichiometric ratio

The age, design, load fluctuation, and capacity factor of the combustion unit may have an impact on variables including temperature, residence time, reagent distribution in the flue gas, and CO/O<sub>2</sub> concentrations. These factors can also be impacted by the kind and composition of the fuel. In general, the costs related to the implementation of an SCR are higher if compared to SNCR, as shown in Tab. 2 and 3.

Industrial-Commercial Boilers	>100 MMBtu/hr	NA	NA (\$900–\$2,500/MMBtu/hr or \$9,000–\$25,000/MW)	2006\$
	21–844 MMBtu/hr	NA	See Figure 1.2	2006\$b
	89–285 MMBtu/hr	Wood	NA (\$0.924–\$1.786 million)	2006\$b
	>250 MMBtu/hr	NA	NA (\$0.5–\$1.0 million)	2000\$b
	100–1,000 MMBtu/hr	Coal	NA (\$2,600–\$5,300/MMBtu/hr) [R]	1999\$
	100–1,000 MMBtu/hr	Gas	NA (\$2,100–\$4,200/MMBtu/hr) [R]	1999\$
	100–1,000 MMBtu/hr	Oil	NA (\$2,000–\$4,100/MMBtu/hr) [R]	1999\$
	350 MMBtu/hr	Gas and paper sludge	NA (\$0.775 million) [N] [\$0.50–0.75 million] <sup>e</sup>	1997\$
	155 MMBtu/hr	Medium Density Fiberboard waste and wood waste	NA (\$0.24 million) [N]	1996\$
	900 MMBtu/hr	Wood	NA (\$1.1 million)	1999\$b

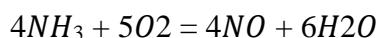
Table 2 Capital costs related to the implementation of a SNCR system in industrial commercial boiler [1]

Industrial-Commercial Boilers	350 MMBtu	Coal	NA (\$10,000–\$15,000/MMBtu/hr)	1999\$	Estimated	Retrofit costs. Authors of referenced document estimated the low end of the range assuming a cost of about \$100/kW for a 100 MW (1000 MMBtu/hr) utility boiler and assuming that economies of scale would be greater for utility boilers than for industrial boilers (so that the cost for a 350 MMBtu/hr industrial boiler would be comparable to or greater than the cost for a 1000 MMBtu/hr utility boiler on a \$/MMBtu basis).
	100–1,000 MMBtu/hr	Coal	NA (\$7,300–\$14,600/MMBtu/hr)	1999\$	Estimated	Retrofit costs. Generally costs available for one boiler with each type of fuel. Authors of referenced document estimated costs for other sizes assuming ratio of small-to-large \$/MMBtu costs are related to ratio of large to small heat inputs raised to the 0.3 power.
	100–1,000 MMBtu/hr	Oil	NA (\$5,550–\$11,100/MMBtu/hr)	1999\$	Estimated	
	100–1,000 MMBtu/hr	Gas	NA (\$4,010–\$8,010/MMBtu/hr)	1999\$	Estimated	
	100 MMBtu/hr	Gas	NA (\$7,500/MMBtu/hr)	1999\$b	Vendor	Cited source in reference [15] is an unpublished letter from a vendor.
	350 MMBtu	Oil, Gas, or Wood	NA (\$4,000–\$6,000/MMBtu/hr)	1999\$	Estimated	
	57 MMBtu/hr	Wood	NA (>\$560,000 and \$9,500/MMBtu/hr)	1999\$c	Actual/Estimate	Costs for a new boiler.
	321 MMBtu/hr	Wood	NA (\$1,980/MMBtu/hr)	2006\$	Likely Estimated	
	650 MMBtu/hr	Gas or refinery fuel gas	NA (\$3,100–\$25,800/MMBtu)	2004\$c	Estimated	Retrofit costs. Equipment costs based on range of costs found in literature search (references were not provided). Installation costs estimated using factors from the Control Cost Manual for thermal and catalytic incinerators.

Table 3 Capital costs related to the implementation of a SCR system in industrial commercial boiler [1]

## Effect of the temperature

The reaction's temperature has a significant impact on how effective the procedure is. In case of SNCR,  $NH_3$  should be reacted with temperatures between 850 and 1000 °C, while urea should be reacted with at temperatures between 800 and 1100 °C. [2] Reduced temperatures cause reduction processes to move excessively slowly, which increases ammonia slip (flue gas concentration of unreacted ammonia). On the other hand, when the top temperature is surpassed, the oxidation of ammonia could take place, which results in the "regeneration" of NOx.



*Oxidation of ammonia and "regeneration" of NOx for temperatures higher than 1000°C*

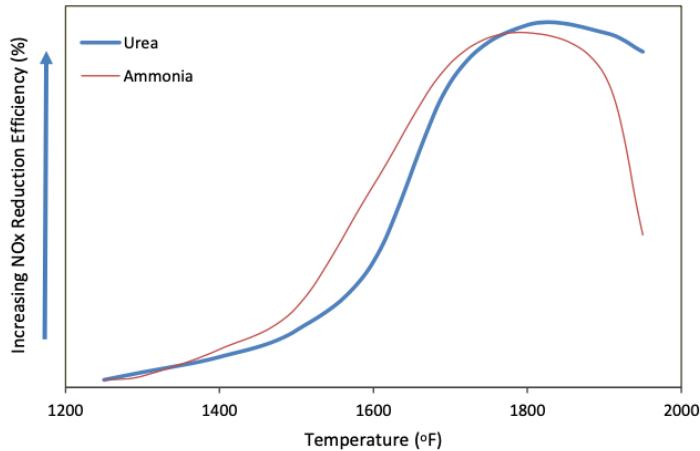


Figure 6 NOx reduction efficiency in function of the temperature

In figure 6 [1], the effect of the increase in temperature is compared with the increase of NOx reduction efficiency. The higher the temperature, the higher the reaction efficiency, until a plateau point, which is around 930°C for ammonia and 980°C for urea. After this temperature, the efficiency drops, mainly in the case of ammonia, where it strongly decreases. Keeping the temperature of reaction in the optimal ranges guarantees the best removal performance of NOx both for ammonia and urea.

In figure 7 (lab-scale experiment performed in a cylindrical stainless steel reactor) [3], NOx reduction efficiency is evaluated in function of the temperature for Normalized Stoichiometric Ratio (NSR) from 1 to 2 for 3 different reagents: NH<sub>3</sub>, urea, and methane. The NOx reduction efficiency for ammonia at an NSR of 1.5, urea at an NSR of 1.5, and methane at an NSR of 2 was 80-85% with T=975°, 66-69% for a T=975°C, and 32% for T=900°C, respectively. Therefore, under these specific conditions, ammonia shows the best reduction efficiency.

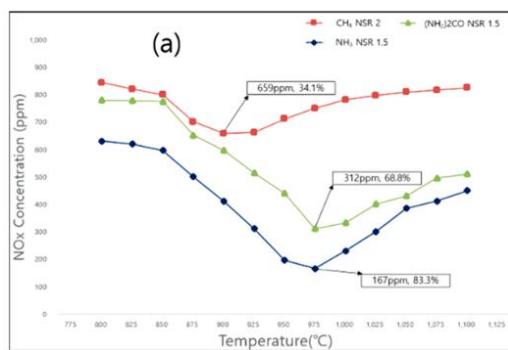


Figure 7 Effects of temperature on the levels of NOx obtained under optimal NO = 900 ppm, NO<sub>2</sub> = 100 ppm, O<sub>2</sub> = 7%, NH<sub>3</sub> and (NH<sub>2</sub>)<sub>2</sub>CO NSR = 1.5, CH<sub>4</sub> NSR = 2 for (NH<sub>2</sub>)<sub>2</sub>CO, NH<sub>3</sub>, and CH<sub>4</sub> as reducing agents.

Although installing urea-based systems is more widespread than ammonia-based technologies, operating data show ammonia reagent results in higher NOx reductions.

Type of source category	Fuel	NO <sub>x</sub> reduction reagent	Average boiler size	Median NO <sub>x</sub> reduction (%)
Electric utility	Coal	Urea	320 MW	25
Co-generation	Primarily wood, some coal, biomass, and tires	Urea	360 MMBtu/hr	50
Pulp & paper (P&P)	Primarily bark and wood waste, supplemented with a variety of other fuels	Urea	410 MMBtu/hr	50
Municipal waste combustion (MWC)	Municipal solid waste (MSW)	Urea	270 MMBtu/hr	37
Refinery CO boilers	Typically refinery fuel gas	Urea	320 MMBtu/hr	60
Miscellaneous combustion units	Primarily wood, MSW, or coal	Ammonia	400 MMBtu/hr	65
Miscellaneous combustion units	Primarily crude oil or gas	Ammonia	110 MMBtu/hr	61

Table 2 Summary of NO<sub>x</sub> reduction efficiencies obtained using SNCR on different types of boilers in the U.S.

The median reductions for ammonia-based SNCR systems in different industry source categories range from 61 to 65 percent, whereas the median reductions for urea-based SNCR systems range from 25 to 60 percent.

Industry and Units	% Reduction	
	Ammonia-Based	Urea-Based
Cement Kilns	12–77	25–90
Chemical Industry	NA <sup>a</sup>	35–80
Circulating Fluidized and Bubbling Bed Boilers	76–80	NA
Coal, Wood and Tire Fired Industrial and IPP/Co-Generations Boilers	NA	20–75
Coal-Fired Boilers	38–83	20–66
Gas- and Oil-Fired Industrial Boilers	30–75	NA
Glass Melting Furnaces	51–70	NA
Steel Products Industry	NA	42.9–90
Municipal Waste Combustors	45–70	16–87
Oil- and Gas-Fired Heaters	45–76	NA
Process Units	NA	40–85
Pulp and Paper Industry	NA	20–62
Refinery Process Units and Industrial Boilers	NA	20–75
Stoker-Fired and Pulverized Coal-Fired Boilers	50–83	NA
Stoker-Fired Wood-Fueled Boilers	40–75	NA
Vapor, Sludge and Hazardous Waste Incinerators	65–91	NA

<sup>a</sup>NA means not available.

