A MULTI-CRITERIA DECISION ANALYSIS OF NO_X ABATEMENT OPTIONS FOR REFINERIES

A Case Study of Shell Pernis

MSc Thesis

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By

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PREFACE

This master's thesis is the pinnacle of a fulfilling, 21-week research adventure, forming part of my studies in the Energy track of the Master Complex Systems Engineering and Management course at TU Delft. This hands-on experience was kindly offered by Shell PLC, within which I undertook my graduation internship in the energetic and progressive Energy and Utility Technology department.

It's essential that I extend my deepest gratitude to all those who provided support during this graduation internship. Firstly, my sincerest thanks go to Shell PLC and the Energy and Utility Technology team. As part of this team, I was privileged to tap into their wealth of expertise and insight, along with their fervent motivation. They also facilitated introductions to key personnel within Shell, which considerably propelled my research.

A special acknowledgement must go to my daily supervisor, Marc van Spaandonk, whose unwavering cooperation and readiness to answer my multitude of queries was an invaluable asset to my progress. His guidance was a guiding light during my academic journey.

Additionally, I wish to express heartfelt thanks to my thesis supervisor, Lydia Stougie, from TU Delft. Her enlightening guidance and constructive feedback, time after time, were not only vital but pivotal to my graduation journey. Likewise, I'm indebted to Jan Anne Annema for his useful feedback, helping to steer me on the right course throughout my research. Thank you both for providing a compass during my studies.

Last, but by no means least, I would like to convey my warmest thanks to my friends, family, and my supportive girlfriend. Their unwavering faith in me and constant words of encouragement have served as the bedrock of my academic journey. To all of you, thank you for being the foundation that kept me grounded, even amidst the whirlwinds of academia.

Martijn de Jager

EXECUTIVE SUMMARY

The escalating concern regarding nitrogen oxides (NOx) pollution has compelled governments and industries to take measures to reduce NOx emissions and mitigate its detrimental effects on health and the environment. NOx emissions, resulting from the high-temperature processing of fossil fuels in refineries, contribute significantly to air pollution. Recognizing the urgency, the Dutch government has implemented measures to curb these emissions, such as lowering Emission Limit Values (ELV), encouraging cleaner fuels, and providing subsidies for emission reducing technologies. Furthermore, the European Commission's Best Available Techniques (BAT) outlines key technologies for NOx reduction.

A review of the literature indicated a rich body of work on various NOx abatement technologies, including Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), Low NOx burners, and advanced combustion techniques. However, a glaring gap exists in comparative analyses between these technologies, which would be essential for decision-makers to consider various factors such as reduction efficiencies, costs, and maintenance. The lack of comprehensive comparisons could hamper informed decision-making.

The research is conducted with the case of Shell Netherlands Refinery (SNR), which has already implemented certain NOx reduction measures such as steam injection in gas turbines and Low NOx Burners in furnaces. The decisions to implement these technologies were primarily based on the level of NOx emissions and financial considerations. This thesis aims to support decision-makers by providing a comprehensive comparison of multiple NOx abatement systems based on multiple criteria.

SNR has various emission sources for NOx, such as burners in furnaces with the emission point being the stack. Each emission point and NOx source within SNR has its own technical limitations and possibilities, which have been carefully assessed to determine the appropriate NOx abatement systems for each emission point.

The Multi-Criteria Decision Analysis (MCDA) approach was employed to answer the above research question. MCDA is a structured approach that evaluates and compares different options or alternatives based on a set of criteria. It enables decision-makers to make informed and objective decisions by considering multiple criteria and weighting their relative importance.

This research involved numerous meetings with vendors of NOx abatement systems to gather in-depth information about NOx abatement technologies. The information acquired, which ranged from operational aspects to cost estimates, was utilized in the third step of the MCDA process. Vendors presented their technologies and used questionnaires to understand specific requirements for applying their technologies to a sample emission point. This exercise provided further insights into potential performance and costs of different systems. Shell's previous experience with Ultra Low NOx Burners (ULNB) and (Ultra) Dry Low NOx (U)DLN burners also proved valuable, offering a rich source of internal data on these systems' performance and impact, which was helpful in evaluating their suitability as NOx abatement solutions.

This thesis developed its evaluation criteria through literature review and collaborative brainstorming sessions with decision-makers at SNR. Using the Hierarchy Decision Tree, an initial set of criteria was developed. These initial criteria were then discussed and refined during subsequent brainstorming sessions with the decision-makers at Shell. Through these discussions, additional criteria were suggested, existing ones were modified, and each criterion was tied to measurable outcomes for precise evaluations. The final list of criteria included maintenance requirements, fuel/power requirements, plant footprint, NOx and other emission reductions, waste streams, Capital expenditures (CAPEX), Operational expenditures (OPEX), overall safety, and industry experiences.

The Multi-Attribute Utility Theory (MAUT) is used to assign values to the criteria and evaluate the desirability of each alternative. MAUT allows for the integration of qualitative and quantitative data, flexibility in assigning weights to criteria, and the conversion of disparate units into a common value/utility for comparison.

Weighing of criteria is an essential aspect of the MCDA process, as it reflects decision-makers' preferences and priorities. The weights for the criteria in this research are determined through collaborative discussions and brainstorming sessions with decision-makers at SNR.

The study concludes that combustion-based systems, specifically ULNB for furnace burners and (U)DLN burners for gas turbines, are more advantageous than end-of-pipe systems for NOx reduction in SNR. However, in cases where combustion-based technologies are not technically feasible, the integration of end-of-pipe systems is necessary. In such scenarios, the ClO_2 wet scrubber is recommended due to its high final utility score. SCR, SNCR, and LOTOX technologies are generally not advised due to their lower final utility scores but SCR or LOTOX could be viable when high NOx emission reductions are required (>90%).

According to outcomes of MAUT, the ULNB was identified as a particularly effective NOx abatement technology, showcasing a consistently high final utility score at numerous emission points, specifically O, P, Q, N, L, I, J, E, M, F, D, B, and H. in contrast, at emission points R, A, E, G, K, S, and W, the most efficient solution was found to be the ClO_2-based wet scrubber system, which achieved the highest final utility score. For the final emission points, namely T, U, and V, the (U)DLN burners scored the highest final utility score, thereby earning the recommendation as the preferred NOx abatement technology for these emission points.

However, this study had its limitations. The cost analysis conducted was somewhat superficial. A more in-depth exploration of the CAPEX and OPEX, coupled with the use of complexity factors per emission point, could refine the MCDA outcomes. It is recommended that future studies integrate Cost-Benefit Analysis (CBA) into the MCDA for a more rigorous examination.

Another constraint was the limited scope and quality of data used. It is recommended that subsequent research take a more rigorous approach to data collection, including engaging factories that have already implemented NOx abatement systems. Such an approach could yield a more comprehensive dataset, enhancing the reliability of MCDA outcomes.

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NOMENCLATURE

Acronyms

BAT	Best Available Technique
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CoSEM	Complex System Engineering and Management
DeNOx	Process of reducing or removing nitrogen oxides from flue gas
EB	Electron Beam
ELV	Emission Limit Value
FGR	Flue Gas Recirculation
HS 1	High Stack 1
HS 2	High Stack 2
LCA	Life-Cycle Assessment
LOTOX	Low Temperature Oxidation
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
Nm^3	Normal Cubic Metre
NOx	Nitrogen Oxides
NTP	Non-Thermal Plasma
OPEX	Operational Expenditure
PM	Particulate Matter
Photo-SCR	Photo-Selective Catalytic Reduction
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SNR	Shell Netherlands Refinery
TRL	Technology Readiness Level
(U)DLN	(Ultra) Dry Low NOx
ULNB	Ultra Low NOx Burners
UV	Ultraviolet
VOC	Volatile Organic Compounds

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1. INTRODUCTION

1.1. Context

In recent years, there has been growing concern about nitrogen oxides (NOx) pollution and its impact on society. The Dutch government has implemented several measures to reduce NOx emissions from refineries, including setting emissions limits and promoting the use of cleaner fuels (Ministry of Infrastructure and Water Management, 2022; European Commision, 2014). The government also offers subsidies and tax incentives to encourage the development and implementation of cleaner technologies and processes in the refining industry (Netherlands Enterprise Agency, 2022).

NOx emissions are produced by a variety of sources, including transportation, power generation, and industrial activities such as refining. NOx is a family of air pollutants that poses significant health and environmental risks. NOx contributes to the formation of ground-level ozone, acid rain, and fine particulate matter, which can harm human health and damage ecosystems. Additionally, NOx can react with other compounds in the atmosphere to form nitrogen compounds, including ammonia and nitrates, which can act as a fertilizer. This can lead to eutrophication, which can threaten the biodiversity of aquatic and terrestrial ecosystems (RIVM, 2020).

The industrial sector is a contributor to NOx emissions, particularly in activities such as refining, where large amounts of fossil fuels are burned to produce gasoline, diesel, and other products (RIVM, 2020). In the refining process, high temperatures and pressure are used to break down complex hydrocarbons into simpler molecules, which can produce NOx emissions as a by-product. It is essential to find ways to reduce the negative impact of the processes used to create these products, on the environment and human health. To address the NOx problem in the refining industry, a range of strategies have been proposed and implemented. These include improving combustion efficiency, using Low-NOx Burners, and installing emission control technologies such as Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) (Ali, et al., 2021; European Commision, 2014).

In 2014 the European Commission created the Best Available Techniques (BAT) for the refining of mineral oil and gas industry (European Commision, 2014). The BAT document suggests technologies that can be used to reduce NOx emissions in refineries. However, these often include outdated technologies or those based on obsolete performance metrics. Developments and new technologies have since then been introduced that add to the list of possible technologies for NOx reduction for the refining industry.

The problem refineries are facing is to choose the best NOx abatement technology at each emission point while doing this in a cost-effective manner. As each of the NOx abatement technologies has different reduction efficiencies, costs, safety, and maintenance requirement, the question arises which one is the best option to choose for each process in the refinery. Conversely, the processes and emission points also dictate which technologies can be used. This makes it difficult to choose the best suitable technologies for the refinery. The selection of appropriate NOx abatement systems for emission points in refineries is crucial to ensure effective reduction of NOx and compliance with environmental regulations. In this specific context, the literature appears to have limited information on the best NOx abatement technology. The literature analysis, in Chapter 1.3., concludes that there is limited knowledge which NOx abatement technology should be chosen by decision-makers within refineries. This research will conduct a Multi-Criteria Decision Analysis (MCDA) to support decision-makers in providing the recommended NOx abatement option for each emission point.

The case of Shell Netherlands Refinery (SNR) is used to conduct a MCDA and provide decision-makers at Shell with insights into which NOx abatement systems could best be used at each emission point in SNR. The goal of this thesis will be to showcase which NOx abatement options are recommended to be chosen per emission point. Furthermore, this research aims to provide other refineries with insights into how MCDA can improve and support decision-making when choosing suitable NOx abatement systems.

In conclusion, the NOx issue in the refining industry presents a significant challenge that requires continued attention and proactive measures. By implementing effective strategies to reduce NOx emissions, the refining-industry can and should do their part in moving towards a more sustainable and healthy future.

1.2. Legislation on NOx Emissions

One of the primary governmental approaches to reducing NOx emissions in the refining industries is through the implementation of Emission Limit Values (ELV). ELVs set the maximum permissible limit of NOx emissions that an industrial facility can release into the atmosphere. Traditionally, the BAT were utilized as a benchmark to determine the preferred technologies for NOx emissions reduction (European Commision, 2014). An analysis, by the European Commission was conducted on the top quartile (25%) of the refining industry to assess their NOx emissions. The emission levels derived from this analysis were then employed as a standard to establish the ELVs (Ministry of Infrastructure and Water Management, 2022). Since August 2021, the NOx ELVs for refinery installations have been reduced (Ministry of Infrastructure and Water Management, 2022) and will be lowered over time. Table 1-1 presents the ELVs for existing gas-fired installations.

Table 1-1: Emission Limit Values (ELV) for NOx emissions (Ministry of Infrastructure and Water Management, 2022).

Installations	**ELVs before August 2021, at 3% O_2 [mg/Nm^3]**	**Current ELVs at 3% O_2 [mg/Nm^3]**	**Future (post 2030) ELVs at 3% O_2 [mg/Nm^3]**
Gas Turbine	225	100	<100
Furnace	150	100	<100

In 2024 it is expected that a new refinery BAT document will be introduced (Shell, 2023). This document will ensure that the ELVs for the refining industries will be lowered. These lower limits will require refineries to invest in advanced emission control technologies, process modifications, and operational improvements to comply with the tightened standards.

1.3. Literature Analysis and Knowledge Gaps

The objective of this chapter is to conduct a literature analysis. The approach for this literature analysis was to collect articles that showcase the best NOx abatement technique, specifically within refineries. Figure 1-1 shows the keywords used in this literature analysis. Furthermore, snowballing was used to find articles that could also be relevant.

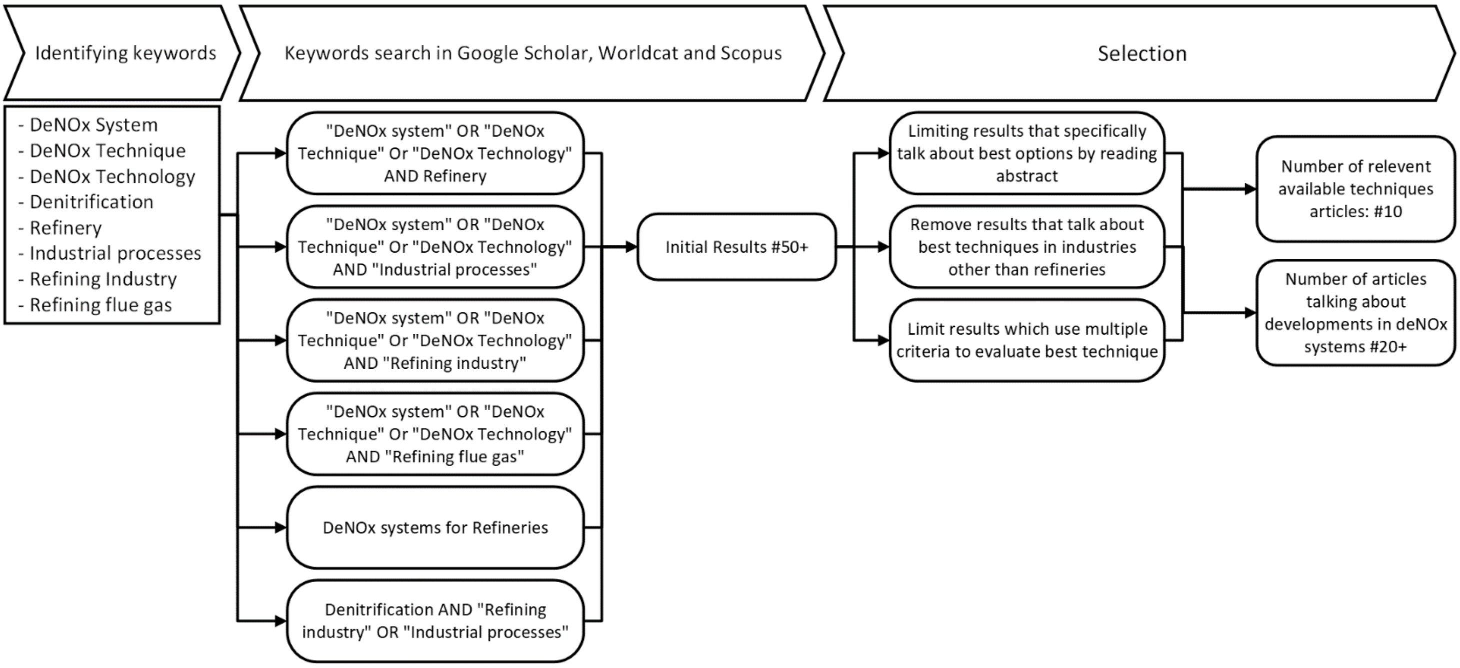


Figure 1-1: Visualisation of article search for thesis

The literature analysis highlights the wide range of technologies available for NOx reduction, including but not limited to SCR, SNCR, Low NOx burners, and advanced combustion techniques. There is a broad literature that explains the technical capabilities and limitations of these technologies (Gholami, et al., 2020; Skalska, Miller, & Ledakowicz, 2010; Sun, Zwolińska, & Chmielewski, 2015; Orfanoudakis, et al., 2004; Zabetta, Hupa, & Saviharju, 2005; Ballester, et al., 1997; Baukal, et al., 2004; European Commision, 2014). Each technology has its own advantages, limitations, and applicability depending on the specific emission source and operational conditions.

Additionally, the literature review revealed numerous scientific articles discussing improvements in technologies and introducing new methods that could significantly reduce NOx. The article of Ângelo et al. (2013) discusses several NOx abatement technologies that use the photocatalytic phenomena. The article discusses the various technological issues of photocatalysis and its potential for NOx abatement. The article reviews the different developments of the technologies. The preferred metal as a semiconductor is discussed and new materials are presented within the article. The article of Si et al. (2021), primarly discusses the various oxidants that are used to oxidize and then reduce the NOx. The article provides an overview of oxidants and their technicallity, characteristics, limitations and advantages.

A notable knowledge gap identified through the literature analysis is the lack of comparative analyses among the NOx reducing technologies. While numerous studies and reports describe the individual performance of different NOx reduction methods, as discussed above, there is a scarcity of comprehensive assessments that directly compare and evaluate their efficiency, cost-effectiveness, and environmental impacts. One specific article provides insights in what NOx abatement options there are for the petrochemical and refining industries written by Baukal, et al. (2004). Even though the article describes SCR, SNCR, and Low NOx Burners, the data and technologies discussed and compared are outdated. The Low NOx burners discussed are the predecessor of the Ultra Low NOx Burners (ULNB), which have higher NOx abatement performance and lower capital cost (Shell, 2023). Furthermore, new technologies have been introduced that are not compared in the article, such as the oxidation of NOx with ozone and the use of a wet scrubber. The comparative analysis done in the article is clearly outdated for today's application.

This poses a significant challenge as decision-makers seek to select the optimal technology for each emission point. Factors such as emission reduction efficiency, cost-effectiveness, energy consumption, maintenance requirements, and compatibility with existing infrastructure all come into play (Skalska, Miller, & Ledakowicz, 2010). Without a thorough understanding of how different technologies perform in relation to these criteria, decision-makers may face uncertainty and make suboptimal decisions. Comparative analyses would facilitate a holistic view of the available options, allowing decision-makers to identify the most suitable technology for each emission point based on a range of factors.

In conclusion, the lack of comparative analyses makes it challenging for decision-makers to determine the optimal technology for each emission point within their industries. Conducting comprehensive comparative analyses would provide decision-makers with the necessary information to make well-informed choices, taking into account factors such as performance, cost, and operational requirements.

1.4. Selection of Method

Assessing the NOx abatement options available to reduce NOx emissions at refineries and considering the possibilities and limitations of each technique would typically require both qualitative and quantitative research approaches.

Qualitative research can be used to identify the different NOx abatement techniques that are available and to describe the specific characteristics and limitations of each technique. This could involve a literature review of relevant studies and reports, as well as consultations with industry experts and stakeholders. Qualitative research might also involve a review of the existing equipment and processes at Shell Pernis, in order to identify any potential limitations or constraints that may impact the feasibility of different NOx abatement techniques (McCusker & Günaydin, 2015).

Quantitative research, on the other hand, would be necessary to estimate the costs, benefits, and technical feasibility of each NOx abatement option (McCusker & Günaydin, 2015). This could involve developing detailed engineering designs of each option, estimating the capital and operating costs of each option, and modelling the expected NOx reduction and associated economic benefits. These analyses could then be used to compare the different NOx abatement options and to identify the recommended solutions for refineries and in this study for Shell Pernis.

The used method in this study, Multi-Criteria Decision Analysis (MCDA), MCDA can be helpful in making informed decisions about the adoption of new technologies or strategies. MCDA is a structured approach used to evaluate and compare different options or alternatives based on a set of criteria or objectives. The aim of an MCDA is to help decision-makers make more informed and objective decisions by considering multiple criteria and weighing their relative importance (Carayannis, et al., 2018; Linkov & Moberg, 2012).

Furthermore, MCDA involves a systematic and transparent process that often involves stakeholder engagement to evaluate and weigh the different criteria (Carayannis, et al., 2018; Gamper, Thöni, & Weck-Hannemann, 2006). The results of an MCDA can help decision-makers understand the trade-offs and benefits of different options and select the most suitable alternative based on their specific needs and requirements (Keeney, 1982). For example, a renewable energy project may have a higher initial cost than a traditional fossil fuel-based project but may also have significant environmental benefits. By using MCDA, decision-makers can evaluate the relative importance of economic and environmental criteria and make an informed decision that balances these factors.

MCDA utilizes various quantitative techniques, such as weighting methods, scoring models, aggregation methods, and mathematical algorithms, to analyze and rank alternatives according to their performance on the identified criteria. The calculations involved in MCDA generate numerical scores, utilities, or rankings that facilitate the decision-making process (D'Agostino, Parker, & Melià, 2019; Linkov & Moberg, 2012). However, it is worth noting that MCDA can also incorporate qualitative aspects. Qualitative criteria and preferences can be included in the analysis by assigning qualitative descriptions or linguistic terms to criteria, which are then translated into quantitative values (Baumann, et al., 2019).

Methods such as Cost-Benefit Analysis (CBA) are limited in that they cannot accommodate qualitative data, which is a significant drawback for the comparative analysis that this research aims to conduct (Gamper, Thöni, & Weck-Hannemann, 2006). In the assessment, there will be several qualitative criteria that SNR intends to take into consideration. The inability to incorporate qualitative aspects would restrict the scope and depth of the evaluation, potentially leading to an incomplete assessment of the options under consideration.

While a life-cycle assessment (LCA) is a valuable method for evaluating the environmental impacts of different processes or products throughout their entire life cycle, it may not be the most suitable approach for the specific research being conducted. One of the reasons is that the focus of the research is on NOx abatement techniques within a refinery, which involves a more localized and specific scope. LCA typically considers a wide range of environmental aspects, such as raw material extraction, manufacturing, transportation, product use, and disposal (Jacquemin, Pontalier, & Sablayrolles, 2012). However, in this case, the primary objective is to assess and compare NOx abatement options within the refinery, considering factors such as technical feasibility, economic viability, and social implications. Thus, utilizing a more targeted assessment method, such as an MCDA, would better align with the research goals and provide a more relevant and actionable framework for decision-making.

Another method that could be considered is the Delphi method. The Delphi method, known for gathering consensus from a panel of experts (Skulmoski, Hartman, & Krahn, 2007), may not be the most optimal choice for this research. Given the focus on evaluating and comparing NOx abatement techniques within a refinery, considering factors like technical feasibility, economic viability, and social implications, the Delphi method's iterative nature and resource requirements might pose limitations (Skulmoski, Hartman, & Krahn, 2007).

The factors outlined previously are the cornerstone of why MCDA has been selected as the method in this research to assist decision-makers in determining which NOx abatement technology is recommended to be chosen for each emission point. Through its capacity to adeptly handle complexity, incorporate both qualitative and quantitative criteria, and facilitate transparent trade-offs that consider varying preferences, MCDA emerges as an instrumental tool in making informed and balanced recommendations.

Multi-Attribute Utility Theory

There are many MCDA theories, such as Multi-Attribute Utility Theory (MAUT), Analytical Hierarchy Process, Elimination and Choice Expressing Reality, Weighted Sum Method, Technique for Order Preference by Similarity to Ideal Solution, and many more (Baumann, et al., 2019). In this research MAUT is chosen.

MAUT is a theory that involves assessing the relative importance of different attributes (criteria) and evaluating alternatives (NOx abatement systems) based on those attributes. MAUT uses a utility function to assign values to different attributes and evaluate the overall desirability of each alternative. MAUT offers the ability, with the utility score to convert performance values of several different criteria (Baumann, et al., 2019). Furthermore, the use of qualitative and quantitative data is possible within MAUT (Cinelli, Coles, & Kirwan, 2014).

