UNIVERSITY OF TWENTE

DEPARTMENT OF GOVERNANCE AND TECHNOLOGY FOR SUSTAINABILITY

Balancing Energy Transition Policies & Sulfur Recovery Efficiency in the Netherlands

Master of Environmental & Energy Management (MEEM) Program

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Academic Year: 2022-2023

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August, 2023

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Abstract:

The present study explores the complex relationship between sulfur recovery efficiency and Dutch energy transition policies. With the global shift towards renewable energy, managing sulfur, a by-product of fossil fuel industries, becomes a pivotal concern. This issue takes on greater significance in the Netherlands, given its robust policies on green energy transition. The key research question this study addresses is: How can sulfur recovery efficiency in the Netherlands be optimized within the context of Dutch energy transition policies?

The research utilizes in-depth interviews and reviews of policy documents to investigate the synergies and trade-offs between sulfur recovery and energy transition. By gaining an understanding of these dynamics, it aims to establish strategies for optimizing sulfur recovery efficiency in line with energy transition goals. The study also strives to identify best practices that balance sulfur recovery and energy transition policies, insights of which may be applied globally.

The research's significance lies in its potential environmental, economic, policy, and academic contributions. Efficient sulfur recovery can reduce harmful emissions and contribute to global environmental sustainability efforts. From an economic perspective, optimizing sulfur utilization could lead to new economic opportunities, supporting the overall economic stability of the country. In terms of policy, insights into the interaction between sulfur recovery and energy transition policies could guide policy adjustments, inform industry practices, and influence strategic direction. Moreover, this research bridges a gap in the academic understanding of sulfur recovery within energy transition frameworks, potentially stimulating further research and discussions in the academic community.

The study's findings are expected to offer valuable guidance for policymakers, industry partners, and researchers navigating the delicate balance between resource recovery and energy transition. While focused on the Netherlands, the research may have wider implications, with strategies potentially applicable to other countries facing similar challenges. Overall, the study promises critical insights into creating a future where environmental sustainability and economic efficiency coexist within the energy sector.

Keywords: Sulfur recovery efficiency, Energy transition policies, Renewable energy, Green energy transition, Resource management, Greenhouse gas emissions, Sulfur utilization, Climate change, Energy sector strategy.

Acknowledgments

First and foremost, I would like to extend my deepest gratitude to my First Supervisor, Dr. L. Sanderink (Lisa). Her unwavering support and insightful comments have illuminated my path throughout this research journey. Lisa, you have taught me how to navigate and tackle complex multidisciplinary problems, always encouraging me to view challenges from a fresh perspective.

I am equally grateful to my Second Supervisor, Dr. S.R. McGreevy (Steven). His holistic insights and invaluable feedback have greatly enhanced the quality and depth of my work. Steven, I deeply appreciate the wisdom you brought to this endeavor.

To my beloved husband, thank you for being my rock. Your steadfast companionship, encouragement, and love have carried me through the highs and lows of this master's journey. Together, we nurture our two radiant children, who serve as a constant reminder and motivation for me to consider the future impacts of my work on the environment and resources.

A heartfelt thank you to my brother, whose unwavering encouragement has fueled my ambition to chase my dreams relentlessly.

Finally, I would like to acknowledge the experts who provided their insights, enabling me to delve deeper into the intricate evaluations that have always intrigued me. Your guidance was pivotal in elevating my research.

Maryam
August 2023

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LIST OF ACRONYMS/ABBREVIATIONS

ACRONYMS	DEFINITION
BAT	Best Available Technique
BREF	Best Reference
CCU	Carbon Capture Utilization
CO_2	Carbon Dioxide
ETP	Energy Transition Policies
H_2S	Dihydrogen Sulfide
MCA	Multi-Criteria Analysis
NEN	Nederlands Normalisatie Instituut
SO_2	Sulfur Dioxide
SRU	Sulfur Recovery Unit
ULSD	Ultra-Low Sulfur Diesel

1. Introduction

1.1. Background

Acid rain was a big problem that the world faced during the 1970s-1990s, and it was caused mainly by harmful substances like sulfur dioxide and nitrogen oxides. These substances were produced by cars, power plants, and factories. When these pollutants met the water in the air, they transformed into sulfuric and nitric acids, causing acid rain. Acid rain was harmful to the environment, people's health, and buildings life span (Grennfelt et al., 2020).

In response to the growing concern over acid rain, public awareness accelerated governmental action, culminating in the development and adoption of technologies to reduce sulfur emissions. Innovative solutions like flue gas desulfurization and the usage of low-sulfur fuels emerged. Moreover, established processes, such as the Claus process, which converts hydrogen sulfide into water and sulfur dioxide, underwent refinements (Davis et al., 2018). The concerted efforts in sulfur recovery and emission control notably mitigated the acid rain threat (Shao et al., 2022).

Concurrently, as the sulfur recovery advancements were unfolding, the global narrative began to emphasize energy transition. This shift signifies a transition from environmentally detrimental energy sources to greener and more sustainable alternatives. Representing a blend of societal needs and technological innovations, energy transition epitomizes socio-technical changes—where societal factors and technological trajectories mutually influence and shape each other's progression (Smith et al., 2005).

The Netherlands presents a particularly intriguing case in this intertwined landscape of sulfur recovery and energy transition. Understanding the general interplay between sulfur recovery and energy transition is crucial before delving into the specifics of the Dutch scenario.The nation's proactive approach to energy transition against the backdrop of the global climate crisis provides a dynamic context for the investigation. (Robinson, 2017; International Energy Agency, 2020). The country's distinct position as a pivotal European trading hub, maritime climate, and dense population distribution create a unique blend of challenges and opportunities.

The choice to focus on the Netherlands is rooted in its pioneering role in harmonizing energy transition policies with sulfur recovery techniques. The nation's explicit and ambitious goals in both arenas position it as an exemplar of managing potential friction between environmental initiatives. Analyzing the Dutch approach provides a blueprint that can inform and guide other nations grappling with similar challenges.

However, navigating the balance between sulfur recovery and energy transition is intricate. Predominant sulfur recovery mechanisms, like the Claus process, emit sulfur dioxide—a greenhouse gas. This poses an inherent contradiction, as the essence of energy transition revolves around curtailing greenhouse gas emissions (International Energy Agency, 2020; Shi & Wu, 2021). Thus, the journey ahead necessitates the design and realization of sulfur recovery solutions that synergize with the broader objectives of the energy transition.
The central challenge becomes: how can countries, like the Netherlands, develop and implement strategies that balance the dual imperatives of efficient sulfur recovery and sustainable energy transition?

1.2. Research problem and significance

The global transition towards renewable energy has placed countries in a challenging position, especially those like the Netherlands, where sulfur—a by-product of fossil fuel industries—presents both a challenge and an opportunity. The inherent contradiction arises from the need to efficiently recover and utilize sulfur, all the while adhering to green energy transition policies that push for reduced reliance on fossil fuels (Bader & Oostra, 2022; Beck et al., 2022).
In addition to reducing harmful emissions, efficient sulfur recovery plays a crucial role in environmental protection and sustainability.Therfore, optimizing the process of sulfur recovery can significantly contribute can be made towards global environmental efforts (Chan et al., 2023).
From a policy and practice standpoint, the research has vast implications. It can provide critical insights into how sulfur recovery interacts with energy transition policies. Such insights can guide the adjustments to existing policies, inform best practices, and ultimately influence the strategic direction of both the sulfur recovery industry and the broader energy sector (Kemp & Rotmans, 2009; Vringer & Carabain, 2020).

The economic implications of the research cannot be overlooked. Enhanced sulfur recovery efficiency can have economic benefits. Utilizing sulfur more efficiently could create new economic opportunities. This would contribute to the overall economic growth and stability of the country, presenting a viable solution to the management of by-products from fossil fuel industries (Ibrahim, Ashour, Gadalla, et al., 2023).

While the primary focus of this research is on the Netherlands, the findings could have broader relevance. Countries facing similar challenges could apply the strategies developed through this research, amplifying its impact on a global scale (Laes, Gorissen, & Nevens, 2014).
Interms of academic contribution, This research addresses the current lack of knowledge regarding the optimization of sulfur recovery in the context of energy transition frameworks.This novel insight could inspire more research and discussions in academia, providing a fresh viewpoint on how to balance resource recovery and energy transition effectively. (Huang, Keisler, & Linkov, 2011).

1.3. Research objectives and questions

This study aims to examine the intricate balance between optimizing sulfur recovery efficiency and aligning with Dutch energy transition policies. The pressing importance of this balance hinges on the simultaneous achievement of environmental protection, efficient resource management, and policy objectives.

Main Research Question:
How can sulfur recovery efficiency in the Netherlands be optimized within the context of Dutch energy transition policies?

Sub-questions:
1. What are the principal energy transition policies in the Netherlands that influence sulfur recovery practices?
2. What intersections and discrepancies exist between energy transition policies and sulfur recovery in the Netherlands?
3. How to amplify beneficial overlaps and navigate inherent tensions to enhance sulfur recovery efficiency?

Research Objectives:
1. Analyze the interplay between sulfur recovery and energy transition in the Netherlands.
2. Develop strategies that heighten sulfur recovery efficiency by leveraging insights from Dutch energy policies and practices.
3. Highlight best practices from the Netherlands that can inform sulfur recovery and energy transition efforts in other global contexts.

In embarking on this inquiry, the complex and dynamic nature of the topic is recognized. However, the complexity of the study highlights its importance. The outcomes are anticipated to offer actionable insights for stakeholders aiming for environmental sustainability and economic viability in the energy domain. Additionally, this research endeavors to sharpen my own analytical skills concerning intricate socio-technical challenges, essential for my professional journey.

2. LITERATURE REVIEW

2.1. Overview of Sulfur Recovery Units (SRUs)

Sulfur Recovery Units (SRUs) are integral to many industrial operations, notably refineries and natural gas processing plants. Their chief function is the conversion of hydrogen sulfide (H_2S) into elemental sulfur, thus limiting harmful emissions and recovering a valuable by-product (Rybinskaya et al., 2019).

The Claus process stands as the most widely used method in SRUs. It consists of a thermal stage in the Reaction Furnace where H_2S undergoes partial oxidation to form Sulfur Dioxide (SO_2). This is followed by several catalytic stages where SO_2 interacts with H_2S to produce sulfur. The typical reactions include:

$$2 H_2S + 3 O_2 \rightarrow 2 SO_2 + 2 H_2O$$
$$4 H_2S + 2 SO_2 \rightarrow 3 S_2 + 4 H_2O$$

However, refining this process for greater efficiency remains a challenge. There have been various techniques investigated in order to enhance the rates of sulfur recovery, including optimizing process conditions, managing catalysts, and implementing tail gas treatment. (Hashemi et al., 2020).

Emerging technologies aim to further reduce energy consumption and emissions in SRUs. Among them are oxygen-enriched air combustion and CO_2 capture and utilization (Arthur & Nielsen, 1997; Maurice & Stewart Jr., 2014).

Studies by Hashemi (2020) and Ibrahim et al. (2023) emphasize the significance of sulfur recovery in refining, suggesting strategies for process optimization. An encompassing study by

Ibrahim et al. (2021) demonstrated the importance of evaluating the full system surrounding SRUs, including sour water stripper and amine regenerator units.

Further, molecular sieves for SRU tail gas treatment could improve sulfur recovery efficiency (Zhang et al., 2023). An innovation by Axens Co. known as the SmartSulf solution is noteworthy. This SRU achieved a 99.5% sulfur recovery rate without tail gas treatment (Axens, 2022). In line with this, the Modified Claus Process, depicted in Figure 1 from Penn State University, offers a visualization of a multi-staged approach for better sulfur recovery. Each converter-condenser unit in the series intensifies the recovery, reaffirming the industry's stride towards optimization.