Table 3 SNCR NO<sub>x</sub> Reduction efficiency by industry and reagent type

Table 3 demonstrates that many urea-based systems have lower reduction efficiencies while almost all ammonia-based systems have reduction efficiencies more than 40%.

As a consequence of this, it is evident that the reagent type plays a crucial role in the NO<sub>x</sub> reduction efficiency, and the proper choice of the temperature of reaction must be evaluated based on the reagent used. SNCR is typically not employed for gas turbines since it is less effective than other existing control methods when there is a low NO<sub>x</sub> concentration in the flue gas [4]

## Effect of the residence time

The length of time that the reactants are present inside a chemical reactor is known as residence time. The conversion rate of NO<sub>x</sub> removal efficiency increases as the stay of the flue gasses into the reactor lengthens, so the NO<sub>x</sub> removal normally increases as the residence time for mass transfer and chemical reactions increases.

The flue gas velocity determines residence time in the reactor and the boiler design establishes flue gas velocity.

Additionally, a longer residence time is needed to obtain the same NO<sub>x</sub> reduction level as the temperature for the reaction is lowered. The range of residence time in the system is 0.001 to

10 seconds, but usually is 0.2-0.5 seconds for SNCR [4]. Actually, performance is seen to degrade for residence intervals less than 0.2 seconds, and gains in performance are often minor for residence times more than 0.5 seconds.

The size of the boiler gas channel and the volumetric flow rate are also affecting the residence time.

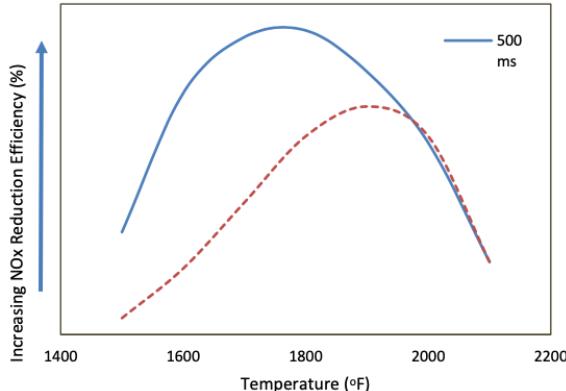
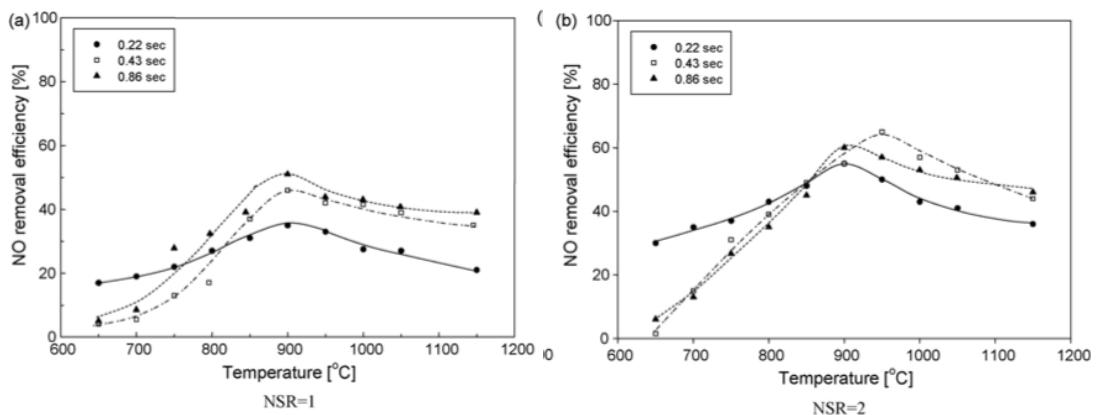


Figure 8 Effect of residence time on NOx reduction

The removal efficiency is always influenced by the temperature, together with the residence time into the reactor. In graph 8 [1] it is shown how the NOx reduction efficiency changes with temperature, with the flue gasses staying in the reactor for 500 milliseconds (blue line). If the time in the reactor decrease, the NOx removal efficiency is lowered (dashed line).

The denitrification efficiency for various retention durations (from laboratory scale reactor) is also shown in figure 9 in relation to reaction temperature and NSR [5]. Increases in retention time result in a drop in NO reduction efficiency at relatively low temperatures, vice versa increases in retention time result in an increase in NO reduction efficiency at high temperatures. This was due to the fact that in the denitrification reaction at low temperatures, the mixing intensity of the fluid due to the flow velocity has a greater impact on the reaction rate than the reaction time does.

The greatest NO removal efficiency was found at about 900 °C when the Normalized Stoichiometric Ratio (NSR) was increased from 1 to 3. It rose from 35 to 62% with a retention period of 0.22 s, from 45 to 66% with 0.43 s, and from 50 to 69% with 0.86 s. In all the cases anyway, it is possible to observe that at 900°C, so when the NOx reduction is maximum, an increase of the retention time of the flue gases into the reactor always leads to a higher removal efficiency.



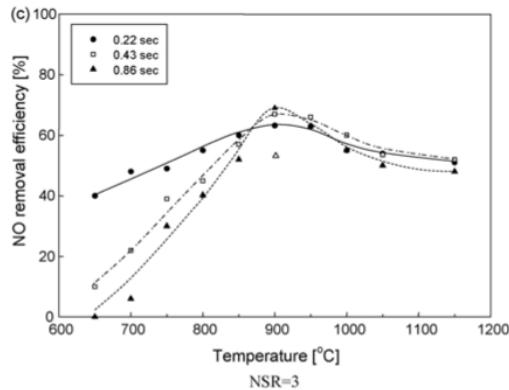


Figure 9 NOx removal efficiency in function of the temperature and retention time in the reactor

## Normalized Stoichiometric Ratio

The quantity of reagent required to accomplish the desired NOx reduction is specified by the normalized stoichiometric ratio (NSR).

Theoretically, two moles of NO can be removed with one mole of urea or two moles of NH<sub>3</sub> and one mole of NO<sub>2</sub> requires one mole of urea and two moles of NH<sub>3</sub>. Since NOx is mainly comprised of NO (approximately 95%), the theoretical NSR for NOx is close to one mole of NH<sub>3</sub> per mole of NOx and 0.5 moles of urea per mole of NOx.

In order to achieve a particular degree of NOx reduction in practice, more reagent must be injected into the boiler than it is necessary in theory.

This is caused by mixing restrictions between the injected reagent and flue gas (rate kinetics), as well as the intricacy of the actual chemical reactions involving NOx and the injected reagent. NSR values typically range from 1.5 to 2.5 moles of NH<sub>3</sub> per mole of NOx in the case of SNCR [1]. The right NSR must be chosen because capital and operating costs are based on the amount of reagent used.

The increment of NOx reduction increase as NSR rises, till a plateau point. In fact, for NSR levels greater than 2-2.5, adding more reagent does not significantly boost the NOx reduction, as demonstrated in Fig. 10 [1].

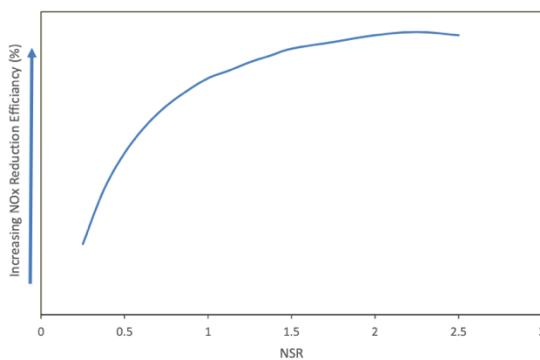


Figure 10 effect of NSR on NOx reduction

The denitrification efficiency for various NSR is shown in Fig. 11 in relation to temperature and initial NO concentration [5]. As the NO removal reaction happens easily when the NH<sub>3</sub> concentration in the reactor is high, the greatest NO removal efficiency was always recorded with rising NSR at a temperature of 900°C. Additionally, the maximum efficiency increased

from 45 to 62% with an NSR of 1, from 60 to 72% with a ratio of 2, and from 72 to 80% with a ratio of 3 when the starting NO concentration was raised from 100 to 500 ppm.