MAUT is a more flexible approach compared to other MCDA theories as it allows decision-makers to consider more complex decision scenarios where there are multiple attributes to consider (Bukhsh, et al., 2018; Alinezhad & Khalili, 2019). Decision-makers can explicitly assign weights based on their preferences, reflecting the relative importance of each criterion. This feature allows for customization and accommodates the specific context and decision problem at hand. Other MCDA theories may have more rigid weighing schemes or rely on pairwise comparisons, which may not capture decision-makers' preferences as accurately (Alinezhad & Khalili, 2019).

Suppose that there are three criteria in the MCDA: Reliability, NOx reduction and plot space. There can be no integration of these criteria as they do not have similar meaning and units. Reliability has no unit; NOx reduction can be described as mg/Nm^3 and plot space in m^2. It is impossible to combine these criteria into a single measure. MAUT resolves the disparate units into a value/utility which makes comparison possible (Linkov & Moberg, 2012; Kossiakoff, et al., 2011).

Furthermore, gathering information about the importance of each criterion compared to other criterion is necessary. The importance of each criterion is provided by the decision-maker. In other words, the main considerations of MAUT are, how great is the effect of an alternative (score) and how important is the criteria compared to all other criteria (the weights of each criterion) (LinKov & Ramadan, 2005). As this research is being conducted in close collaboration with Shell, who is the decision-maker, gathering information about the importance of each criterion is expected to be relatively straightforward. This accessibility to critical information makes MAUT a particularly useful theory for this research, as it efficiently accommodates the incorporation and weighing of various criteria based on the insights and preferences provided by Shell.

1.5. Research Objective and Questions

The objective of this thesis is to address the knowledge gaps regarding the selection of NOx abatement technologies for each emission point in refineries. The existing literature reveals a significant lack of comprehensive research and guidance in this area, impeding decision-makers in refineries from making informed choices. This study aims to bridge this gap by utilizing the MCDA approach to facilitate the selection of the recommended NOx abatement technology per emission point in a refinery.

SNR has a multitude of sources which emit NOx, such as the burners in furnaces. The flue gas generated by the burners which contains the NOx, is directed to the stack, which is the emission point. This means that a stack can have multiple sources of NOx. Each emission point, and NOx source, within SNR will have their own technical limitations and possibilities, which will alter the solution space for each emission point. As technical limitations can restrict the use of certain NOx abatement systems.

Until now, SNR, for whom this research is conducted in the form of a graduation internship, has been adapting several NOx reducing measures. Such as using steam injection in their gas turbines and installation of Low NOx Burners on several furnaces (Shell, 2023). However, these decisions to implement the technologies at certain furnaces or gas turbines were based on which systems emitted the most NOx and on financial reasoning (Shell, 2023). This thesis aims to support decision-makers by showing which NOx abatement system is recommended to be implemented by comparing multiple NOx abatement systems while looking at multiple criteria.

The research outcomes, along with the MCDA approach, will contribute to the development of best practices for NOx abatement technology selection in refineries. SNR could serve as a case study for other refineries, sharing valuable insights and experiences that can guide decision making in similar contexts.

Main research question

What are the recommended NOx abatement options for reducing NOx emissions at Shell Netherlands Refinery, considering environmental, technical, economic, and social factors?

The main research question in this thesis is obtained through answering several sub-questions listed down below. The deliverable of this main research question is to provide insights into which techniques are recommended to be used per emission point in SNR to reduce the NOx emissions, comparing multiple NOx reducing systems while looking at multiple criteria.

Sub-questions

The following sub-questions are formulated to answer the main research question stated above.

SQ1. What are the types of NOx abatement technologies available, and what are their generic constraints and possibilities?

SQ2. What are the specific NOx emission points at Shell Pernis, and what are the associated technical limitations or possibilities related to these emission points?

SQ3. What are the criteria utilized in the Multi-Criteria Decision Analysis (MCDA) for evaluating NOx abatement technologies?

SQ4. How will the criteria be weighted in the MCDA to compare NOx abatement technologies?

SQ5. How do the NOx abatement technologies perform in terms of scores or rankings for each emission point?

SQ6. To what extent are the research findings applicable to other similar refineries?

1.6. Link With CoSEM

The investigation of NOx reduction techniques for the refinery industry from a techno-economic perspective aligns well with the research scope of a thesis in Complex System Engineering and Management (CoSEM). In the CoSEM program, you learn to consider various factors such as regulations, subsidies, distribution channels, infrastructures, interests, cultures, and human behaviour when designing technological innovations in complex socio-technical environments. The search for NOx reduction techniques for the refinery industry involves similar considerations, as it requires integrating technical solutions with economic and regulatory factors. This means that simply searching for new technologies to reduce NOx emissions is not enough. These technologies must also be economically viable and compatible with existing regulations and infrastructures. In addition, the energy track of CoSEM focuses on improving energy markets and future energy systems through interventions such as investment in physical components, changes in operation, and changes in regulation. The search for NOx reduction techniques for the refining industry aligns with this track by offering a potential intervention for improving the sustainability of the refining industry (McCusker & Günaydin, 2015).

In conclusion, the search for NOx reduction techniques for the refinery industry on a techno-economic level is a real-world complex and multi-dimensional challenge that requires the application of interdisciplinary skills, such as engineering and management learned during the CoSEM master.

1.7. Scientific and Societal Relevance

While there are various NOx abatement technologies available for reducing NOx emissions in refineries, there is limited scientific research that provides a thorough comparison and evaluation of the performance, costs, and operational efficiency of these different technologies in specific refinery environments. A clear lack of scientific knowledge exists regarding the optimal selection and application of NOx abatement systems in refineries taking into account multiple factors. Robust scientific research addressing this gap could provide valuable insights to enhance decision-making and provide optimal NOx abatement solutions tailored to the specific needs of refineries.

Furthermore, according to Skalska, Miller, & Ledakowicz (2010), studying the possible options for NOx abatement in refineries is scientifically relevant because the process of air pollution control in chemical industry is highly complex. The chemical composition of flue gases in chemical plants is unique for each type of plant and varies depending on process parameters. Many of the existing technologies used in stationary and mobile combustion processes can be applied in chemical plants. Additionally, some technologies, such as ozone injection followed by absorption processes, may offer increased effectiveness and efficiency in NOx abatement in refineries.

The societal relevance of this research lies in the potential to reduce the negative impacts of NOx emissions on the health of individuals, as well as the environment. By reducing NOx emissions at Shell Pernis, and possibly other refineries, the local community can experience improved air quality and overall quality of life (RIVM, 2020). Furthermore, reducing NOx emissions can help to mitigate climate change, which is a major societal challenge. Especially in the Netherlands, where the NOx emissions have led to the Dutch Nitrogen Crisis (NOS, 2022). The Dutch government is obliged to protect the Natura 2000 areas, according to European agreements. Thus, limit the NOx emissions in the Netherlands.

Overall, this research can contribute to the development of sustainable solutions to reduce NOx emissions and improve air quality, which can have positive impacts on both the scientific community and society.

1.8. Thesis Structure

This thesis is composed of 8 more chapters. Chapter 2 elucidates the research method, detailing the chosen approach and procedures for data collection and analysis. In Chapter 3, the formation of NOx is explained, followed by an overview of NOx abatement technologies acquired through desk research and expert consultations; the Technology Readiness Level framework is utilized to narrow down the selection. Chapter 4 presents a comprehensive overview of emission points within Shell refineries, emphasizing the importance of understanding their unique characteristics. Chapter 5 is centred around the implementation of the MCDA, which involves identifying criteria, assigning weights, and scoring alternatives. In Chapter 6, the results of the MCDA are analysed, and a weight sensitivity analysis is conducted to assess the robustness and reliability of the MAUT theory. Chapter 7 concludes the research by summarizing the findings and answering the main research question and sub-questions. Chapter 8 discusses the research as a whole. Finally, chapter 9 provides recommendations.

2. METHOD

Performing a MCDA can be structured in several steps (Linkov & Moberg, 2012; Gamper, Thöni, & Weck-Hannemann, 2006). Figure 2-1 provides an overview of the five steps that comprise the MCDA process.

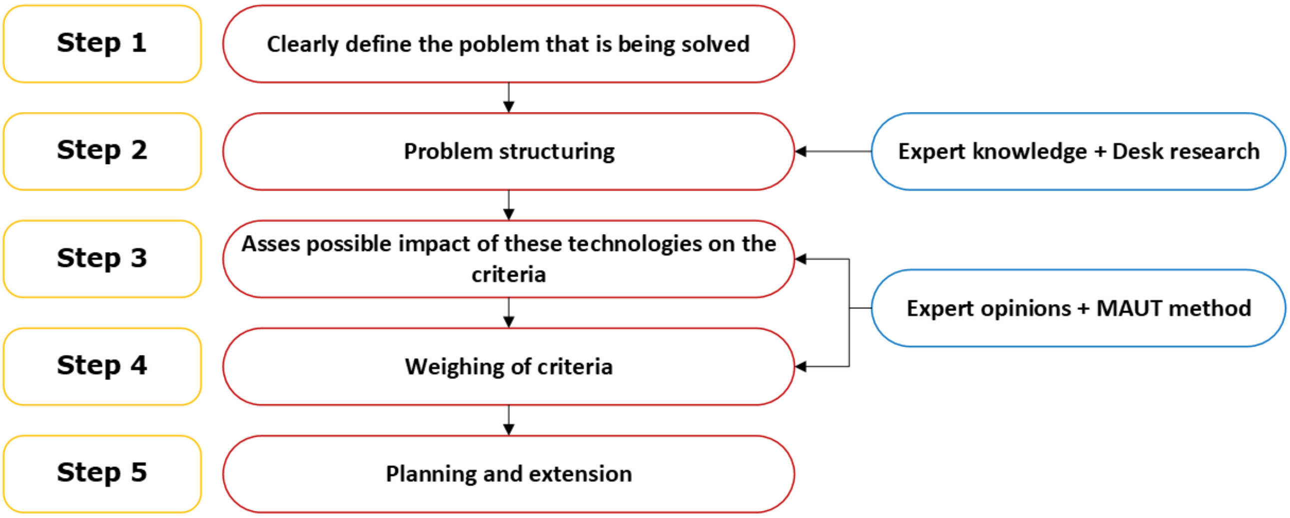


Figure 2-1: Overview of the MCDA process according to Linkov & Moberg (2012)

1. Clearly define the problem that is being solved

This can be done by determining the scope and objectives of the MCDA (Linkov & Moberg, 2012). The problem in the case of SNR in this research is to provide decision-makers the information about the most recommended NOx abatement system for each emission point at SNR based on several criteria.

2. Problem structuring

This entails identifying alternative solutions and the criteria (Linkov & Moberg, 2012). Alternatives in this research are the various NOx abatement technologies that can be implemented. These technologies need to be identified and researched. This includes their technical specifications, operating costs (OPEX), capital costs (CAPEX) and potential benefits. This is done by desk research and through talking to experts and companies that produce and have knowledge of the various NOx abatement systems. During the literature analysis in Chapter 1.3., various papers have been found that discuss and explain NOx abatement technologies. The papers discuss advancements in technologies but also discuss new technologies. These (new) technologies discussed in the papers are not yet all available on a commercial scale. The Technology Readiness Level (TRL) serves as an initial screening criterion to ensure the inclusion of commercially available technologies. If a certain technology's TRL level is below 7, no further information is gathered for that particular technology. This rationale also underlies the dedicated section that specifically describes commercially available technologies, which possess a TRL level of at least 7. These technologies are considered as alternatives in the MCDA.

Furthermore, to gain more information about the NOx abatement technologies a multitude of meetings have been set up with vendors of NOx abatement systems. These meetings provided additional information about NOx abatement systems, from how these systems work and operate to what the possible capital and operational costs would be like if applied to a certain emission point. This information was then used in step 3 of the MCDA process.

The information-gathering process for alternatives involved meetings with vendors. Table 2-1 provides an overview of these meetings. An "X" indicates that the vendor provided information about the alternatives. During each meeting, vendors showcased their respective technologies. Following the presentations, vendors independently employed questionnaires to gain a preliminary understanding of the specific requirements associated with their technologies in the context of an exemplar emission point (in this research emission point O is taken as an exemplar emission point). Afterwards, the vendor would provide additional information regarding the cost and implementation details of their system at the emission point, further gaining insights into how the alternatives would possibly score on the criteria.

Table 2-1: Overview of Meetings with vendors for information gathering on alternatives

Alternative: **Vendor:**	**(Ultra) Dry Low NOx**	**Ultra Low NOx Burners**	**LOTOX**	**Wet scrubber using ClO_2**	**SCR**	**SNCR**
Valmet			X	X	X	X
Elessent			X			
Linde			X			
Zeeco		X			X	
YARA					X	X
John Zink Hamworthy		X			X	
Callidus		X				

Furthermore, within Shell, specific attention is given to ULNB and (U)DLN burners due to their past utilization within the company. As Shell has previously employed these burners, a wealth of information regarding their performance, operational characteristics, and environmental impact is readily available. This internal knowledge base within Shell offers valuable data for evaluating the feasibility and effectiveness of ULNB and (U)DLN burners as potential NOx abatement solutions.

Criteria (such as environmental impact and cost) will be the basis how these technologies are evaluated. The criteria describe the performance of the technologies (Linkov & Moberg, 2012). The criteria should be obtained by literature review, but also by stakeholder participation, in order to make sure that all interests are represented in the MCDA (Gamper, Thöni, & Weck-Hannemann, 2006). In this thesis the criteria are obtained through literature review, but also through discussions and brainstorm sessions with decision-makers within SNR. The SNR decision-makers, an Energy and Utility Technologist and an Energy and Utility Technology Manager, actively participated in the brainstorming sessions, where their extensive experience and domain knowledge were leveraged to identify and refine the essential criteria for the MCDA. These sessions provided a deeper understanding of the decision context, ensuring that the criteria capture all factors and considerations which were important for SNR. A robust set of criteria was established for the MCDA process.

An initial set of criteria was established prior to the brainstorming session, utilizing the Hierarchy Decision Tree methodology. This approach allowed for the decomposition of the complex problem into a series of manageable decisions and sub-decisions, yielding a comprehensive list of criteria for evaluating the potential NOx abatement technologies. The initial set of proposed criteria were: Costs (CAPEX & OPEX), NOx reduction, Ease of Implementation NOx abatement technology, Reliability of NOx abatement Technology, Operational safety, Footprint (size of NOx abatement technology, Wastes (during operation and construction of NOx abatement technology), Other emissions reduction, and Lifespan.

In the subsequent brainstorming session, these initial criteria were presented and clarified for the decision-makers at Shell. This involved in-depth discussions regarding the implications and evaluation metrics of each criterion, with each one tied to specific measurable outcomes to ensure objectivity and precision in the evaluation process. The decision-makers at Shell proposed both the inclusion of additional criteria and modifications to the scoring of existing criteria. Their expertise and knowledge of the company's specific objectives enriched the list of criteria. Resulting in the following criteria: T1: Maintenance requirements, T2: Fuel/Power requirements, T3: Reliability, T4: Plant footprint, N1: NOx reduction, N2: Other emission reduction, N3: Waste streams, E1: CAPEX, E2: OPEX, S1: Overall safety, and S2: Industry Experiences.

3. Asses possible impact of these technologies on the criteria

The different criteria will have different measures, such as euros for capital costs and ton/year for NOx reduction. Some of the criteria will have a scale, as there is no unit that can be assigned to these criteria, for example safety is a dimensionless criterion which will have to be scored on the scale 1 to 5. To compare the values of different criteria the MAUT is used in this thesis.

The MAUT method utilizes a decision matrix to determine the input information. The decision matrix captures the alternatives and attributes by incorporating the information provided by the decision-maker, as show in Equation 1.1. Equations 1.1-1.5. in this work have been sourced from the article authored by Alinezhad & Khalili (2019).

$$X = \begin{bmatrix} R_{11} & \cdots & R_{1j} & \cdots & R_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ R_{i1} & \cdots & R_{ij} & \cdots & R_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ R_{m1} & \cdots & R_{mj} & \cdots & R_{mn} \end{bmatrix}_{m \times n} ; i = 1, \ldots, m, j = 1, \ldots, n \tag{1.1}$$

In Equation 1.1, the element R_{ij} represents the value in the decision matrix corresponding to the ith alternative and jth criterion. Subsequently, the decision-maker provides the weight of attributes [w_1, w_2, …, w_n].

As previously discussed, the values in the decision matrix need to be normalized. The way this is done depends on if the value is a positive or negative type of criterion. Normalizing positive criteria is done using Equation 1.2 and normalizing negative criteria is done with Equation 1.3.

$$R_{ij}^{*} = \frac{R_{ij} - \min(R_{ij})}{\max(R_{ij}) - \min(R_{ij})} ; i = 1, \ldots, m, j = 1, \ldots, n \tag{1.2}$$

$$R_{ij}^{*} = 1 + (\frac{\min(R_{ij}) - R_{ij}}{\max(R_{ij}) - \min(R_{ij})}); i = 1, \ldots, m, j = 1, \ldots, n \tag{1.3}$$

R^*_{ij} is the normalized value of the decision matrix of ith alternative in jth criteria. With the normalized values in the decision matrix the marginal utility score is determined. Equation 1.4, where u_{ij} represents the marginal utility score of ith alternative in jth criterion.

$$u_{ij} = \frac{e^{(R^*_{ij})^2} - 1}{1.71} \; ; i = 1, \dots, m, j = 1, \dots, n \tag{1.4}$$

Note that, the number 1.71 is a normalization constant that is commonly used in the literature to scale the utility scores generated by the MAUT method. The purpose of this constant is to ensure that the overall utility scores of the alternatives are on a similar scale, regardless of the number or range of the attributes used in the theory (Alinezhad & Khalili, 2019).

4. **Weighing of criteria**

The values obtained from the previous step cannot be compared as a unit of preference as the values do not reflect the preference of the stakeholder (Gamper, Thöni, & Weck-Hannemann, 2006). This research will assign weights between 0 and 1 for each criterion, with 0 being not important at all and 1 being very important. Weighing the criteria is important when using the MAUT method (Linkov & Moberg, 2012). The re-calculated scores are summed up for each alternative and put in an adjusted impact matrix. Again, brainstorm sessions with decision-makers within SNR will provide the weights for the criteria in this research, which is in accordance with the MAUT methodology (Alinezhad & Khalili, 2019).

After calculating the marginal utility score, the final utility score is calculated using Equation 1.5. The final utility score provides the ranking of alternatives in a descending order. The alternative with the highest utility score is the best alternative.

$$U_i = \sum_{j=1}^{n} u_{ij} \cdot w_j \; ; i = 1, \dots, m \tag{1.5}$$

The assignment of weights to the criteria for the MCDA has been an inclusive process involving collaborative brainstorming sessions with the decision-makers at SNR. By engaging decision-makers in this collaborative endeavour, the MCDA framework can truly reflect the priorities, and values of SNR. This participatory approach not only strengthens the validity and credibility of the MCDA but also reinforces a sense of ownership and accountability among the decision-makers at SNR (Linkov & Moberg, 2012).

5. **Planning and extension** is the final step in the MCDA

It entails examining and utilizing the prioritized list of alternatives to make a conclusive decision and develop subsequent planning strategies (Linkov & Moberg, 2012). Also, a sensitivity analysis will be performed to identify if the MCDA is sensitive to changes in the weights per criterion (Gamper, Thöni, & Weck-Hannemann, 2006).

CAPEX and OPEX calculations

The calculation of CAPEX and OPEX for deNOx systems follows a specific approach, starting with a base case unit/emission point, in the case of SNR emission point O was used. The initial step involves estimating the CAPEX cost for each alternative for the emission point O, which serves as a reference point. To determine the CAPEX for other units at SNR, a factor based on the flue gas emissions from each unit is employed. This factor compares the flue gas emissions from a specific unit, referred to as unit X, with the emissions from unit O. By utilizing this factor, the CAPEX cost estimated for O is scaled accordingly to calculate the CAPEX for other units at SNR, Equation 1.6 gives the formula used for this calculation (Shell, 2023). This approach accounts for variations in the size and capacity of units, allowing for an estimation of the CAPEX required for deNOx systems in each specific unit. The equation is the same for OPEX calculations.

$$CAPEX_{unit.x} = CAPEX_{Emission\ point\ O} \times FlueGasFactor_{unit.x} \tag{1.6}$$

In addition to the aforementioned considerations, a complexity factor can be incorporated in the Excel tool, to address variations in the installation complexity of deNOx systems across different units. For now, this is not incorporated in this study, as there was too little time to find all the information about the units at SNR. This factor, can for example, acknowledge that not all units possess the same level of complexity when it comes to implementing these systems. The complexity factor considers various aspects such as process limitations and the availability of plot space. It captures the challenges associated with installing a deNOx system within the given plot space. Units with higher complexity ratings may face constraints or limitations that make the installation process more intricate and demanding. By incorporating the complexity factor into the calculation, the CAPEX estimation for each unit considers the unique circumstances and difficulties associated with installing deNOx systems. Equation 1.7 provides the formula that uses such complexity factor.

$$CAPEX_{unit.x} = CAPEX_{reference\ unit} \times FlueGasFactor_{unit.x} \times ComplexityFactor_{unit.x} \tag{1.7}$$

The CAPEX estimation for ULNB is a bit different. A reference case ULNB is used to compare the ULNB that will be installed in other units. In this research a reference case for a ULNB has an initial CAPEX of 45k for a 10MW burner (Shell, 2023). The CAPEX will differ for the MW size, instead of the flue gas flow for other NOx abatement systems. Equation 1.8 is the formula used to scale the ULNB to other unit sizes. This formula is used within Shell and has been checked by using real CAPEX costs for the units which have been installed with ULNB.

$$CAPEX.ULNB_{unit.x} = CAPEX.ULNB_{reference} \times (MW.Burner_{unit.x}/10)^{0.8} \times \#\ Burners \tag{1.8}$$

$CAPEX.ULNB_{unit.x}$: This represents the estimated CAPEX for installing ULNB technology in unit "x" of the plant or refinery.

$CAPEX.ULNB_{reference}$: This is a reference CAPEX for a known system. It serves as a base value for scaling the cost to other units with different parameters.

$MW.Burner_{unit.x}$: This term denotes the burner capacity in unit "x" of the plant or refinery, measured in megawatts (MW).

10: This is a normalizing factor, corresponding to the capacity of the reference burner used for the $CAPEX.ULNB_{reference}$.

^0.8: This factor is a common one in cost estimation models and comes from empirical observation. It reflects the economies of scale often seen in industrial processes – i.e., as the size of a system increases, the cost does not increase linearly but at a slower rate.

♯Burners: This symbol represents the number of burners in the specific unit "x".

Limitations and Delimitations MAUT

It is important to critically evaluate the boundaries and potential shortcomings of MAUT to ensure a comprehensive understanding of its applicability and potential challenges.

MAUT involves the aggregation of subjective judgments and preferences of decision-makers (D'Agostino, Parker, & Melià, 2019). The weighing of criteria and the selection of utility functions can introduce biases based on individual preferences, experiences, and cognitive limitations. These subjective factors may influence the final decision outcomes and potentially compromise the objectivity of the analysis.

The effectiveness of MAUT is heavily dependent on the availability and reliability of data. Data collection and measurement can be resource-intensive and subject to errors or biases (Keeney, 1982). Incomplete or inaccurate data can adversely affect the quality and validity of the MAUT analysis, potentially leading to unreliable results and recommendations.

MAUT is primarily designed to address decision problems with multiple criteria but often focuses on identifying the optimal alternative or ranking alternatives based on an aggregate score. The method may not incorporate explicit trade-offs or decisions involving conflicting objectives that cannot be easily reduced to a single criterion (Guitouni & Martel, 1998).