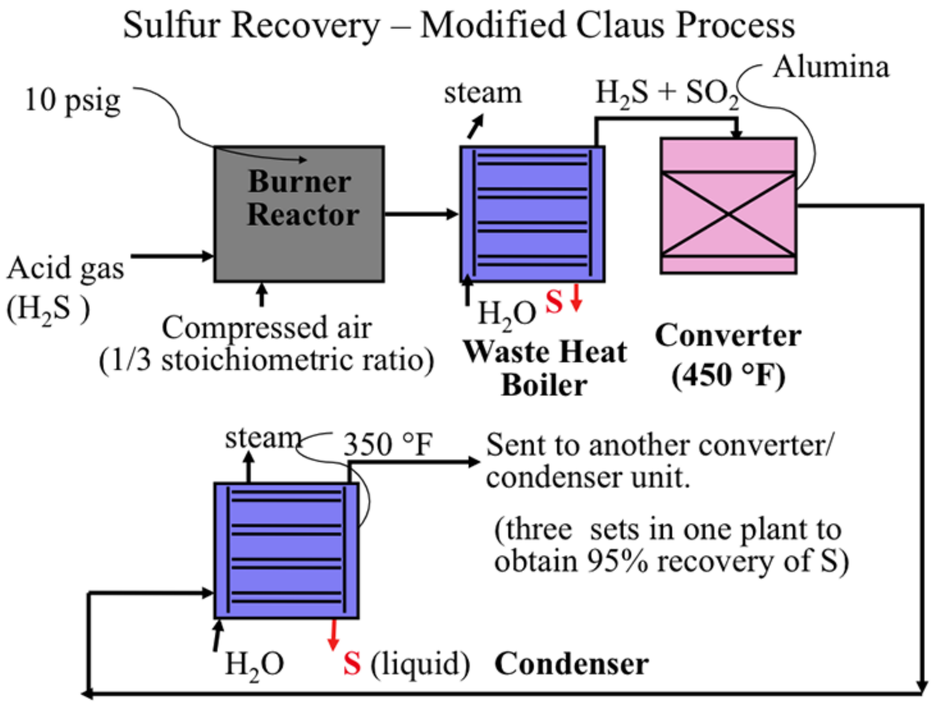

Figure 1 The Modified Claus Process.

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As global environmental regulations tighten, innovative SRU technologies and methodologies become even more vital. Techniques like heat integration and energy recovery can decrease energy consumption, and tail gas treatment can further enhance sulfur recovery (Maurice & Stewart Jr., 2014). Modern process optimization and control technologies also play a role in maximizing efficiency (Ibrahim et al., 2023).

The integration of CO2 capture and utilization technologies offers potential for mitigating SRU-associated greenhouse gas emissions (Rajabloo et al., 2023). Continuous R&D is essential for furthering improvements in SRUs, especially in catalyst management for the Claus process and tail gas treatment.Future studies could delve into hybrid systems that combine multiple approaches for synergistic efficiency gains.

2.2. The Landscape of Sulfur Recovery in the Netherlands

The Netherlands' unique energy landscape necessitates a comprehensive understanding of its sulfur recovery intricacies. While the fossil fuel industry stands out as the primary user of Sulfur Recovery Units (SRUs), other sectors are becoming increasingly relevant in this context, especially as the energy transition unfolds (Maslin et al., 2022).

SRUs' significance transcends fossil fuels. For instance, the global sulfur crisis, which jeopardizes green tech development and food security during decarbonization, resonates deeply within the Dutch context (Maslin et al., 2022). As the demand for sulfur in renewable energy and agriculture heightens, dwindling SRU feedstocks due to decarbonization may shift focus to biogas. This organic waste byproduct, being in line with the Netherlands' waste management and energy strategies, offers a promising solution (Ministry of Economic Affairs and Climate Policy, 2019).
The vast applications of sulfur in the Dutch context, from agriculture to pharmaceuticals, underline its central role in various industries (Marcus, 2013). Major refineries around Rotterdam and prominent companies like Shell Nederland Raffinaderij and Nerefco BV play significant roles in the Dutch sulfur landscape. However, a shift towards low-sulfur products presents challenges, not only in terms of emissions but also for the future of SRUs (Shi & Wu, 2021).

This move towards low-sulfur products has dual implications: it meets environmental targets while simultaneously altering sulfur demand dynamics. With a decline in high-sulfur feedstocks, traditional SRUs could witness efficiency drops. Furthermore, regulatory pressures amplify these shifts. For instance, the Netherlands abides by NEN technical standards and the Best Available Techniques (BAT), with the BAT Reference Document (BREF) giving clarity on SRU emissions (European Commission, 2021).

To sum up, the ongoing energy transition in the Netherlands is reshaping its sulfur recovery sector. This transition, filled with both challenges and opportunities, fosters novel SRU technologies, promising an innovative trajectory for sulfur recovery in the country.
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2.3. Energy transition policies in the Netherlands

The energy transition policies in the Netherlands reflect the country's increasing recognition of the impacts of climate change and dedication to meeting the European Union's 2030 climate and energy goals. This marks a conscious effort to bring about societal change. (European Commission, 2018). Central to these policies is the Dutch Climate Agreement, guiding the nation's endeavors to cut carbon emissions across various economic sectors (Bader and Oostra, 2022).
The Netherlands has strategically discontinued fossil fuel subsidies, reallocating these funds towards renewable energy infrastructure (Dutch Ministry of Economic Affairs and Climate Policy, 2019). Offshore wind energy has been a primary focus, driving the nation's shift to renewables while also stimulating economic growth (Bader and Oostra, 2022).

Public-private partnerships have been instrumental in accelerating the energy transition and bridging the gap between conceptualizing and deploying green technologies (Dutch Ministry of Economic Affairs and Climate Policy, 2019). Kemp et al. (2009), Kern et al. (2008), and Verbong and Sovacool (2007) offer insightful analyses of the Dutch energy transition, emphasizing the importance of co-production strategies, governance and transition pathways, and adaptive policy responses.

Feenstra et al. (2021) highlight the importance of incorporating societal considerations, arguing for an energy transition that does not marginalize the most vulnerable. These sentiments are echoed in other research, emphasizing the role of collective renewable energy prosumers and the legitimacy of energy transition policies (Inês et al., 2020; Vringer and Carabain, 2020).

Despite progress, challenges remain. The existing grid infrastructure needs enhancement to manage the rising renewable energy production and consumption (CBS, PBL, RIVM & WUR, 2020). Public acceptance of renewable energy projects, social equity considerations, and issues of energy poverty are also pressing issues that necessitate comprehensive and iterative policy responses (CBS, PBL, RIVM & WUR, 2020; Feenstra et al., 2021).

Beck et al. (2022) argue that oil and gas companies can play a significant role in the energy transition by decarbonizing their operations, investing in renewable energy projects, and exploring carbon capture technologies. These measures align with the sentiments expressed by Griffiths et al. (2022), who underscore the importance of technological innovation, policy measures, and social acceptance in facilitating the energy transition.

Rajabloo et al. (2023) highlight the potential of carbon capture and utilization, offering promising technological advances to mitigate climate change. In summary, while the Dutch journey towards a sustainable energy future presents certain challenges, it serves as a compelling case study of sustainable transition through commitment, extensive planning, and ongoing learning and adaptation.

2.4. Impact of energy transition policies on sulfur recovery

The implications of the various energy transition policies on the sulfur recovery industry are complex and multi-dimensional, given that they extend to regulatory compliance, market dynamics, technological innovation, investment opportunities, and collaboration and partnerships (Bader and Oostra, 2022). These transition policies are underpinned by a 'Transition Management', which emphasizes long-term visions, system innovation, and learning through stakeholder involvement (Kern & Smith, 2008b).

The energy transition policies that could have the most direct impact on Sulfur Recovery Units (SRUs) are primarily those relating to environmental regulations, technological innovations, and the market dynamics in the energy sector. Investment opportunities and policies promoting collaboration and partnerships may also play a role in influencing the future of SRUs.

The Energy Investment Allowance (EIA) also has a direct implication on the economic aspects of the SRUs. In this revision, each policy is evaluated against the transition effectiveness criteria derived from the Transition Management model used by the Dutch Ministry of Economic Affairs for restructuring energy systems towards sustainability that Kern and Smith (2008b) proposed: focus on robust elements, competitive advantage, strength of demand, support, substance, robustness, feasibility, innovativeness, costs and benefits, and pace. These criteria are selected based on their relevance to the specific policies and the implications these policies have on the sulfur recovery industry. Here's the simplified table 1 for policies with a more direct impact on SRUs:

Table 1. Dutch Energy Transition Policies with Significant Impact on SRUs

Policy	Targets	Reference
Dutch Climate Agreement	Significant reduction in greenhouse gas emissions	Bader and Oostra, 2022
Environmental Regulations (for Sulfur Emissions)	Adapting and investing in more efficient sulfur recovery technologies	Horikawa et al., 2004; ADB, 2021
Market Dynamics (Renewable Energy Transition)	Adapt to declining fossil fuel demand and capitalize on opportunities in cleaner natural gas and biogas production	Provolo et al., 2018; Fetisov et al., 2023
Technological Innovations (Clean Energy Push)	Innovate and invest in more eco-friendly sulfur recovery processes	Okoro & Sun, 2019; Liu et al.,2017; Chen et al., 2021
Investment Opportunities (Sustainable Technologies)	Adopt innovative solutions and improve environmental performance of sulfur recovery units	Olab et al., 2022; Ghavam et al., 2021
Collaboration and Partnerships	Collaborate to identify new opportunities, develop innovative solutions, and share best practices	Richard, 2016
Energy Investment Allowance (EIA)	Investment in energy-efficient technologies and renewable energy	RVO, 2023

Regulatory compliance is significantly influenced by stricter environmental regulations such as the Dutch Climate Agreement and BAT and BREF Recommendations (Horikawa et al., 2004; European IPPC Bureau, 2023). These regulations necessitate the adoption of best available techniques and encourage industries to invest in more efficient sulfur recovery technologies. This shift stimulates the demand for advanced sulfur recovery systems and process improvements (ADB, 2021). However, the dominance of existing industry practices and structures may hinder the full realization of radical changes in the sulfur recovery industry (Kern & Smith, 2008b).

The market dynamics of the sulfur recovery industry are also influenced by the energy transition policies, particularly the phasing out of fossil fuel subsidies and the shift towards renewable energy sources (Dutch Ministry of Economic Affairs and Climate Policy, 2019). While the demand for traditional fossil fuels may decline, opportunities in cleaner natural gas and biogas production emerge (Provolo et al., 2018; Fetisov et al., 2023). These changes, along with the financial incentives from the EIA, MEP, and SDE+ policies, create an environment conducive for investment in more eco-friendly and efficient sulfur recovery processes (RVO, 2023).

Technological innovation, a key aspect of the sulfur recovery industry, is accelerated by the push for cleaner energy and reduced emissions. The demand for novel desulfurization methods and

carbon capture, usage, and storage (CCUS bolstered by public-private partnerships in green technologies and investment opportunities presented by policies such as the Green Projects Scheme and the EIA (Dutch Ministry of Economic Affairs and Climate Policy, 2019; RVO, 2023).
Lastly, the global drive towards a sustainable energy future, as represented in policies like the Dutch Climate Agreement and the Green Projects Scheme, promotes collaboration between different stakeholders including sulfur recovery industries, policymakers, and research institutions (Richard, 2016; Bader and Oostra, 2022). These partnerships help identify new opportunities, develop innovative solutions, and share best practices to address challenges and seize opportunities arising from the energy transition.

In conclusion, the direct and indirect impacts of energy transition policies on sulfur recovery units are multilayered. They represent both challenges and opportunities for sulfur recovery industries to innovate, adapt, and contribute towards a sustainable energy future. This trend is technologies increase (Okoro & Sun, 2019; Liu et al., 2017; Chen et al., 2021).

3. ANALYTICAL FRAMEWORK

3.1. Concept and Application of Multi-Criteria Analysis (MCA)

As strategic management and energy-related sectors grapple with increasingly intricate challenges, there is a pressing need for advanced decision-making tools. These tools must accommodate a broad spectrum of qualitative and quantitative factors. The necessity arises from the evolving nature of these sectors, where decision-making has to be data-driven and also take into account a multitude of interconnected impacts stemming from diverse variables. This is where the adoption of robust computational systems and decision-support tools comes into play.