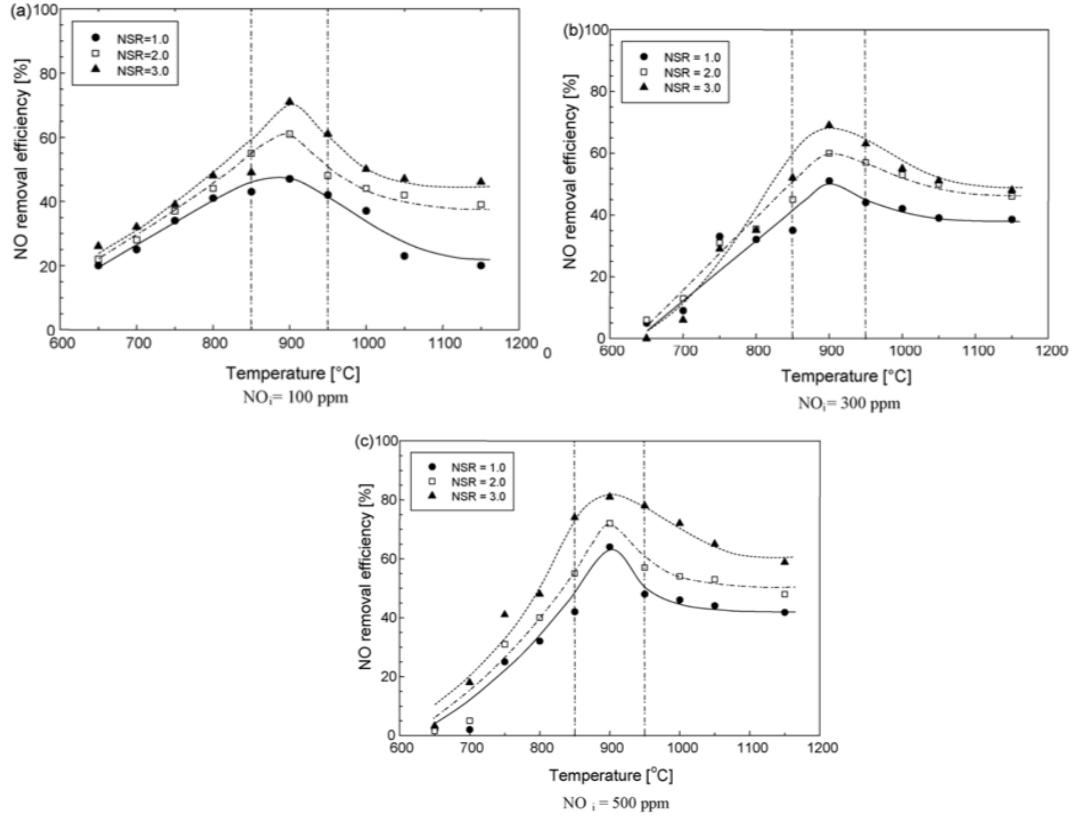


Figure 11 NO removal efficiency in function of the temperature and NSR with NO<sub>i</sub>= 100, 300 and 500 ppm

## Ammonia slip

Ammonia process involves the occurrence of unreacted ammonia in flue gases, which causes ammonium salts to develop on flue gas duct components and increases the concentration of ammonia in combustion byproducts (fly ash and slag). It is a result of the need for an excess of reagent in order to produce an efficient SNCR procedure. This is generally considered undesirable because it means that ammonia is being wasted and can lead to increased ammonia emissions into the environment. For SNCR systems, usually values of NH<sub>3</sub> slip are <10 mg Nm<sup>-3</sup> [2].

The reagent injection rate, an operational setting that can be changed depending on the desired NOx reduction and permitted ammonia slip, determines the NOx reduction and ammonia slip for any given SNCR.

Figure 12 [1] provides an illustration of the NOx reduction efficiency that can be attained for a 120 ppm uncontrolled NOx level and various ammonia slip levels. The NOx reduction seems to increase, when the ammonia slip increases. This is due to the fact that the higher is the quantity of NH<sub>3</sub> present in the reactor, the higher is the reaction capability with NOx, up to a plateau point where the excess of NH<sub>3</sub> is not beneficial anymore for the reaction to occur.

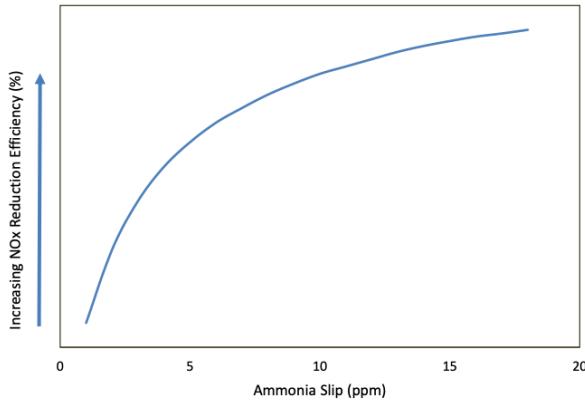


Figure 12 NO<sub>x</sub> reduction for various ammonia slip levels

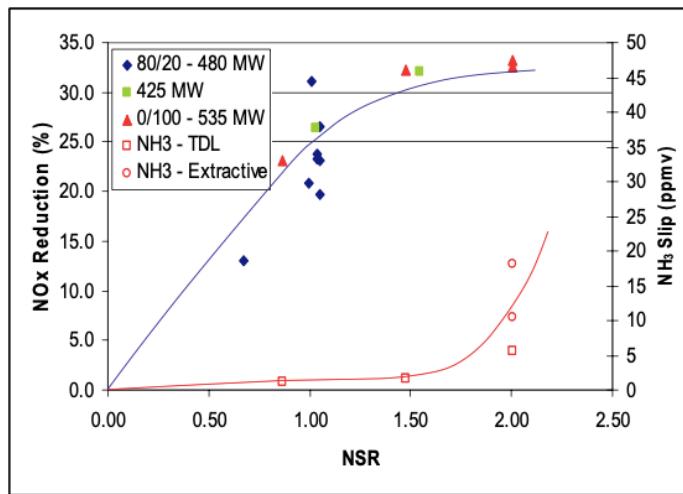


Figure 13 NO<sub>x</sub> reduction in function of NSR and NH<sub>3</sub> slip

Results from SNCR testing conducted while firing the 80/20 fuel blend at a boiler load of nominally 480 MW, show the relationship between the NO<sub>x</sub> reduction, NSR and NH<sub>3</sub> slip [6]. For values of NSR higher than 1.5, there is an increase in the ammonia slip, because there is a higher amount of unreacted ammonia. On the other side, increasing NSR leads to an increase of NO<sub>x</sub> reduction, until an almost constant value (30% of NO<sub>x</sub> reduction) reached for NSR values higher than 1.5.

When NH<sub>3</sub> is fed into the reactor using various techniques (premixing, injection), the NH<sub>3</sub>-slip concentration in relation to temperature and NSR is depicted in Fig. 14 [5]. Low temperatures and a high NSR results in a high NH<sub>3</sub> slip. In comparison to when NH<sub>3</sub> is premixed with the bulk gas, the NH<sub>3</sub>-slip tends to be lower when NH<sub>3</sub> is injected along with air. The injection-induced mixing increases the reaction of NH<sub>3</sub> at the same temperature.

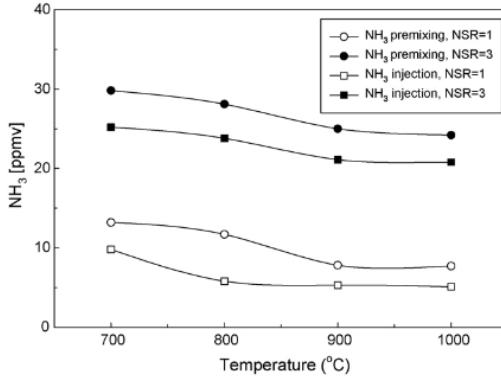


Figure 14 effect of the temperature on the NH<sub>3</sub>-slip with NSR and NH<sub>3</sub> input conditions (NO<sub>i</sub>=300 ppm, retention time=0.43s)



Figure 15 Ammonia storage tanks, Mehldau & Steinfath Umwelttechnik GmbH, Germany

## SCR

The catalytic reactor consists of a series of cells which contain a catalyst, i.e. a substance which accelerates chemical reactions without undergoing permanent alterations. In the case of catalytic reactors, the catalyst present inside the reactor favors the reaction between nitrogen oxides and ammonia (NH<sub>3</sub>), converting them into nitrogen (N<sub>2</sub>) and water (H<sub>2</sub>O).

The catalytic reactor works by heating the flue gases to a temperature high enough for chemical reactions to take place. In this way, the catalyst present in the reactor increases the speed of chemical reactions, improving the efficiency of combustion and reducing harmful emissions. The efficiency of this type of system is usually around 80-95% [1].

The presence of the catalyst lets to provide the reaction at a lower temperature, than in case of SNCR method, is usually in the range of 250/300-400 °C [7].



Figure 16 Metalcor by DCL catalyst

SCR has the highest efficiency of all DeNOx techniques, up to 90% [8]. When running costs and investment costs are combined, the approach is also the most expensive, with catalyst replacement or regeneration playing the largest role. Users must therefore take all necessary steps to limit the mechanisms that contribute to SCR catalyst deactivation.

SCR leads to the need for compressed air and steam, increased self-consumption of power, and management of catalysts (regeneration and/or replacement). As a result, the environmental effect of the energy output with SCR installation increases.

The quantity of NOx eliminated from the flue gas depends on how quickly the reduction reaction proceeds. The primary operating and design elements that influence the NOx removal efficiency of SCR are the same analyzed for SNCR. The following are some of the previously discussed SNCR factors:

- Temperature
- residence time
- Normalized Stoichiometric Ratio
- ammonia slip

## Effect of the temperature

Only a specific range of temperatures may effectively drive the NOx reduction reaction, also considering the SCR system. This system in fact minimizes the temperature range necessary to maximize the NOx reduction reaction by using a catalyst. The ideal temperature in an SCR system relies in fact on the type of catalyst being used in the process as well as the make-up of the flue gas. The working temperatures for the SCR process for the bulk of commercial catalysts (metal oxides) are between 250 and 430°C [1]. Temperatures below the prescribed range slow down the reaction kinetics and NH<sub>3</sub> slips through the boiler.

Meanwhile, at temperatures above the range given the generation of N<sub>2</sub>O increases, the catalyst deactivates, and minimal ammonia slip occurs. Figure 17 [7] depicts the NOx removal effectiveness for a common metal oxide catalyst as a function of temperature.