Understanding these limitations and delimitations is crucial for interpreting the MAUT results accurately and managing the expectations of decision-makers and stakeholders. By acknowledging these factors, it is possible to appropriately contextualize the findings and ensure that the MAUT analysis provides meaningful insights for the decision-making process in choosing the best NOx abatement technology for emission points in the refinery.

Excel MCDA Tool

An Excel-based tool was developed to conduct the MCDA. This tool, tailored specifically for SNR, will serve as a comprehensive platform for conducting MCDA, allowing decision-makers to assess and evaluate various technologies on predefined criteria. Recognizing that the landscape of technologies is constantly evolving, the tool has been designed to be adaptable. As more information becomes available on current technologies or new technologies emerge, decision-makers at SNR can easily update the tool to incorporate latest findings and insights.

3. NOX FORMATION AND ABATEMENT

This chapter, will initially delve into the explanation of NOx formation, as comprehending this process is fundamental for understanding the functioning of NOx abatement technologies. Additionally, this chapter encompasses a discussion on NOx abatement techniques that are either under development or are presently employed in various industries. Specifically, this thesis focuses on strategies to curtail NOx emissions during both the combustion process and after combustion. Subsequently, the second segment of this chapter addresses commercially available NOx abatement systems, which frequently incorporate a combination of different NOx abatement technologies in their setups.

3.1. NOx Formation

NOx formation has three primary mechanisms: Thermal, Fuel and Prompt NOx formation (Arachchige, 2020). Each mechanism contributes their own part in the NOx emission, shown in Figure 3-1 below.

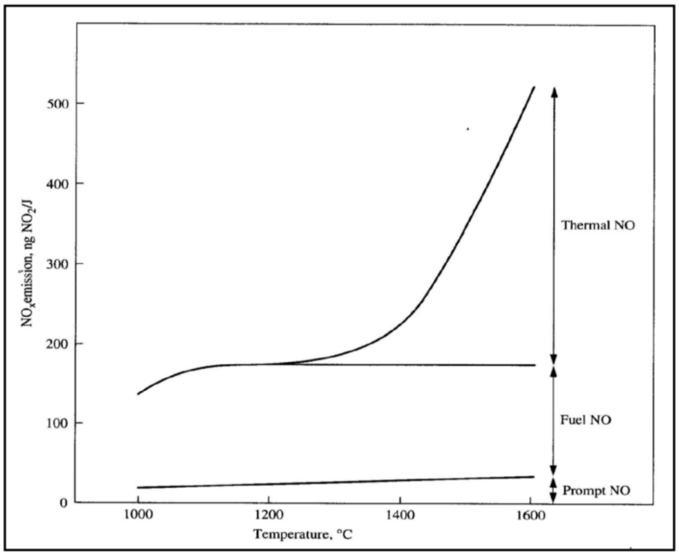


Figure 3-1: NOx formation in combustions processes. Three NOx formation mechanisms and their contribution to NOx emissions depending on temperature (Myrhaug, et al., 2012)

Thermal NOx

Thermal NOx refers to the formation of NOx due to high temperatures in combustion processes. Nitrogen and oxygen molecules from the air react and form the NOx compounds (Maroa & Inambao, 2020). Equation 3.1 describes the reaction involved in the formation of NO, while Equation 3.2 represents the reaction responsible for the formation of NO_2.

$$\mathrm{N_2 + O_2 \rightarrow 2NO} \tag{3.1}$$

$$\mathrm{N_2 + 2O_2 \rightarrow 2NO_2} \tag{3.2}$$

The flame temperature of carbohydrate combustion quickly exceeds 1600°C. Thus, Thermal NOx is the main contributor within Shell for NOx emissions.

Fuel NOx

In Fuel NOx the nitrogen which attached in the fuel itself forms into NOx, fuels such as coal and oil have high fuel bond nitrogen. The reaction between N_2 and oxygen form N_2O. The N_2O reacts with oxygen to form NO

(Maroa & Inambao, 2020). In 2009 SNR switched to gaseous fuels, which contain very little amounts of nitrogen. Thus, fuel NOx plays a very limited role in the NOx formation at SNR.

Prompt NOx

Prompt NOx involves the reaction of fragmented hydrocarbons with atmospheric nitrogen at low temperatures. A chain of reactions results in the formation of NOx, essentially, hydrocarbon radicals initiate a reaction with N_2, producing amines or cyano compounds. These newly formed compounds undergo further transformations into intermediate substances, which finally culminate in the formation of NOx (Maroa & Inambao, 2020). Prompt NOx occurs at the early stages of the combustion process (Maroa & Inambao, 2020). The prompt NOx mechanism only contributes to a small fraction of the overall NOx emissions, as seen in Figure 3-1.

3.2. NOx Abatement Techniques

This chapter explores NOx abatement techniques, grouped into two categories: combustion zone and end-of-pipe methods. Focusing on strategies to both prevent and treat NOx emissions, the aim is to provide a comprehensive overview of current best practices and innovations in the field.

3.2.1. Combustion Zone NOx Reduction Techniques

The combustion zone is the area in a combustion system where fuel is burned to produce heat. However, during this process, a significant amount of NOx is produced due to the high temperatures and presence of oxygen. This chapter will provide an overview of the different techniques that can be used for NOx reduction in the combustion zone, including their underlying principles, operating conditions, and potential benefits and drawbacks. The aim of this chapter is to provide a comprehensive understanding of the various NOx reduction techniques that are available in the combustion zone, which can aid in the selection of the most appropriate technique for a given combustion system.

Air/Fuel Staging

Air staging and fuel staging (fuel reburning) are techniques used to reduce NOx emissions in combustion processes. Air staging involves dividing the combustion air into two or more streams, introducing them into the combustion chamber at different locations (Zabetta, Hupa, & Saviharju, 2005). The primary air stream, containing most of the oxygen, enters first, followed by the secondary air stream (Orfanoudakis, et al., 2004). This creates zones of different air-to-fuel ratios, lowering the flame temperature and thus enabling lower NOx emissions. Similarly, fuel staging divides the fuel into multiple streams and introduces them at different locations, creating zones of different fuel-to-air ratios (Su, et al., 2009; Smart & Morgan, 1994). Both strategies can reduce NOx emissions by 30% to 60% and can be used individually or in combination, depending on the combustion system and operating conditions (Hodžić, Kazagić, & Smajević, 2016; Zabetta, Hupa, & Saviharju, 2005). In some cases, air staging can be achieved through multiple rotating air flows when burner size limitations exist, as in boiler applications. Appendix A.1 provides a more in-dept explanation of air or fuel staging.

Flue Gas Recirculation

Flue gas recirculation (FGR) is a technique used in NOx abatement technology to reduce NOx emissions in combustion processes. There are two types of FGR: internal and external. Internal FGR involves reintroducing a portion of the flue gas directly into the combustion chamber, reducing the temperature and oxygen concentration to lower NOx formation (Baolu, et al., 2018). External FGR introduces flue gas from outside the combustion system, typically from the flue stack, achieving significant NOx reduction but requiring larger and costlier equipment. The choice between internal and external FGR depends on factors such as application requirements, cost, efficiency, and emissions reduction goals (Baolu, et al., 2018). For a more in-dept explanation of internal and external FGR, Appendix A.2 provides a broader explanation.

Water/Steam Injection

Water or Steam is injected into the combustion process to reduce the flame temperature and limit the formation of thermal NOx (Londerville, et al., 2018). The injection process involves injecting water or steam into the flue gas stream prior to the catalytic converter (if present), which helps to lower the temperature of the gas stream and increases the amount of water vapor present (Schorr, 1999). More steam must be used to achieve the same NOx reduction as water injection (Shell, 2023). The injection of steam prior to the SCR reactor helps to improve the efficiency of the process by ensuring that the NOx is properly distributed throughout the catalyst bed, and by preventing hotspots and other temperature variations that can reduce the effectiveness of the catalyst. Additionally, the increased water content in the gas stream helps to prevent the formation of sulphur trioxide (SO_3) and other acidic compounds that can damage the catalyst and other downstream equipment (Shell, 2023).

The disadvantages of water or steam injection are reduced thermal efficiency, the flame can become instable and other pollutants emission may increase, such as CO (Londerville, et al., 2018). In many cases, water or steam injection is employed as an adjustment method to complement other techniques like ULNBs, aiming to maintain NOx levels below the permissible limits (Londerville, et al., 2018).

3.2.2. End-of-pipe Techniques

End-of-pipe techniques refer to the methods used to control NOx emissions after they have been generated in a combustion system. There are several end-of-pipe techniques available for NOx reduction, including, SCR, SNCR, wet scrubbing, electron beam, non-thermal plasma, and electrochemical NOx abatement. Each technique has its own unique advantages and disadvantages, and the choice of technique depends on the specific industry and operating conditions.

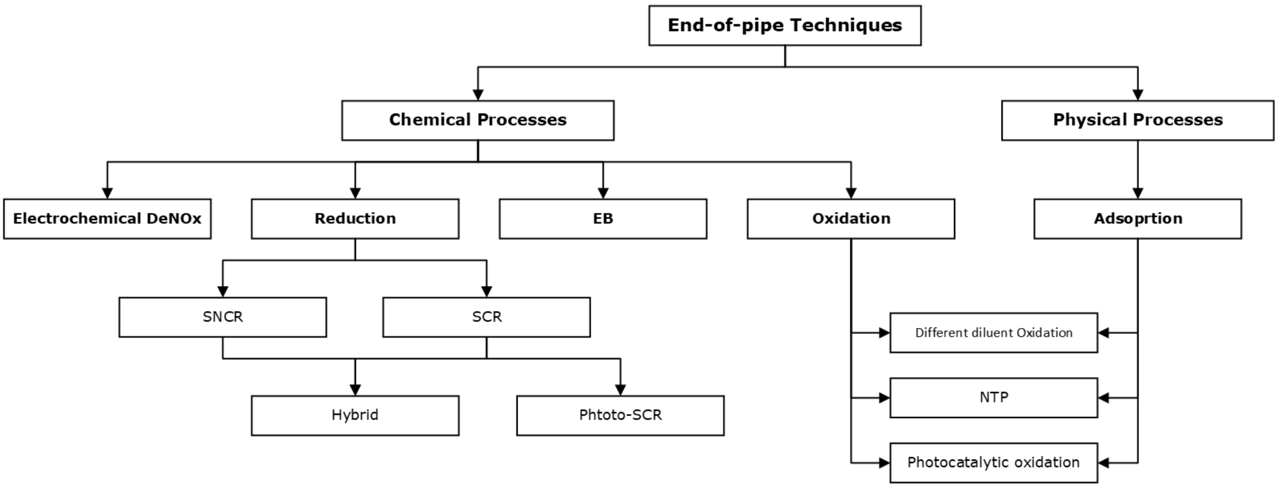


Figure 3-2: Overview of End-of-Pipe DeNOx Technologies. Note that NTP (Non-Thermal Plasma) includes all type of reactor set ups.

This chapter aims to provide an overview of the various end-of-pipe techniques that can be used for NOx reduction, including their underlying principles, operating conditions, and potential benefits and drawbacks. The chapter will also discuss the latest advancements in end-of-pipe techniques for NOx reduction.

Selective Catalytic Reduction

SCR involves injecting a reductant, typically urea or ammonia, into the exhaust stream. The exhaust gas containing NOx passes through a catalyst bed, where it comes into contact with the reductant. At high temperatures, the reductant decomposes into ammonia, which reacts with NOx in the presence of the catalyst, converting it into N_2 and H_2O (Ali, et al., 2021).

Selective Non-Catalytic Reduction

SNCR involves injecting a reducing agent, typically ammonia or urea, into the combustion chamber or flue gas stream at high temperatures. The injected reductant reacts with NOx in the presence of oxygen, resulting in a chemical reaction that converts the NOx into N_2 and H_2O through a series of intermediate reactions (Ali, et al., 2021). Unlike SCR, SNCR does not require a catalyst to facilitate the reaction but uses high temperatures. SNCR is a cost-effective solution for reducing NOx emissions, but its efficiency depends on factors such as temperature, residence time, and optimal injection locations

Electron Beam Irradiation

Electron beam (EB) irradiation is a dry-scrubbing technique that uses high-energy electrons to reduce NOx and SO_2 emissions in a gas stream at low temperatures (Alves, et al., 2022). The process involves humidifying the gas stream and then subjecting it to high-energy electrons, which create reactive species that interact with the pollutants, leading to various chemical reactions (Park, et al., 2019). Ammonia is added as an additive to oxidize and remove the NOx and SO_2, resulting in the production of valuable by-products that can be used as agricultural fertilizer or explosives (Alves, et al., 2022). However, the EB system has limitations such as high initial investment costs, high energy requirements, equipment complexity, and radiation concerns (Gholami, et al., 2020). Microwave enhanced EB technology shows promise in reducing the overall cost of the process (Sun, Zwolińska, & Chmielewski, 2015). For additional details on EB irradiation, please refer to Appendix A.3, which offers an in-depth exploration of the topic.

Photocatalytic DeNOx, Photo-SCR and Photo-oxidation

Appendix A.4 offers a comprehensive explanation of the following three methods employed for NOx abatement, providing a deeper understanding of each approach.

Photocatalytic decomposition

Photocatalytic DeNOx is a process that utilizes a photocatalyst, such as titanium dioxide (TiO2), to convert NOx into harmless substances like N_2 and O_2 (Nguyen, et al., 2020). The photocatalyst is exposed to UV light, which excites electrons and enables them to react with NOx molecules, breaking them down. The efficiency of the process depends on factors like light intensity, flow rate, photocatalyst concentration, humidity, and pollutant concentration (Ângelo, et al., 2013). The addition of compounds like silver nanoparticles can enhance the photocatalytic activity. This method shows promise for reducing NOx emissions in vehicle exhaust systems and industrial emissions (Lasek, Yu, & Wu, 2013).

Photo-Selective Catalytic Reduction

Photo-Selective Catalytic Reduction (photo-SCR) is an energy-efficient method of removing NOx pollutants by converting them into harmless N_2 using a catalyst excited by light irradiation (Lasek, Yu, & Wu, 2013). The reducing agents used in this process are NH_3 and CO, with CO being preferred due to its lower risk of NH_3-slip. Similar to traditional SCR, the role of a reductant like ammonia is to provide electrons that reduce NOx to nitrogen on the photocatalyst's surface. The photocatalyst facilitates the reaction by providing an active surface for adsorption and the necessary energy from absorbed UV light (Nguyen, et al., 2020). Photo-SCR offers advantages such as lower operating temperatures, reduced reductant usage, and improved NOx removal efficiency, making it a promising technology for reducing NOx emissions in industrial processes (Nguyen, et al., 2020).

Photocatalytic oxidation of NOx

Photocatalytic oxidation of NOx involves irradiating the surface of a photocatalyst, such as TiO_2, with light to generate electron-hole pairs. Water is also broken down into H+ and OH-. Active oxygen is produced on the photocatalytic surface, which reacts with NOx to form nitric acids (HNO_3) (Lasek, Yu, & Wu, 2013). The process requires the subsequent removal of nitric acid using a wet scrubber. Researchers are exploring various methods to enhance the activity of photocatalysts, including metal doped TiO_2 and carbon-based photocatalysts (Khanal, et al., 2021). The efficiency of photo-oxidation processes ranges from 20% to over 90% NOx reduction (Abdelsalam, et al., 2020; Khanal, et al., 2021), but these advancements are still in the early stages of development.

Electrochemical DeNOx

Electrochemical DeNOx is a process that uses electrochemical reactions to remove NOx and N_2O from flue gases. The exhaust gas is passed through a catalyst-coated electrode, where NOx is reduced to nitrogen gas and water through an electrochemical reaction (Alves, et al., 2022). This process utilizes a two-electrode system with an anode and a cathode separated by an electrolyte membrane. The cathode and anode sides are typically made of metal oxides or carbon-based materials (Gholami, et al., 2020). The reduction of NOx is still in the early stages of development, primarily in laboratory settings, and operates within a temperature range of 400°C - 800°C (Hansen K. , 2018; Alves, et al., 2022). This process offers potential advantages such as compactness, self-electricity production, and absence of by-products. Appendix A.5 provides further information about electrochemical DeNOx.

Non-Thermal Plasma

Non-thermal plasma (NTP) alone is not effective in reducing NOx emissions in the presence of oxygen (Paulauskas, et al., 2019). However, when combined with other techniques, it becomes a viable method for NOx reduction. The process involves applying a high voltage electrical discharge to the flue gas, breaking down NOx molecules into reactive species. These species then react with injected NH_3 to form n and water (Talebizadeh, et al., 2014; Xu, et al., 2009). The remaining NOx is further reduced on a catalyst bed using metals like platinum, palladium, or rhodium. This plasma-assisted catalytic reduction DeNOx process offers advantages such as increased efficiency, lower operating temperatures, reduced energy consumption, and improved catalyst lifespan (Skalska, Miller, & Ledakowicz, 2010). It is widely adopted in industrial facilities such as power plants and refineries. Two types of reactors, namely, Dielectric Barrier Discharge and Corona Discharge Reactors, are used to generate non-thermal plasma, for more information Appendix A.6.

Wet Scrubbing

Wet scrubbing is a process used to remove pollutants, from exhaust gases. It involves passing the gas through an aqueous solution that absorbs the pollutants. Various scrubbing liquids such as Fe(II)EDTA, hydrogen peroxide, potassium permanganate, sodium chlorite, urea, and ozone can be used (Gholami, et al., 2020; Sun, Zwolińska, & Chmielewski, 2015). The process is carried out in a scrubber, where the gas comes into contact with the liquid, allowing the pollutants to be captured. The efficiency of wet scrubbing depends on factors like gas composition, NOx concentration, temperature, humidity, and the type and concentration of the scrubbing liquid (Deshwal, et al., 2008). While wet scrubbing has the advantage of simultaneously removing SO_2 and NOx (Deshwal, et al., 2008), it generates a significant amount of liquid waste that can be mostly recycled but the remaining water needs cleaning (Sun, Zwolińska, & Chmielewski, 2015). For additional details on wet scrubbing, please refer to Appendix A.7.

Technology Readiness Level

Not all mentioned technologies are mature enough to be used at SNR. To limit the search for systems which can be implemented in SNR, SNR has asked to put a threshold of a Technology Readiness Level (TRL) of at least 7. Which means that the technology at least has a prototype that is tested in a realistic environment. The TRL scores of the technologies are based on information found in literature and personal communication with researchers that have been contacted via e-mail or via an online Teams meeting. Table 3-1 shows the TRL score of each abatement option and shows which options are below the TRL score of 7. This means that the following technologies will be used to further search for commercially available systems: Air/fuel staging, internal FGR, water/steam injection, SCR & SNCR, and Wet scrubbing. A more elaborate explanation of the TRL-levels is found in Appendix B.

Table 3-1: The TRL of each NOx abatement Technology. A higher TRL score indicates a greater level of technology application in the real world (Straub, 2015)

Technology	*TRL*	*Source*
Air/fuel staging	9	Used in ULNB
Internal FGR	8	Used in ULNB
External FGR	6	Tests have been done, however, not applied in a realistic environment yet (Shell, 2023)
Water/steam injection	9	(Groebe, Domanski, & Gebhardt, 2021) Also, used in the gas turbines at SNR
SCR & SNCR	9	Systems are in use worldwide (YARA, 2023; Valmet, 2023)
Electron beam irradiation	6	(Basfar, et al., 2008; Park, et al., 2019; Holz, 2023)
Wet scrubbing	9	Companies exist that provide wet scrubbers for industrial purposes (Valmet, 2023; Elessent, 2023)
Photocatalytic decomposition	4	(Nguyen, et al., 2020; Lasek, Yu, & Wu, 2013)
Photo-SCR	4	(Yamamoto, Teramura, & Tanaka, 2016)
Photo-catalytic oxidation	4	(Abdelsalam, et al., 2020)
Electrochemical DeNOx	4	(Duarte, 2023; Hansen K. K., 2023)
Non-Thermal Plasma	6	(Talebizadeh, et al., 2014; Ma, et al., 2017)

3.3. Commercially Available NOx Abatement Systems

There are several commercially available NOx abatement systems, including Ultra Low NOx Burners (ULNB), SCR, SNCR, and hybrid systems that combine multiple techniques which have been discussed earlier in this chapter. Each system has its own advantages and limitations. This chapter aims to provide a comprehensive overview of the commercially available NOx abatement systems, their potential benefits and drawbacks, and the challenges associated with their implementation. The information presented in this chapter can be used as a guide for industries and policymakers in selecting the most appropriate NOx abatement system for their specific needs and complying with environmental regulations.

3.3.1. (Ultra) Dry Low NOx Burners and Ultra Low NOx Burners

(Ultra) Dry Low NOx Burners

Ultra-Dry Low NOx ((U)DLN) burners, a combustion zone abatement technology, operate on a set of principles that are designed to reduce the production of NOx. The first principle is the preheating of combustion air. Before being introduced into the burner, the combustion air is heated to high temperatures, resulting in a lean air-fuel mixture that effectively reduces NOx formation during combustion.

Secondly, the design of the burner itself plays a crucial role in minimizing NOx generation. The burner is structured to produce a stable and well-dispersed flame, which reduces NOx production. Notably, (U)DLN burners integrate specially crafted fuel injectors, combustion chambers, and flame holders to enhance the efficiency of the air-fuel mixture, further reducing the formation of NOx.

Another integral feature of (U)DLN burners is the incorporation of advanced control systems. These systems, equipped with high-end sensors and feedback mechanisms, offer precise regulation of the combustion process, which is instrumental in curbing NOx emissions. They provide real-time adjustments to the air-fuel ratio and other combustion parameters, ensuring optimal operation.

As a result of these combined features, (U)DLN burners achieve significantly low levels of NOx emissions, making them highly suitable for applications where stringent emission regulations are in place. In terms of compatibility, (U)DLN burners can be adapted for numerous gas turbines. These gas turbines utilize a lean, premixed flame in the combustor, which is different from the turbulent diffusion flame used in conventional gas combustors. In a lean, premixed gas combustor, the fuel and a surplus of air are mixed before entering the combustion zone, leading to reduced flame temperature and hence lower NOx production.

While retrofit (U)DLN may not be compatible with all gas turbine models, they have been successfully installed in many gas turbines in the U.S. (Shell, 2023). However, these retrofitting processes present varying levels of challenges. For instance, apart from silo combustors that are external to the turbine body, retrofitting could require modifications or replacements of the turbine's combustor section, related piping, and combustion control systems. Yet, with ongoing technological advancements, more manufacturers are offering gas turbines with guaranteed emissions as low as 9 ppm, marking a significant stride towards achieving lower NOx emissions (Thomassen Energy, 2023).

Ultra Low NOx Burners

Ultra Low NOx Burners (ULNB), a combustion zone abatement technology, employs innovative strategies such as fuel-staging, internal flue gas recirculation, and precise burner design to effectively minimize the generation of NOx emissions. Here's a breakdown of how these methods work:

6. Fuel-staged technology: ULNB utilize a fuel-staged approach, introducing the fuel in two distinct stages as illustrated by the green arrows in Figure 3-3. Initially, a lean fuel combustion zone is created where the majority of NOx is typically formed due to thermal NOx contribution. This is followed by a fuel-rich combustion zone, resulting in an overall cooler flame. By limiting the amount of air in the first stage, the availability of oxygen for NOx formation is reduced.
7. Internal Flue gas recirculation: The temperature of the flame plays a crucial role in NOx formation. ULNB achieves lower flame temperatures through various means, one of which involves recirculating flue gas from within the combustion zones. This process, depicted by the yellow and red arrows in Figure 3-3, involves reintroducing flue gas, which has a lower temperature compared to the flame.
8. Burner design: The design of the burner, particularly the shape of the orifice, also contributes to NOx reduction. ULNB employs specialized nozzles, both primary and secondary, equipped with exceptionally small orifices, typically less than 2mm in diameter. This precise design allows for better control over the combustion process, resulting in reduced NOx emissions.