According to Belton & Stewart (2001), such technologies have revolutionized traditional decision-making approaches by offering precision and facilitating multi-layered analyses.
In recent times, strategic management and energy sectors have witnessed an evolution characterized by increasing complexities. Such intricacies are driven by a myriad of intertwined challenges that go beyond conventional decision-making models. It's clear that addressing these challenges demands an amalgamation of data-driven methodologies and a deep understanding of multifaceted variables (Belton & Stewart, 2001; Saaty, 1990).

The nature of these complexities underscores the critical need for tools equipped to evaluate both qualitative and quantitative dimensions. Traditional decision-making processes, reliant on singularly qualitative or quantitative criteria, often fall short in addressing contemporary challenges in these sectors. This has spurred the search and adoption of more versatile and comprehensive decision-making tools.

One such tool that has gained prominence in navigating these challenges is Multi-Criteria Analysis (MCA). This approach distinguishes itself by its ability to assess a spectrum of alternatives grounded in diverse criteria. These criteria encompass quantitative aspects, such as costs, and delve into qualitative facets, including stakeholder sentiments and values (Hobbs & Meier, 2000; Belton & Stewart, 2001). The inherent strength of MCA lies in its ability to provide

a multi-dimensional lens, particularly critical when traditional cost-benefit analyses might not capture the entirety of a scenario.
Using the research focus on sulfur recovery efficiency and energy transition policies as a case in point, one can elucidate the nuanced challenges that merit the application of MCA. This research domain is rife with multi-dimensional problems. At its core, various stakeholders, each equipped with their perspectives, must converge to decide upon a cohesive direction. This process is further complicated when factoring in the nuanced relationships between technological innovations and their multi-pronged societal, environmental, and economic repercussions (Kano & Hayashi, 2021; Eden & Ackermann, 2004).

MCA's adaptability and comprehensiveness make it suitable for addressing complex challenges with multiple facets. It offers a meticulously structured framework that evaluates a broad range of, sometimes conflicting, factors. This includes collating objective data while simultaneously considering the rich tapestry of subjective inputs. In an MCA-driven approach, one can account for varied influences such as policy nuances, stakeholder inclinations, and expert testimonies. This approach underscores the importance of striking a harmony between metrics-driven objectivity and the nuances of human subjectivity (Huang et al., 2011; Keeney & Raiffa, 1993).

However, like all methodologies, MCA is not without its obstacles. A fundamental challenge arises when weights are assigned to specific criteria. This process can inadvertently introduce an element of subjectivity, potentially biasing the analysis. Furthermore, when diverse criteria types intertwine, especially those that traditionally stand in opposition, like environmental considerations versus economic gains, deriving a clear and balanced decision can become daunting (Belton & Stewart, 2001; Triantaphyllou, 2000).

But despite these challenges, the essence of MCA's strength is its holistic ethos. The process begins with a deep dive into data collection. Here, tools such as extensive surveys, one-on-one interviews, and a plethora of other resources are utilized to set the stage for a comprehensive analysis. The use of modeling as an analytical method, central to this research, refines the decision-making process. Systematically dissecting the problem enhances our capability to anticipate potential outcomes and trends (Huang et al., 2011; Figueira et al., 2005).

Enriching the MCA framework further are the components that form its backbone – objectives, ideals, and decision matrices. For instance, when one examines energy transition policies in regions like the Netherlands, a layered understanding emerges. This involves assessing cost-effectiveness, gauging environmental impacts, and understanding their interplay in a strategic framework (Belton & Stewart, 2001; Vincke, 1992).

In closing, MCA is much more than a decision-making tool. It's a comprehensive framework that weaves together varied criteria, providing researchers with a panoramic view of the decision-making landscape. As the research navigates the interconnected realms of sulfur recovery efficiency and energy transition, MCA emerges as the torchbearer, ensuring a journey marked by depth, breadth, and informed outcomes. In the following chart (Figure 2), the general model of the decision-making process in the research is presented:

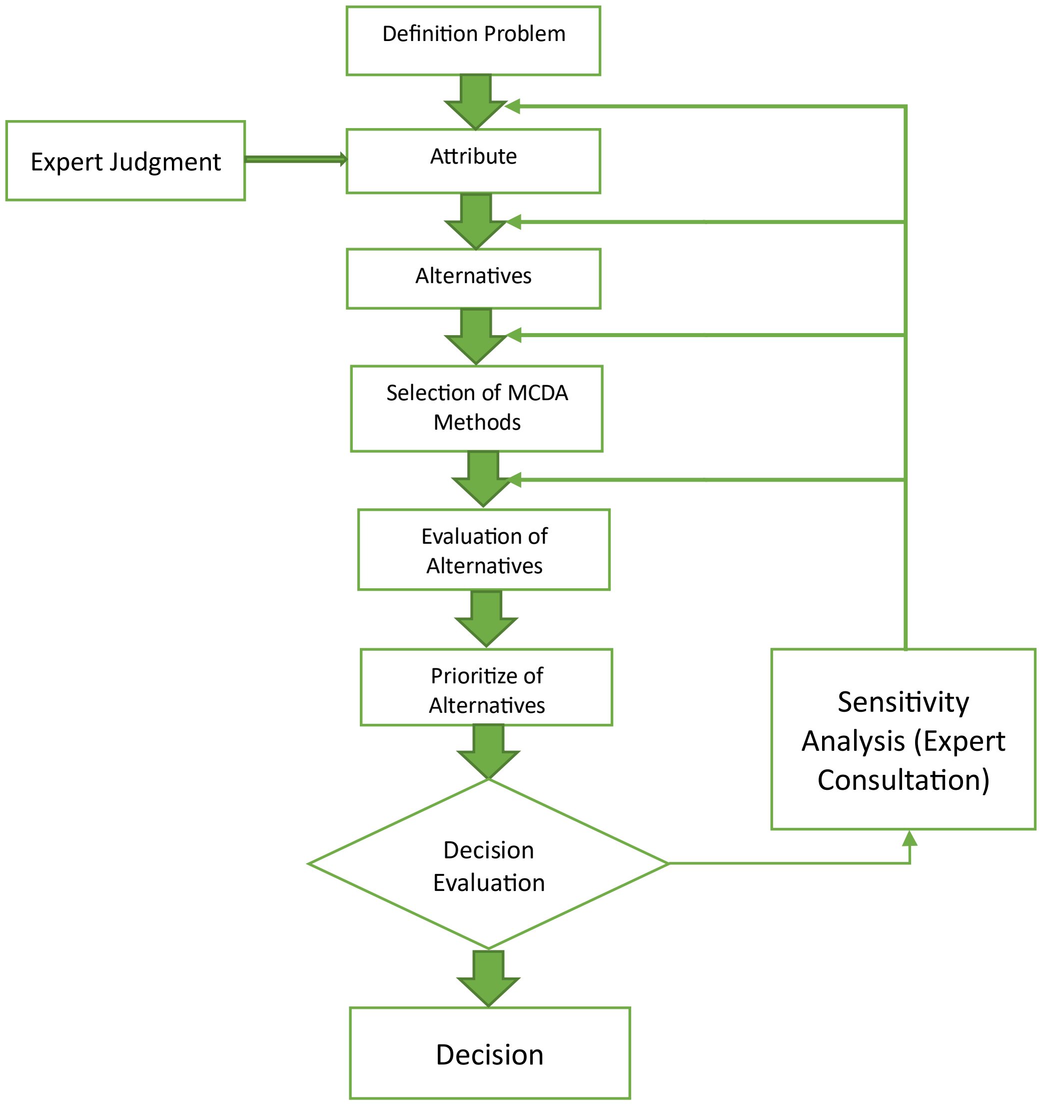

Figure 2. The general model of the decision-making process in my research.

3.2. Focus on Qualitative Assessment

Qualitative assessment holds great importance in decision-making, especially in areas that involve complexity and subjectivity. Its significance cannot be overstated.Qualitative assessment reveals perspectives, emotions, experiences, and attitudes that may not be conveyed through numerical and statistical translations, unlike its quantitative counterpart. (Patton, 2002).

The application of Multi-Criteria Analysis (MCA) in fields such as strategic management and energy transition relies heavily on qualitative assessments. This reliance stems from the inherent nature of these fields, where decision-making is often influenced by a host of non-measurable or non-quantifiable factors such as stakeholder values, beliefs, experiences, and perceptions (Huang et al., 2011). Consider, for instance, the implementation of a new energy transition policy. While quantitative factors like cost, time, and efficiency play significant roles in deciding the policy's feasibility and attractiveness, several qualitative factors also weigh in. Stakeholder attitudes towards the policy, public perception of its implications, and subjective assessments of its potential environmental impact are all qualitative aspects that can significantly sway the decision-making process.

These qualitative aspects require specialized tools and methodologies to be adequately captured and interpreted, and this is where the strength of MCA lies. MCA, particularly in its qualitative form, offers a robust tool to capture and evaluate these aspects (Belton & Stewart, 2001). It accommodates the complexity and subjectivity of decision-making, providing a platform for various perspectives and voices to be heard and considered. The qualitative MCA approach promotes deliberation, negotiation, and consensus-building among stakeholders, fostering a more inclusive and democratic decision-making process.

One of the primary methods employed in qualitative MCA is the use of semi-structured interviews. These interviews are instrumental in gathering detailed information about individuals' experiences, opinions, and feelings towards a particular subject (DiCicco-Bloom & Crabtree, 2006). In the context of energy transition, for instance, interviews could be conducted with various stakeholders - policymakers, industry professionals, community representatives, and academics - to gain insights into their perceptions of different energy transition strategies and their potential impacts.

Additionally, document analysis forms another cornerstone of qualitative MCA. Policy documents, reports, white papers, and articles can be analyzed to understand the policy context, historical trends, and current debates in the field of energy transition (Bowen, 2009). To accommodate the potential challenges associated with interpreting qualitative criteria and managing stakeholder bias, MCA integrates mechanisms such as sensitivity analysis. This technique helps in assessing the stability and robustness of the decision-making process under varying assumptions and preferences, adding a layer of credibility and reliability to the process (Belton & Stewart, 2001).

In conclusion, the focus on qualitative assessment in MCA stresses the importance of human dimensions in decision-making processes. It acknowledges the fact that, while numbers and hard data are vital, they are not always sufficient in capturing the full range of considerations in complex decision-making scenarios. It recognizes that human experiences, perceptions, values, and judgments carry weight and significance in decisions that could have far-reaching societal, economic, and environmental impacts.

3.3. Reflecting on MCA Challenges in the Current Study

The practical application of Multi-Criteria Analysis (MCA) in my research unveiled challenges that echo those identified in established literature (Belton & Stewart, 2001; Triantaphyllou, 2000). The interplay between diverse criteria, particularly when they seemingly conflict, posed intricacies. For instance, energy transition policies occasionally exhibited tensions between economic feasibility and environmental or societal ramifications (Vincke, 1992). While my study avoided dilemmas of weight assignment by focusing on qualitative methods, the balancing of qualitative perspectives became central.

We navigated these challenges by deeply engaging with stakeholder sentiments and emphasizing qualitative evaluations (Keeney & Raiffa, 1993). Sensitivity analysis was unique in my approach, rooted heavily in expert consultations. Experts from the Netherlands and guidance from supervisors proved invaluable in refining my methodologies. Their insights, especially from interviewees No.2 and 4, ensured a robust multi-criteria decision analysis (MCDA) and enhanced the study's global resonance (Figueira et al., 2005).

Despite the comprehensive nature of MCA offering depth, the challenge lay in processing extensive qualitative information. Ensuring no detail was missed necessitated meticulous efforts (Huang et al., 2011). Additionally, while MCA champions inclusivity, reconciling diverse perspectives was occasionally arduous. This reiterated that achieving complete representation in final decisions remains challenging (Keeney & Raiffa, 1993).

In summation, my research's MCA challenges mirrored some from literature but also yielded unique learning avenues. This not only fortified my MCA approach but also illuminated nuances inherent to energy transition policies.