The graph demonstrates that the rate of NOx elimination rises as temperature rises. The reaction rate and subsequent NOx removal efficiency start to decline when the temperature rises above 400°C.

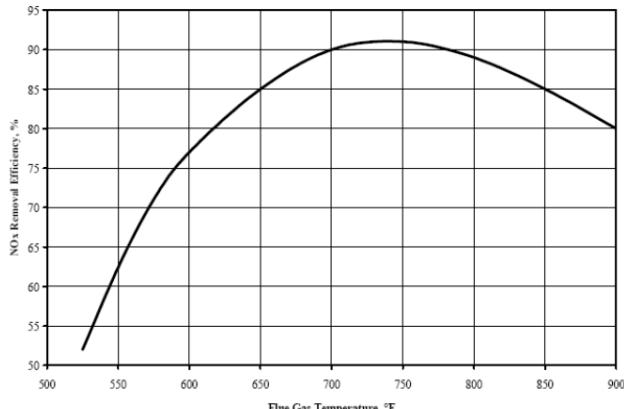


Figure 17 removal versus temperature

Less catalyst volume is required to remove NOx with the same efficiency when flue gas temperature approaches its optimum. Graph 18 displays the variation in necessary catalyst volume as a function of temperature [2]. The necessary catalyst volume decreases by around 40% when flue gas temperature rises from 320°C to the ideal range 370–400°C. The annual cost of operation and maintenance is reduced as a result of using less catalyst.

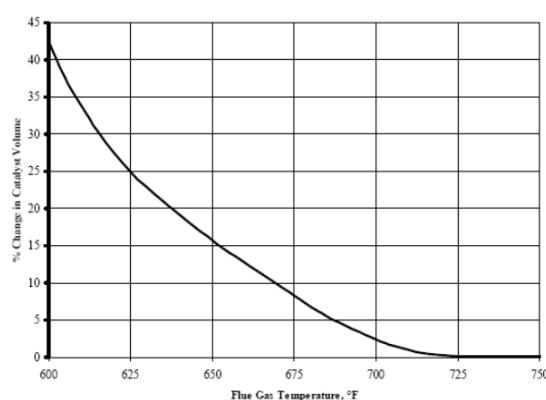


Figure 18 change in catalyst volume vs temperature

The difficult functions of the catalyst formulation and design are the relationships between flue gas temperature, catalyst volume, and NOx elimination. Each catalyst is designed with specific working circumstances in mind while designing its physical and chemical characteristics. The necessary catalyst amount or temperature range for a specific catalyst formulation may even vary from one catalyst manufacturer to another. Therefore, the performance and functioning of the SCR system depend greatly on the choice of the catalyst.

For reactors positioned downstream of the air preheater, re-heating of the flue gas may be necessary. Reheating greatly raises the expense of running an SCR.

Due to their high catalytic activity and sulfur tolerance in actual flue-gas conditions, V2O5-WO3/TiO2-based catalysts are the most widely used commercial catalysts for NH<sub>3</sub>-SCR. These catalysts are only effective between a range of temperatures from 300 to 400°C. As active catalytic materials, vanadium (V) and supports of titanium dioxide (TiO<sub>2</sub>) are typically utilized. W-Ti catalysts only show no activity in the temperature range of 200-400°C and this suggests that vanadium oxides species are the main activity phase of V-W-Ti catalysts. A suitable amount of V doping increases NO conversion and broadens the active temperature range. The SCR activity exhibits a monotonic increase from 0 to 0.02 in V doping molar

quantity. The activity is reduced when the level of vanadium doping is increased further to 0.036. NO conversion for the V<sub>0.02</sub>W<sub>0.04</sub>Ti catalyst was achieved at 90% across a wide temperature range (200-400 °C) with a gas hourly space velocity (GHSV) of 50 000 h<sup>-1</sup>. [9]

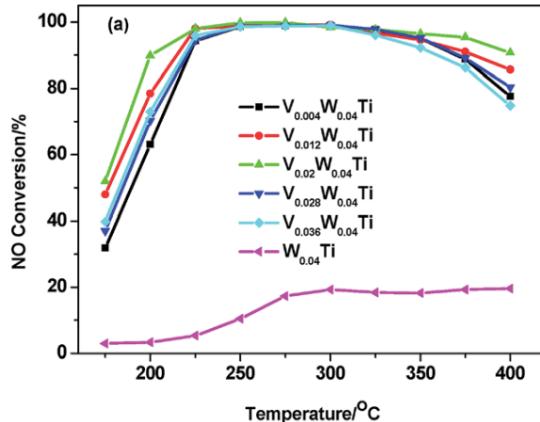


Figure 19 NO conversion in function of the temperature and different V doping molar quantity

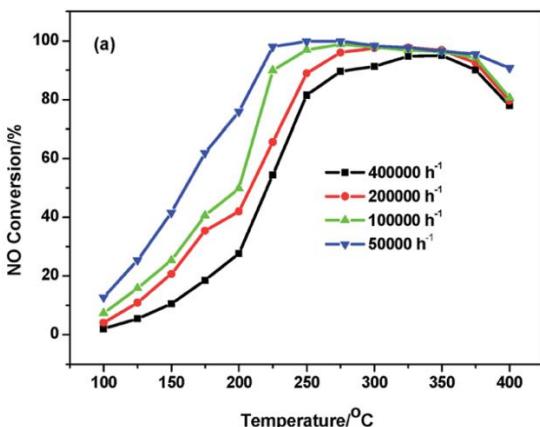


Figure 20 NO conversion in function of the temperature at different GHSV

In standard-SCR conditions, NOx conversion using urea as the reductant is analyzed with a primary residence time of approximately 5.2 s (Figure 21, complete line). At 200 °C, NOx conversion reaches 45%; at 350 °C, it reaches a high of 92%; and at 500 °C, it gradually drops to 82%. For comparison, the same conditions were used to record the NOx conversion with NH<sub>3</sub> as the reductant (dashed line). Urea and gaseous NH<sub>3</sub> produce very similar NOx conversions, indicating that the supplied reductant is used similarly. [10]

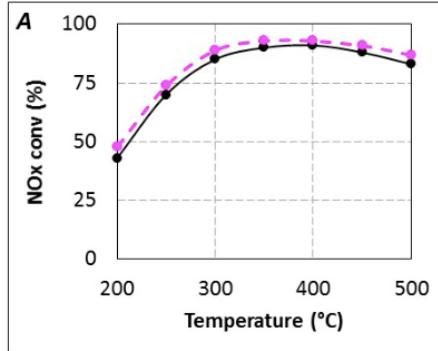


Figure 21 urea-SCR ( $t_r=5.2$  s) under standard condition (400 ppm NO, 400 ppm NH<sub>3</sub>, 8% H<sub>2</sub>O, 10% CO<sub>2</sub>, 10% O<sub>2</sub>) NO<sub>x</sub> conversion versus temperature. Catalyst used is zirconia based acidic oxide

## Effect of the residence time

Reactants are in the reactor during their residence time. Higher NO<sub>x</sub> elimination rates are typically the result of longer residence durations. Also in the case of SCR, the necessary residence time is influenced by temperature. As the temperature gets closer to the ideal temperature for the reduction reaction, the required residence time shortens. The inverse of residence time, space velocity, is a common way to express it. A reactor's space velocity can be calculated experimentally by dividing the measured flue gas flow rate by the surface reactor volume. For a given flue gas flow rate, the NO<sub>x</sub> removal efficiency rises with decreasing space velocity (i.e., increasing catalyst volume).

Referring to Fig. 22, which is a result of a lab test [9], as the GHSV rises from 50 000 to 400 000  $\text{h}^{-1}$ , the NO conversion decreases across the entire temperature range. This is because the catalysts have less time to react with the reactant gas.

NO conversion is anticipated to grow n-times when the space velocity lowers n-times.

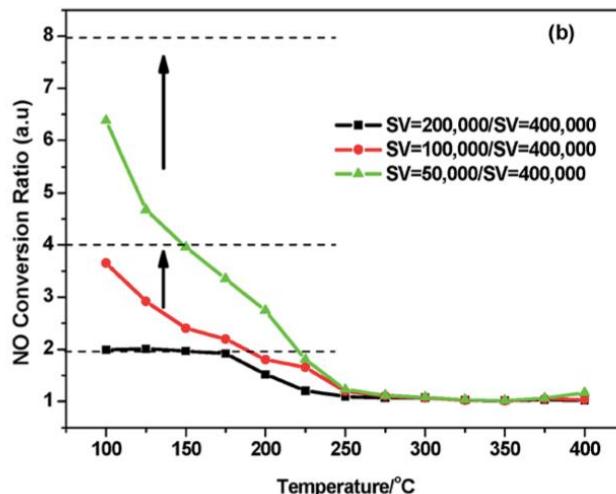


Figure 22 NO conversion ratio in function of the temperature and the space velocity. Catalyst used is V0.02W0.04Ti. Experiment carried out in standard conditions.

Moreover, sufficient decomposition of urea before/on the catalyst for urea-SCR condition is suggested with a urea residence time of 5.2 s. [10]

The residence period, however, appears to be substantially shorter in actual exhaust pipe than 5.2 seconds, which could affect the urea-SCR's overall DeNOx performance. In actual SCR systems, the urea residence time can be less than one second. This period of time might not be long enough to fully extract NH<sub>3</sub> from urea before the SCR catalyst.

Indeed, the behavior of the DeNOx gas is significantly changed when the urea residence time is reduced to 4.0 s.