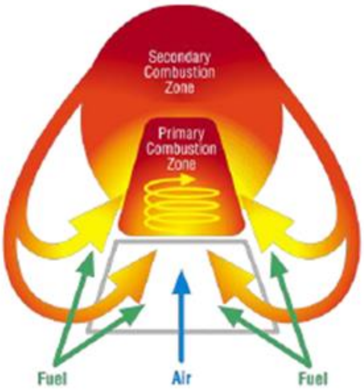


Figure 3-3: Schematic overview of ULNB. ULNB combines fuel staging with internal FGR (Baukal J. C., 2018).

Overall, ULNBs are designed to provide precise control over the combustion process, minimize the amount of oxygen available for NOx formation, keep the flame temperature low, and optimize the air-fuel mixture to reduce NOx emissions.

The latest generation of ULNB incorporates External FGR technology. External FGR is a technique that utilizes a minor stream of recycled flue gas outside the furnace firebox. This innovation can effectively reduce NOx emissions to as low as 30 mg/Nm^3 (Shell, 2023). However, implementation of this technique typically involves higher investment costs due to necessary modifications to the furnace and the installation of a blower to facilitate the recycle stream. Additionally, external FGR is associated with certain safety risks, such as the potential for pipe leakage on the process side, which could result in recycling flammable compounds into the flame. Despite its advantages, due to limited information availability, this technology is not yet included in this research. It is noteworthy that as more data becomes available and the technology matures, its potential for reducing NOx emissions could be evaluated further.

Difference (U)DLN and ULNB

(U)DLN burners are characterized by preheating combustion air and utilizing specialized burner designs, as well as advanced control systems. This results in lean air-fuel mixtures and a stable, well-dispersed flame that limits NOx formation. These features, in combination with their adaptability to numerous gas turbines, make (U)DLN burners an effective solution in applications requiring significantly low NOx emissions. On the other hand, ULNBs employ fuel-staging technology, internal flue gas recirculation, and precise burner design to mitigate NOx emissions. Fuel-staging results in an overall cooler flame, while internal flue gas recirculation lowers flame temperature, both processes effectively reducing the generation of NOx. Additionally, the specialized nozzle design in ULNBs provides better control over the combustion process.

Importantly, the application of these burners differs significantly: (U)DLN burners are typically employed in gas turbines due to their efficiency and emission performance, while ULNBs find broader use in a variety of industrial combustion applications but are generally not used in gas turbines. The choice between these technologies is dictated by the specific requirements of the combustion process, operational constraints, and regulatory compliance needs.

3.3.2. Low Temperature Oxidation (LOTOX)

LOTOX, an end-of-pipe NOx abatement system, is a patented technology designed to remove NOx and other pollutants from waste gas streams. It functions as an end-of-pipe system by utilizing total oxidation of NOx, to convert them into soluble N_2O_5, which is then absorbed in a wet scrubbing system. The LOTOX process typically involves the injection of a reducing agent, ozone (O_3), into the exhaust gas stream. The reducing agent reacts with the NOx in the presence of a catalyst to N_2O_5. The catalyst used in the LOTOX process is typically a metal oxide or a combination of metal oxides (Groebe, Domanski, & Gebhardt, 2021).

$$\mathrm{NO} + \mathrm{O_3} \rightarrow \mathrm{NO_2} + \mathrm{O_2} \tag{3.3}$$

$$2\mathrm{NO_2} + \mathrm{O_3} \rightarrow N_2\mathrm{O_5} + \mathrm{O_2} \tag{3.4}$$

Liquid phase reaction:

$$\mathrm{N_2O_5} + \mathrm{H_2} \rightarrow 2\mathrm{HNO_3} \tag{3.5}$$

The initial gas phase reaction occurs almost instantly, followed by a second swift gas phase reaction, resulting in the formation of N_2O_5. The third reaction, which takes place in the liquid/gas phase, is completed within seconds. Previous publications and patents on LOTOX technology have stipulated that it is imperative to convert all NO to NO_2 before it can be reduced to NOx. It's worth noting that the reduction of gaseous NOx emissions has a trade-off in the form of waste water treatment, particularly in terms of the handling of nitrates (Groebe, Domanski, & Gebhardt, 2021). Figure 3-4 and 3-5 provide a schematic overview of the LOTOX combined with a wet scrubbing system would look like.

The LOTOX technique works at lower temperatures than traditional NOx abatement (NOx removal) techniques, which typically operate at temperatures greater than 200°C. The LOTOX process can operate at temperatures as low as 50°C (Linde, 2023), making it suitable for a wide range of applications where low-temperature exhaust gases are generated. One of the advantages of the LOTOX technique is its ability to operate under variable exhaust gas conditions, such as varying flue gas rates.

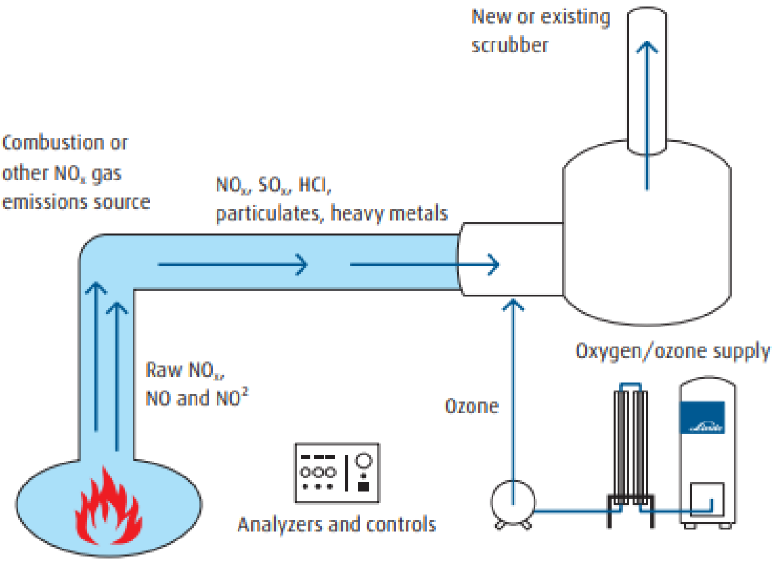


Figure 3-4: Schematic overview of LOTOX process (Groebe, Domanski, & Gebhardt, 2021).

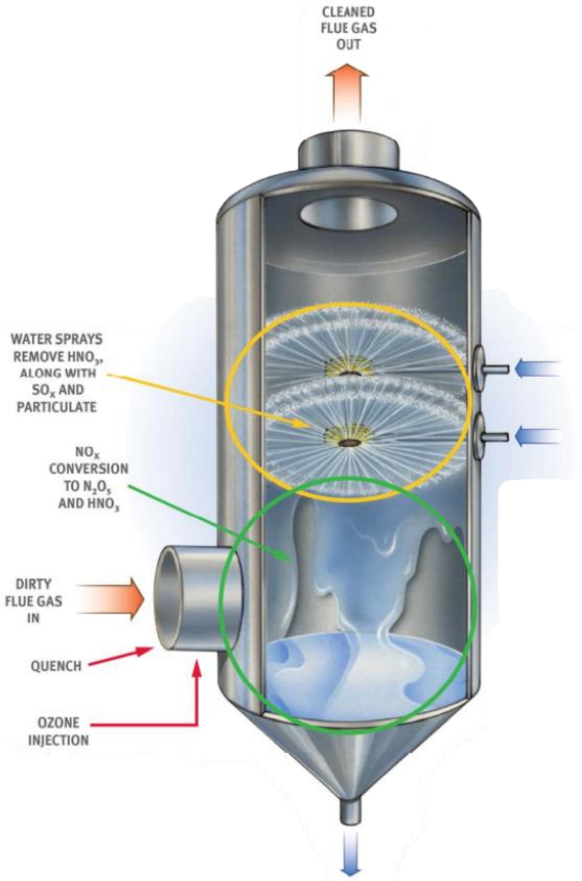


Figure 3-5: Overview of wet scrubber (Elessent, 2023)

Overall, the LOTOX technique offers an efficient and cost-effective way to remove NOx from industrial exhaust gases, making it an attractive option for a wide range of industrial applications.

3.3.3. Wet Scrubber using ClO_2

Oxidation of NOx is also done with other compounds, such as chlorine dioxide (ClO_2). The scrubber looks similar to the scrubber depictured in Figure 3-5, with the exception that ClO_2 is injected instead of ozone. ClO_2 solution is sprayed in the scrubber inlet to rapidly oxidize NO to NO_2 in the first stage of the scrubber, see Equation 3.6. The second stage of the scrubber NO_2 is absorbed to the circulation liquid, the circulation liquid consists of NaOH + sulfuric compound, shown in Equation 3.7 - 3.9. Absorption is controlled by adding sulfuric compounds to the washing process, this means that flue gas containing SO_2 will decrease the need of using additional sulphur. The liquid waste (effluent) is continuously removed from the process to the wastewater treatment (Valmet, 2023).

$$5NO + 2ClO_2 + H_2O \rightarrow 5NO_2 + 2HCl \tag{3.6}$$

Scrubbing reaction

$$3NO_{2(g)} + H_2O \ \rightarrow \ 2HNO_3 + NO \tag{3.7}$$

$$NaOH + NO + NO_2 \rightarrow NaNO_2 + H_2O \tag{3.8}$$

$$2NaOH + \ NO_2 \rightarrow NaNO_2 + NaNO_3 + H_2O \tag{3.9}$$

Higher inlet NOx concentrations, and thus larger reduction need, cause significantly higher chemical consumption. ClO_2 is generated on-site, as ClO_2 is an unstable and can decompose very quickly. There are multiple acid solutions which can be used to create ClO_2. In industries sodium chlorate is used as a raw material for the generation of ClO_2 (Jin, et al., 2006). One of the advantages of using ClO_2 and a wet scrubber is the simultaneous removal of SO_2 in the wet scrubber, which is a greenhouse gas that contributes to global warming.

3.3.4. SCR System

Selective Catalytic Reduction (SCR), an end-of-pipe NOx abatement technology, mixes ammonia or urea, air and NOx gas with the presence of a catalyst, typically this catalyst are metallic oxides (ceramics). To reduce cost of SCR systems aqueous ammonia can be used instead of urea (Valmet, 2023). As urea is a more expensive compound. Under high temperature the NO is reduced to N_2 and water (Ali, et al., 2021). Equation 3.10, 3.11 and 3.12, give the chemical reactions that take place in the SCR system.

$$4NH_3 + 4NO + \ O_2 \ \rightarrow 4N_2 + 6H_2O \tag{3.10}$$

$$2NO_2 + 4NH_3 + \ O_2 \ \rightarrow 3N_2 + 6H_2O \tag{3.11}$$

$$NO + NO_2 + 2NH_3 \ \rightarrow 2N_2 + 3H_2O \tag{3.12}$$

The flue gas containing NOx is directed into the SCR reactor, which contains a catalyst bed. The reducing agent is injected into the flue gas stream, which typically takes place at temperatures between 170°C and 550°C, in the most widely used SCR systems an outstanding efficiency was achieved at 300°C to 400°C (Shin, Choi, & Hong, 2022). Lower temperatures will decrease the conversion rate significantly (Shin, Choi, & Hong, 2022). The ammonia and NOx diffuse into the catalyst bed located in a reactor vessel, where they come into contact with the catalyst surface. On the catalyst surface the NOx and ammonia react and form N_2 and H_2O (vapor), which are released into the atmosphere.

The SCR process requires the use of a specialized catalyst that is capable of promoting the desired chemical reactions. Typically, the catalyst is a ceramic, such as, vanadium oxide (V_2O_5), titanium oxide (TiO_2) or Tungsten trioxide (WO_3) supported on a substrate such as silica or alumina (Shin, Choi, & Hong, 2022; Roy, Hegde, & Madras, 2009). The catalyst is designed to have a large surface area and high activity for the SCR reaction. Figure 3-6 presents a schematic overview of a SCR system.

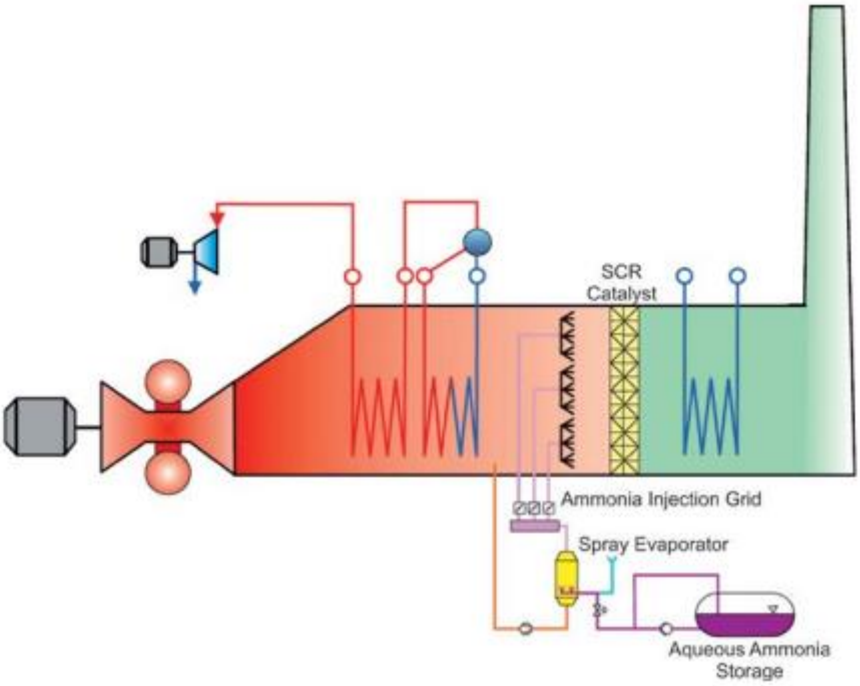


Figure 3-6: Schematic overview SCR (YARA, 2023)

To ensure optimal performance of the SCR system, ammonia is typically injected in a higher stoichiometric ratio, this results in ammonia slip (NH_3-slip). Thus it is important in the system design to maintain a proper balance between the NOx and ammonia concentrations in the exhaust gas. This can be achieved by monitoring the NOx emissions and adjusting the amount of ammonia added to the system accordingly to limit ammonia slip (Sargent & Lundy, 2022). Additionally, the SCR system may require periodic maintenance to replace the catalyst and ensure that the reactor vessel is free from fouling or other forms of degradation that could impair its performance.

3.3.5. SNCR System

The Selective Non-Catalytic Reduction (SNCR) process, an end-of-pipe NOx abatement technology, involves injecting a reagent, typically NH_3 or urea, into the combustion flue gas, which reacts with the NOx to form N_2 and H_2O, which is the same reaction used in SCR, presented by Equations 3.10, 3.11, and 3.12. The reaction occurs at high temperatures, typically between 850°C and 1175°C (Javed, Irfan, & Gibbs, 2007). The high temperature is needed as SNCR is known as a process that does not require a catalyst to promote the reaction.

The success of the SNCR process depends on several factors, including the temperature, residence time, and mixing of the flue gas and reagent. The injection location and pattern also play an important role in optimizing the process (Locci, et al., 2018). Like SCR the SNCR experiences NH_3 slip, due to excess ammonia.

SNCR can achieve NOx reductions of up to 90% for small incinerators (<10MW), but the effectiveness of the process depends on the specific application and operating conditions. This means that at higher powers, the effectiveness lies between 40-60%, due to the larger volumes of gas that must be treated under the constraints as discussed above (Locci, et al., 2018).

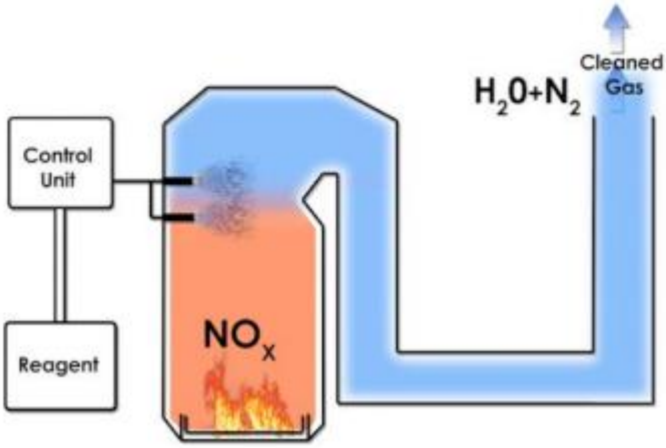


Figure 3-7: Schematic overview SNCR (YARA, 2023)

3.3.6. Systems Not Included in the MCDA

There are systems that have not been taken into account in the MCDA, as they are not installed enough, the system has outdated technology, or information scarcity about the system.

SCONOx

SCONOx is a catalytic system that operates after combustion to eliminate both NOx and CO from the exhaust of gas turbines, without the need for ammonia injection. It utilizes platinum as the catalyst, and potassium carbonate as the active reagent for NOx removal (Schorr, 1999).

The SCONOx process operates by introducing exhaust gases from a gas turbine into a reactor where they react with potassium carbonate coated on the platinum catalyst surface. The platinum catalyst oxidizes CO to CO_2, which is then released up the stack. NO is oxidized to NO_2 and reacts with the potassium carbonate absorber coating on the catalyst surface to form potassium nitrites and nitrates. The effective operating temperature range is 140 to 400°C, with the optimal temperature for NOx removal being 260 to 370°C, which is similar to SCR (Schorr, 1999).

To regenerate, a dilute hydrogen reducing gas (diluted to less than 4 percent hydrogen using steam) is passed across the surface of the catalyst in the absence of oxygen. The sections of reactor catalyst undergoing regeneration are isolated from exhaust gases using sets of louvers on the upstream and downstream side of each reactor box. When regeneration is completed in the three reactor boxes, the louvers on those reactors open, and the louvers on three other reactors close, and those reactors enter the regeneration cycle. Motor drives outside each box drive the shaft that opens and closes the louvers on each side of the box (inlet and outlet sides) (Shell, 2023).

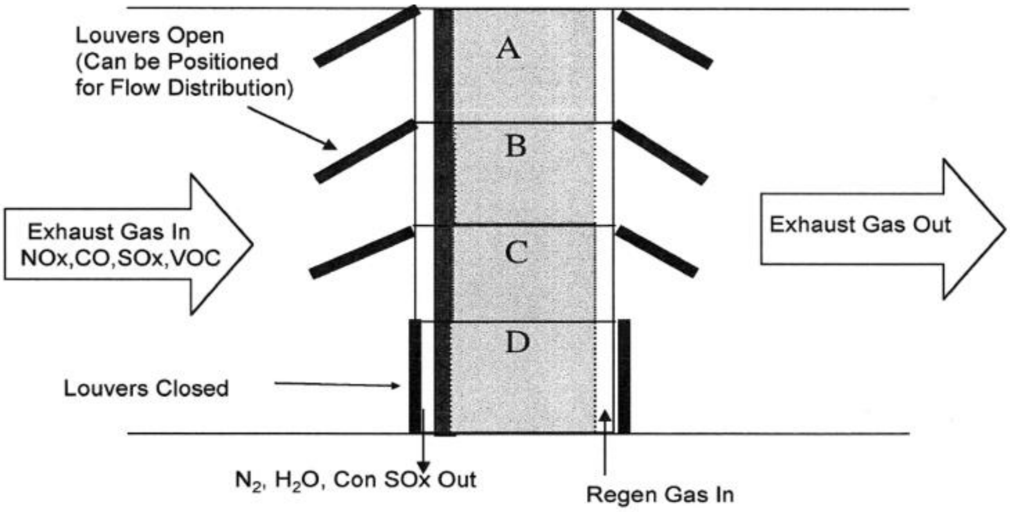


Figure 3-8: Diagram of SCONOx^{TM} (Shell, 2023)

Overall, SCONOx systems are effective in reducing NOx emissions from refineries, which can improve air quality and reduce the environmental impact of these facilities. However, there are several issues associated with the use of SCONOX. Firstly, it is highly sensitive to sulphur, even in small amounts in pipeline natural gas. Sulphur deteriorates the catalyst, making SCONOx not applicable to systems firing fuels other than natural gas (Shell, 2023). Secondly, the initial capital cost is about three times the cost of SCR, though this may reduce with increased operation. Thirdly, it has moving parts, and reliability and performance degradation due to leakage may be significant issues, especially when scaling up to larger gas turbines. Lastly, using any exhaust gas treatment technology (SCR or SCONOx) results in a pressure drop that reduces gas turbine efficiency (Schorr, 1999). Therefore, by adding a backend clean-up system, more fuel must be burned to reduce NOx, and SCONOX produces about twice the pressure drop of SCR.

While SCONOx was extremely effective in controlling both NOx and CO, SCONOx system required steam from the HRSG and natural gas from the supply pipeline to operate, which reduced overall unit efficiency by approximately 4%. The system costs Redding Power Plant approximately $1.2 million annually, including regular catalyst replacement costs, operations and maintenance costs, and efficiency losses. (Power, 2019). This resulted in Redding Power Plant to remove the SCONOx system and use SCR instead (Power, 2019), which shows that the SCONOx system is outdated and outperformed by a SCR unit. For this reason the SCONOx system will not be used as an alternative in the MCDA.

3.4. Advantages and Disadvantages of NOx Abatement Systems

Table 3-2 provides an overview of all the commercial NOx abatement systems and their advantages or disadvantages.

Table 3-2: Advantages and disadvantages of NOx abatement systems. Sources used: [1] (General Electric Gas Power, 2023), [2] (Thomassen Energy, 2023), [3] (Shell, 2023), [4] (Linde, 2023), [5] (Elessent, 2023), [6] (Valmet, 2023) and [7] (YARA, 2023),

NOx abatement System	Advantages	Disadvantages
(U)DLN [1] [2]	- Increased operational flexibility - Outage extension - Increased utilization - Extended turndown (50%) - Around 40% NOx reduction - Lower emissions of CO_2 - Fast and reliable ignition	- NOx reduction is limited compared with other systems (such as SCR) - Flashback can occur; upstream in the burner the fuel can ignite prematurely which damages the turbine - Sensitivity to fuel properties. Which allows only the use of natural gas.
ULNB [3]	- Cost-effective retrofitting of old burners - Enhanced combustion efficiency - Lower maintenance requirements (compared to other NOx abatement systems) - Enhanced operational flexibility - €45k for a 10MW burner, which means that overall, the CAPEX cost are very little compared to other NOx reduction methods	- Limited NOx reduction compared to other NOx abatement technologies, maximum of 50% - Increased CO - New combustion dynamics and operational challenges - Space and installation requirements.
LOTOX [4] [5]	- 95% NOx removal. - Removal till 1500 mg/Nm3. - Flue gas temperatures are below 200°C - Lower CAPEX than SCR - Easy to integrate into existing process - Flexible in plot space. Except for the wet scrubber. - Flexible operations (instantaneous startup/shutdown) - Low maintenance - Limited pressure drops	- Wastewater (denitrification) is required. - 7 ton/O_2 per hour for 5 ton/hour NOx reduction. 100kg O_3 costs around 2 million (high oxygen Consumption). Thus, high OPEX - Need for cooling water - Large electricity consumption: the generation of 1kg ozone requires 7.5 kW/h

	- SOx removal in the wet scrubber - No catalyst used. So, no catalyst deactivation or periodic replacements needed.	
Wet Scrubber using ClO_2 [6]	- 85% NOx removal - Low electricity consumption - Chemical consumptions can be adjusted continuously to reduction need - Lower CAPEX than LOTOX - Flue gas heat recovery available - If sulfur compounds are in the flue gas, efficiencies go up.	- Chloride in the wastewater, which needs to be treated. - ClO_2 can pose safety and handling challenges. - Higher efficiencies require adding sulfur compound. - ClO_2 generation at site required
SCR [6] [7]	- 90% NOx reduction. - 500.000 euro for a unit with a flue gas flow ~90 kNm^3/day - Catalyst can be rejuvenated - Lower operating temperature than SNCR. 300 - 400°C - Fuel flexibility - Continuous and reliable operation	- < 2 PPM NH_3-slip - Slight pressure drops (lowers GT efficiency), pressure drop from 1-15 mbar - Catalyst degradation or even poisoning - Maintenance every 1-5 years (depending on the flue gas composition) - High energy consumption - Large plot space is required - NH_3 can pose safety and handling challenges
SNCR [6] [7]	- Lower CAPEX than SCR - No catalyst needed - Low energy consumption compared to SCR - Simplicity in design and operation - Fast response time (rapid adjustments) - Reduced maintenance requirements (compared to SCR)	- 65% NOx reduction - NH_3 slip (10-20 mg/Nm3] - High energy if flue gas needs to be heated - Limited operating temperature +850°C - NH_3 can pose safety and handling challenges - Large pressure drops due to pre-heating 10-30 mbar

4. CASE OF SHELL: EMISSION POINTS

The case location is Shell Netherlands Refinery (SNR). SNR has in total 18 stacks that emit flue gas from various plants at the site. Each stack has different flue gas flows and NOx emissions, which result in the NOx load per year. In general, the larger the flue gas flow, the bigger the DeNOx system such as an SCR, should be to treat all the flue gas, resulting in higher cost. Furthermore, installing ULNB requires an assessment of the number of burners that should be replaced and what the duties are of these burners. Higher duties require larger burners, which are more expensive. As discussed before, the emission point itself is not the source of NOx formation, the fired equipment is the source of NOx formation. And multiple sources can be combined in a single stack. Table 4-1, provides the overview of the emission points of SNR.