3.4. Synergies and trade-offs in sulfur recovery and energy transition

Navigating the domains of sulfur recovery and energy transition requires a nuanced understanding of multifaceted decision-making. At the heart of this complexity is the convergence of technological, environmental, economic, and societal dimensions. It's within this intricate web that synergies and trade-offs arise, demanding discerning and sustainable decision-making strategies. A holistic approach like Multi-Criteria Analysis (MCA) offers a structured way to comprehend and navigate these interdependencies, championing well-informed and sustainable choices (Belton & Stewart, 2001).

Synergies in sulfur recovery and energy transition context denote instances where initiatives aimed at augmenting sulfur recovery can concurrently bolster energy transition objectives. Illustratively, when a novel sulfur recovery technology is introduced, the ripple effect might not only enhance recovery efficiency but also curtail energy usage. This dual benefit aids in achieving broader energy conservation and minimizing greenhouse gas emissions. Recognizing such synergies paves the way for decisions that capture dual benefits, streamlining decision-making processes (Huang et al., 2011).

Conversely, trade-offs surface when endeavors advantageous to one aim potentially hamper another. For instance, a policy championing sulfur recovery might inadvertently escalate energy consumption or amplify other environmental consequences. This exemplifies a trade-off between environmental aspirations and either economic or technological pursuits. Grasping these trade-offs is pivotal for achieving equilibrium in decisions and navigating potential objective clashes (Triantaphyllou, 2000).

Central to MCA's prowess is its systematic proficiency in discerning, evaluating, and harmonizing these synergies and trade-offs. The method offers an avenue for varied stakeholders to immerse themselves in the decision matrix, reflecting their multifarious viewpoints, values, and priorities (Keeney & Raiffa, 1993). Such diverse stakeholder participation crystallizes a collective comprehension of the inherent synergies and trade-offs, spurring collaborative and consensus-driven decision processes.

Leveraging qualitative tools intrinsic to MCA, like semi-structured dialogues and document scrutiny, is invaluable for illuminating these interdependencies. Stakeholder interactions can be a wellspring of profound insights, unraveling perceptions regarding the interplay between sulfur recovery and energy transition. Parallelly, document exploration elucidates broader policy landscapes, historical trajectories, and prevailing discourses in these domains (Figueira et al., 2005).

Additionally, MCA fosters decision-making marked by transparency and introspection. By meticulously delineating decision criteria and fostering avenues for dialogue and compromise, MCA emphasizes a transparent, reflective decision ethos. Such clarity and self-awareness in the process help mediate potential discord and trade-offs, instilling mutual trust and fostering stakeholder collaboration (Vincke, 1992).

To encapsulate, discerning the intricate balance of synergies and trade-offs in sulfur recovery and energy transition is indispensable for forging judicious and enduring decisions. Harnessing MCA, with its accent on qualitative scrutiny and stakeholder inclusivity, offers a formidable, comprehensive framework to traverse these complexities. By employing MCA, the trajectory towards holistic, informed, and sustainable decision-making is illuminated, aligning seamlessly with overarching sustainable development and energy transition goals.

4. Research Design

This research employed a qualitative Multi-Criteria Analysis (MCA) approach to analyze the synergies and trade-offs between sulfur recovery efficiency and energy transition policies in the Netherlands. The study involved reviewing policy documents, gathering stakeholder input and expert opinions, and developing a clear framework for evaluating and prioritizing sulfur recovery options. The research aims to identify the most suitable options for optimizing sulfur recovery within the Dutch policy landscape.

4.1. Method For Data Collection and Analysis

4.1.1. Literature Review:

A systematic literature review has been conducted to gather information on energy transition policies in the Netherlands, sulfur recovery practices, and the synergies and trade-offs between the two. The review followed several steps, regarding the database, I searched academic databases (e.g., Scopus, Web of Science) and grey literature (e.g., policy documents, industry reports) for relevant articles using a combination of keywords related to sulfur recovery, energy transition policies, and the Netherlands. Then I established criteria to screen the identified literature for relevance, such as language (English or Dutch), publication date (within the last 10-15 years), and topic relevance. After that for each included article, I extracted relevant information such as study objectives, methods, key findings, and implications for policy or practice. Finally, I synthesized the extracted information to identify trends, gaps, and potential areas for optimization in sulfur recovery and energy transition policies in the Netherlands.In summary, literature review help me to primarily identified the main parameters of MCA matrix as I explained in conceptual framework and then I would endorse them during the interviews.

4.1.2. Semi-structured Interviews:

To gather stakeholders' perspectives on policies and practices, I conducted semi-structured interviews with approximately 5 participants, including policymakers, industry experts, and researchers. First, the participants were asked to endorse the MCA matrix that was initially derived from the literature review. This endorsement process validated the parameters identified in the literature and may introduce new elements for consideration in the MCA. Next, participants were asked to evaluate the options for sulfur recovery units (SRUs) against the endorsed criteria. This evaluation process would involve discussing the strengths and weaknesses of each option in relation to the established criteria. Therefore, the interviews served two main purposes in the MCA: the validation and possibly expansion of the MCA matrix, and the qualitative assessment of SRU options.

The interviews addressed Energy Transition Policies, Sulfur Recovery, and Real-world Implications, How stakeholders perceive the impact of energy transition policies on sulfur recovery practices and efficiency, as well as their practical experiences with the synergies and trade-offs between these areas. This should also include their suggestions for optimizing these relationships. Stakeholders' opinions on relevant criteria for evaluating sulfur recovery options, including environmental, economic, and social factors. Stakeholders' opinions on best practices for balancing sulfur recovery and energy transition policies in the Netherlands that could be applied in other countries.

I have prepared table 2 of targeted stakeholders for this research, which can be found below. The interview process involved semi-structured interviews with open-ended questions, allowing participants to provide their insights and opinions on the research topic. The main goal is to operationalize the conceptual framework by gathering valuable insights to address the practical applications for balancing sulfur recovery units (SRUs) and energy transition policies.

Table 2. Targeted stakeholder

Stakeholder Category	Specific Stakeholders
Government agencies and policymakers	Dutch Ministry of Economic Affairs and Climate Policy, Dutch Environmental Protection Agency, other agencies responsible for energy transition policies and environmental regulations
Industry professionals and businesses	Companies in the oil, gas, and petrochemical sectors that operate SRUs, technology providers, consultants in the field of sulfur recovery and energy transition

Research institutions and academic experts	Researchers and academics working on sulfur recovery processes, energy transition, and environmental policy in the Netherlands and internationally
Non-governmental organizations (NGOs)	Environmental advocacy groups and organizations focused on sustainable development and energy transition in the Netherlands
International organizations	European Union institutions, global organizations dealing with energy policies, environmental protection, and climate change mitigation

Below table 3 shows the final interviewees which have ideas and knowledge regarding one or both areas of my thesis topic ETP and /or SRU. Managers from two designer and vendor of SRU, two engineers who have the up to date knowledge in SRU design and one diplomat who knows about the perspective in energy advocacy. See the interview question lists and summary of transcripts in Appendix lll.

Table 3. Interview Lists

Code	Interview Dates	Institution	Institution Remarks	Position	Experience
Interviewee 1	22-Jun-23 In person	Bilfinger Tebodine	An international engineering and consultancy firm	Consultant	Extensive experience in SRUs and energy transition policies
Interviewee 2	23-Jun-23 Online	Bilfinger Tebodine	An international engineering and consultancy firm	Energy Section Manager	Extensive experience in SRUs and energy transition policies
Interviewee 3	24-Jun-23 Online	Duiker	A combustion reactor vendor, with focus on SRUs and energy transition	Process Development Manager	Strong background in combustion engineering and SRU industry, actively aligning expertise with energy transition policies
Interviewee 4	29-Jun-23 Remote *	Worley	A global provider of professional project and asset services in the energy, chemicals, and resources sectors	Engineering Coordinator and Process Specialist	3 years of experience in the sulfur recovery unit
Interviewee 5	23-Jun-23 Online	Retired Diplomat	Previously a diplomat advocating for sustainable energy solutions	Retired Diplomat	Advocacy for sustainable energy solutions

* Opted for email responses due to time constraints

From table 3, it is evident that while the reaserch identifies key governmental bodies like Dutch Ministry of Economic Affairs and Climate Policy, despite a lot of effort just one retired diplomat may offer insights from policy makers perspectives and international organizations especially on sustainable energy solutions.The research successfully covered the category of Industry professionals and businesses with representatives from Bilfinger Tebodine, Duiker, and Worley.

These stakeholders come from businesses that have direct relevance to sulfur recovery and energy transition. According to research institutions and academic experts, there was no direct representation in the interviews. However, we extensively used relevant reports and results found in the literature review to fill the gap.NGO's did not explicitly represent in the interview list indicating the area where the research could be expanded for comprehensive understanding.

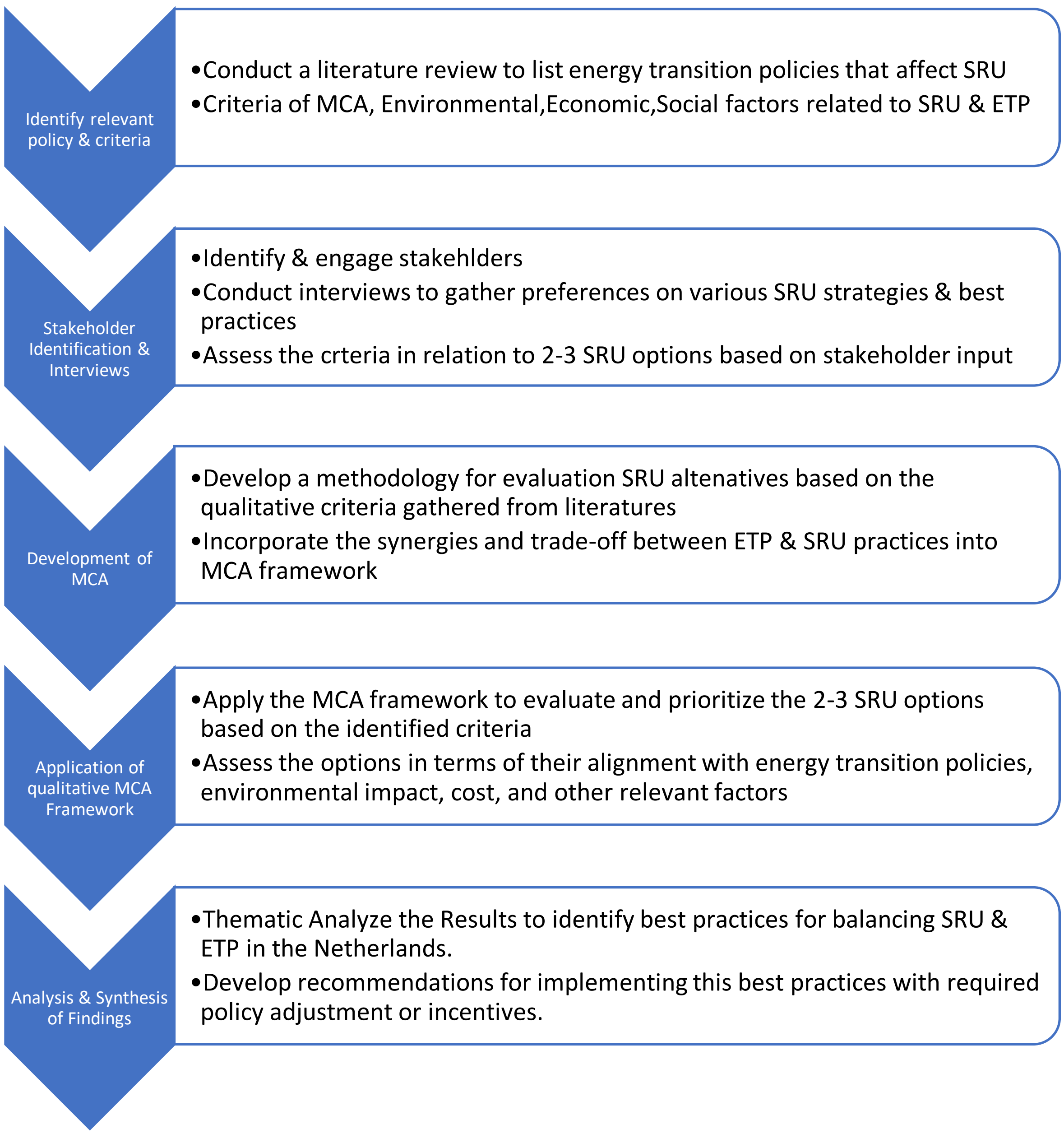

Figure 3 Stepwise framework

Figure 3 shows my stepwise framework and I must added in the research's decision-making process, a unique approach to sensitivity analysis was undertaken, emphasizing expert consultations. Rooted in real-world experiences, I collaborated with experts to validate the problem's definition. For attributes, the Netherlands' experts offered insights, enhancing the research's global relevance. My supervisors provided pivotal guidance on methods and alternatives. The true embodiment of sensitivity analysis was during the evaluation phase. Two separate experts from my interviewees No.2 and 4 were asked to scrutinize the results, assessing the robustness and reliability of the multi-criteria decision analysis (MCDA) under varying assumptions. Their feedback, combined with targeted interviews, fortified the study's credibility and ensured that outcomes remained consistent across diverse expert perspectives.