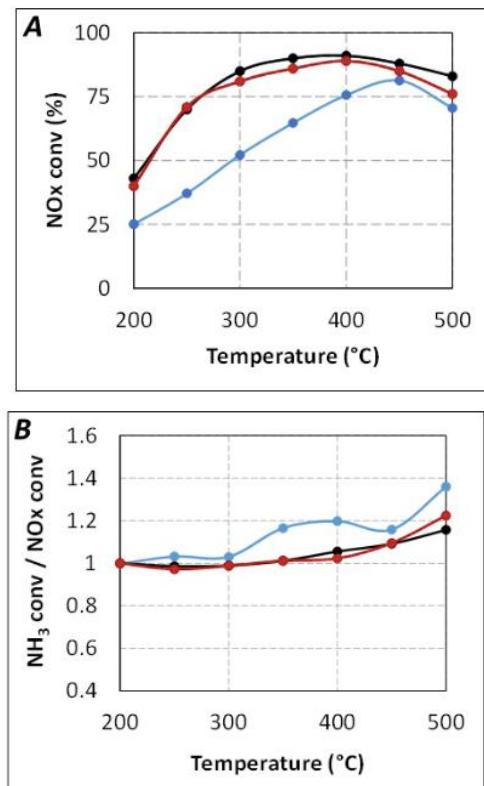


Figure 23 Influence of residence time in standard-SCR (400 ppm NO, 400 ppm NH<sub>3</sub>, 8% H<sub>2</sub>O, 10% CO<sub>2</sub>, 10% O<sub>2</sub> in A) NOx conversion B) NH<sub>3</sub> conversion/NOx conversion ratio. Blue line refers to tr=4s, red line tr=5.2s and black line tr=6.1s. Catalyst used is zirconia based acidic oxide.

With a residence time of 4.0 s (blue line, Fig. 23A), NOx conversion ranges from 25 to 75% in the temperature range of 200–400°C. By increasing the residence time to 6.1 s, the NOx conversion raises to 40–90% in the same temperature range (black line).

Figure 23B shows how temperature and residence time affect the NH<sub>3</sub> conversion/NOx conversion ratio. With a residence time equal to 5.2 s/6.1 s (corresponding to fast and/or conventional SCR stoichiometry), this ratio, as expected, remains extremely near to 1 until 400 °C. However, at residence time of 4.0 s, considerable variances are seen, particularly in the 350–400 °C temperature range. In these temperature ranges, the ratio of (NH<sub>3</sub> conversion/NOx conversion) is 1.16 and 1.20.

All these results highlight that the use of ammonia with short residence time directly impacts the SCR reactions and the evolution of the NH<sub>3</sub>/NOx ratio and the conversion efficiency of NOx (depending also on the temperature). More in particular, the lower is the residence time, the higher is the NSR needed to achieve the same removal efficiency (more reagent is needed for a shorter contact with the flue gases).

## Normalized Stoichiometric Ratio

The amount of reagent required to achieve the desired NOx reduction is determined by the stoichiometric ratio factor (the moles of reagent injected per mole of NOx eliminated). It is theoretically possible to remove one mole of NO with one mole of ammonia and one mole of NO<sub>2</sub> with two moles of ammonia. The theoretical stoichiometric ratio for NOx is also in the case of SCR close to 1.05 moles of ammonia per mole of NOx because NO is the main component of NOx (around 95% by volume).

As a result, 1.05 moles of ammonia are commonly used in SCR systems for every mole of NOx. Up to an almost 85% decrease in NOx, this assumption of a nearly 1:1 linear relationship between the quantity of reagent and the NOx eliminated is valid. Above 85%, the removal efficiency starts to plateau, and due to reaction rate constraints, more ammonia is needed to remove extra NOx than is theoretically necessary. The NSR for SCR ranges from 0.8 to 1 usually [1]. The amount of reagent used determines capital and operating costs, hence the stoichiometric ratio factor is a crucial design component that the SCR designer must account for.

Under standard condition (400 ppm NO, 400 ppm NH<sub>3</sub>, 8% H<sub>2</sub>O, 10% CO<sub>2</sub>, 10% O<sub>2</sub>), very similar NH<sub>3</sub>/NOx conversion ratios can be obtained with urea and gaseous NH<sub>3</sub> [10].

Regardless of the reductant used, the NH<sub>3</sub> conversion/NOx conversion ratios are extremely close to 1 until 400 °C (under the assumption of the same residence time into the reactor), demonstrating that the DeNOx process adheres to the fast and/or conventional SCR stoichiometry. The kinetics of the reaction has an impact on the conversion ratio as well. Because the reductant has less time to complete the reaction and may experience ammonia slip as a result, reducing the retention time into the reactor, in particular, causes the ratio to slightly increase (when compared to a longer time). (Table 3)

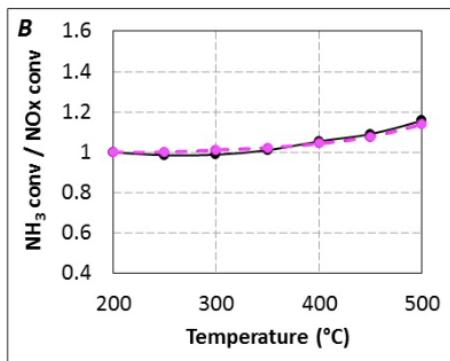


Figure 24 NH<sub>3</sub> conversion/ NOx conversion ratio in function of the temperature. Standard condition (400ppm NO, 400 ppm NH<sub>3</sub>, 8%H<sub>2</sub>O, 10% CO<sub>2</sub>, 10% O<sub>2</sub>) were set. Catalyst used is zirconia based acidic oxide.

Temperature	Reducant		
	NH <sub>3</sub>	Urea, $t_R = 5.2 \text{ s}/6.2 \text{ s}$	Urea, $t_R = 4.0 \text{ s}$
200 °C	1.00	1.00	1.00
250 °C	1.00	0.99	1.03
300 °C	1.01	0.99	1.03
350 °C	1.02	1.01	1.16
400 °C	1.04	1.05	1.20
450 °C	1.08	1.09	1.16
500 °C	1.14	1.16	1.36

Figure 3 NH<sub>3</sub> conversion/NOx conversion ratio depending on the temperature and the reductant from lab testing. Standard condition (400ppm NO, 400 ppm NH<sub>3</sub>, 8%H<sub>2</sub>O, 10% CO<sub>2</sub>, 10% O<sub>2</sub>) were set. Catalyst used is zirconia based acidic oxide.

## Ammonia slip

The term "ammonia slip" describes extra reagent that enters the reactor. The impact of ammonia in the flue gas on human health, the visibility of the stack effluent, the salability of the fly ash, and the generation of ammonium sulfates are the same for SNCR. SCR performance is restricted by regulatory thresholds or design criteria that set upper bounds on permissible ammonia slip (<5 mg Nm<sup>3</sup> [1]).

As the SCR system runs, ammonia slip does not remain constant but instead rises as the catalyst activity falls. Low ammonia slip levels, or less than 2 ppm, are maintained by properly constructed SCR systems that function close to the theoretical stoichiometry and provide enough catalyst volume. Although ammonia slip values are normally between 2 and 10 ppm in operating permits, in reality slip levels are lower and only approach limit levels when the catalyst is getting close to the end of its service life.

The NSR ratio causes an increase in ammonia slip. NH<sub>3</sub> slip is in fact influenced by two main parameters, which are the NH<sub>3</sub>/NO<sub>x</sub> ratio and the temperature of reaction. [11]

## NH<sub>3</sub>/NO<sub>x</sub> ratio

Figure 25, from lab testing, depicts the impact of the NH<sub>3</sub>/NO<sub>x</sub> ratio on ammonia slip at 300 °C for the catalyst. NH<sub>3</sub> was introduced into the catalyst carrier after 50 seconds had passed. The ammonia saturation storage level (which is the maximum amount of ammonia that can be dissolved in a given volume of a liquid) increased as soon as NH<sub>3</sub> was added. With rising NH<sub>3</sub>/NO<sub>x</sub> ratio, the curve for ammonia saturation storage level showed a strong gradient. NH<sub>3</sub> slip happens at the outflow as the ammonia saturation storage level rose up to a threshold. This ammonia slip threshold changed with NH<sub>3</sub>/NO<sub>x</sub> ratio. The ammonia slip thresholds were 79%, 75%, and 76%, with an average of 76.7%, for NH<sub>3</sub>/NO<sub>x</sub> ratio values of 0.7, 1.0, and 1.4. The time threshold of the ammonia slip, denoted by  $t_s$ , is used to define the moment the ammonia slip threshold occurs. This time threshold moves forward as the ratio of NH<sub>3</sub>/NO<sub>x</sub> increases. So, for a specific NH<sub>3</sub>/NO<sub>x</sub> ratio,  $t_s$  might be estimated based on the ammonia saturation storage level. The higher is NSR, the higher is the ammonia slip.