Table 4-1: Overview of Emission Points at SNR. Disclaimer: the numbers are based on real numbers but have been altered because of confidentiality. These numbers, to a level, reflect reality. Some of the furnaces have already ULNB installed

Emission point	Flue gas Flows [kNm^3/d]	Average NOx emission [mg/ Nm^3]	NOx load [ton/year]	Total Duties [MW]	Number of Burners	Specification
HS1	5300	106	203	280		
HS2	13455	91	455	741		
O	77	196	6.5	20	2	
P	124	198	10	20	2	
Q	134	185	9.5	25	2	
N	46	99	2	11	2	
R	223	58	5	13	4	ULNB
I	1557	283	165	79	16	Horizontal burners
J	1337	145	73	70	15	Some ULNB
K	1053.4	68	25	35	6	ULNB
L	597	146	30	40	5	
M	619	182	41	37	15	
S	4099	55	80	180	1	SCR already in place
T	3462	163	200	162	1	
U/V	3710	140	195	170	1	
W	207	112	9	150	150	

Table 4-2 provides an overview of the plants that emit their flue gas through either High Stack 1 (HS1) or High Stack 2 (HS2). In this preliminary stage of evaluation and comparison for each emission point, the plants behind these HS 1&2 are analysed instead of the total stack. This is also done as it is easier to assess the individual plants than the whole stack in the case of these stacks. There may be a potential benefit in consolidating flue gas flows from multiple plants into an end-of-pipe NOx abatement technology, a strategy that could substantially lower overall costs and optimize the cost-efficiency of the NOx abatement technology.

Table 4-2: Overview of the plants that channel their flue gas to one of the High Stacks. Disclaimer: the numbers are based on real numbers but have been altered due to confidentiality. These numbers, to a level, reflect reality.

	Plant	Flue gas flows [kNm^3/d]	Average NOx Emission [mg/Nm^3]	NOx load [ton/year]	Duties [MW]	Number of Burners	Specification
HS1	A	2500	70	60	170	130	ULNB
	B	1600	80	57	80	4	
	C	1200	195	55	70	10	Some burners have ULNB
HS2	D	5050	140	257	277	24	Some burners have ULNB
	E	5000	70	119	280	25	ULNB
	F	3055	65	70	135	29	
	G	100	40	3	22	4	
	H	250	30	5	40	2	ULNB

5. OPERATIONALISATION MCDA

This chapter will provide an overview of the MCDA and its application in the selection of NOx reduction techniques for SNR. The chapter will discuss the different steps involved in the MCDA process, including the identification and weighing of criteria, and the evaluation of alternatives.

5.1. Identification of Criteria

The criteria for the MCDA were developed through a combination of literature review and collaborative brainstorming sessions with decision-makers within SNR. A hierarchy decision tree was used to assess which criteria can be used in this research (D'Agostino, Parker, & Melià, 2019) and guide the brainstorming session, Figure 5-1 provides the Hierarchy decision tree with the eventual set of criteria.

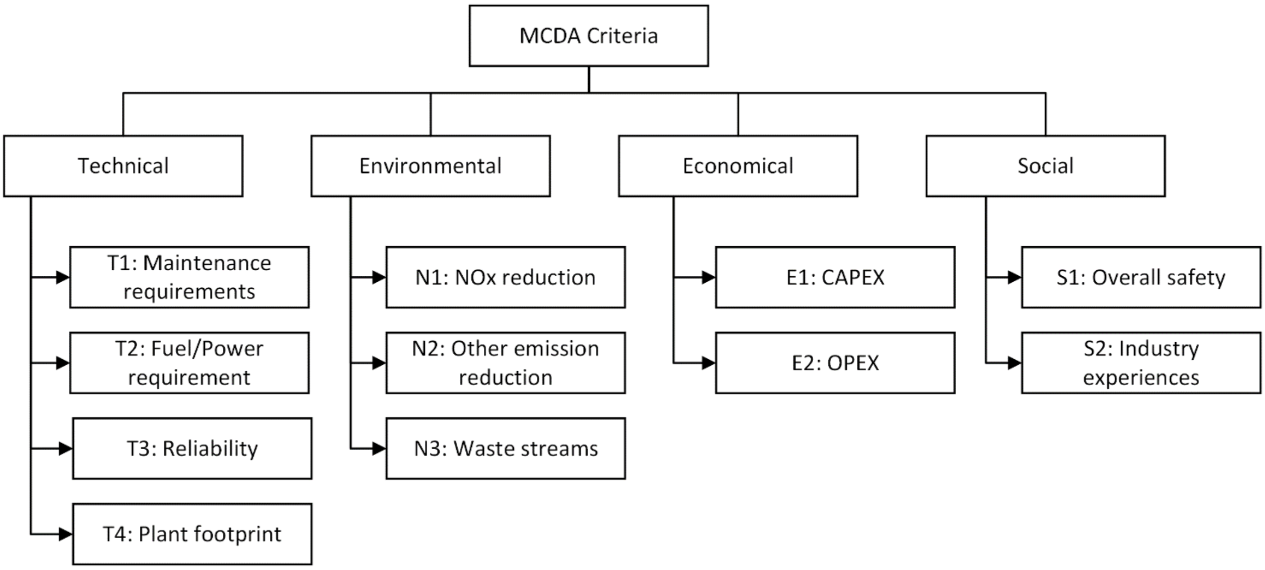


Figure 5-1: Hierarchy decision tree to assess which criteria are important to use in the MCDA (D'Agostino, Parker, & Melià, 2019)

Technical Criteria

T1: Maintenance requirements

Maintenance requirements are considered a criterion in the MCDA due to the fact that they directly affect the operational efficiency and longevity of NOx abatement systems. One might include this criterion within the OPEX, but the maintenance requirement by itself can provide the decision-maker with the ability to assess the level of effort, resources, and expertise needed to maintain and ensure the optimal functioning of the NOx abatement system. High maintenance requirements can lead to increased downtime, costly repairs, and the need for specialized personnel, impacting overall system performance. Systems with low maintenance requirements are more likely to be considered favourable choices, as they offer reduced effort and resources while maintaining consistent emissions control.

To quantify and compare maintenance requirements, a scale ranging from 1 to 5 is used. A rating of 1 indicates low maintenance requirements, implying minimal intervention, infrequent inspections, and straightforward maintenance procedures. A rating of 5 signifies high maintenance requirements, indicating complex procedures, and extensive monitoring and upkeep.

T2: Fuel/Power requirements

While it may seem somewhat unconventional to include fuel/power requirements as a criterion in a MCDA, it is, in fact, an important consideration. Typically, as with criteria T1, one might expect such requirements to fall under the operational expenditure (OPEX) category. However, the inclusion of fuel/power requirements as a separate criterion acknowledges its significant impact on the feasibility of implementing a NOx abatement system, particularly in complex industrial settings like refineries.

The reason for considering fuel/power requirements as a distinct criterion is rooted in practicality. High power demands associated with certain NOx abatement systems can pose challenges for their implementation within a refinery or similar contexts. Refineries often have specific power constraints and limited infrastructure, making it crucial to evaluate whether the available resources can accommodate the energy needs of the NOx abatement system. By considering fuel/power requirements as a criterion, decision-makers can proactively address potential hurdles related to power demand, preventing costly retrofitting or modifications to the facility.

A scale from 1-5 is used to score alternatives on this criterion. The scale emphasizes the importance of selecting NOx abatement systems with lower fuel/power requirements, as a lower score (1) indicates favourable characteristics that align with low requirements. A higher score (5) represents higher energy consumption, which is less desirable.

T3: Reliability

The reliability criterion assesses the system's ability to consistently perform its intended function without failure or breakdowns. It reflects the system's stability, durability, and dependability over time. High reliability ensures that the NOx abatement system operates consistently and effectively, minimizing the risk of unexpected downtime or inefficiency, and allowing for continuous emissions reduction. The scale used in MCDA for reliability ranges from 1 to 5, with 1 representing low reliability and 5 indicating high reliability.

T4: Plant footprint

The plant footprint of a NOx abatement system is a crucial criterion in a MCDA due to its direct impact on the physical space required for system implementation. The plant footprint refers to the actual size or area occupied by the NOx abatement system within the plant or facility. The size of the system can significantly affect the overall layout and utilization of the plant. A smaller footprint may be preferable in situations where space is limited or expensive, as it allows for efficient utilization of available resources. On the other hand, a larger footprint may be acceptable if the plant has ample space or if the system offers significant benefits in terms of performance or compliance with regulatory requirements. Plant footprint is measured in square meters [m^2].

Environmental Criteria

N1: NOx reduction

The reduction of NOx emissions from a NOx abatement system is measured in ton/year reduced NOx in this research. The reduction of NOx is a widely recognized and quantifiable indicator of environmental performance. It directly measures the effectiveness of a NOx abatement system in reducing harmful emissions, making it a straightforward and easily understood criterion. The ton/year of NOx reduction achieved provides a clear and concise metric to assess the environmental impact and overall efficiency of different NOx abatement technologies or strategies.

N2: Other emission reduction

Other emission reduction is a criterion, firstly, as it helps ensure a comprehensive evaluation of the environmental impact of the system beyond its primary objective of reducing NOx emissions. By assessing the system's effectiveness in reducing other harmful pollutants such as particulate matter, SO_2, Volatile Organic Compounds (VOC), and carbon monoxide, a more holistic understanding of its overall environmental performance can be obtained. Secondly, considering other emissions reductions reflects the broader regulatory framework and environmental goals. Governments and regulatory bodies often establish emission limits and standards for multiple pollutants, emphasizing the need for comprehensive emission control strategies. Hence, a system that scores high on this criterion not only achieves its primary objective of NOx reduction but also contributes significantly to the broader environmental goals of reducing air pollution and promoting environmental sustainability.

The scoring of this criterion is typically based on the percentage of reduction of these additional emissions. Each pollutant's reduction is calculated as a percentage of the total potential reduction achievable, and these percentages are then added together to give a cumulative score. For instance, if the system reduces particulate matter by 70%, SO_2 by 50%, and VOCs by 60%, the total score would be 180. The scoring of this criteria was formed by the brainstorm sessions with the decision-maker.

N3: Waste streams/emissions

The NOx abatement systems are designed to reduce NOx emissions from various industrial processes. However, the NOx abatement process often generates waste streams or by-products that need to be managed and treated appropriately, such as, wastewater. The inclusion of waste as a criterion in MCDA acknowledges the importance of sustainable and responsible waste management practices. The impact of these wastes on the environment, including potential contamination of soil, water, or surrounding ecosystems, is a critical consideration. Additionally, the potential health hazards associated with the handling, disposal, or release of these wastes can significantly impact human well-being.

Although the primary purpose of a NOx abatement system is to reduce NOx emissions, it is important to consider the potential by-products or secondary air emissions generated during the process. These by-products can include gases such as carbon monoxide (CO), carbon dioxide (CO_2), or ammonia (NH_3). Including air emissions as a criterion in MCDA allows decision-makers to assess the overall environmental performance and sustainability of different NOx abatement systems or technologies.

Scoring is done through a scale 1-5 with a score of 1 a system will not have any waste streams or emissions and a score of 5 a system will have large waste streams or emissions. The overall score considers the severity of emissions or waste, considering that a higher score reflects not only the quantity but also the detrimental impact of a specific emission or waste.

Economic Criteria

E1: CAPEX

CAPEX for a NOx abatement system is a criterion because it represents a crucial financial aspect that decision-makers need to consider when evaluating alternative options. The CAPEX criterion reflects the initial investment required to implement a NOx abatement system, including the costs associated with purchasing, installing, and commissioning the equipment. By including CAPEX as a criterion, decision-makers can assess the financial feasibility of different NOx abatement system options and compare their upfront costs. Moreover, considering CAPEX within the MCDA framework promotes cost-effectiveness and efficient resource allocation. Decision-makers can evaluate different NOx abatement system options and prioritize those that provide the best value for money, ensuring optimal utilization of financial resources while achieving the desired emission reduction goals. This criterion will be measured in Euros. Chapter 2 provides the logic behind the CAPEX calculations.

E2: OPEX

OPEX represents the ongoing costs associated with operating and maintaining the NOx abatement system. It includes expenses such as energy consumption, chemical reagents, maintenance, personnel, and other operational costs. OPEX provides insights into the economic efficiency of the system. Lower operating costs indicate higher cost-effectiveness and potential savings for refineries. Comparing the OPEX of different NOx abatement systems allows decision-makers to evaluate their financial viability and select the most economically advantageous option. OPEX will be measured in Euros/year.

Social Criteria

S1: Overall safety

The safety of NOx abatement systems is a crucial criterion in MCDA due to its significant impact on both process safety and personal safety. Process safety refers to the measures and practices that need to be put in place to prevent accidents, mitigate risk, and maintain the integrity of the overall process. Personal safety, on the other hand, pertains to the protection of workers from potential occupational hazards, including exposure to harmful substances or risks of accidents during system maintenance and operation.

Including safety as a criterion allows decision-makers to assess and compare the safety performance of different NOx abatement systems. The scale from 1 to 5, with 1 representing low safety and 5 indicating good safety.

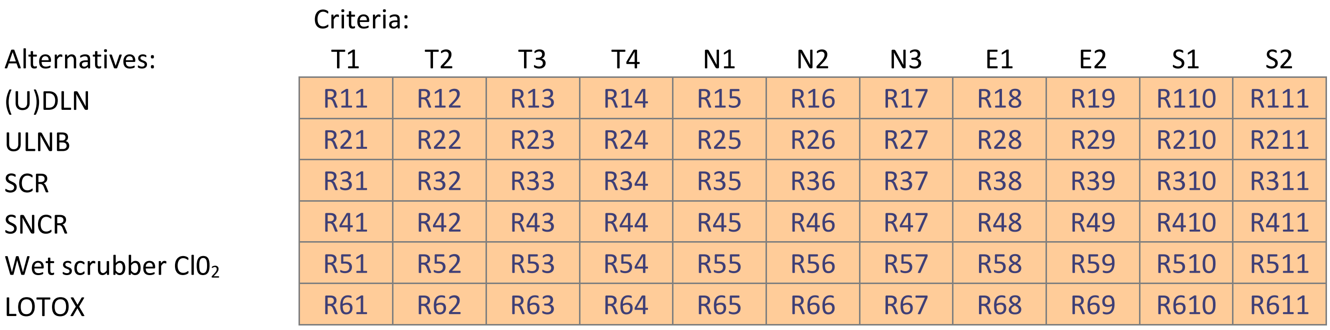
S2: Industrial experience

Industry experience reflects the track record and performance of a specific NOx abatement system in real-world applications. Industry experience helps decision-makers gauge the level of familiarity and acceptance of a particular NOx abatement system within the industry. A system with a strong industry presence and positive reputation is likely to have a wider network of suppliers, technical support, and available expertise, which can be advantageous during implementation and ongoing operations. Considering industry experience as a criterion in MCDA ensures that decision-makers prioritize solutions with a proven track record, minimizing the risks associated with adopting novel or untested technologies. The measurement unit of this criterion is a simple scale 1-3. With a score of 1 <100 references, a score of 2 is 100-250 and a score of 3 is >250 references.

Decision matrix

With the criteria and alternatives, the decision matrix can be created which is used in the MAUT method. Table 5-1 shows how the decision matrix looks like for the above-mentioned criteria and alternatives. The element R_{12} represents the value in the decision matrix corresponding to score alternative 1 ((U)DLN) scores on criteria 2 (Fuel/Power requirements).

Table 5-1: Decision matrix of MAUT with alternatives and criteria



	Criteria:										
Alternatives:	T1	T2	T3	T4	N1	N2	N3	E1	E2	S1	S2
(U)DLN	R11	R12	R13	R14	R15	R16	R17	R18	R19	R110	R111
ULNB	R21	R22	R23	R24	R25	R26	R27	R28	R29	R210	R211
SCR	R31	R32	R33	R34	R35	R36	R37	R38	R39	R310	R311
SNCR	R41	R42	R43	R44	R45	R46	R47	R48	R49	R410	R411
Wet scrubber $Cl0_2$	R51	R52	R53	R54	R55	R56	R57	R58	R59	R510	R511
LOTOX	R61	R62	R63	R64	R65	R66	R67	R68	R69	R610	R611

5.2. Weighing and Scoring

Weighing Criteria

Table 5-2 provides the weights that have been assigned to each criterion, with a score of 0 being not important at all and 1 being very important. Subsequently, a weight of 0 will ensure that the criterion is not considered in the MCDA. The Excel tool provides the decision-maker with the opportunity to deselect criteria. Which could be used when the decision-maker would prefer to look only at the NOx reduction and costs of systems or exclude other criteria.

It's essential to understand that the weight of the criterion “Overall safety” doesn't signify a lack of emphasis on safety by Shell. The installation of NOx abatement systems would not proceed without satisfying Shell's fundamental safety standards. The safety criterion offers perspective on the potential hazards associated with substances used within a NOx abatement system. Substances posing greater dangers should be managed with more stringent risk mitigation and safety protocols, which could add in the complexity of installing the system.

Table 5-2: The weights assigned to the criteria by the decision-maker

	Criteria:	Score unit:	Weight:
T1	Maintenance requirement	scale 1-5	0,65
T2	Fuel/Power requirements	scale 1-5	0,40
T3	Reliability	scale 1-5	0,70
T4	Plant footprint	m^2	0,75
N1	NOx reduction	Ton/year	1,00
N2	Other emission reduction	% + %	0,80
N3	Waste streams	scale 1-5	0,60
E1	CAPEX	€e3	0,90
E2	OPEX	€e3/year	1,00
S1	Overall safety	scale 1-5	0,40
S2	Industrial experiences	scale 1-3	0,40

Scoring the NOx abatement Alternatives

By combining information obtained from meetings with vendors of NOx abatement systems and leveraging the internal expertise within Shell, a comprehensive understanding of the alternatives can be achieved. This ensures a robust and informed decision-making process for selecting the most suitable NOx abatement system for the desired application.

The data gathered for each alternative is converted into a distinct score per criterion. As illustrated in Table 5-2, each criterion's score is expressed in different units. The following sections detail the scores allocated for each alternative according to the different criteria, ultimately determining the utility score of each alternative. This, in turn, will inform the final ranking of the alternatives.

T1: Maintenance requirements (scale 1-5)

1. (U)DLN: 2

(U)DLN burners typically have moderate maintenance requirements. Their maintenance needs may include periodic cleaning, inspection, and potential replacement of burner components (Shell, 2023).

2. ULNB: 2

ULNB also have moderate maintenance requirements. Similar to dry low NOx burners, they may require regular cleaning, inspection, and potential component replacements (Shell, 2023).

3. SCR: 4

SCR systems generally have higher maintenance requirements compared to burners. They involve the use of catalysts, ammonia injection systems, and temperature control mechanisms. Maintaining optimal catalyst performance, monitoring and replenishing reagent supplies, and periodic inspections are necessary for efficient operation (Valmet, 2023; YARA, 2023).

4. SNCR: 3

SNCR systems typically have moderate maintenance requirements. They rely on injecting ammonia or urea into the combustion process to reduce NOx emissions. Maintenance involves ensuring accurate injection rates, periodic calibration, and occasional cleaning of injection nozzles (Valmet, 2023).

5. Wet Scrubber using ClO_2: 3

Wet scrubber systems utilizing ClO_2 (chlorine dioxide) generally have moderate maintenance requirements. They involve the use of chemical reagents, pumps, and mist eliminators. Regular reagent replenishment, monitoring of PH levels, cleaning of mist eliminators, and periodic inspections are necessary for proper functioning (Valmet, 2023).

6. LOTOX: 4

LOTOX systems, a wet scrubber and ozone (O_3) injection, typically have higher maintenance requirements. They involve the use of ozone generators, chemical reagents, and associated equipment (Linde, 2023). Maintenance tasks include periodic cleaning, ozone generator maintenance, reagent replenishment, and inspections of the wet scrubber system (Elessent, 2023).

T2: Fuel/Power requirements (Scale 1-5)

1. (U)DLN: 1

(U)DLN burners, typically, do not have more fuel requirements than conventional burners (Shell, 2023). Which is why the (U)DLN scores a 1 on fuel and power requirements.

2. ULNB: 1

ULNB have also marginal fuel consumption differences compared to conventional burners (Shell, 2023). Which is why the ULNB also scores a 1 on fuel and power requirements.

3. SCR: 4

SCR systems use large amounts of ammonia or urea, which is injected in the flue gas system to reduce NOx. Subsequently, SCR systems have large power consumption due to controlling of injection of reagent and the control systems that monitors and optimizes the SCR process (YARA, 2023; Valmet, 2023).

4. SNCR: 3

Similar to SCR, SNCR uses large amounts of ammonia or urea, which is injected in the flue gas system. In general the electrical need for SNCR systems is lower than that of an SCR system (Valmet, 2023).

5. Wet scrubber using ClO_2: 4

The wet scrubber uses vast amounts of sodium chlorite to generate ClO_2 (Jin, et al., 2006). This generation requires electricity as well. Subsequently, the water circulation and treatment systems are needed for the wet scrubber (Valmet, 2023). These systems include pumps, water treatment equipment, and monitoring devices that consume electricity.

6. LOTOX: 5

The LOTOX system requires a large amount of O_2 for the generation of O_3. The conversion of O_2 to O_3 is an energy-intensive process, which requires a substantial amount of electricity and cooling water to facilitate the transformation (Linde, 2023). On top of that the LOTOX system, also has a wet scrubber, which requires the water circulation and treatment systems.

T3: Reliability (Scale 1-5)

1. (U)DLN: 4

(Ultra) dry low NOx burners are known for their high reliability. They have been extensively used in industrial applications and have proven to be reliable and effective in reducing NOx emissions.

2. ULNB: 4

ULNB are generally reliable and have been widely adopted in various industries to achieve low NOx emissions, as well as in SNR.

3. SCR: 5

SCR is a highly reliable NOx abatement technique. SCR systems have been extensively used in power plants and industrial facilities, and they have a proven track record of reliability and effectiveness in reducing NOx emissions.

4. SNCR: 3

While SNCR can be effective in reducing NOx emissions, its reliability can vary depending on factors such as temperature, residence time, and uniform distribution of the reagent. Proper design and operation are crucial to achieving optimal performance and reliability.