4.1.3. Qualitative Multi-Criteria Analysis (MCA):

The MCA framework, endorsed and possibly enhanced through the stakeholder interviews, is utilized to evaluate and prioritize sulfur recovery options. The assessment of each option is based on the qualitative evaluations provided by the interview participants, allowing for a comprehensive comparison of the options' performance against the endorsed criteria. This approach provided an overall ordering of options, from the most preferred to the least preferred, based on the multiple objectives. The purpose/ of the MCA is to aid decision-making by providing a clear, transparent, and comprehensive evaluation of the options (Wognum et al., 2009).
The methodology for evaluating and prioritizing alternatives within the MCA framework involves several key steps. This process ensures that the assessment is transparent, consistent, and easy to understand for decision-makers and stakeholders.

1. Define the decision criteria: Clearly identify the criteria that is used to evaluate the sulfur recovery options. These criteria should be based on environmental, economic, and social factors, as well as any other relevant factors identified in the literature review and stakeholder interviews. Given the qualitative focus of the research, the assignment of weights is avoided to reduce the risk of bias and subjectivity.
2. Establish performance indicators: Develop performance indicators for each criterion that would be used to measure and compare the sulfur recovery options. These indicators should be specific, measurable, and aligned with the qualitative data collected in the literature review and interviews. , it's important to note that these indicators do not engage in quantitative measurement, reflecting the study's qualitative orientation.
3. Predefine and evaluate the alternatives: Three predefined sulfur recovery options (to be defined based on the literature review and stakeholder interviews) were qualitatively assessed against the decision criteria and performance indicators. This evaluation were based on qualitative techniques, such as expert opinions or stakeholder preferences.
4. Compare the alternatives: After evaluating each option against the decision criteria, the alternatives were compared based on the aggregated qualitative assessments. This allowed for a comprehensive understanding of each option's strengths and weaknesses within the context of the defined criteria.
5. Prioritize the alternatives: Alternatives were prioritized based on their overall qualitative performance against the decision criteria. This step does not involve calculating weighted.

For further clarity, I've compiled a matrix outlining the Data, Methods, and Analysis corresponding to each research question, presented in Table 4.

Table 4. Matrix of Sub-questions, Data, Methods, and Analysis.

Main & Sub-question	Data	Method	Analysis
How can sulfur recovery efficiency in the Netherlands be optimized while taking into account Dutch energy transition policies?	Policy documents, academic articles, industry reports, Sulfur recovery efficiency data, energy consumption data, greenhouse gas emissions data	Literature review Stakeholder interviews	Thematic analysis Qualitative analysis
1. Key energy transition policies affecting sulfur recovery practices	Policy documents, academic articles, industry reports	Literature review	N/A
2. Synergies and trade-offs between energy transition policies and sulfur recovery practices	Sulfur recovery efficiency data, energy consumption data, greenhouse gas emissions data	Stakeholder interviews	Thematic analysis Qualitative analysis
3. Optimizing synergies and addressing trade-offs	N/A	Stakeholder interviews	Thematic analysis, content analysis (Qualitative analysis)

5. FINDINGS

This chapter describes the results from the literature review and semi-structured interview to first finalized the MCA matrix and then address research questions through the findings.

5.1. Reviewing SRU Options

Based on the literature review, several options exist for Sulfur Recovery Units (SRUs) at the industrial scale, particularly in the context of the Netherlands. These options reflect advancements in technology, local regulations, environmental considerations, and the global trend of reducing carbon emissions.

Claus Process: The Claus process is a foundational method for sulfur recovery, having been extensively adopted across industries. It's crucial to include this conventional method in the analysis as it offers a benchmark, giving context to the advancements of modified processes and ensuring that the full spectrum of options, from the most established to the most innovative, is considered. The process involves a two-step conversion where hydrogen sulfide (H2S) is initially transformed to sulfur dioxide (SO_2) via combustion. Subsequently, the SO_2 reacts with the remaining H_2S to produce elemental sulfur. This method can recover up to 95-97% of sulfur from the acid gas stream (Kohl & Nielsen, 2016). To further enhance sulfur recovery efficiency, the Claus process is often paired with a Tail Gas Treatment Unit (TGTU), which can push recovery rates above 99%.

Modified Claus Process: Innovations and technological improvements have led to modified versions of the Claus process. Oxygen-enriched Claus processes utilize oxygen instead of air for the combustion stage, which increases sulfur recovery rates and reduces the size of equipment required (Caton, 2005). Sub-dew point Claus processes operate below the sulfur dew point, further enhancing sulfur recovery efficiency (Rahman et al., 2018). These modifications offer improved performance and energy efficiency compared to the conventional Claus process.

Adsorption Processes: Some SRUs employ adsorption processes using solid desiccants like activated carbon to remove H_2S from gas streams. The H_2S is adsorbed onto the desiccant material, and then released and converted to sulfur using established methods (Chan et al., 2023). Adsorption processes can be an alternative or complementary approach to the Claus process, providing flexibility in sulfur recovery operations.

In the Netherlands, there is a strong emphasis on sustainable energy transition and reducing carbon emissions. The country's policies encourage the adoption of cleaner technologies and emission reduction in industrial sectors, including oil and gas. Therefore, selecting SRUs with high sulfur recovery efficiency, low energy consumption, and minimal environmental impact is of paramount importance (Bader & Oostra, 2022; Griffiths et al., 2022).

Considering the focus on reducing carbon emissions, the capture and utilization of carbon dioxide (CO_2) from sulfur recovery processes are emerging trends. Integrated processes that capture and utilize CO_2 (CCU - Carbon Capture and Utilization) can provide additional value streams for the SRU process, improving economics while reducing the carbon footprint (Rajabloo et al., 2023; Chen et al., 2021).In the decision-making process for implementing SRUs, a comprehensive evaluation is necessary, taking into account multiple criteria such as cost-effectiveness, technical feasibility, environmental impact, and alignment with regulatory standards and social acceptance. Advanced process simulations and optimization tools can assist in this decision-making process by predicting the performance and potential environmental impact of different SRU options (Belton & Stewart, 2001; Huang et al., 2011; Bolf et al., 2009; Hashemi, 2020; Ibrahim et al., 2023).

In summary, the literature review highlights various current options for SRUs in the Netherlands. The Claus process, modified Claus processes, and adsorption processes offer different approaches to sulfur recovery, each with its own advantages and considerations. The focus on sustainability and carbon emissions reduction drives the exploration of advanced technologies, such as CCU, and underscores the need for comprehensive evaluations when selecting SRU options. By carefully considering the available options and aligning them with the goals of the energy transition, the Netherlands can achieve efficient and environmentally responsible sulfur recovery processes.

5.2. Identifying criteria from ETP context

The evaluation and selection of appropriate sulfur recovery technologies in the context of energy transition policies require the consideration of various criteria. Drawing from the literature review findings, the following criteria have been identified as influential in the assessment of different SRU technologies:

Contribution to National Emission Reduction Targets: The ability of each SRU technology to contribute to national emission reduction targets is a crucial criterion. This encompasses the reduction of greenhouse gas emissions, particularly sulfur emissions, in line with the Netherlands' climate commitments. (Kern & Smith, 2008; Horikawa et al., 2004)

Compliance with Renewable Energy Targets: As the Netherlands aims to increase the share of renewable energy in its energy mix, the alignment of SRU technologies with renewable energy targets becomes significant. This criterion evaluates the compatibility of each technology with the utilization of renewable energy sources in sulfur recovery processes. (Inês et al., 2020; Provolo et al., 2018)

Potential for Efficiency Improvements: The potential for enhancing the efficiency of SRU technologies is an essential criterion for energy transition policies. Evaluating the capability of each technology to improve its energy efficiency over time ensures the continuous advancement and optimization of sulfur recovery processes. (Ibrahim et al., 2023; Caton, 2005)

Technological Maturity and Reliability: While technological maturity might seem like a general criterion, in the context of energy transition, it's about leveraging reliable and proven technologies to ensure a smooth transition. The readiness and proven track record of SRU technologies ensure that they can be rapidly scaled and integrated into existing systems to meet energy transition goals (Kohl & Nielsen, 2016; Rahman et al., 2018).

Economic Feasibility: Within the energy transition context, evaluating the economic viability of SRU technologies is about considering not only their cost-effectiveness but also potential financial incentives that support sustainable technologies (Beck et al., 2022; Ghavam et al., 2021).

Contribution to Sustainable Development Goals (SDGs): The alignment of SRU technologies with the Sustainable Development Goals is an important criterion for evaluating their sustainability. This includes assessing their potential to address environmental, social, and economic aspects of sustainable development. (Loorbach et al., 2008; Olabi et al., 2022)

Public Acceptance and Social License to Operate: The acceptance and social license to operate of SRU technologies within local communities and society are critical for successful implementation. This criterion considers the level of public acceptance, addressing concerns, and ensuring the engagement and participation of relevant stakeholders in the decision-making process. (Vringer & Carabain, 2020; CBS, PBL, RIVM & WUR, 2020)

Potential for CO2 Capture and Utilization: The potential of each SRU technology to capture and utilize CO2 emissions is increasingly important in the context of carbon neutrality and climate change mitigation efforts. This criterion evaluates the ability of the technologies to contribute to CO_2 reduction and utilization through innovative processes. (Chen et al., 2021; Rajabloo et al., 2023)

Below table 5. summarizing the influential criteria in the context of energy transition policies and their link to the existing Dutch energy transition policies in table 1.

Table 5. Influential criteria in the context of Energy Transition Policies

Criteria	Relevant Policies	Reference
Contribution to National Emission Reduction Targets	Dutch Climate Agreement	Bader and Oostra, 2022
Compliance with Renewable Energy Targets	Market Dynamics (Renewable Energy Transition)	Provolo et al., 2018; Fetisov et al., 2023
Potential for Efficiency Improvements	Technological Innovations (Clean Energy Push)	Okoro & Sun, 2019; Liu et al.,2017; Chen et al., 2021; RVO, 2023
Technological Maturity and Reliability	Environmental Regulations (for Sulfur Emissions)	Horikawa et al., 2004; ADB, 2021
Economic Feasibility	Investment Opportunities (Sustainable Technologies)	Olab et al., 2022; Ghavam et al., 2021
Contribution to Sustainable Development Goals (SDGs)	Collaboration and Partnerships	Richard, 2016
Public Acceptance and Social License to Operate	Collaboration and Partnerships	Richard, 2016
Potential for CO_2 Capture and Utilization	Potential for CO_2 Capture and Utilization	Olab et al., 2022; Ghavam et al., 2021; Bader and Oostra, 2022

To compare the various SRU technologies based on these criteria, I used Multi-Criteria Analysis (MCA) method. Table 6 was my initial MCA matrix which helped me understand how well each technology aligned with the identified factors.