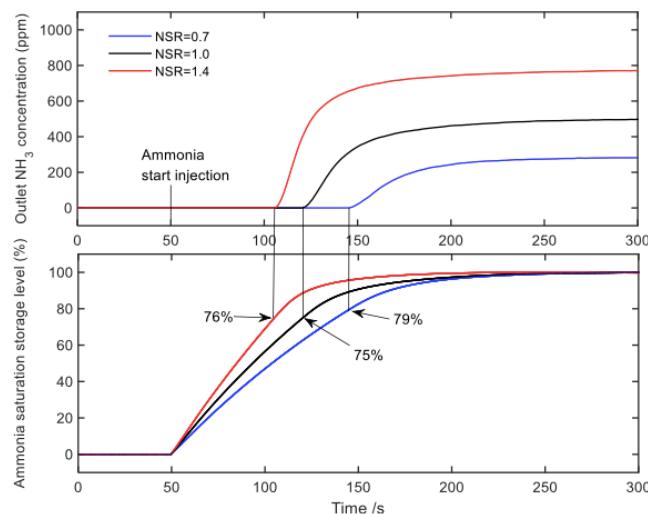


Figure 25 effects of NH<sub>3</sub>/NO<sub>x</sub> ratio on ammonia slip under standard conditions. Catalyst used is V2O<sub>5</sub>WO<sub>3</sub>TiO<sub>2</sub>

## Catalyst temperature

To show the effect of the temperature on ammonia slip, the NH<sub>3</sub>/NO<sub>x</sub> ratio was set to 1.0, space velocity was 30,000 h<sup>-1</sup>, and the NO gas at the carrier inlet had a concentration of 750 ppm. The temperature of the catalyst carrier was changed to 250°C, 300°C, or 350°C. Fig.26 demonstrates that a higher catalyst temperature promotes the NH<sub>3</sub>-NO<sub>x</sub> reaction and greater NO<sub>x</sub> conversion efficiency because NH<sub>3</sub> slip occurred at  $t_s=120$  s and decreased with increasing catalyst temperature. Additionally, the NH<sub>3</sub> slip threshold time  $t_s$  was mostly unaffected by the catalyst temperature.

The effects of the catalyst temperature on NH<sub>3</sub> slip were less significant than those of the NH<sub>3</sub>/NO<sub>x</sub> ratio.

The ammonia saturation storage level in at different temperatures showed readings of 77.2%, 75%, and 75.2%, with an average of 75.8%.

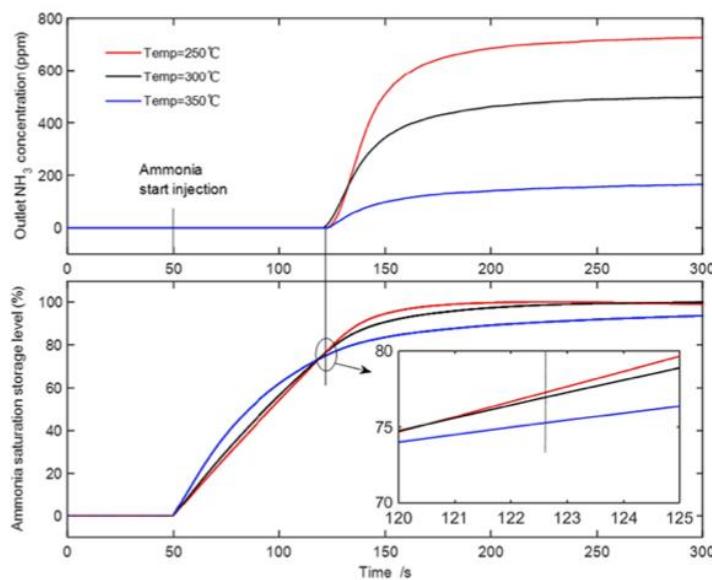


Figure 26 Effects of catalyst temperature on ammonia slip under standard conditions. Catalyst used is V2O<sub>5</sub>WO<sub>3</sub>TiO<sub>2</sub>

In conclusion, the results indicated that the catalyst temperature and the NH<sub>3</sub>/NO<sub>x</sub> ratio affected NH<sub>3</sub> slip, with the NH<sub>3</sub>/NO<sub>x</sub> ratio having a bigger impact. Furthermore, despite changes in catalyst temperature, the NH<sub>3</sub> slip threshold time  $t_s$  remained constant. The ammonia saturation storage level corresponding to the NH<sub>3</sub> slip threshold was roughly 75–79% when the catalyst temperature was between 250 and 350 °C and the NH<sub>3</sub>/NO<sub>x</sub> ratio was between 0.7 and 1.4. The results also showed that there was no NH<sub>3</sub> slip within this range for ammonia saturation storage level, and that the NO<sub>x</sub> conversion efficiency was highest between 68.2 and 73%. Therefore, by optimizing the SCR system to maintain the ammonia saturation storage level in the range 68.2–73%, it is possible to obtain improved NO<sub>x</sub> conversion efficiency along with no NH<sub>3</sub> slip.

Finally, the impact of the NH<sub>3</sub>/NO<sub>x</sub> ratio on NO conversion efficiency and NH<sub>3</sub> slip is shown in Figure 27. When the NH<sub>3</sub>/NO<sub>x</sub> ratio falls from 1.4 to 0.7, the output ammonia concentration rapidly declines from 790 to 310 ppm. It is evident that as the NH<sub>3</sub>/NO<sub>x</sub> ratio falls, the amount of NH<sub>3</sub> slip also reduces. However, as the NH<sub>3</sub>/NO<sub>x</sub> ratio falls, the efficiency of the NO

conversion somewhat declines. Therefore, a lower NH<sub>3</sub>/NO<sub>x</sub> ratio aids in reducing NH<sub>3</sub> slip, but at the expense of less effective NO conversion.

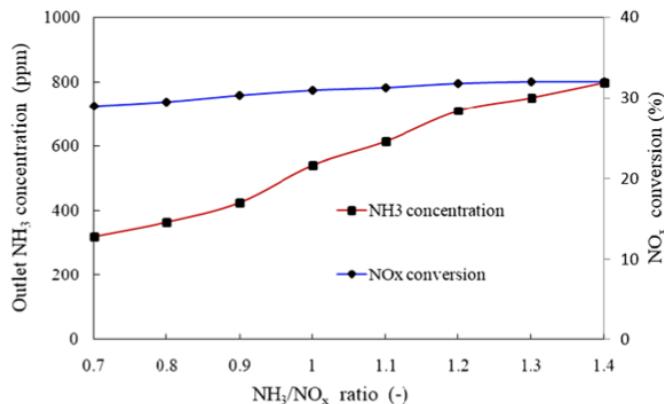


Figure 27 effect of the NH<sub>3</sub>/NO<sub>x</sub> ratio on NO conversion efficiency and ammonia slip under standard conditions. Catalyst used is V205WO<sub>3</sub>TiO<sub>2</sub>

Between the SCR and the air heater, facilities commonly place ammonia slip monitors that can measure at one or more sites.

These devices keep an eye on ammonia slip and aid in keeping slip levels at or below 2-3 parts per million by volume (ppmv). One ammonia slip monitoring device is projected to have a capital cost of \$40,000 for a single measurement point and up to \$70,000 for three measurement points [12].

In the following table, a summary of the main parameters analyzed is proposed:

	SCR	SNCR
<b>Temperature</b>	250-430°C for metal oxyde catalysts [U.S. Environmental Protection Agency]	850-1000°C (NH <sub>3</sub> ), 800-1100°C (urea) [EPRI (Electric Power Research Institute). SNCR Guidelines]
<b>NO<sub>x</sub> reduction efficiency</b>	80-95% [EPA]	30-50% [EPA]
<b>NSR (NH<sub>3</sub>/NO<sub>x</sub>)</b>	0.8-1 [EPA]	1.5-2.5 [EPA]
<b>residence time</b>	from fractions of a second to a few seconds (strongly inflenced by the type of catalyst) [EPA]	0.2-0.5 s [Institute of Clean Air Companies (ICAC)]
<b>NH<sub>3</sub> slip</b>	<5 mg Nm <sup>-3</sup> [Cichanowicz, J., L. Muzio, and M. Hein.]	<10 mg Nm <sup>-3</sup> [EPRI (Electric Power Research Institute)]

## SCR application to a waste incinerator

An example of possible industrial implementation of an SCR system to a hazardous waste incinerator is provided by the article “*NOx reduction in waste incinerators by selective catalytic reduction (SCR) instead of selective non catalytic reduction (SNCR) compared from a life cycle perspective: a case study*” (J.V. Caneghem, J.De Greef, C. Block, C. Vandecasteele). In order to reduce NOx emissions from waste incinerators, the document investigates the possibility that selective catalytic reduction (with TiO<sub>2</sub>/V<sub>2</sub>O<sub>5</sub>/WO<sub>3</sub> catalyst) could take the place of selective non-catalytic reduction (SNCR) techniques. The study notes that SNCR is now the favored technology because of its cost-effectiveness and that the current limitations for NOx emissions in waste incinerators are 200mg/Nm<sup>3</sup>. However, the industry would require a shift in NOx reduction techniques if these emission limitations were reduced to 100mg/Nm<sup>3</sup>. From this comes the need to implement a SCR system.

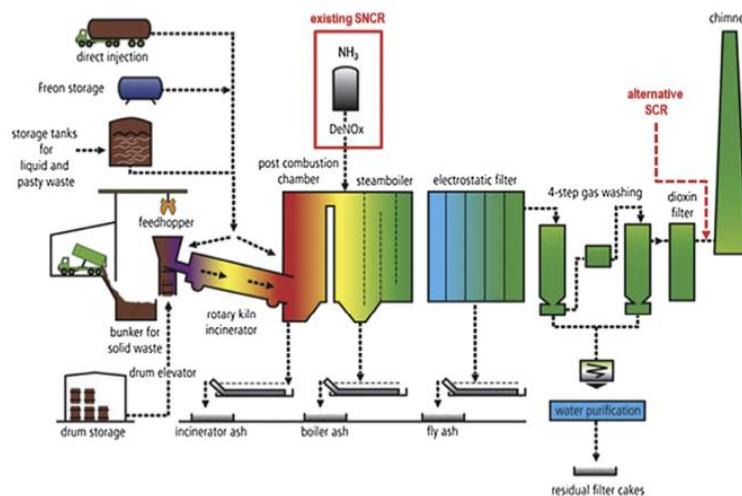


Figure 28 Schematic representation of the hazardous waste incinerator under study.