5. Wet scrubber using ClO_2: 3

The reliability of such systems can be influenced by factors like chemical dosing, pH control, and the presence of other pollutants in the flue gas. Proper maintenance and operation are essential to ensuring reliable performance.

6. LOTOX: 3

The reliability of this technique can be influenced by factors such as ozone generation, control of reaction conditions, and the potential for other byproducts. Careful system design and operation are important for maintaining reliability.

T4: Plant footprint (m^2)

In assessing the plant footprint criterion for each NOx abatement system (except (U)DLN & ULNB), this research utilizes emission point O as a reference case. This approach is adopted due to the direct correlation between the size of the system's footprint and the flue gas flow it handles. Since larger plants tend to accommodate higher flue gas flows, the scoring is adjusted based on the flue gas flow factor relative to the Emission point O. This method ensures a fair evaluation by considering the scalability and efficiency of the NOx abatement systems across different plant sizes.

1. (U)DLN: 10 [m^2]

Require a very small extra footprint compared to conventional gas turbines. The score the (U)DLN will have on this criterion is 10 m^2.

2. ULNB: 1 [m^2]

The required footprint for ULNB are similar to conventional burners (Shell, 2023). There is hardly any extra space needed to retrofit ULNB in furnaces.

3. SCR: 100 [m^2]

The footprint of an SCR system includes the reactor, catalyst beds, ammonia/urea storage and injection systems, as well as associated infrastructure.

4. SNCR: 80 [m^2]

The footprint of an SNCR system is generally smaller compared to SCR. It includes the injection system, storage tanks, and associated infrastructure.

5. Wet scrubber using ClO_2: 25 [m^2]

Typically, a wet scrubber system for ClO_2 injection consists of several key components; the scrubber vessel, ClO_2 injection system and generation system, scrubbing solution delivery system (which include pumps and piping) (Elessent, 2023; Valmet, 2023). The overall footprint will be around 25 square meters.

6. LOTOX: 35 [m^2]

The footprint of a LOTOX system is similar to that of a wet scrubber with ClO_2 injection. It includes the wet scrubber components, ozone injection system, and associated infrastructure. The footprint of both the ozone generator and wet scrubber will be around 35 square meters (Elessent, 2023; Linde, 2023).

N1: NOx Reduction (%)

The reduction percentage will be used to calculate the NOx reduction achieved by the technology if installed in a unit.

1. (U)DLN: 40%

According to systems that have been placed the NOx reduction that can be achieved with (U)DLN are around 40% (Shell, 2023).

2. ULNB: 50%

The ULNB that have been installed at SNR have a NOx reduction percentage of around 50 (Shell, 2023).

3. SCR: 90%

According to YARA and Valmet their systems can achieve 90% NOx reductions (YARA, 2023; Valmet, 2023). The SCR system can achieve higher reduction percentages, approximately around 95%. However, with these high reduction levels, the occurrence of NH_3-slip becomes a significant issue, which is undesirable.

4. SNCR: 65%

Typically, the SNCR systems have a lower reduction rate than SCRs, as there is no catalyst used. According to YARA and Valmet their SNCR systems can in general achieve around 65% NOx reductions (YARA, 2023; Valmet, 2023).

5. Wet scrubber using ClO_2: 85%

The wet scrubber that uses ClO_2 injection to oxidize the NOx, can according to Valmet (2023), achieve a NOx reduction rate of 85%.

6. LOTOX: 95%

The system that reduces the NOx the most is the LOTOX system. LOTOX systems combine the injection of ozone (O_3) into the flue gas with a wet scrubber. This system can reduce NOx to 95% (Linde, 2023).

N2: Other emission reduction (% + %)

1. (U)DLN: VOC (15%)

The (U)DLN burners also reduce the formation of VOC. Typically around 15% VOC reduction is achieved.

2. ULNB: CO (20%) and VOC (20%)

Next to NOx, ULNB also reduce CO and VOC. The reduction of CO is around 20% and for VOC the reduction is also around 20%.

3. SCR: 0
4. SNCR: 0
5. Wet scrubber using ClO_2: SO_2 (80%) and PM (30%)

The wet scrubber can achieve high SO_2 removal rates (90%) and high Particulate Matter (PM) (30%) (Valmet, 2023; Elessent, 2023).

6. LOTOX: SO_2 (80%) and PM (30%)

The wet scrubber can achieve high SO_2 removal rates (90%) and high Particulate Matter (PM) (30%) (Valmet, 2023; Elessent, 2023).

N3: Waste streams (Scale 1-5)

1. (U)DLN: 0

No waste streams due to the (U)DLN.

2. ULNB: 0

No waste streams due to the ULNB.

3. SCR: 4

SCR systems inject ammonia into the flue gas stream to react with NOx and reduce its concentration. However, a small amount of ammonia may slip through the catalyst and be emitted along with the treated flue gas (YARA, 2023). Furthermore, the catalyst itself does not generate a waste stream as a by-product. However, over time, the catalyst may gradually lose its activity or become deactivated due to factors such as fouling or poisoning. This deactivation of the catalyst requires periodic replacement or regeneration of the catalyst material. When the catalyst needs replacement, the used catalyst becomes a waste stream.

4. SNCR: 5

The SNCR also has ammonia slip. Which is larger than that of an SCR (YARA, 2023). Ammonia is seen as a worse pollutant than NOx, which is why the SNCR scores lower than an SCR, even though there is no catalyst waste stream.

5. Wet scrubber using ClO_2: 2

ClO_2 Contaminated Water. Wet scrubbers that employ ClO_2 injection can generate wastewater containing chlorine dioxide, which requires appropriate treatment before disposal (Valmet, 2023).

6. LOTOX: 3

Ozone Residues. The LOTOX system, which includes ozone injection and a wet scrubber, may generate residues of ozone that need to be effectively managed and treated. Furthermore, the wastewater, generated by the wet scrubber should be denitrified (Linde, 2023).

E1: CAPEX (€e3)

Note: these costs exclude the installation cost, they reflect only the cost of the system itself. The real cost for installation, ductwork, and utilities is much higher for a refinery.

1. (U)DLN: 100k per ~175 MW

In this study it is assumed, that the gas turbines can be retrofitted with a (U)DLN package. The cost is considered around 100k.

9. ULNB: 45k per 10 MW unit

45k euro is the typical cost of a 10 MW burner, which have been installed in the past at SNR (Shell, 2023). The CAPEX of smaller or bigger units is calculated with the equation 1.8 in chapter 2.

10. SCR: 500k

A SCR is estimated to cost around 500k for Emission point O (YARA, 2023).

11. SNCR: 300k

As a SNCR is cheaper compared to a SCR, the estimated cost of a SNCR is around 300k for Emission point O (YARA, 2023)

12. Wet scrubber using ClO_2: 275k

The wet scrubber using ClO_2 consists of the wet scrubber and the ClO_2 production unit. The cost of this system is around 275k (Valmet, 2023).

13. LOTOX: 350k

150k for LOTOX, this includes the production of ozone + 200k for the wet scrubber (Linde, 2023; Valmet, 2023)

E2: OPEX (€e3/year)

1. (U)DLN: 25.000 per (U)DLN burner

The OPEX for (U)DLN typically includes maintenance costs for the burner, replacement cost of broken components and periodic inspections.

14. ULNB: 2.500 per ULNB

The OPEX cost for a ULNB are very difficult to precisely calculate, as not every year maintenance is required and there is only extra cost in the case something breaks down (part renewal). In other words, the maintenance is more on the call, if there are problems maintenance will be done. For example, some burners installed at SNR there has been no break downs since installation, thus no replacements needed of parts (Shell, 2023). An assumption is made that the cost for burners will be around 2.500 euros per burner.

2. SCR: 50.000

The OPEX for SCR includes the cost of the reagent, energy consumption for the system, periodic catalyst replacement, and maintenance. The estimated annual OPEX can range from 30,000 to 50,000 euros (YARA, 2023).

3. SNCR: 30.000

The OPEX for SNCR includes the cost of the reagent, energy consumption, periodic maintenance, and inspections. The estimated annual OPEX can range from 20,000 to 30,000 euros (YARA, 2023).

4. Wet scrubber using ClO_2: 17.500

The OPEX for this technology includes the cost of ClO_2 reagents, water consumption, energy for pump operation, and periodic maintenance. The estimated annual OPEX can range from 10,000 to 17,500 euros (Valmet, 2023).

5. LOTOX: 50.000

The OPEX for LOTOX includes the cost of ozone generation, water consumption, energy for pump operation, and periodic maintenance. The estimated annual OPEX can range from 30.000 to 50,000 euros (Linde, 2023).

S1: Overall Safety (Scale 1-5)

1. (U)DLN: 5

Their dry low NOx combustion process reduces the risk of corrosive damage. However, they may require careful management of combustion conditions to prevent incomplete combustion and other operational issues (Thomassen Energy, 2023).

2. ULNB: 5

They require precise control over combustion conditions, which might pose operational challenges but don't inherently cause significant safety concerns (Shell, 2023).

3. SCR: 3

The SCR system has a track record of being safe to use. However, this criterion looks at how dangerous the systems could be. This includes the materials used in the process. SCR uses NH_3 which is a dangerous substance for the environment and personal health (Centers for Disease Control and Prevention, 2023).

4. SNCR: 3

While SNCR can achieve significant NOx reduction, it may have lower efficiency compared to SCR and may result in increased ammonia slip, which can be a safety concern if not properly managed (Centers for Disease Control and Prevention, 2023).

5. Wet scrubber using ClO_2: 2

The use of ClO_2 may introduce additional safety considerations, as it is a strong oxidizing agent and requires proper handling and control to avoid hazards. Careful monitoring and maintenance are essential for safety (ChemicalSafetyFacts, 2022). ClO_2 is considered the most hazardous material compared to O_3 and NH_3.

6. LOTOX: 4

Ozone is a highly reactive and potentially hazardous substance. Ozone generators require proper safety measures, including monitoring ozone concentrations and ensuring adequate ventilation (GreenFacts, 2023).

S2: Industrial experience (Scale 1-3)

1. (U)DLN: 3

Many (U)DLN are installed worldwide. However, newer systems could have lower industrial experience than the older ones.

2. ULNB: 3

Within SNR there are already several ULNB installed, worldwide this will be well over 250 installed burners. As with the (U)DLN burners, newer systems could have lower industrial experience than the older more known ones.

3. SCR: 3

The companies that have been contacted have a combined a list of references over 1000 (YARA, 2023; Valmet, 2023; Mitsubishi Power, 2023). Considering there are more companies that sell these systems the industrial experience will be well over 250.

4. SNCR: 2

According to YARA (2023), industries generally show a preference for SCRs over SNCRs, resulting in lower industrial experience with the latter. This preference stems from the fact that SNCRs may be considered less future proof, especially as ELVs are being lowered.

5. Wet scrubber using ClO_2: 2

Wet scrubbing systems are common in the industry. However, the wet scrubber which uses ClO_2 is used less often. Valmet (2023) provided a list of 150 units that have been installed with a ClO_2 wet scrubbing system.

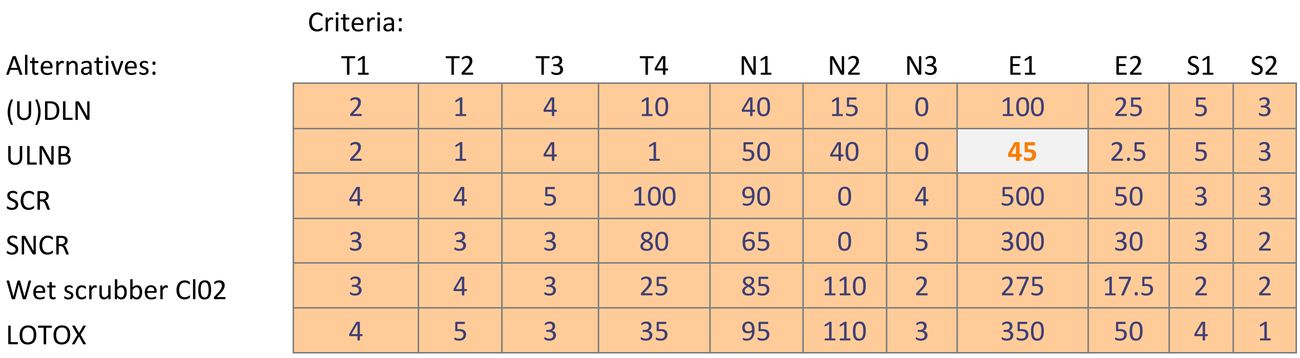
6. LOTOX: 1

Linde (2023) provided a reference list of 60 units that have been installed.

Filled Out Decision Matrix

Table 5-3 presents the decision matrix, calculated based on the assigned values. The scores for criteria T1, T2, T3, N2, N3, S1, and S2 remain constant for each emission point. Criteria T4, N1, E1, and E2 vary among the emission points, influenced by the flue gas flow and the number of burners at each emission source, which are given in Tables 4-1 and 4-2. Table 5-3 forms the foundational decision matrix for each emission point, with slight variations due to criteria T4, N1, E1, and E2. Moreover, not all alternatives are applicable to every emission point. If an alternative is unviable for a specific stack, it will be marked as "NA" for all criteria in the Excel file, leading to an eventual utility score of zero.

Table 5-3: Filled out decision matrix. Note that the N1 criteria is filled out as percentages.



Criteria:

Alternatives:	T1	T2	T3	T4	N1	N2	N3	E1	E2	S1	S2
(U)DLN	2	1	4	10	40	15	0	100	25	5	3
ULNB	2	1	4	1	50	40	0	**45**	2.5	5	3
SCR	4	4	5	100	90	0	4	500	50	3	3
SNCR	3	3	3	80	65	0	5	300	30	3	2
Wet scrubber Cl02	3	4	3	25	85	110	2	275	17.5	2	2
LOTOX	4	5	3	35	95	110	3	350	50	4	1

For each emission point in the excel file the final utility score of each alternative will be calculated. The final utility score will dictate the ranking of alternatives per emission point. A higher final utility score the higher the ranking is of the alternative. The calculation of the final utility score is done in the MCDA (MAUT) tab of the excel file. Appendix D provides an overview of the calculations that lead to the final utility score, of one of the emission points (emission point O) as an example. The excel file can also be examined for the calculations of all other emission points.

6. RESULTS AND SENSITIVITY ANALYSIS

Chapter 6 introduces the findings of the MCDA conducted for each emission point within SNR. This chapter provides a comprehensive evaluation and interpretation of the results obtained through the MCDA. Section 6.1 delves into the individual results of the MCDA for each emission point. It meticulously evaluates and interprets these results, facilitating an understanding of how various alternatives perform against the set of criteria. Section 6.2 shifts the focus towards a sensitivity analysis. Recognizing the inherent uncertainty and variability in the inputs of the MCDA, a rigorous sensitivity analysis is conducted to assess the robustness of the decision recommendations.

6.1. Results

The ranking of alternatives is done by looking at the final utility score. The higher the final utility score compared with other final utility scores of alternatives, the higher the ranking of the alternative will be for the emission point.

Table 6-1: Final utility scores of the alternatives for all emission points. The columns represent the emission points and the rows represent the alternatives.

	Emission point:																				
Alternatives:	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	18	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	10	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	10

Upon examining the results in Table 6-1, similar final utility scores of alternatives across certain emission points are observable. Such resemblances can be attributed to the comparable characteristics of these emission points in terms of flue gas flow, average NOx emission, and the number of burners. For instance, emission point O when looking at Table 4-1 has similar characteristics meaning it can serve as a representative for other points like P, Q, and N. However, Table 6-1 reveals that emission point O may also symbolize several other emission points with larger flue gas flows and a greater number of burners. This observation suggests that the specific input values of the MCDA for a particular emission point do not substantially impact the outcome. Consequently, emission points O, P, Q, N, B, C, D, F, H, I, J, L and M exhibit similar utility scores for each alternative.

The similarity in scores might be due to the absence of the complexity factor, which is a factor discussed in detail in Chapter 2. Each emission point has its own complexity which would make it more difficult per alternative to be installed at a certain emission point, this complexity factor captures that complexity. While there exist minor differences in the utility scores of the alternatives per emission point, the ranking of alternatives remains consistent across the named emission points.

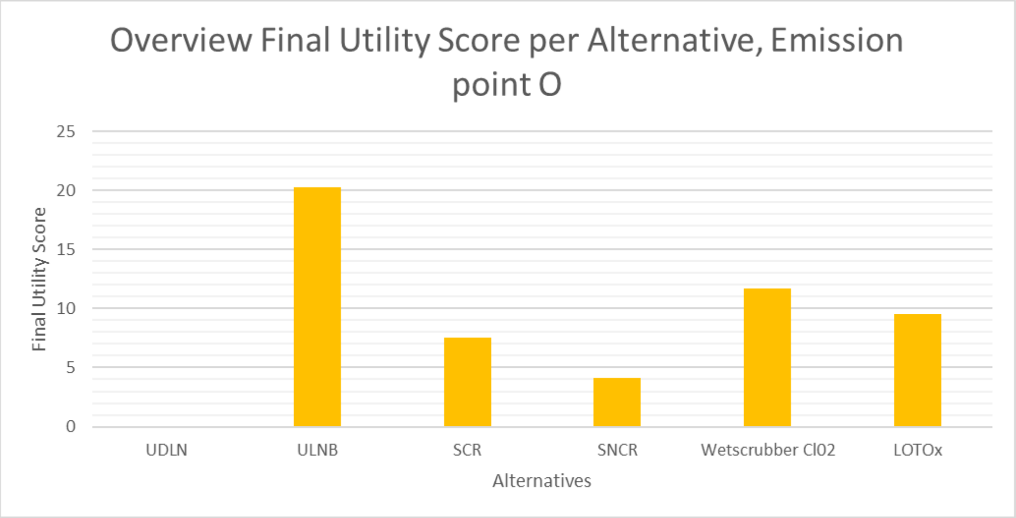


Figure 6-1: Overview Final Utility Score per Alternative for Emission Point O. This figure also represents the same final utility scores of emission points P, Q, N, B, C, D, F, H, I, J, L and M.

For the above mentioned emission points, all alternatives barring (U)DLN are considered, as it is not technically possible to install such system. The MCDA assigns the highest score to the ULNB, followed by the Wet Scrubber implementing ClO_2. The LOTOX system with a Wet Scrubber secures the third position, trailed by the SCR and finally, the SNCR. Figure 6-1 presents a column chart that provides a comprehensive overview of the final utility scores of each alternative for emission point O.

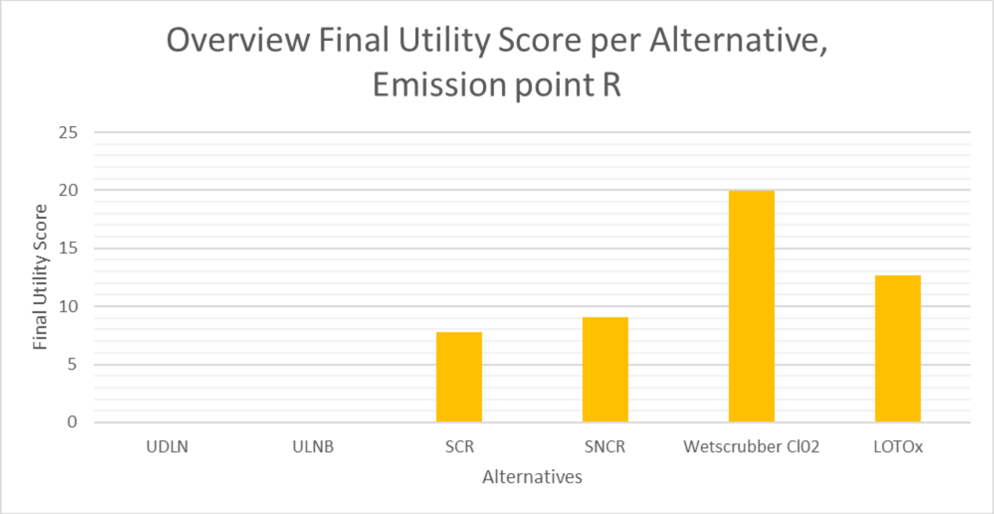


Figure 6-2: Overview Final Utility Score per Alternative for Emission Point R. This figure also represents the same final utility scores of emission points A, E, G and K

For the emission points where ULNB have been employed in the past and where (U)DLN implementation is not feasible, the outcomes are depicted in Figure 6-2. Again, a group of emission points, specifically A, E, G, K, and R, exhibit comparable results this is shown in Table 6-1. Despite the variances in flue gas flows across these emission points, the MCDA outcome appears to be relatively unaffected. Any changes in flue gas flow only have limited influence on the utility score, without significantly altering the outcome.

An intriguing observation emerges in the comparison between SNCR and SCR systems. Contrary to the trend observed in Figure 6-1, where SNCR markedly underperformed relative to SCR, for emission points R, A, E, G and K SNCR exhibits a final utility score which is a little bit higher than the SCR final utility scores for the units in consideration here.

Moreover, the Wet Scrubber using ClO_2 registers the highest utility score for emission points R, A, E, G, and K. Hence, with the current weights assigned to the criteria by the decision-maker, the Wet Scrubber could be considered a viable installation choice for these specific emission points.

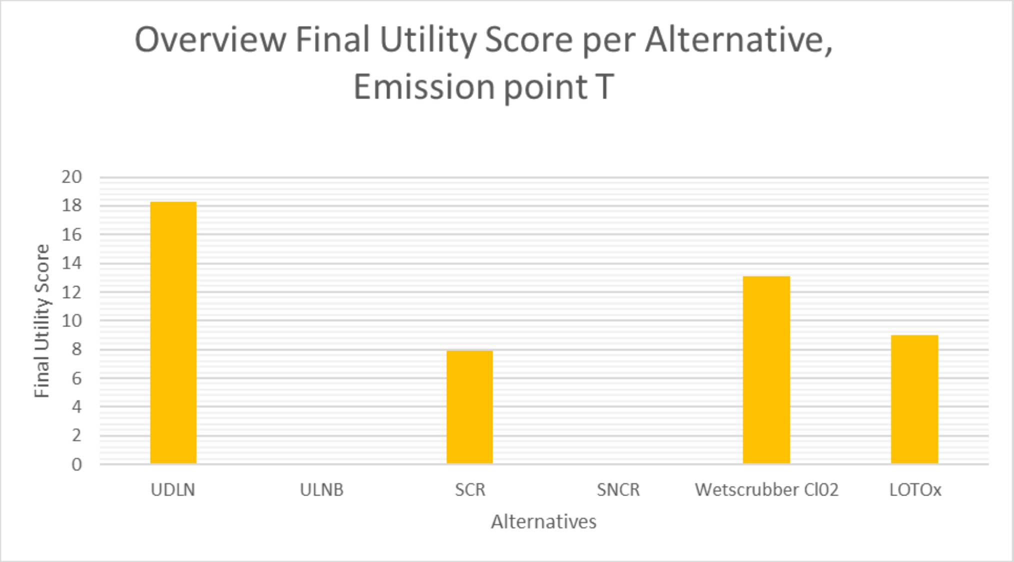


Figure 6-3: Overview of Final Utility Score per Alternative of Emission point T. This figure also represents the same final utility scores of emission points U and V.

Figure 6-3 presents the final utility scores for emission point T. Identical scores are observed for emission points U and V, also gas turbines. Given that the emission points are gas turbines, ULNB are not considered a technical feasible denitrification solutions. Simultaneously, due to the associated pressure drop, SNCR is deemed technically unfeasible as well. This narrows down the feasible options to four: (U)DLN, SCR, a wet scrubber utilizing ClO_2, and LOTOX.

The utility scores suggest that (U)DLN is the optimal solution for emission point T (and by extension, U and V). In scenarios where end-of-pipe systems are preferable, the wet scrubber with ClO_2 emerges as a promising alternative. For those instances requiring higher reduction levels, LOTOX and SCR perform similarly, though SCR holds a slight disadvantage.