Table 6. Initial MCA Matrix

Criteria/Sub-criteria Related to ETP in the Netherlands	Claus Process	Modified Claus Process	Adsorption Processes
Contribution to National Emission Reduction Targets			
Compliance with Renewable Energy Targets			
Potential for Efficiency Improvements			
Technological Maturity and Reliability			
Economic Feasibility			
Contribution to Sustainable Development Goals (SDGs)			
Public Acceptance and Social License to Operate			
Potential for CO_2 Capture and Utilization			

5.3. Qualitative MCA

The evaluation for each criterion was underpinned by an exhaustive exploration of the relevant literature, authoritative sources, and expert insights. Established guidelines, domain-specific frameworks, and best practices also informed these evaluations. The aim was to capture the contemporary academic consensus on specific criteria and their underlying facets.

The Claus Process was notably commended for its role in supporting national emission reduction goals, as emphasized by Kohl & Nielsen (2016). Its distinguished efficacy in curbing greenhouse gas emissions, especially those of sulfur, marked it as a crucial instrument for emission mitigation across diverse industries. The Modified Claus Process, too, was recognized for its substantial contributions, with Rahman et al. (2018) highlighting its augmented emission reduction capacity. In contrast, the effectiveness of Adsorption Processes in emission reduction appeared to be moderate. A notable lack of comprehensive references for Adsorption Processes makes it tough to substantiate this moderate impact conclusively.

Rahman et al. (2018) observed that the Claus Process showed minimal alignment with renewable energy objectives due to its pronounced dependence on fossil fuels and limited engagement with renewable sources. Conversely, the Modified Claus Process reflected a fair degree of alignment, given its potential for partial renewable integration. Provolo et al. (2018) and Fetisov et al. (2023) emphasized the significant compatibility of Adsorption Processes with renewable energy targets, applauding its flexibility in adapting to the reduced fossil fuel dependency and its inclination towards sustainable natural gas and biogas production.

Kohl & Nielsen (2016) contended that the Claus Process had moderate potential for efficiency upgrades, a perspective shaped by its technological maturity and existing advancements. In contrast, both the Modified Claus Process and Adsorption Processes showed encouraging prospects for enhancement. Their capacity for improving energy efficiency in sulfur recovery and optimizing both efficiency and ecological performance is praiseworthy, as elaborated by Okoro & Sun (2019), Liu et al. (2017), and Chen et al. (2021).

In terms of technological maturity and dependability, the Claus Process received distinct praise, notably from Kohl & Nielsen (2016), due to its pervasive industrial use and consistent outcomes. The Modified Claus Process also received positive remarks for its proven efficacy in sulfur recovery applications from Rahman et al. (2018). Yet, Adsorption Processes secured a middle-ground position, mainly stemming from the lack of extensive references.

From an economic standpoint, the Claus Process was highlighted for its financial viability by Kohl & Nielsen (2016) due to its well-established infrastructure, cost advantages, and widespread industrial endorsement. The Modified Claus Process had a more nuanced economic evaluation, with Rahman et al. (2018) emphasizing potential capital expenditures and operational complexities. On the other hand, the Adsorption Processes stood out for their economic potential, as outlined by Olab et al. (2022) and Ghavam et al. (2021).

In sync with the Sustainable Development Goals (SDGs), the Claus Process offered a balanced contribution, notably in terms of emission curtailment and ecological betterment as observed by Rahman et al. (2018). The Modified Claus Process was seen to resonate strongly with multiple SDGs, while the Adsorption Processes also indicated a solid contribution to areas like environmental conservation and energy enhancement.

Public acceptance and social licensing saw both the Claus Process and Modified Claus Process receive moderate ratings. The latter, in particular, emphasized the need for extensive stakeholder participation regarding sulfur recovery decisions. Conversely, Adsorption Processes garnered significant public approval, as deduced by Bader & Oostra (2022), due to their perceived eco-friendly impact and energy proficiency.

In the domain of CO2 capture and utilization potential, the Claus Process was seen as trailing, with limited capabilities noted by Kohl & Nielsen (2016). Conversely, Rahman et al. (2018) highlighted the Modified Claus Process for its strong potential, largely due to its alignment with carbon capture innovations. However, The Adsorption Processes, due to scarce references, receive a conservative appraisal.

Table 7. MCA Assessment based on Literature Review

Criteria/Sub-criteria	**Claus Process**	**Modified Claus Process**	**Adsorption Processes**
Contribution to National Emission Reduction Targets	High (Kohl & Nielsen, 2016)	High (Rahman et al., 2018)	(?)
Compliance with Renewable Energy Targets	Low (Rahman et al., 2018)	Moderate (Rahman et al., 2018)	(?)
Potential for Efficiency Improvements	Moderate (Kohl & Nielsen, 2016)	High (Rahman et al., 2018)	(?)
Technological Maturity and Reliability	Very High (Kohl & Nielsen, 2016)	High (Rahman et al., 2018)	(?)
Economic Feasibility	High (Kohl & Nielsen, 2016)	Moderate (Rahman et al., 2018)	(?)
Contribution to Sustainable Development Goals (SDGs)	Moderate (Rahman et al., 2018)	High (Rahman et al., 2018)	(?)
Public Acceptance and Social License to Operate	(?)	(?)	(?)
Potential for CO2 Capture and Utilization	Low (Kohl & Nielsen, 2016)	High (Rahman et al., 2018)	(?)

Following the literature review results in table 7, the interviews elucidated more profound insights into the role and challenges of SRUs and Adsorption Processes in the energy transition.

One recurrent theme was the intricate relationship between economic feasibility and environmental sustainability. As Interviewee 5 articulated on 23 June 2023, "Although the importance of SRUs and Adsorption Processes in energy transition cannot be understated, we also need to focus on their economic feasibility. Investments in these technologies should also make business sense." This was further corroborated by Interviewee 4 on 29 June 2023, who noted that the "economics of SRUs and Adsorption Processes will directly influence their public acceptance and social license to operate."

The importance of considering societal costs and benefits was emphasized by Interviewee 1 on 22 June 2023, stating, "In the context of economic feasibility, we must not overlook the societal costs and benefits. It's essential that we integrate broader sustainability goals into our economic evaluations." This captures the essence of a holistic evaluation encompassing both immediate economic impacts and long-term societal benefits.

Regarding the potential of Adsorption Processes, Interviewee 3 on 24 June 2023 highlighted their significance in CO2 capture and utilization, especially in contexts with high CO2 concentrations. However, this same interviewee also cautioned against overly relying on one technology, advocating a diversified approach to CO2 mitigation, inclusive of other energy solutions such as wind and solar.

The need for intensive research and development for Adsorption Processes was accentuated by Interviewee 4 on 29 June 2023, suggesting the development of "high-selectivity adsorbents for efficient separation processes and rapid thermal cycles."

Technological maturity and reliability surfaced as another predominant theme. The Modified Claus process's successful track record was commended by Interviewee 3 on 24 June 2023, juxtaposing it with other sulfur production methods. The sentiment was underpinned by a clarion call from Interviewee 1 on 22 June 2023 for constant innovation, especially concerning energy efficiency.

In sum, as shown on table 8 the interviewees collectively point out the centrality of SRUs and Adsorption Processes in energy transition endeavors. They emphasized the balance of economic feasibility with environmental imperatives, the potential of Adsorption Processes in CO2 mitigation, and the consistent call for technological innovation and refinement. These insights profoundly shape the discourse on how SRUs and Adsorption Processes can be integrated into future energy transition strategies.

Table 8. Final MCA including Interview Insights

Criteria/Sub-criteria	Claus Process	Modified Claus Process	Adsorption Processes
Contribution to National Emission Reduction Targets	High	High	High
Compliance with Renewable Energy Targets	Low	Moderate	High
Potential for Efficiency Improvements	Moderate	High	High
Technological Maturity and Reliability	Very High	High	High
Economic Feasibility	High	Moderate	Moderate
Contribution to Sustainable Development Goals (SDGs)	Moderate	High	High
Public Acceptance and Social License to Operate	Moderate	Moderate	Moderate
Potential for CO2 Capture and Utilization	Low	High	High

5.3.1. Contribution to National Emission Reduction Targets
The imperative of national emission reduction has cast various sulfur recovery processes into the spotlight. Kohl & Nielsen (2016) extolled the Claus Process for its commendable role in emission reduction. Complementing this, Rahman et al. (2018) explored the merits of the Modified Claus and Adsorption Processes. Conversations with industry veterans further bolstered this view, with many emphasizing the SRUs' importance for national targets [5 Interviewees]. Conclusively, both literature and firsthand experiences demonstrate the Claus Process's and other SRUs' vital roles in emission reduction.

5.3.2 Compliance with Renewable Energy Targets
The alignment of sulfur recovery processes with renewable energy objectives remains a subject of scrutiny. Rahman et al. (2018) observed the Claus Process's somewhat limited alignment, while emphasizing that other processes hold greater potential. This academic insight finds resonance among experts who view the Adsorption Process as pivotal for renewable energy targets [4 Interviewees]. Collectively, there's a growing consensus on the need to explore processes beyond Claus to meet renewable goals.

5.3.3 Potential for Efficiency Improvements
In the quest for optimal efficiency, the Claus Process's potential was found to be moderate by Kohl & Nielsen (2016), while Rahman et al. (2018) envisioned the Modified Claus Process and Adsorption Processes as more promising. This perspective is echoed in industry insights that emphasize the vast potential of Adsorption, particularly in areas like CO2 capture [3 Interviewees]. Thereby, the potential for technological advancements in sulfur recovery processes remains high, especially with Adsorption.

5.3.4 Technological Maturity and Reliability
The maturity and dependability of sulfur recovery processes have been documented extensively. Rahman et al. (2018) and Kohl & Nielsen (2016) both acclaimed the Claus Process for its reliability, with the latter also lauding the Modified Claus Process. These findings were further enriched by industry experts who vouched for the Modified Claus Process's practical successes [3 Interviewees]. Hence, there's a collective agreement on the Claus processes' reliability, both in theory and in practice.

5.3.5 Economic Feasibility
Balancing economic feasibility with environmental goals is pivotal. Kohl & Nielsen (2016) acknowledged the Claus Process for its economic soundness, while Rahman et al. (2018) presented a nuanced view on the Modified Claus and Adsorption Processes. Industry perspectives similarly indicated the challenges and opportunities in reconciling these dual objectives, with some emphasizing the Modified Claus Process's balance [5 Interviewees]. Therefore, the journey toward economic and environmental balance in sulfur recovery continues, with the Modified Claus Process showing promise.

5.3.6 Contribution to Sustainable Development Goals (SDGs)
The intertwining of sulfur recovery processes with global SDGs is undeniable. Literature reveals the Claus and Modified Claus Processes' tangible contributions, while also recognizing the

strides made by Adsorption Processes. Corroborating this, industry experts accentuated the alignment of technologies like the Modified Claus with global sustainability objectives [5 Interviewees]. Thus, sulfur recovery technologies remain at the forefront of sustainable industrial advancements.

5.3.7 Public Acceptance and Social License to Operate

For any technology, gaining public trust and acceptance is paramount. Kohl & Nielsen (2016) and Rahman et al. (2018) provided insights into the Claus and Modified Claus Processes' public reception. In parallel, the industry feedback reflected a growing endorsement for Adsorption Processes by communities [4 Interviewees]. Conclusively, the industry's future hinges on its alignment with public sentiment, with Adsorption Processes leading the way.

5.3.8 Potential for CO2 Capture and Utilization

The potential for CO2 capture in sulfur recovery processes remains a pivotal research area. Both Kohl & Nielsen (2016) and Rahman et al. (2018) commented on the varying capabilities of these processes. Reinforcing these findings, industry views spotlight the Modified Claus Process's potential for CO2 capture [4 Interviewees]. Thus, the future for CO2 capture in sulfur recovery looks promising, led by processes like the Modified Claus.