The report highlights that from a competitive and sustainability point of view, a full evaluation of the lifetime of treatment systems and the likelihood of overcoming practical limits must be done. Emission inventories and impacts are calculated and normalization factors are used in the analysis.

Several modifications happened when SCR was used in place of SNCR.

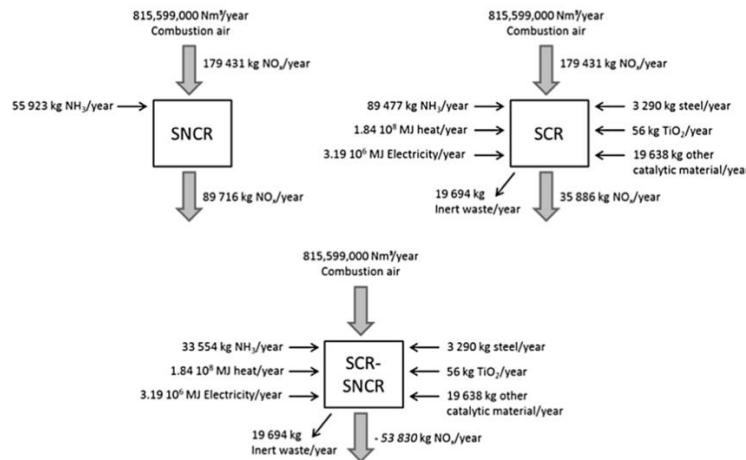


Figure 29 Schematic representation of the considered mass flows in the SCR and SNCR alternative and the difference between these two alternatives.

First off, compared to SNCR, SCR considerably boosted the effectiveness of NOx reduction, reducing NOx emissions by up to 90%.

Second, there were variations in how the various strategies affected the environment. Because of lower NOx emissions, replacing SNCR with SCR lowered the incinerator's direct environmental impact in terms of acidification, eutrophication, and photo-oxidant production. It's crucial to remember, though, that SCR also brought about greater indirect effects, particularly in terms of resource consumption and pollutant emissions connected to the creation and maintenance of the catalyst unit.

The alterations were also influenced by the choice of energy source used to reheat the flue gas. If fuel oil was used, the indirect effects of SCR were greater in several impact categories than the direct effects avoided by decreased NOx emissions. But when natural gas was employed, all three impact categories (acidification, eutrophication, and photo-oxidant production) resulted in a net environmental gain.

Overall, the switch from SNCR to SCR increased the incinerator's overall environmental impact, especially in the area of impact related to global warming.

## **SWOT Analysis**

### **Strengths of SCR systems and GEE :**

- GEE is based on well-established statistical theory, and very high computational power for large data, ever covering the who world.
- GEE let us to access to a vas repository of satellite imaginary and geospatial database.
- In GEE there is no need to download the data from other sources, we can access just by a few Jawa script formula.
- It is a well-developed and consolidated technology. It is widely used in automative sector (mainly in diesel powered vehicles [11]), in power plants (e.g. in cyclone boilers [6], in renewable energy, waste incinerators [13] and also in rail transportation systems and marine industry).
- SCR systems have a higher NOx reduction efficiency compared to SNCR, achieving up to 80% reduction in NOx emissions, compared to 30-50% of SNCR [1].
- SCR system requires a lower temperature range compared to SNCR (230°C for TiO<sub>2</sub>/V<sub>2</sub>O<sub>5</sub>/WO<sub>3</sub>, compared to 850-1000°C (NH<sub>3</sub>), 800-1100°C (urea) [2].
- SCR systems can have lower ammonia slip compared to SNCR systems, thereby minimizing the release of ammonia into the environment, ensuring adherence to environmental regulations. Properly constructed SCR systems can maintain low ammonia slip levels, typically below 2 ppm. [1]

### **Weaknesses of SCR system and GEE:**

- Learning GEE and required knowledge of JavaScript and geospatial analysis, which might be difficult for beginners.
- GEE depends on internet, it is a cloud based platform which require a stable internet.
- GEE process the large date with long time. So it depends for what purpose we use it.
- SCR systems can require reheating of the combustion gas before it enters the catalyst unit, which consumes additional energy from natural gas or fuel oil (Gohlke et al., 2010). SCR are in fact sensitive to plugging by dust and corrosion by SO<sub>3</sub> (Kling et al., 2007). Therefore, in most existing waste incinerators, the catalysts can only be placed downstream of the flue gas cleaning installation where the temperature of the combustion gas is generally around 100°C or lower. This energy consumption adds to the overall environmental impact.
- If the residence time is inadequate, the NOx reduction efficiency may be compromised. Indeed, for SCR system NOx reduction is limited to the residence time of the flue gases into the reactor and the optimal temperature range, which is specific of each type of catalyst.
- NH<sub>3</sub> slip at high NSR: High NSR values can result in increased ammonia slip. This may require additional measures to control and minimize ammonia slip levels. [1]
- Efficiency dependent on catalyst activity: The efficiency of the SCR system is influenced by catalyst activity, which can decrease over time. This may require periodic maintenance and replacement of catalysts to maintain optimal performance, which leads to an increase of the costs required for the proper operation of the reactor. [2]

### **Opportunities of SCR systems and GEE:**

- GEE provide a good opportunity in education area, use in educational institutions for teaching remote sensing and geospatial data to everyone.
- GEE provides good opportunities in environmental monitoring disaster and climate change in a very high accuracy.
- With proper design and installation, SCR systems can be optimized to achieve higher temperature efficiency, allowing for improved energy recovery and reduced environmental impacts.
- Advances in catalyst technology and design can potentially help reduce the reactor size, lowering the cost and footprint of SCR installations.
- Ongoing research and development can improve the catalyst performance, enabling SCR systems to achieve higher NOx reduction efficiencies at lower NOx concentrations.
- Further advancements in SCR catalysts and control systems can help minimize ammonia slip, leading to more environmentally friendly operations.

### **Threats of SCR systems and GEE:**

- There are some powerful geospatial analysis platforms, like Esri's powerful software ArcGIS, GIS Pro, GIS online.
- Change in data access policies and regulations can impact the availability of certain datasets.
- In GEE the data privacy and security is a barrier for some organization.
- The longer residence time in SCR systems can lead to potential catalyst deactivation due to dust accumulation or other fouling factors. [4]
- SCR systems may not be as cost-efficient or effective when compared to SNCR, especially at lower NOx concentrations, which may pose a threat to its widespread adoption.
- Despite generally lower ammonia slip in SCR systems, there is still a risk of environmental ammonia emissions, which need to be controlled and minimized to comply with regulations and ensure environmental sustainability.

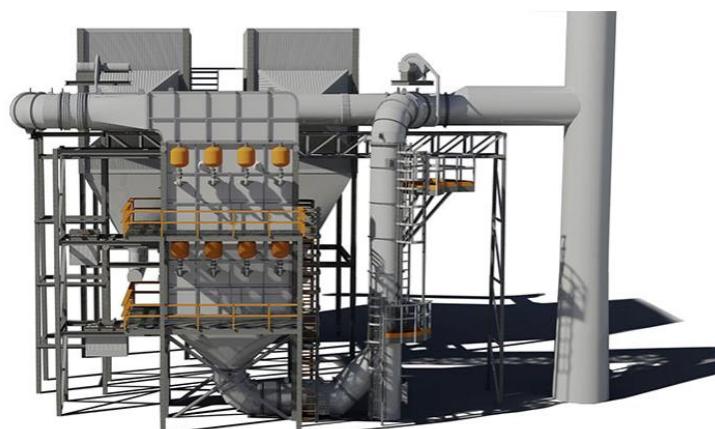


Figure 30 SCR by BD group industries company

In conclusion, SCR has drawbacks including high energy consumption and sensitivity to catalyst plugging, even if it has potential advantages in temperature control, residence time and improved NOx reduction efficiency. In the upgrade of the waste incinerator plant [13], the NH<sub>3</sub>-slip at the stack is considered equal for both alternatives. According to the authors, this assumption is based on the literature (Goemans et al., 2004; Beckmann et al., 2009; Villani et al., 2012), where NH<sub>3</sub> concentrations of 0.5-5 mg/Nm<sup>3</sup> stack gas are reported both for incinerators equipped with SNCR or with SCR. This assumption though, is valid for waste incinerators, but for other this of plants (gas boilers, cement kilns, coal fire boilers, pulp and paper industry) experimental evidences highlighted that for SCR, ammonia slip values are <5mg Nm<sup>3</sup> [Cichanowicz, J., L. Muzio, and M. Hein] and for SNCR are usually higher (<10 Nm<sup>3</sup>) [2]. This should be taken into account when calculating the LCA of the system, because the impacts related to the ammonia slip strongly influence the environmental risk.

In the article, the main source of energy consumption seems to be the placement of the SCR reactor (tail-end configuration), which was forced due to the lack of space in the existing configuration of the waste incinerator and the sensitivity to plugging of the catalyst and this leads to the need of reheating the flue gases. The energy consumption could be reduced though, by placing the reactor for example after the combustion chamber, where the temperature is still high, in the case the place available for the system is adequate. In this case, strict controls to avoid fouling of the catalyst must be carried out. Under this hypothesis, the advantage would be the decreased overall environmental impact of SCR, especially on the global warming.