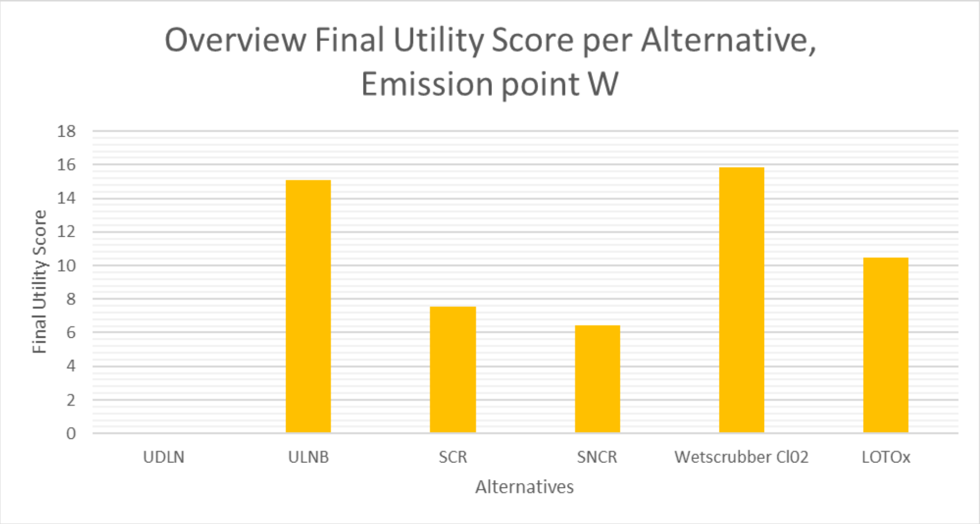


Figure 6-4: Overview of Final Utility Score per Alternative of Emission point W

Emission point W exhibits a distinct scoring pattern compared to the other emission points. Among the available technologies, ClO_2 Wet scrubbing stands out with the highest utility score, followed closely by the installation of ULNB, and then LOTOX. Conversely, the SCR and SNCR systems appear to have the lowest utility scores.

The uniqueness of emission point W stems from its multitude of burners (150 in total), which significantly escalates the cost associated with replacing each individual burner. Despite their small size, the overall expense involved in replacing these burners seems greater than that of implementing a ClO_2 wet scrubber. Furthermore, while the LOTOX system boasts lower CAPEX when compared to ULNB, it lags significantly behind ULNB in the final utility score. However, it is worth noting that the OPEX of LOTOX is nearly twice as high as that of ULNB, a factor that ultimately contributed to ULNB achieving a higher overall utility score.

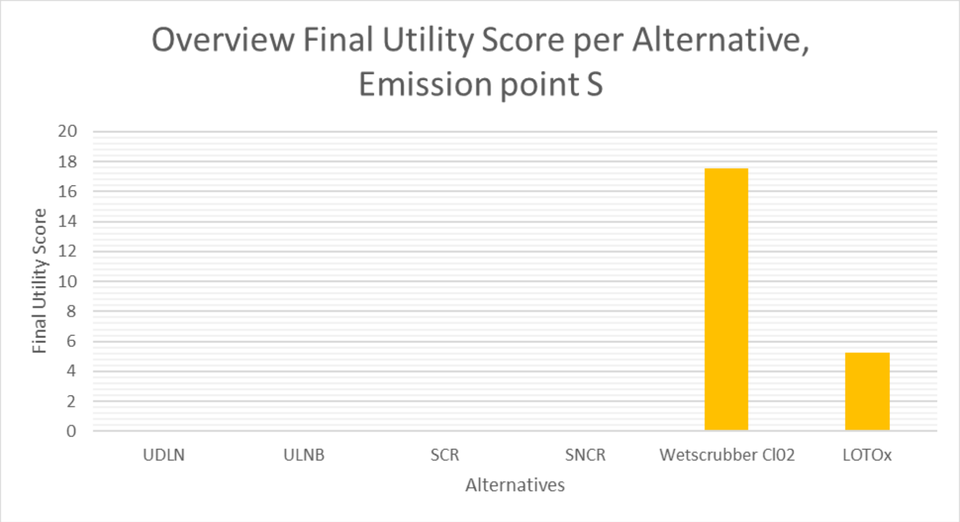


Figure 6-5: Overview of Final Utility Score per Alternative of Emission point S

The overview of the final utility score for the alternatives at emission point S is presented in Figure 6-5. This particular emission point stands out due to its existing SCR system, which was previously installed to mitigate emissions. As a result, to further decrease NOx emissions, only wet scrubbing solutions can be implemented.

Based on the final utility score, the recommended system for this emission point would be the ClO_2 wet scrubbing system.

One advantage of utilizing a wet scrubber following an SCR system is its capability to not only further reduce NOx emissions but also address NH_3, which is a by-product (known as NH_3-slip) of the SCR process. This combination ensures the most favourable emission profile for this specific emission point, providing comprehensive abatement of both NOx and NH_3.

6.2. Sensitivity Analysis

The sensitivity analysis will be carried out to assess the robustness and reliability of the MCDA (Cinelli, Coles, & Kirwan, 2014). This study will undertake a sensitivity analysis focusing on the weights assigned to the criteria, which is a conventional practice in MCDA methodology (Baumann, et al., 2019). The sensitivity analysis entailed a systematic procedure in which ranges were established at ± 0.1 relative to the respective values of the weights. Each weight underwent both an augmentation and reduction, while all other weights remained constant as set by the decision-maker.

The final utility score is the paramount output of MAUT, offering a definitive ranking of alternatives for a given emission point to the decision-maker. It is crucial that the final utility score remains relatively stable and doesn't undergo significant fluctuations which could affect the ranking of alternatives in response to alterations in criteria weights. In other words, the ranking of alternatives per emission point should not change if the weights of the criteria are changed!

An examination of the sensitivity analysis data in Excel, which is provided in Appendix E, reveals that none of the modifications to the weights led to a different ranking of alternatives for each of the emission points. While the final utility score of each alternative did exhibit variation, this did not bear an impact on the ultimate ranking of the alternatives per emission point, shown in Table E-2 of Appendix E. This indicates that the results of MCDA, as designed in Excel, remain robust and trustworthy, even when factoring in changes to the weights.

7. CONCLUSION

This chapter presents the conclusions drawn from this study and addresses the primary research question. In this research the MCDA method with MAUT was used to provide the answer to the central question of this research. The central question of this research is ***"What are the recommended NOx abatement options for reducing NOx emissions at Shell Netherlands Refinery, considering environmental, technical, economic, and social factors?"***.

For each of the 22 emission points at SNR, 6 NOx abatement technologies have been look at to see which option is most recommended per emission point. The NOx abatement technologies were: (Ultra) Dry Low NOx burners ((U)DLN), Ultra Low NOx Burners (ULNB), LOTOX, Wet scrubber using ClO_2 injection, Selective Catalytic Reduction (SCR) and Selective Non Catalytic Reduction (SNCR).

The NOx abatement technologies were evaluated against several criteria: T1: Maintenance requirements, T2: Fuel/Power requirements, T3: Reliability, T4: Plant footprint, N1: NOx reduction, N2: Other emission reduction, N3: Waste streams, E1: CAPEX, E2: OPEX, S1: Overall safety, and S2: Industry Experiences. Each criterion was assigned a weight by the decision-makers at SNR, the weights represent the relative importance of different criteria.

The findings provide valuable insights into the NOx abatement strategies for Shell Netherlands Refinery. The results from the MAUT demonstrated that the ULNB emerged as the most viable NOx abatement technology due to its consistently high final utility score across several emission points, specifically O, P, Q, N, L, I, J, E, M, F, D, B, and H. Meanwhile, at emission points R, A, E, G, K, S, and W, the ClO_2-based wet scrubber system stood out as the most recommended solution, displaying the top utility score. For the remaining emission points T, U, and V, the (U)DLN showed a higher final utility score, making it the recommended NOx abatement technology for these areas.

The research highlights that the SCR, SNCR, and LOTOX technologies are consistently discouraged as viable options due to their lower utility scores. However, it should be noted that SCR and LOTOX technologies may be considered in scenarios where NOx emissions must be reduced to levels exceeding 90% for a specific emission point, this could become reality when the ELV is lowered drastically. The SCR and LOTOX technologies offer the potential to achieve such high emission reduction percentages.

Given the unique operational characteristics of individual refineries, the results may not be applicable in general, but the application of the MCDA model is decidedly beneficial in aiding decision-making across the industry.

In conclusion, this research provides valuable insights for NOx abatement options at the Shell Netherlands Refinery. The ULNB, (U)DLN, and ClO_2 wet scrubber technologies emerge as the most favorable choices based on their utility scores and technological feasibility. These findings contribute valuable insights for decision-makers in implementing effective NOx abatement strategies that align with the refinery's technological and economic requirements.

8. DISCUSSION

In light of the findings, this research successfully demonstrated the significance of considering multiple criteria in the selection of NOx abatement systems using the MCDA model. A key finding was the affirmation of the model's prediction that the ULNB would be a preferable NOx abatement system, which aligns with the frequent installations in Pernis. This endorsement, however, was dependent on the number of burners in a furnace - as the number of burners increased, the utility score for ULNBs decreased.

However, it is important to note that while these combustion-based technologies show promise, their individual reduction rates may not be sufficient to meet the stringent emission limit values. Therefore, the adoption of an end-of-pipe system becomes necessary to achieve adequate NOx reduction. In cases where combustion-based systems cannot be implemented, the ClO_2 wet scrubber emerged as the top recommendation, as indicated by its highest utility score.

A significant limitation of this study stems from the relatively superficial treatment of cost analysis. For a more robust and comprehensive MCDA, an extensive exploration of CAPEX, inclusive of complexity factors, is warranted. This would potentially result in more refined, nuanced, and differentiated outcomes, enhancing the validity and reliability of the MCDA. In the current study, the absence of these detailed analyses has resulted in homogenized results for certain units, suggesting an oversimplification in the cost evaluation component of the model. A combined MCDA with a CBA could have resulted in a more robust and comprehensive argumentation and help support decision-makers.

Furthermore, using the complexity factor for each unit as a second scaling tool could aid in extrapolating the estimated cost of a system from smaller to larger units. This scalability assessment could provide more accurate cost projections for implementing NOx abatement systems in larger units, further enhancing the robustness of the MCDA and ultimately leading to more informed and accurate decision-making.

The quality and comprehensiveness of data also played a limiting role in this research. A more robust approach to data collection, including extensive interactions with commercial vendors, would have furnished the MCDA with a firmer base, making the results more reliable. However, the constraints of time precluded such exhaustive data collation. Moreover, in addition to reaching out to commercial vendors that offer NOx abatement systems for data collection, an alternative approach would involve directly contacting factories that have already implemented these technologies. This approach can potentially improve data availability and yield a greater pool of referenced data, thereby contributing to the creation of a more comprehensive and reliable dataset for the MCDA.

This study didn't delve into the forward-thinking analysis or 'future-proofness' of the NOx abatement systems. For instance, in the case of evolving emission standards that could push ELVs down further, an investment in a technology such as a wet scrubber, currently capable of reducing emissions by up to 85%, might become insufficient in the long term. If future ELVs were to mandate emission levels below this reduced rate, the refinery would find itself needing to invest yet again in a more efficient but also more expensive system, like the LOTOX.

The installation of a more costly unit with higher reduction capabilities might seem financially burdensome in the short term, but could prove to be more economically viable and environmentally sound in the long term, should stricter regulations come into play. It's crucial to incorporate this long-term perspective when choosing NOx abatement systems, especially given the potential for significant regulatory changes in the environmental sector.

9. RECOMMENDATIONS

Future research directions to complement this study can take several paths, addressing both the NOx abatement systems and the MCDA approach used for the selection of NOx abatement systems in refining industries.

This study didn't explore the potential of employing combinations of NOx abatement systems, such as SCR and wet scrubbing technologies, which could provide a more flexible and adaptive solution to meet changing regulatory standards and achieve superior NOx removal. Future research should consider this dimension to further optimize NOx abatement system selection and implementation.

Given the scarcity of literature on this topic, future research could focus on creating a repository of case studies and best practices regarding NOx abatement implementations in refineries. By sharing experiences and lessons learned from previous NOx abatement implementations, decision-makers would be better equipped to make informed decisions, ultimately improving the overall efficiency and environmental performance of their refinery's NOx reduction efforts.

It's essential to recognize that NOx emissions are not the only pollutants that refineries need to control. Future research should therefore address the interaction of NOx abatement technologies with other emission control systems. This could help identify synergistic or antagonistic effects, potentially affecting the overall effectiveness of emission control strategies.

A specific recommendation for a follow-up study could be to explore the feasibility of combining furnace installations, such as emission point O and P into a single stack. This research could potentially reveal more cost-effective and efficient installation options, further optimizing the application of NOx abatement systems.

Future research should also seek to enhance the MCDA model used in this study, perhaps by incorporating more detailed cost analyses, as expressed before, or exploring different combinations of NOx abatement systems. This could help in providing a more nuanced and reliable decision-making tool for refinery operators.

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APPENDIX A – IN-DEPTH EXPLANATION NOX ABATEMENT TECHNOLOGIES

A.1. Air/Fuel Staging

Air staging involves dividing the combustion air into two or more streams and introducing them into the combustion chamber at different locations (Zabetta, Hupa, & Saviharju, 2005). The primary air stream, which contains most of the oxygen needed for combustion, is introduced into the combustion chamber first, followed by the secondary air stream, which is introduced at a later time through a special wind-box (Orfanoudakis, et al., 2004). The fuel is also introduced into the combustion chamber in stages, corresponding to the different air streams. This creates zones of different air-to-fuel ratios within the combustion chamber, which allows for more complete combustion and lower NOx emissions.

By staging the air and fuel, the combustion process can be optimized to reduce the formation of NOx by controlling the temperature, oxygen concentration, and residence time of the combustion products. In particular, the primary air stream can be used to create a fuel-rich zone where the fuel is partially combusted and the temperature is relatively low, which reduces the formation of NOx. The secondary air stream is then introduced to complete the combustion process, providing additional oxygen to ensure that the fuel is fully burned.

Fuel staging, on the other hand, involves dividing the fuel into two or more streams and introducing them into the combustion chamber at different locations (Zabetta, Hupa, & Saviharju, 2005; Su, et al., 2009). The primary fuel stream, which contains most of the fuel, is introduced into the combustion chamber first, followed by the secondary fuel stream, which is introduced at a later time. This creates zones of different fuel-to-air ratios within the combustion chamber, which allows for more complete combustion and lower NOx emissions (Smart & Morgan, 1994).

By staging the fuel, the combustion process can be optimized to reduce the formation of NOx by controlling the temperature, oxygen concentration, and residence time of the combustion products. In particular, the primary fuel stream can be used to create a fuel-rich zone where the fuel is partially combusted and the temperature is relatively low, which reduces the formation of NOx. The secondary fuel stream is then introduced to complete the combustion process, providing additional fuel to ensure that the oxygen in the combustion air is fully consumed.

Overall, air staging and fuel staging are effective strategies for reducing NOx emissions from combustion processes by optimizing the combustion process to reduce the formation of NOx, ranging from 30% to 60% reduction (Hodžić, Kazagić, & Smajević, 2016; Zabetta, Hupa, & Saviharju, 2005). The choice of staging strategy depends on the specific combustion system and operating conditions, and both strategies can be used in combination for even greater NOx reduction.

A.2. Flue Gas Recirculation

In the context of NOx abatement technology, flue gas recirculation (FGR) refers to the process of introducing a portion of the flue gas from a combustion source back into the combustion chamber. There are two kinds of FGR, internal and external (Baolu, et al., 2018).

In the process of internal FGR, instead of extracting flue gas from the exhaust stack, internal FGR recirculates a portion of the flue gas directly within the combustion system. This recirculated flue gas is reintroduced into the combustion chamber or furnace at specific locations. Internal flue gas is recirculated back into the combustion process to reduce the temperature and amount of oxygen available for the formation of NOx, thus lowering the NOx concentration (Baolu, et al., 2018).

The recirculated gas is mixed with fresh air and fuel before entering the combustion process. This dilutes the oxygen concentration in the combustion chamber, which in turn reduces the temperature of the flame (Baolu, et al., 2018). Since NOx is formed at high temperatures, reducing the temperature of the combustion process helps to reduce the formation of NOx. Internal FGR systems require careful engineering and control to optimize the recirculation rate, location and mixing for effective NOX reduction.

Overall, internal FGR is an effective technique for reducing NOx emissions in industrial processes. It is a simple and cost-effective method that can be used in combination with other NOx reduction techniques to achieve even greater levels of emissions control.

External FGR, involves the introduction of flue gas into the combustion chamber from a source outside of the boiler or furnace, typically from the flue stack (Prakash, et al., 2018). The flue gas may first undergo treatment processes before reentering the furnace. External FGR can achieve 25-40% reduction for gas turbines, however, External FGR particularly works well when there are high temperatures and high pressures, resulting in 40+% reduction of NOx emissions (Prakash, et al., 2018).

External FGR is a simpler and more effective method for reducing NOx emissions, but it comes with some potential drawbacks. For example, because the flue gas is recirculated outside of the furnace the equipment may become large and costly (Baolu, et al., 2018). Internal FGR may be more complex, but it can provide a more controlled and stable combustion process with lower risk of corrosion and fouling. The choice between these methods depends on the specific requirements of the application and the trade-offs between cost, efficiency, and emissions reduction.

A.3. Electron Beam Irradiation

Electron beam (EB) irradiation process is a prosperous method investigated extensively as it reduces NOx and SO_2 emissions simultaneous (Alves, et al., 2022). Electron beam irradiation is a dry-scrubbing technique that uses high-energy electrons to break down pollutants in a gas stream at relatively low temperatures (<150°C) (Alves, et al., 2022). The gas stream is first humidified and then the stream is irradiated by high-energy electrons. Where molecules are excited and ionized, creating very reactive species, such as N_2^+ and H_2O^+. These reactive species interact with the flue gas molecules, generating multiple different chemical reactions (Park, et al., 2019). After, the NOx and SO_2 are oxidized, and ammonia is added as an additive for the NOx and SO_2 removal process (Park, et al., 2019). Ammonia creates the by-products $(NH_4)_2SO_4$ and NH_4NO_3, which can be commercialized as agricultural fertilizer or explosives (Alves, et al., 2022). These by-products create added value to the process.

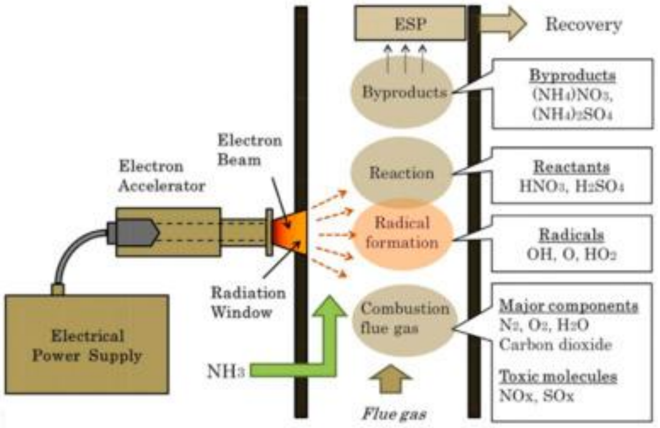

Figure A-1: Schematic Overview of Electron Beam Irradiation (Park, et al., 2019)

The limitations of EB systems are the high initial investment cost, high energy input to achieve high removal efficiencies, complexity of equipment, and problems regarding radiation of the process. Microwave enhanced EB could be a promising technology to reduce the cost of the whole process (Gholami, et al., 2020). The hybrid technology proves to be more efficient for NOx reduction, as NOx removal requires more energy (Sun, Zwolińska, & Chmielewski, 2015). To further increase the NOx removal a higher temperature of the inlet flue gas should be used, however, this does decrease the removal efficiency of the SO_2 (Basfar, et al., 2008).

A.4. Photocatalytic DeNOx, Photo-SCR and Photo-oxidation

Photocatalytic decomposition

Photocatalytic DeNOx or photocatalytic decomposition of NOx is a process that uses a photocatalyst to convert NOx into harmless substances such as N_2 and O_2 on the surface of the photocatalyst (Nguyen, et al., 2020).

The process works by first exposing the photocatalyst to light, usually ultraviolet (UV) light. This excites electrons in the photocatalyst, which are then able to react with molecules of NOx, splitting them into nitrogen and oxygen. This reaction occurs at the surface of the photocatalyst, which acts as a catalyst for the reaction.

The most commonly used photocatalyst for DeNOx applications is titanium dioxide (TiO_2), which is an inexpensive and abundant material that has strong photocatalytic properties (Ângelo, et al., 2013). The TiO_2 catalyst acts as a photocatalyst, meaning that it can facilitate chemical reactions through the absorption of light energy. TiO_2 can be used in both powder and thin-film forms, and is often coated onto a substrate to increase its surface area and efficiency.

The photocatalytic activity is highly dependent on several conditions, such as; light intensity and light spectrum, flow rate or residence time, concentration of the photocatalyst, air humidity, and concentration of pollutant in the flue gas (Ângelo, et al., 2013).

In order to make the process more efficient, additional compounds can be added to the system to enhance the photocatalytic activity of the TiO_2. For example, adding silver nanoparticles can improve the efficiency of the process by acting as electron traps, which helps to reduce the recombination of electrons and holes in the photocatalyst.

Overall, photocatalytic DeNOx is a promising method for reducing harmful NOx emissions, especially in applications such as vehicle exhaust systems and industrial emissions (Lasek, Yu, & Wu, 2013).

Photo-Selective Catalytic Reduction

Photo-Selective Catalytic Reduction (photo-SCR) removes the NOx by transforming the pollutant into N_2, without the use of high temperatures. Making photo-SCR a less energy demanding process compared to normal SCR (Nguyen, et al., 2020). As with normal SCR the technique uses a catalyst, but in photo-SCR the catalyst is exited using light irradiation. The reducing agents used are NH_3 and CO. CO is preferred, because using NH_3 can result into NH_3-slip.

In the presence of a reductant, such as ammonia, NOx can be reduced to nitrogen through a series of chemical reactions on the surface of the photocatalyst. The reaction are the same as for thermal SCR (Lasek, Yu, & Wu, 2013). The ammonia acts as a reducing agent, providing the necessary electrons to reduce NOx to harmless nitrogen.

The role of the photocatalyst in this process is to facilitate the reaction by providing an active surface for the adsorption of the NOx and the reductant, as well as providing the necessary energy to initiate the reaction. The UV light is absorbed by the photocatalyst, creating electron-hole pairs that are able to interact with the adsorbed species and promote the desired chemical reactions.

Overall, Photo-SCR offers several advantages over traditional SCR processes, including lower operating temperatures, reduced use of reductants, and improved NOx removal efficiency. It is a promising technology for reducing NOx emissions from industrial processes, such as power generation and refining, and has the potential to contribute to a cleaner and more sustainable future.

Photocatalytic oxidation of NOx

Irradiation on the photocatalyst (e.g. TiO_2) surface with light, positively charged holes (h^+) and negatively charged photoelectrons (e^-), in other words, electron-hole pairs are generated. Also, water breaks down into H^+ and OH^-. On the photocatalytic surface active oxygen is produced which reacts with NOx to form nitric acids (HNO_3) (Nguyen, et al., 2020; Lasek, Yu, & Wu, 2013).

$$\mathrm{NO} + \mathrm{OH}* \rightarrow \mathrm{HNO_2} \tag{A.1}$$

$$\mathrm{HNO_2} + \mathrm{OH}* \rightarrow \mathrm{NO_2} + \mathrm{H_2O} \tag{A.2}$$

$$\mathrm{NO_2} + \mathrm{OH}* \rightarrow \mathrm{HNO_3} \tag{A.3}$$

Photocatalytic oxidation differs from the other two photocatalytic NOx removal processes, as after the oxidation the nitric acid needs to be removed via a wet scrubber.