6. DISCUSSION

The discussion section started with the key findings and then delved into the meaning, importance, and relevance of my result. I conducted an analysis of my data to identify any correlations and provided explanations for any unexpected findings.. Next, I presented the significance and consequences of my research and explored the novel perspectives it brings..

6.1. Synergies and trade-offs

The intersection between sulfur recovery processes and energy transition policies in the Netherlands is multifaceted, revealing both promising synergies and inevitable trade-offs. We are exploring the alignment to better understand the overall effects and nuances of these intersections, and analyze their implications.The most palpable synergy between sulfur recovery and energy transition lies in their shared objective of reducing environmental harm. With energy transition policies targeting reductions in greenhouse gas emissions and sulfur recovery practices focusing on diminishing sulfur emissions, the commitment to environmental protection is evident.

Processes like Adsorption show promising potential, particularly in their alignment with energy transition policies. Their capability for CO2 capture is a notable illustration of this synergy. By incorporating such innovative technologies, sulfur recovery practices can progressively align with the larger energy transition objectives, benefitting both the environment and the economy. However, trade-offs cast shadows on this optimistic synergy. The reliance on fossil fuels, especially in Claus and Modified Claus processes, stands in stark contrast to the overarching objectives of energy transition policies. This inconsistency points to the need for either significant modifications in sulfur recovery practices or nuanced readjustments in energy transition strategies.

The economic feasibility of these processes, especially when juxtaposed against their environmental impact, further emphasizes the need to strike a balance. In a globally competitive market, while transitioning to cleaner energy sources and ensuring efficient sulfur recovery is paramount, so is ensuring the economic viability of these practices.

The journey of reconciling the goals of sulfur recovery with those of energy transition necessitates a well-thought-out strategy. Investing in research and development is paramount. Newer, more energy-efficient, and low-carbon sulfur recovery technologies can serve the dual purpose of aligning with energy transition goals while also enhancing sulfur recovery efficiency. Public-private partnerships, knowledge sharing, and robust regulations can further streamline this alignment, ensuring that both energy transition and sulfur recovery progress hand in hand, complementing each other.

Incorporating the perspectives of stakeholders offers a panoramic view of the challenges and opportunities at hand. They emphasize the pressing need for sulfur recovery practices to evolve in tandem with energy transition policies. The recurring theme of research, innovation, and partnership from these perspectives offers a roadmap for the future, highlighting the necessity for continuous evolution in sulfur recovery practices.

The challenge of aligning sulfur recovery with energy transition policies is evident, but it's not insurmountable. There is a dire need for a cohesive approach, which considers both sulfur recovery's role in emission reductions and its alignment with energy transition objectives. Policy support, incentive mechanisms, and a holistic view of environmental and economic implications can guide this alignment.

The dialogue between sulfur recovery processes and energy transition policies is multifarious, reflecting both convergences and divergences. While the shared goals offer a promising platform for collaboration, the trade-offs underline the challenges that lie ahead. Nevertheless, with strategic alignment, robust research, and an integrative approach, these challenges can be transformed into opportunities for a sustainable future.

The information presented in this chapter calls for a more thorough analysis, exploring the complex intersections, challenges, and opportunities that lie at the crossroads of sulfur recovery and energy transition in the Netherlands. The upcoming chapters will provide a more in-depth understanding of the subject matter, providing valuable insights and analysis to guide us towards the future.

6.2. Recommendations for Optimizing Synergies and Addressing Trade-offs

Encourage Biotechnological Advancements in SRUs

As our energy landscape shifts towards more sustainable sources like biogas, the adaptation of sulfur recovery processes becomes paramount. Biotechnological methods for sulfur recovery present themselves as a promising avenue, especially considering their potential to efficiently process smaller-scale sulfur emissions typical of biogas production.

During my initial interviews with industry experts, there was a consistent emphasis on the potential and interest in biotechnological solutions for sulfur recovery. This aligns with findings by Show, K., Lee, D. H., & Pan, X. (2013) which highlighted advancements in simultaneous biological removal of nitrogen, sulfur, and carbon, revealing its efficacy in this domain1. In their study, the authors underscore the promise of such biotechnological processes, especially when juxtaposed with traditional large-scale methods.

Facilitate Gradual Transition

As the Claus and Modified Claus processes are heavily reliant on fossil fuels, implementing a gradual transition strategy might prove to be more feasible. Policymakers can take into account the inherent long-term nature of SRUs and accordingly incorporate gradual transition provisions within energy transition policies. This allows SRUs sufficient time and resources to adapt their operations. A phased transition, including smaller milestones and clear trajectories, can foster a sense of direction, reducing uncertainty and promoting stakeholder collaboration.

Foster Investment in CO2 Capture Technologies

While stakeholders show preference for renewable energy investment, my study highlights the potential of CO2 capture technologies in aligning SRUs with energy transition goals. Therefore, a balanced approach, promoting immediate investment in renewable energy sources like bio gas, while also supporting research and development in CO2 capture technologies, could offer a well-rounded solution.

Improve Economic Viability of Adsorption Processes

Despite the high potential of Adsorption processes for efficiency improvements and CO2 capture, their economic viability was found to be moderate. To better position these processes as sustainable alternatives in the future, policymakers and industry stakeholders should explore the economic aspects of Adsorption processes further, identifying strategies to improve their cost-effectiveness without compromising environmental benefits.

Enhance Public Engagement and Communication

Public acceptance and understanding are crucial for the adoption of new technologies like the Adsorption process and biotechnology methods. Efforts should be made to enhance public engagement through improved communication strategies. These could involve open dialogues, information sessions, and demonstrations that make complex technical processes accessible and understandable to the general public.

Foster Cross-Sector Collaboration

Collaboration across sectors can promote the exchange of ideas, resources, and technological advancements, leading to more sustainable and integrative solutions. I recommend establishing partnerships between the sulfur recovery industry and the renewable energy sector. Shared platforms and joint projects or research initiatives can foster this collaboration, encouraging the development of integrated solutions.

Create Incentives for SRUs to Align with Energy Transition Policies

To enhance alignment of SRUs with energy transition policies, incentives could be offered to sulfur recovery operators to adopt practices in line with these policies. Incentives such as grants, subsidies, or tax breaks could be given to SRUs that reduce their dependence on fossil fuels, transition to biotechnological methods or adopt new technologies like Adsorption processes. These incentives could play a significant role in encouraging alignment of SRUs with energy transition goals.

In conclusion, the intricate dynamics between SRUs and energy transition policies offer unique challenges and opportunities. As the energy landscape evolves, so too must the strategies government employ to navigate it. Through recognizing and addressing the identified trade-offs, and actively seeking to optimize synergies, society can move towards a more sustainable and effective energy transition that includes and benefits all stakeholders. Future research should focus on exploring these dynamics in greater depth, identifying practical and cost-effective strategies to enhance synergies and mitigate trade-offs.

7. Conclusion

This thesis undertook a comprehensive examination of the intricate interplay between sulfur recovery practices and energy transition policies in the Netherlands. Guided by the central research question, "How can sulfur recovery efficiency in the Netherlands be optimized in line with the country's energy transition policies?", this work seeks to offer both insights and actionable recommendations.

My exploration found that the energy transition policies, such as the National Climate Agreement (NCA), the Environmental Management Act (EMA), the Industrial Emissions Directive (IED), and the Best Available Techniques Reference Documents (BREFs), have a profound impact on the operations of sulfur recovery units (SRUs). The study revealed both synergies and trade-offs between the energy transition and sulfur recovery practices. Notably, a significant trade-off was observed in the dependence of conventional sulfur recovery units on fossil fuels, which contradicts the energy transition's objective of reducing fossil fuel use.

Nevertheless, strategic approaches like research and development in energy-efficient sulfur recovery technologies, incentivizing cleaner practices, fostering public-private partnerships, and effective communication between policymakers and SRUs can help overcome these challenges.

The limitations of the study need to be acknowledged. The number of interviews conducted may not capture the full diversity of stakeholder perspectives. Also, the timeframe limited the depth of research, making it primarily qualitative. Despite these limitations, the insights derived offer valuable contributions to our understanding of the interplay between sulfur recovery and energy transition.

Looking ahead, future research should explore broader aspects such as biological processes for sulfur recovery and examine the alignment with local and international standards. Additionally, deeper investigation into the potential for CO2 capture and utilization is recommended. Further research could also focus on the role of incentives for cleaner sulfur recovery practices, and delve into the effectiveness of partnerships between government agencies and SRUs.

This study offers significant contributions to both practice and science. For practitioners, it provides a roadmap for optimizing sulfur recovery efficiency while navigating the challenging landscape of energy transition. It offers strategies and insights that can guide policy formulation and encourage innovative, low-carbon sulfur recovery practices. For the scientific community, this study enriches the understanding of the synergies and trade-offs between industrial practices and environmental policies, shedding light on the dynamics of sustainable transitions. This research can serve as a launching pad for further exploration in this crucial field.

In summary, the research presents an insightful exploration of the complex intersection between sulfur recovery practices and energy transition policies. The findings and recommendations provide a useful guide for navigating the complex journey towards a sustainable and energy-efficient future. This contributes to the broader aim of promoting environmental sustainability.

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APPENDIX I

Interview Invitation

Dear Sir/Madam,

I hope this message finds you well.
My name is Maryam Sahlabadi, and I am currently a graduate student at the University of Twente, studying within the Master of Environmental Energy Management (MEEM) program.
My research focuses on the intersection of sulfur recovery units (SRUs) and energy transition policies, particularly within the context of the Netherlands.
As part of this study, I aim to evaluate potential SRU technologies and assess their compatibility with current and future energy transition policies. The primary goal is to enhance decision-making processes, optimize synergies, and manage potential trade-offs between sulfur recovery practices and energy transition targets.
I believe your unique expertise and insights in this field would significantly enrich the depth of my research and help shape a nuanced understanding of the subject matter, and its practical implications.
To this end, I am reaching out to kindly request your participation in a semi-structured interview, which I anticipate will take around 30-60 minutes of your time. The interview can be conducted via a video conference or in person, depending on your preference and convenience.
The interview will cover open-ended questions about your experiences and perspectives on SRU technologies, their alignment with energy transition policies, and potential pathways for balancing these two crucial areas. I will share these questions with you in advance of our discussion.
Please be assured that all your responses will be kept confidential and utilized solely for the purpose of this research. If you do not feel comfortable with the interview being recorded, I can make written notes or provide a transcript of our discussion for your review and approval post-interview.
Your participation in this research is entirely voluntary, and you may withdraw at any time without any consequences.
Kindly let me know at your earliest convenience if you are willing to participate in this research interview. I am flexible and can adjust to suit your schedule.
I truly appreciate your consideration of my request and am confident that your insights and expertise would provide an invaluable contribution to this important area of study.

Kind regards,
Maryam Sahlabadi
MEEM Student,
University of Twente

APPENDIX II

Consent Letter

Introduction:
This study investigates how sulfur recovery efficiency can be improved within the framework of Dutch energy transition policies. It is essential for effective resource management, environmental protection, and policy goal attainment in the Netherlands. The results will provide insights for policymakers, industry partners, and researchers to better align sulfur recovery methods with energy transition targets.

I, ..., voluntarily agree to participate in this research study interview.
• I understand that even if I agree to participate now, I can withdraw at any time or refuse to answer any question without any consequences of any kind.
• I understand that I can withdraw permission to use data from my interview after it, in which case the material will be deleted.
• I have had the purpose and nature of the study explained to me and I have had the opportunity to ask questions about the study.
• I agree to my interview being audio-recorded. Yes ☐ No ☐
• I understand that all information I provide for this study will be treated confidentially.
• I understand that in any report on the results of this research my identity will remain anonymous if preferred to be so. This will be done by not explicitly mentioning my name and disguising any details of my interview which may reveal my identity or the identity of people I speak about.
• I understand that I am entitled to access the information I have provided after the interview.
• I understand that I am free to contact any of the people involved in the research to seek further clarification and information.

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Participant:
Signature of participant:
Date:

APPENDIX III

Interview Questions and Transcript Summary

Target of these questions are addressing & endorsing the highlighted data of MCA.