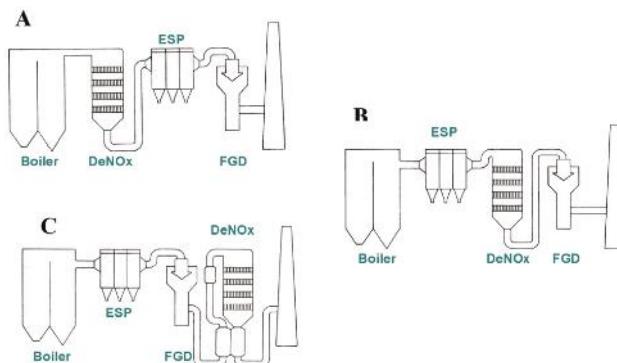


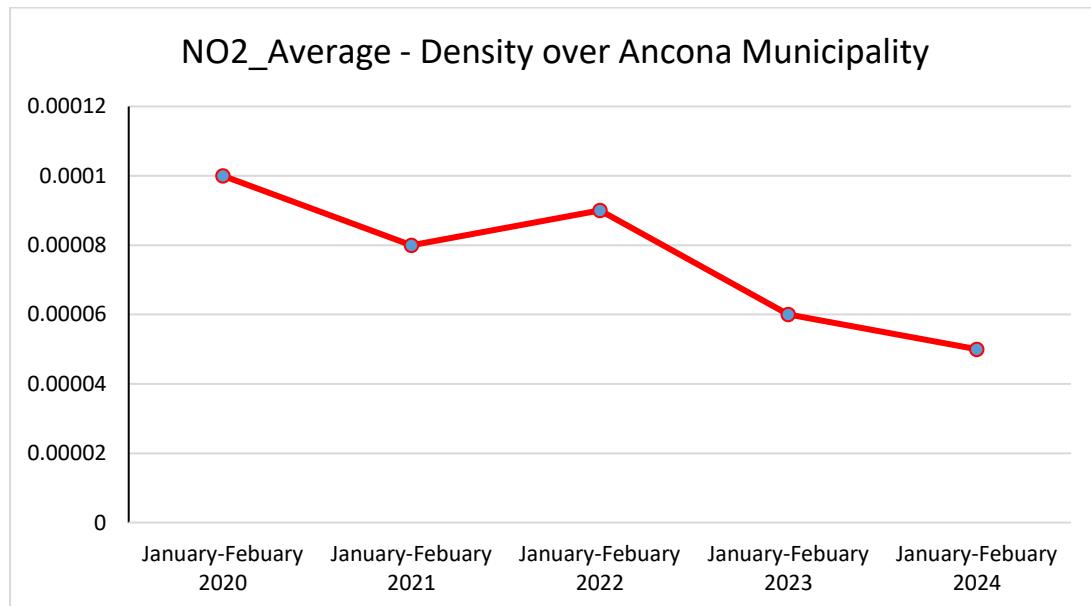
Figure 31 Possible SCR configurations: A) High Dust B) Low Dust C) Tail end [Politecnico di Milano]

On the other hand, SNCR might be more advantageous in terms of cost-effectiveness and residence time control, but it might also be less successful in achieving stricter NOx emission limitations, which could lead to higher ammonia slip. The economic costs and feasibility of implementing SCR were not specifically addressed in the paper, which may present challenges in its practical implementation.

A lifespan analysis and the possibility for technical developments should be taken into account when choosing between SCR and SNCR systems. Each system has unique requirements, constraints, and environmental effects.

## Conclusion

In summary, In this study I analyzed the variation and change in concentration of air pollutants, Nitrogen Dioxide (NO<sub>2</sub>) using spatial temporal of sentinel-5P TROPOMI using MODIS in five different years 2020, 2021, 2022, 2023 and 2024 in months January and February over commune di Ancona city-Italy. In accordance with observed and obtained results NO<sub>2</sub> in January is with high levels of concentration, then in February is still high but lower than January and then again in the summer decreased. If we compare year by year, NO<sub>2</sub> reach in high concentration in January 2020, but decrease again in February 2021, but again a little bit increased in January 2022, but after that increased gradually till January 2024, also in month June in four years from 2020 to June 2023 gradually decreased.



SCR technology requires the use of a catalyst ensures greater NO<sub>x</sub> reduction efficiency, even at low temperatures. SCR systems operate in fact at lower temperatures, require lower NSR values and have stricter limits on ammonia slip.

SNCR technology, on the other hand, does not require the use of a catalyst but gives a less effective reduction of NO<sub>x</sub> and takes place at higher temperatures, have higher NSR requirements, and the ammonia slip can be more challenging to control. It is less expensive than SCR systems but less effective at low temperatures.

In both cases, the effectiveness of NO<sub>x</sub> removal depends on the temperature of the combustion gases, the quantity of ammonia or urea used and the presence of any pollutants which could compromise the functioning of the system.

Although the efficiency is higher, several disadvantages on SCR operation has been reported by Gohlke et al, such as high energy consumption for reheating the flue gases and overcome pressure drop built up in catalyst bed, high capital and operating cost and limited lifetime for catalyst. For waste incinerators, studies on LCA showed that by placing the SCR reactor in tail-end configuration (this choice was due to the risk of plugging and the need for space to install the system), SCR systems require reheating of the combustion gas before it enters the catalyst unit, which consumes additional energy from natural gas or fuel oil. For this reason, the switch from SNCR to SCR increased the incinerator's overall environmental impact, especially in the category global warming. Avoiding the tail end configuration can decrease the environmental

impact of this system, but the cleaning of the catalyst, in this case, would become crucial to avoid fouling effects.

Indeed, even if at first sight, SCR seems to be the best configuration to apply in order to have a better efficiency of the removal of NOx, the cost related to the installation and maintenance of the catalyst, the reheat of the flue gases must be taken into consideration in the choice of the system in the design phase.

Because SNCR only works in a somewhat high, constrained temperature range, not all applications are appropriate for it. To determine if SNCR is practical, site-specific operating and design parameters of the emission unit must be assessed on an individual basis. Temperature, residence time, the ability to install reagent injection ports, and the NOx concentration are some of the variables that determine whether SNCR is a suitable control for a source. If there is no acceptable site for installing reagent injection ports, residence time is too short, temperatures are too low, NOx concentrations are low, SNCR probably would not be suitable. For instance, SNCR is typically not employed for gas turbines since it is less effective than other existing control methods when there is a low NOx concentration in the flue gas [2]. The highest levels of NOx control are often attained by sources with steady temperatures between 843°C and 1066°C, uncontrolled NOx emissions exceeding 200 ppm, and residence periods of 1 second.

In conclusion, the parameters considered in the analysis (temperature, residence time, ammonia slip, NSR and type of reagent) are not the only ones influencing the performances of the reactors and the removal efficiency of NOx. To fully describe the problem, also other parameters (that were just mentioned in the analysis) must be taken into account, like the degree of mixing (as mentioned before, this influences the denitrification reaction at low temperatures), the reactant concentration, the presence of high CO concentrations, which can lower the ideal reaction temperature and the chemical composition of the flue gases, are just some other aspects that must be accounted for in the design phase or upgrade of a plant, to guarantee an optimal reduction of NOx emission and a proper choice of the technology to employ.. The choice between the two technologies depends on the specific needs of the plant and local regulatory requirements.

## References

- [1] EPA technical bulletin, Nitrogen Oxides (NOx) why and how they are controlled, 1999
- [2] EPRI (Electric Power Research Institute). SNCR-SCR Guidelines
- [3] Reaction Characteristics of NOx and N2O in Selective Non-Catalytic Reduction Using Various Reducing Agents and Additives, 2021, P.M Park, Y.K. Park and J.I. Dong
- [4] Institute of Clean Air Companies (ICAC)
- [5] The influence of mixing between  $NH_3$  and NO for a De-NOx reaction in the SNCR process, 2008, J.H. Jung, ,K.J. Oh
- [6] *SUB 0.15 LB/MBTU NO<sub>x</sub> EMISSIONS ACHIEVED WITH ALTA ON A 500 MW CYCLONE-FIRED BOILER, M.A. Cremer, B. Adams, 2014*
- [7] *G. Busca, L. Lietti, G. Ramis, F. Berti, Chemical and mechanistic aspects of the selective catalytic reduction of NO<sub>x</sub> by ammonia over oxide catalysts: A review, Applied Catalysis B: Environmental 18 (1-36), ElSevier, 1998*
- [8] *Foerter, D., and C. Whiteman. Typical Installation Timelines for NO<sub>x</sub> Emissions Control Technologies on Industrial Sources. Institute of Clean Air Companies (ICAC). December 2006*
- [9] Direct synthesis of V-W-Ti nanoparticle catalysts for selective catalytic reduction of NO with NH<sub>3</sub>, 2015, Z.Zhao, G.Jiang et all
- [10] *Use of a  $\mu$ -Scale Synthetic Gas Bench for Direct Comparison of Urea-SCR and NH<sub>3</sub>-SCR Reactions over an Oxide Based Powdered Catalyst, 2015, M.Seneque, F. Can, D.Duprez and X. Courtois*
- [11] Experimental demonstration of NOx reduction and ammonia slip for diesel engine SCR system, G. Yue, T. Qiu, Y.Lei, 2021
- [12] Teleconference from K. Schaffner, RTI International, with W. Dean, Siemens. Discussion of Siemens TDL for ammonia slip monitoring. June 8, 2009
- [13] NOx reduction in waste incinerators by selective catalytic reduction (SCR) instead of selective non catalytic reduction (SNCR) compared from a life cycle perspective: a case study” (J.V. Caneghem, J.De Greef, C. Block, C. Vandecasteele) agency, t. e. (2017). Sentinel-5P operations. european space agency. ESA - Sentinel-5P operations.
- Program, U. E. (2021). chemical pollution actions.  
Pollutants | Free Full-Text | Monitoring Trends of CO, NO<sub>2</sub>, SO<sub>2</sub>, and O<sub>3</sub> Pollutants Using Time-Series Sentinel-5 Images Based on Google Earth Engine (mdpi.com)