Researchers are researching different ways to improve the photocatalyst activity of TiO_2 and many more photocatalysts. Ranging from metal-doped TiO_2, to the use of carbon-based photocatalysts (Nguyen, et al., 2020; Abdelsalam, et al., 2020). For instance, research has shown that nanoparticulate Ta_2O_5 could obtain 2-fold higher efficiencies than TiO_2 catalysts (Khanal, et al., 2021). The efficiency of photo-oxidation processes range from low 20% to 90+% NOx reduction (Lasek, Yu, & Wu, 2013; Khanal, et al., 2021; Abdelsalam, et al., 2020). However, these advances are performed at a lab level, thus have a low TRL.

A.5. Electrochemical DeNOx

Electrochemical DeNOx is a process that uses an electrochemical reaction to remove NOx and N_2O from flue gasses. The process involves passing the exhaust gas through a catalyst-coated electrode, where the NOx is reduced to N_2 and H_2O via an electrochemical reaction (Alves, et al., 2022). The equation of the electrochemical reduction of NOx can be written as:

$$2\mathrm{NO} + 4\mathrm{e}^- \rightarrow \mathrm{N}_2 + 2\mathrm{O}^{2-} \qquad (\mathrm{A.4})$$

The process is typically carried out using a two-electrode system, consisting of an anode and a cathode, which are separated by and electrolyte membrane (Alves, et al., 2022). The cathode and anode sides are typically made of a metal oxide, such as titanium dioxide. However, other materials have also been studied, such as metal oxides and carbon-based materials (Gholami, et al., 2020).

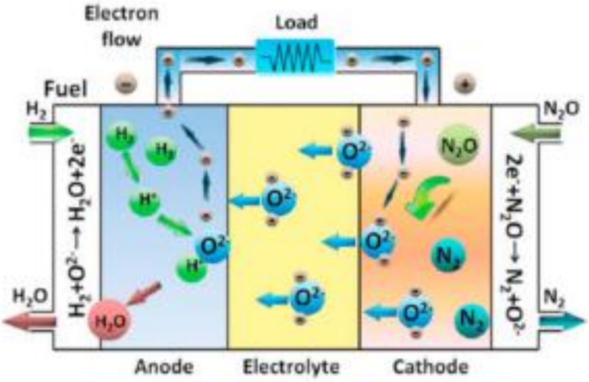

Figure A-2: Schematic Overview of Electrochemical DeNOx (Alves, et al., 2022)

At the cathode, the NOx undergoes a reaction with the flowing electrons in the external circuit, resulting in the production of N_2 and O^{2-}. The polarization potential allows for the permeation of these O^{2-} ions through the electrolyte membrane. At the anode, the O^{2-} ions participate in oxidation reactions (Alves, et al., 2022).

The electrochemical reduction of NOx is in a very early stage of development. Research is still being done on a laboratory scale. The operating temperature range is 400°C - 800°C (Hansen K. , 2018; Alves, et al., 2022). It has several advantages which could be useful in the future when the system is more mature, such as, the system is very compact and has its own electricity production which will lower the OPEX, there are no by-products to worry about (Duarte, 2023).

A.6. Non-Thermal Plasma

Non-thermal plasma itself cannot provide enough high NOx reduction, as it cannot convert NOx to N_2 when oxygen is present in the flue gas (Skalska, Miller, & Ledakowicz, 2010; Paulauskas, et al., 2019). When combined with other techniques it becomes a NOx reduction method. It can greatly improve the catalytic activity for NOx reduction at low temperatures (<200°C) when combined with SCR technologies (Mok, et al., 2004; Skalska, Miller, & Ledakowicz, 2010).

During the plasma treatment step, a high voltage electrical discharge is applied to the flue gas, which breaks down the NOx molecules into reactive species such as O, OH, HO_2 and O_3 (Talebizadeh, et al., 2014; Xu, et al., 2009). These reactive species can then react with ammonia (NH_3), which is injected into the flue gas, to form N_2 and H_2O. The catalytic reduction step occurs on a catalyst bed where the remaining NOx is reduced to N_2 and H_2O. The catalyst typically used is a metal such as platinum, palladium, or rhodium, which acts as a surface for the reaction between the remaining NOx and NH_3 to occur.

The plasma-assisted catalytic reduction DeNOx process has several advantages over traditional catalytic reduction methods. The plasma treatment step creates more reactive species, which can increase the overall efficiency of the process (Mok, et al., 2004; Skalska, Miller, & Ledakowicz, 2010). Additionally, the process can operate at lower temperatures, reducing energy consumption and improving catalyst lifespan. Overall, plasma-assisted catalytic reduction DeNOx is an effective method for removing NOx from industrial flue gas emissions, and is increasingly being used in power plants, refineries, and other industrial facilities. There are two types of reactors that generate non-thermal plasma, namely, Dielectric Barrier Discharge and Corona Discharge Reactors.

Dielectric Barrier Discharge Reactors

This reactor consists of two parallel electrodes that are separated by a dielectric material, such as Aluminium, glass or ceramic (Ma, et al., 2017; Talebizadeh, et al., 2014). The electrodes are connected to a high-voltage power supply that creates a high-frequency electric field between them. When a gas, such as air or oxygen, is introduced into the reactor, the high-frequency electric field causes the gas to ionize and form a plasma. The plasma consists of a mixture of charged particles, such as electrons, ions, and radicals, that can interact with the NOx in the gas and convert it into less harmful compounds . Advantages of using dielectric barrier discharge are that it is easily scalable, low operational cost and effectiveness is high (Talebizadeh, et al., 2014).

Corona Discharge Reactors

Corona discharge reactors are another type of plasma reactor that can be used for NOx reduction. This reactor consists of a single wire electrode surrounded by a concentric cylindrical electrode. When a gas, such as air or oxygen, is introduced into the reactor, a high-voltage power supply is used to create a corona discharge around the wire electrode. This discharge ionizes the gas and forms a plasma (Ma, et al., 2017). The plasma consists of a mixture of charged particles, such as electrons, ions, and radicals, that can interact with the NOx in the gas and convert it into less harmful compounds (Xu, et al., 2009). The mechanism of NOx reduction in a corona discharge reactor is similar to that in a DBD reactor and involves a series of chemical reactions within the plasma. Advantage: conversion of multiple emission compounds.

A.7. Wet Scrubbing

The process involves passing the exhaust gas through aqueous solution, which absorbs the pollutants. In the context of DeNOx, wet scrubbing is used to remove NOx from exhaust gases by dissolving them in a scrubbing liquid, such as Fe(II)EDTA, hydrogen peroxide (H_2O_2), Potassium permanganate ($KMnO_4$), sodium chlorite $NaClO_2$, urea and ozone (Gholami, et al., 2020; Sun, Zwolińska, & Chmielewski, 2015).

The wet scrubbing process typically involves the use of a scrubber, which is a vessel containing a packed bed or a spraying system for contact between the exhaust gas and the scrubbing liquid. As the gas flows through the scrubber, it is sprayed with the liquid, which captures the NOx and other pollutants (Deshwal, et al., 2008).

The efficiency of wet scrubbing for DeNOx depends on several factors, including the composition of the exhaust gas, the concentration of NOx, the temperature and humidity of the gas, and the type and concentration of the scrubbing liquid. The process requires careful monitoring and control to ensure optimal performance and avoid secondary pollution.

Advantage of wet scrubbing is that it simultaneously removes SO_2 and NOx (Deshwal, et al., 2008) and it can be conducted under low ambient temperatures and is highly adaptable to flue gas load. Disadvantage it produces a high volume of liquid waste, which can mostly be recycled (Sun, Zwolińska, & Chmielewski, 2015; Gholami, et al., 2020).

APPENDIX B – TECHNOLOGY READINESS LEVEL

Technology Readiness Level (TRL) is a measure used to assess the maturity of a particular technology. It was developed by NASA in the 1970s and is now widely used in various industries, including aerospace, defense, and engineering (Straub, 2015). TRL is a scale of 1 to 9, with 1 being the least mature and 9 being the most mature.

The TRL scale can be described as follows (Straub, 2015):

1. **Basic principles observed and reported**: This is the lowest level of technology readiness. At this stage, basic research is being conducted, and the concept or idea has not been tested in any practical application.
2. **Technology concept and/or application formulated**: At this stage, the concept or idea has been formulated, and some initial experiments or prototypes may have been created.
3. **Analytical and experimental critical function and/or characteristic proof-of-concept**: This level involves the testing of critical components or subsystems in a laboratory environment. This stage is used to verify that the basic principles and components of the technology are working correctly.
4. **Component and/or breadboard validation in laboratory environment:** At this stage, the technology is still being tested in a laboratory environment, but the individual components or subsystems are being tested together to validate the overall functionality.
5. **Component and/or breadboard validation in relevant environment**: The technology is now being tested in a relevant environment, which may include field or simulation testing. This stage is used to validate the technology's ability to operate in a real-world environment.
6. **System/subsystem model or prototype demonstration in a relevant environment**: At this stage, a prototype of the technology is being tested in a relevant environment. This stage is used to demonstrate the technology's ability to operate in a real-world environment.
7. **System prototype demonstration in a realistic environment**: This stage involves testing the technology in a realistic environment, which may include full-scale testing. This stage is used to demonstrate the technology's ability to perform in a real-world environment with all components working together.
8. **System completed and qualified**: The technology has now been fully developed and qualified. This stage is used to verify that the technology meets all the necessary requirements and specifications.
9. **Actual system proven through successful mission operations**: At this stage, the technology has been deployed in a real-world scenario and has been proven to be successful through mission operations.

APPENDIX C – COMMERCIAL COMPANIES

Table C-1 presents a list of companies that can be contacted for the installation of various NOx abatement options.

Table C-1: Overview commercial companies which sell NOx abatement systems

Company Name:	**Products:**	**Site:**
General Electric	(U)DLN for several gas turbine frames	Dry Low NOx (DLN 2.6) Combustion Upgrade | GE Gas Power
Thomassen	Thomassen-DLN & FlameSheet^{TM} ((U)DLN)	Thomassen Dry Low NOx System - Thomassen Energy BV
Callidus	ULNB, demonstrations with External FGR ULNB.	Callidus Burners (honeywell.com)
Zeeco	ULNB	Zeeco Burners
John Zink Hamworthy	ULNB	Burner Solutions - John Zink Hamworthy Combustion
ClearSign	ULNB	Process Burners – ClearSign
YARA	SCR, SNCR	DeNOx for Industrial Plants | Yara International
Valmet	SCR, SNCR, Wet scrubber ClO_2 and O_3	NOx reduction with SCR, SNCR and Scrubber methods (valmet.com)
Elessent	Wet scrubber (LOTOX)	Alkylation, Sulfuric Acid Regeneration, Hydrotreating, Mild Hydrocracking, Flue Gas Scrubbing – Elessent Clean Technologies (elessentct.com)
Linde	LOTOX	LOTOX | Linde Gas (linde-gas.com)
Andritz	SCR, SNCR, and wet scrubber	Denitrification (DeNOx) (andritz.com)
ISGEC	SCR & SNCR	ISGEC | Air Pollution Control Equipment | Electrostatic Precipitators | Air Pollution Control Equipment Manufacturers
BD Energy Systems	SCR & SNCR	Selective Catalytic Reduction (SCR) System – BDEnergySystems

Solar Turbines	SoLoNOx ((U)DLN)	SoLoNOx Upgrades - Equipment Optimization | Solar Turbines
Tri-Mer Corporation	SCR & wet scrubber	DeNOx | NOx Reduction Over 90%+ (tri-mer.com)
Mitsubishi Power	SCR	Mitsubishi Power | Selective Catalytic Reduction (SCR) System (mhi.com)

APPENDIX D – EXCEL CALCULATIONS

The following tables show the different steps in the MAUT method to finally come to the utility score for each alternative (for emission point O). Table D-1 shows the decision matrix translated for emission point O. It shows the score of each alternative on each criterion. Note that for (U)DLN the score shows "NA" (not applicable), this means that the (U)LNB cannot be installed at this certain emission point and is not taken into account in the MCDA for this emission point.

Table D-1: Decision matrix of the criteria and the score of alternatives on those criteria, for emission point O

Decision matrix (score of alternatives on criteria) for Emission point O

Criteria:

Alternatives:	T1	T2	T3	T4	N1	N2	N3	E1	E2	S1	S2
(U)DLN	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ULNB	2	1	4	1	3,25	40	0	90,0	5	5	3
SCR	4	4	5	100	5,85	0	4	500	50	3	3
SNCR	3	3	3	80	4,225	0	5	300	30	3	2
Wet scrubber Cl02	3	4	3	25	5,525	110	2	275	17,5	2	2
LOTOX	4	5	3	35	6,175	110	3	350	50	4	1

With the scores in the decision matrix of Table D-1, the normalized decision matrix can be calculated, presented in Table D-2. The criteria which are marked in yellow (T1, T2, etc.) represent the negative criteria. The normalized score uses Equation 1.3 instead of 1.2, shown in chapter 2. "#VALUE!" means that the alternative is not applicable to this emission point.

Table D-2: The normalized decision matrix of emission point O

Normalized decision matrix

Criteria:

Alternatives:	T1	T2	T3	T4	N1	N2	N3	E1	E2	S1	S2
(U)DLN	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
ULNB	1,000	1,000	0,500	1,000	0,000	0,364	1,000	1,000	1,000	1,000	1,000
SCR	0,000	0,250	1,000	0,000	0,889	0,000	0,200	0,000	0,000	0,333	1,000
SNCR	0,500	0,500	0,000	0,202	0,333	0,000	0,000	0,488	0,444	0,333	0,500
Wet scrubber Cl02	0,500	0,250	0,000	0,758	0,778	1,000	0,600	0,549	0,722	0,000	0,500
LOTOX	0,000	0,000	0,000	0,657	1,000	1,000	0,400	0,366	0,000	0,667	0,000

With the normalized scores from Table D-2, the marginal utility score of each alternative for each criteria can be calculated which is shown in Table D-3. This is done via Equation 1.4, given in chapter 2.

Table D-3: Marginal Utility score of the alternatives on each criteria for emission point O

Marginal Utility score

Criteria:

Alternatives:	T1	T2	T3	T4	N1	N2	N3	E1	E2	S1	S2
(U)DLN	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
ULNB	3,74	3,74	1,00	3,74	0,00	0,63	3,74	3,74	3,74	3,74	3,74
SCR	0,00	0,38	3,74	0,00	2,88	0,00	0,29	0,00	0,00	0,55	3,74
SNCR	1,00	1,00	0,00	0,29	0,55	0,00	0,00	0,97	0,84	0,55	1,00
Wet scrubber Cl02	1,00	0,38	0,00	2,08	2,19	3,74	1,36	1,17	1,89	0,00	1,00
LOTOX	0,00	0,00	0,00	1,59	3,74	3,74	0,72	0,63	0,00	1,63	0,00

The final utility score is the weight given to each criterion times the score of the alternative on that specific criterion. These are added up which provides the final utility score for each alternative for emission point O, shown in Table D-4.

Table D-4: The Final Utility score of alternatives for emission point O

Alternatives:	
(U)DLN	0
ULNB	20,2
SCR	7,5
SNCR	4,2
Wet scrubber Cl02	11,7
LOTOX	9,6

This process is repeated for each emission point.

APPENDIX E – SENSITIVITY ANALYSIS

Table E-1 shows how adjusting the weights of different criteria changes the final utility scores for each alternative at each emission point. Although these scores change, the rankings of the alternatives should stay the same. Because it's hard to spot these changes in the color-coded columns, Table E-2 was made to make this easier.

Table E-1: The final utility score for each emission point. Beginning with the base case where no changes to the weights have been made. The tables underneath the base case refer to the final utility score when a weight of a criterion is changed with +0.1 or -0.1.

Base case	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	18	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	9	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	9

Weight T1 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	19	19	0	0	0	0	0	0	0	0	0
ULNB	21	21	21	0	21	0	15	0	21	0	0	0	0	21	21	21	21	21	21	0	21	21
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	7	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	12	12	20	12	18	16	20	11	20	20	13	13	12	11	11	11	12	12	20	11	12
LOTOX	10	9	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	9

Weight T1 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	17	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	9	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	9

Weight T2 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	19	19	0	0	0	0	0	0	0	0	0
ULNB	21	21	21	0	21	0	15	0	21	0	0	0	0	21	21	21	21	21	21	0	21	21
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	7	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	18	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	9	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	9

Weight T2 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	7	7	7	8	7	0	7	8	7	8	8	8	8	8	8	8	7	8	8	8	7	7
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	17	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	9	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	9

Weight T3 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	18	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	9	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	9

Weight T3 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	7	7	7	7	7	0	7	7	7	7	7	8	8	7	7	7	7	8	7	7	7	7
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	18	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	9	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	9

Weight T4 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	19	19	0	0	0	0	0	0	0	0	0
ULNB	21	21	21	0	21	0	15	0	21	0	0	0	0	21	21	21	21	21	21	0	21	21
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	12	12	20	12	18	16	20	12	20	20	13	13	12	12	12	11	12	12	20	11	12
LOTOX	10	10	10	13	10	5	11	13	10	13	13	9	9	10	10	10	10	10	10	13	10	10

Weight T4 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	11	11	11	20	12	17	16	20	11	20	20	13	13	11	11	11	11	12	11	20	11	11
LOTOX	9	9	9	12	9	5	10	12	9	12	12	9	9	9	9	9	9	9	9	12	9	9

Weight N1 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	7	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	12	12	20	12	18	16	20	12	20	20	13	13	12	12	12	11	12	12	20	11	12
LOTOX	10	10	10	13	10	6	11	13	10	13	13	9	9	10	10	10	10	10	10	13	10	10

Weight N1 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	7	7	7	8	7	0	7	8	7	8	8	8	8	8	7	7	7	8	7	8	7	7
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	11	11	11	20	12	18	16	20	11	20	20	13	13	11	11	11	11	11	11	20	11	11
LOTOX	9	9	9	12	9	5	10	12	9	12	12	9	9	9	9	9	9	9	9	12	9	9

Weight N2 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	12	12	20	12	18	16	20	12	20	20	13	13	12	12	12	12	12	12	20	12	12
LOTOX	10	10	10	13	10	5	11	13	10	13	13	9	9	10	10	10	10	10	10	13	10	10

Weight N2 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	11	11	11	20	11	18	15	20	11	20	20	13	13	11	11	11	11	11	11	20	11	11
LOTOX	9	9	9	12	9	5	10	12	9	12	12	9	9	9	9	9	9	9	9	12	9	9

Weight N3 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	19	19	0	0	0	0	0	0	0	0	0
ULNB	21	21	21	0	21	0	15	0	21	0	0	0	0	21	21	21	21	21	21	0	21	21
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	12	12	20	12	18	16	20	11	20	20	13	13	12	12	12	11	12	12	20	11	12
LOTOX	10	10	10	13	10	5	11	13	10	13	13	9	9	10	10	10	10	10	10	13	10	10

Weight N3 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	11	20	12	17	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	9	9	9	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	9

Weight E1 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	19	19	0	0	0	0	0	0	0	0	0
ULNB	21	21	21	0	21	0	15	0	21	0	0	0	0	21	21	21	21	21	21	0	21	21
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8

SNCR	4	4	4	9	4	0	7	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	12	12	20	12	18	16	20	11	20	20	13	13	12	11	11	11	12	12	20	11	12
LOTOX	10	10	10	13	10	5	11	13	10	13	13	9	9	10	10	10	10	9	10	13	10	10

Weight E1 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	17	15	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	9	9	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	9

Weight E2 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	19	19	0	0	0	0	0	0	0	0	0
ULNB	21	21	21	0	21	0	15	0	21	0	0	0	0	21	21	21	21	21	21	0	21	21
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	7	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	12	12	20	12	18	16	20	11	20	20	13	13	12	12	12	11	12	12	20	11	12
LOTOX	10	10	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	10

Weight E2 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	11	20	12	17	15	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	10	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	10

Weight S1 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	19	19	0	0	0	0	0	0	0	0	0
ULNB	21	21	21	0	21	0	15	0	21	0	0	0	0	21	21	21	21	21	21	0	21	21
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	7	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	18	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	10	10	13	10	6	11	13	10	13	13	9	9	10	10	10	10	10	10	13	10	10

Weight S1 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	7	7	7	8	7	0	7	8	7	8	8	8	8	8	8	8	7	8	8	8	7	7
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	18	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	9	9	9	12	9	5	10	12	9	12	12	9	9	9	9	9	9	9	9	12	9	9

Weight S2 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	19	19	0	0	0	0	0	0	0	0	0
ULNB	21	21	21	0	21	0	15	0	21	0	0	0	0	21	21	21	21	21	21	0	21	21
SCR	8	8	8	8	8	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
SNCR	4	4	4	9	4	0	7	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	12	12	20	12	18	16	20	11	20	20	13	13	12	12	11	11	12	12	20	11	12
LOTOX	10	10	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	10

Weight S2 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	18	18	0	0	0	0	0	0	0	0	0
ULNB	20	20	20	0	20	0	15	0	20	0	0	0	0	20	20	20	20	20	20	0	20	20
SCR	7	7	7	7	7	0	7	7	7	7	7	8	8	7	7	7	7	8	7	7	7	7
SNCR	4	4	4	9	4	0	6	9	4	9	9	0	0	5	4	4	4	5	4	9	4	4
Wet scrubber Cl02	12	11	12	20	12	17	16	20	11	20	20	13	13	12	11	11	11	12	11	20	11	11
LOTOX	10	10	10	13	10	5	10	13	9	13	13	9	9	9	9	9	9	9	9	13	9	10

Table E-2 serves as a validation check, assessing if the ranking of each emission point stays consistent when the weight of a criteria is adjusted. The base case illustrates the rankings from 1 to 6 (or lower depending on how many alternatives are technically available for the emission point), with rank 1 denoting the alternative with the highest final utility score and rank 6 signifying the one with the lowest score for that particular emission point. This means each column presents a unique ranking of alternatives.

The tables beneath the base case generate rankings of each alternative for each emission point when the weight of the criteria is altered, starting with a +0.1 change in the weight of Criteria T1. To identify any shift in ranking against the base case, the original rank number from the base case is deducted from this number. If the result isn't zero, the ranking differs from the base case, indicating the weight change influences the MCDA outcome. However, as evident in Table E-2, each cell returns a zero (green cells), signifying that altering the weight by ±0.1 of any criterion doesn't impact the ranking of alternatives per emission point!

Table E-2: Checking the ranking of each emission point if the weights of each criteria is changed

Base case	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	6	6	6	5	6	3	6	5	6	5	5	1	1	6	6	6	6	6	6	5	6	6
ULNB	1	1	1	5	1	3	2	5	1	5	5	5	5	1	1	1	1	1	1	5	1	1
SCR	4	4	4	4	4	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
SNCR	5	5	5	3	5	3	5	3	5	3	3	5	5	5	5	5	5	5	5	3	5	5
Wet scrubber Cl02	2	2	2	1	2	1	1	1	2	1	1	2	2	2	2	2	2	2	2	1	2	2
LOTOX	3	3	3	2	3	2	3	2	3	2	2	3	3	3	3	3	3	3	3	2	3	3

Emission points

Weight T1 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Emission points

Weight T1 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Emission points

Weight T2 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Emission points

Weight T2 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Emission points

Weight T3 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight T3 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight T4 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight T4 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight N1 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight N1 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight N2 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight N2 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight N3 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight N3 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight E1 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight E1 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight E2 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight E2 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight S1 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight S1 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight S2 +0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Emission points																					
Weight S2 -0.1	O	P	Q	R	N	S	W	K	L	A	G	T	U/V	I	J	C	M	F	D	E	B	H
(U)DLN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ULNB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SNCR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wet scrubber Cl02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOTOX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0