1. Could you briefly describe your background and experience in the field of SRUs and energy transition policies?
2. How would you assess the environmental impact of the current SRUs within the energy transition context?
3. How would you assess the contribution of Adsorption Processes to national emission reduction targets?
4. Can you comment on the potential for efficiency improvements in Adsorption Processes?
5. How would you assess the technological maturity and reliability of Adsorption Processes?
6. What are your views on the economic feasibility of Adsorption Processes within the context of the Netherlands' energy transition?
7. How would you rate the contribution of Adsorption Processes towards the Sustainable Development Goals (SDGs)?
8. In your opinion, how is the public acceptance and social license to operate for the Claus process, Modified Claus process, and Adsorption processes?
9. Can you comment on the potential of Adsorption Processes for CO2 capture and utilization?
10. Are there any areas where you see potential conflicts or challenges between ETP & RSU, or do you believe they are already well-aligned?
11. In your opinion, what measures or strategies can be implemented to enhance the synergy between SRUs and energy transition policies?

Questions	Interviewee 1(FJ-BT)	Interviewee 2 (AR-BT)	Interviewee 4 (MK-WP)	Interviewee 3 (JJ-DO)	Interviewee 5 (AN-DP)
1-Could you briefly describe your background and experience in the field of SRUs and energy transition policies?	I have limited experience in the field of SRUs, but I have been involved in several feasibility studies where SRUs play a role.	Little on policies but I am senior energy/process engineer responsible for some mainstream projects such as biodiesel, hydrogen and carbon capture projects. Little with SRUs other than small scale biogas sulphur removal or waste to energy flue gas cleaning system.	I have been working as an engineering coordinator and process specialist in the sulfur recovery unit for three years.	As a combustion reactor vendor, our expertise is in designing and developing advanced process technologies for sulfur recovery units (SRUs). We have a strong background in combustion engineering and have been actively involved in the SRU industry for several years. In recent times, we have also been actively aligning our expertise with energy transition policies, focusing on developing more efficient and environmentally friendly combustion reactors.	As a diplomat, my background and experience in the energy sector and advocating for sustainable energy solution.
2-How would you assess the environmental impact of the current SRUs within the energy transition context?	Main environmental impactors are requirement for heating and cooling. If applied well, this can be done efficiently, but there will always be some loss.	SRUs are related to low sulphur emissions generally little impact on the energy transition.	In my opinion carbon capture will support emissions reduction through sulfur oxides (SOx), nitrogen oxide (NOx) and carbon dioxide (CO2) in the SRU thermal oxidizer stacks. Utilizing emissions to produce low-carbon products will require innovative thinking to support the increasing demand.	The current SRUs, including the Claus Process and Modified Claus Process, have made significant contributions to reducing emissions in the sulfur recovery process. However, they still pose challenges in terms of energy intensity and environmental impact. Our company recognizes the importance of addressing these issues and is committed to developing combustion reactors with lower emissions and	SRUs may have certain environmental impacts due to emissions and energy consumption.

				improved environmental performance.	
3-How would you assess the contribution of Adsorption Processes to national emission reduction targets?	Adsorption processes are best effective at high concentration emission points. Therefore they can have a significant contribution to emission reduction targets. On a national level this is more difficult to say, as there are also many small point sources where adsorption technologies have limitations and different solutions are sought (for instance lowering sulphur content in car fuel)	Note that adsorption is not a final conversion of sulphur or carbon and the impact is very much depending on downstream process for final conversion. However once the main feed is polished and high concentrated captured molecules are realeased	With considering optimum process conditions such as excess air coefficient and thermal reactor temperature and also optimization of incinerator and stack	I don't have experience in adsorption but I think Adsorption processes, particularly those utilizing activated carbon, have the potential to make a substantial contribution to national emission reduction targets. However, it's important to consider the maturity and economic viability of these technologies.	Adsorption Processes, in our opinion, may offer short-term benefits, but we should aim for comprehensive renewable energy systems to achieve significant and sustainable emission reductions.
4-Can you comment on the potential for efficiency improvements in Adsorption Processes?	A lot of efficiency improvements can be made with heat integration of unit itself or combined with other heat/cold sources The removal efficiency (especially for active carbon) depends on saturation and eventual breakthrough. Adsorption techniques that work in continuous process can limit this issue	Adsorption process potential can be substantial but depends on the feed conditions. If the heat or pressure is available, PSA, TSA or PTSA can perform as final polishing step with high removal efficiency.	Since efficiency of Claus and modified Claus processes are significantly depends on the reaction furnace temperature the effect of oxygen and acid gas enrichment on the reaction furnace temperature and accordingly on sulfur recovery could be studied more. Also, the methods of increasing the efficiency of process catalysts can also be considered as a suitable options	Advancements in adsorbent materials and regeneration techniques can further improve the efficiency and effectiveness of these processes.	
5-How would you assess the technological maturity and reliability of Adsorption Processes?	The technology is well known and can be applied at a great range of sizes. At the small scale, only adsorption technologies like active carbon are available, so maturity at that level is lower.	Adsorption process is generally reliable as there are little rotating and high temp systems required. Additional beds increases the reliability even more.	Good experience of modified Claus process compared to other methods such as Ferrox, Gluud, Manchester, Stretford, Thylox and SulFerox for the elemental sulfur production over the past several years comparing optimum energy consumption	The maturity and reliability may vary depending on the specific application and scale of the adsorption units. As I said they are not as mature as Clause.	
6-What are your views on the economic feasibility of Adsorption Processes within the context of the Netherlands' energy transition?	As the emissions are already quite low (compared to 80's) the contribution is not so visible anymore, but the Adsorption processes play a significant role in keeping sulphur emissions low	Don't see the relevance here. Energy transition promotes non fossil fuels and within bioenergy other than bio digestion little sulphur is involved. True?	Entrepreneurship and the growth of job opportunities along with dynamic economy and at the same time considering environmental issues	While adsorption technologies offer environmental benefits and energy efficiency, the economic viability may be influenced by factors such as capital costs, operational costs, and the availability of suitable feedstock. Our company recognizes the importance of striking a balance between economic feasibility and environmental sustainability.	we believe that investing in renewable energy technologies will have better long-term economic prospects. The Netherlands, as a country committed to the energy transition, should prioritize the development and deployment of renewable energy infrastructure to create sustainable economic opportunities.
7-How would you rate the contribution of Adsorption Processes towards the Sustainable Development Goals (SDGs)?	My view is that these processes are not well known with the public. Their operation does not cause significant noise, and it removes odours. The public may not realize the importance of the SRUs, but their general stance appears to be neutral anyway.	As long as adsorption processes are top ranked purification/removal systems within applicable range, they will be implemented. Rating is a matter of competitive capex an opex of any process.		Adsorption Processes can make a significant contribution to several Sustainable Development Goals (SDGs), particularly those related to environmental sustainability, clean energy.	
8-In your opinion, how is the public acceptance and social license to operate for the Claus process, Modified Claus process, and Adsorption processes?	This strongly depends on the location of CO2 removal. If it is in a smokestack with high CO2 concentration, it could be a viable solution. However, if it is to be applied for atmospheric CO2 removal, I highly doubt it will be	Public acceptance is probably irrelevant here, I would suggest as long as BATs and BREFs are in favour of modified Claus process in specific sectors, it should be promoted as long as licensors are willing to provide support to the market.	With applying high-selectivity adsorbents to achieve high CO2 uptake at low partial pressures, which means that the separation process should be based on either very strong physisorption or chemisorption with thermal regeneration. It should be noted the main challenge is to develop efficient	The public acceptance and social license to operate for the Claus process and Modified Claus process are relatively established, as these technologies have been in operation for a considerable period and are widely recognized in the industry. They have a track record of reducing sulfur emissions and addressing environmental concerns.On the other hand, the public acceptance	Public acceptance and social license to operate are important considerations in any industrial process. However, we believe that the public's focus should be on the long-term sustainability and environmental impact of energy solutions.

	sufficiently energy efficient.		separation processes with rapid thermal cycles.	and social license for adsorption processes may require more outreach and education. As a combustion reactor vendor transitioning towards ammonia production and promoting more efficient and less polluting combustion reactors, we understand the importance of building public awareness and acceptance of these processes. We are committed to engaging with stakeholders, communities, and regulatory bodies to ensure transparency, address concerns, and build trust in the potential of adsorption processes for emission reduction and sustainable development.	
9-Can you comment on the potential of Adsorption Processes for CO2 capture and utilization?		Within CCUS adsorption process is generally used for dehydration and final polishing of CO2. In recent years upcoming adsorbents are used within lab scale, pilot scale for direct air capture (very low concentration) or solid sorption technology. For example Metal-organic frameworks (MOFs) are interesting development as adsorbent application. There are some examples of PSA systems for CCUS at elevated concentration of CO2(>40%) and 4-6 bar range. Still a (technical readiness level) TRL of 6 to 7.		Adsorption processes have the potential for CO2 capture and utilization, especially when implemented at high concentration emission points. These processes can effectively capture CO2 and contribute to the reduction of greenhouse gas emissions. However, it's essential to consider the specific conditions, such as the concentration and source of CO2, to assess the feasibility and efficiency of adsorption for CO2 capture. As a combustion reactor vendor focused on sustainability and energy transition, we are actively exploring and researching the potential of adsorption processes for CO2 capture and utilization. We are dedicated to developing innovative solutions that align with the goals of decarbonization and contribute to a low-carbon future. Our long-term strategy includes evaluating the feasibility and scalability of ammonia production as a pathway to hydrogen production, which can further support CO2 reduction efforts.	Adsorption Processes can have a certain potential for CO2 capture and utilization, particularly in specific applications with high CO2 concentrations. However, we believe that investing in energy technologies, such as wind, solar, and hydropower, offers a more comprehensive and sustainable solution for addressing CO2 emissions. These technologies have the potential to provide significant reductions in greenhouse gas emissions and mitigate climate change on a larger scale.
10-Are there any areas where you see potential conflicts or challenges between ETP & RSU, or do you believe they are already well-aligned?		Answer: In my opinion, there may be some potential conflicts or challenges between Energy Transition Policies (ETP) and SRUs. While SRUs play a role in reducing sulfur emissions, their relevance within the context of energy transition may be limited. The focus of energy transition is mainly on non-fossil fuel sources, and SRUs are more commonly associated with sectors such as bioenergy where the sulfur content is relatively low. Therefore, there may be a need to evaluate the alignment of SRUs with the broader goals of energy transition and explore alternative solutions that better contribute to sustainable energy production.	I think potential conflicts or challenges between energy transition policies (ETP) and sulfur recovery units (SRU) due to the energy-intensive nature of SRUs and the increasing focus on reducing greenhouse gas emissions. They may also highlight the need for balancing emissions reduction targets with the economic viability of SRUs.		There is a need for balancing the economic feasibility of SRUs with the environmental objectives of energy transition policies.
11-In your opinion, what measures or strategies can be implemented to enhance the synergy between SRUs and		More collaboration between SRU experts, energy transition policymakers, and researchers to identify opportunities for	promoting research and development efforts to improve the energy efficiency of SRUs, exploring innovative sulfur recovery technologies that		I emphasize the importance of policy incentives and support for the adoption of cleaner and more sustainable sulfur recovery processes

energy transition policies?		integrating SRUs into renewable energy projects, such as using SRU waste heat for other energy-intensive processes or exploring co-location possibilities.	align with low-carbon energy transition goals, and incentivizing the adoption of cleaner and more sustainable sulfur recovery processes		like Biological, as well as raising awareness among the public about the importance of SRUs in achieving energy transition goals.
Recommendation:	One additional item: there is also sulfur removal using a biological process. This may be interesting information: https://www.paqell.com/video/thiopaq-o-and-g-process-animation/	MCA Tuning	In your opinion, how do you compare these methods in terms of energy consumption? And what suggestions do you have for optimizing energy?For this investigation, studies should be carried out to obtain the optimal parameters for the production of surface active material, as well as different methods of optimizing the parameters of the Claus process so as to provide the possibility of comparison.	Short term and long term consideration, change is possible but gradually	