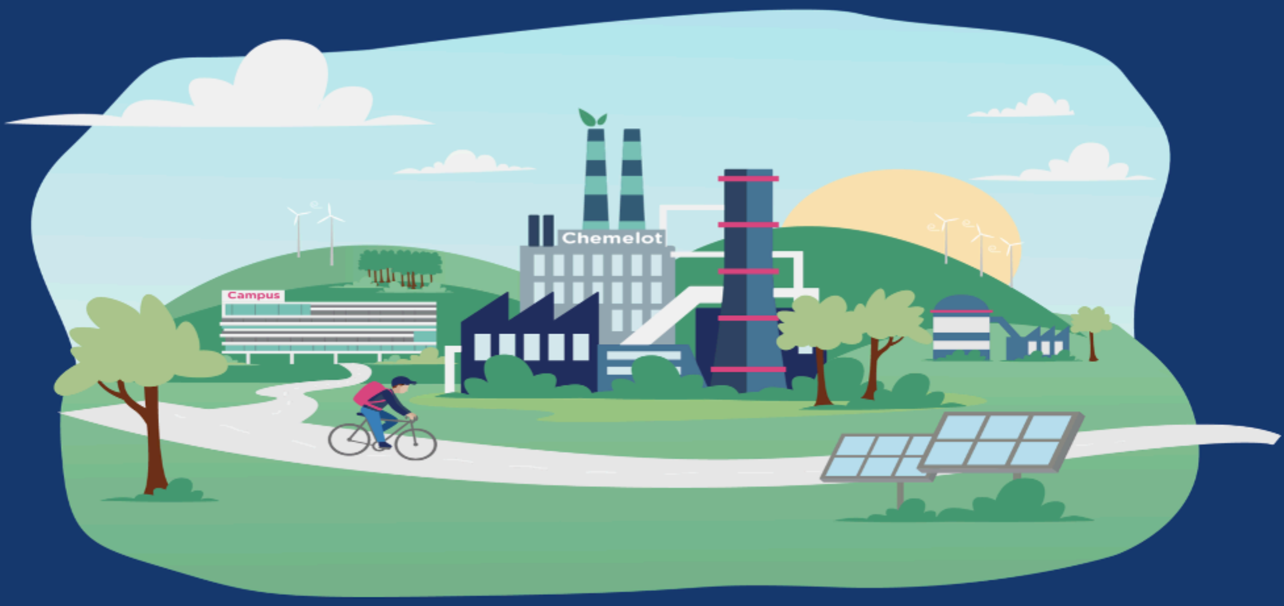
ECO-INNOVATIONS ON CHEMELOT

a technology battle between the future and the past

M. Sliwinski



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ECO-INNOVATIONS ON CHEMELOT

a technology battle between the future and the past

by

M. Sliwinski

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Thesis committee:	Dr. G. van de Kaa,	TU Delft, First Supervisor & Chairman
	Dr. ir. R. M. Stikkelman,	TU Delft, Second Supervisor

TUDelft

Preface

Before you lies my thesis *ECO-INNOVATIONS ON CHEMELOT: a technology battle between the future and the past*. It studies the factors which affect the technology battle of eco-innovations adoption in the chemical industry. I wrote this thesis to fulfil the graduation requirement of the Master Management of Technology at the Delft University of Technology. I worked on this research project from February to August 2021.

The study was conducted at the request of Brightlands Campus located on the Chemelot site where I undertook my graduation internship. Being a part of Brightlands, Brightsite is the initiative for realising a sustainable, competitive chemical industry. I drove past Chemelot many times as a child and was always fascinated by the large industrial plants. Several years later, I got the opportunity to see the operations from the inside and even to conduct research on this chemical site. The research was both challenging and rewarding. I learned a lot about the chemical industry, international relations, and strategic decision-making. Moreover, I was able to apply some of the interesting theories I have studied during my two-year master programme.

I would like to use this moment to express my gratitude to my two supervisors from the faculty of Technology, Policy, and Management Geerten van de Kaa and Rob Stikkelman. As my first supervisor, Geerten offered his guidance through this graduating process. His support and knowledge in standard battles was very welcome in this period. My second supervisor, Rob Stikkelman, was also always available to offer his support and guidance. Since he has experience in the chemical industry, his view on things was useful.

Furthermore, I would like to thank both my company supervisors Rene Slaghek and Paul Brandts for their excellent guidance and support throughout the period. I have enjoyed working with them and I am thankful for their experiences and knowledge from the chemical industry. In addition, I would like to express my appreciation to the experts who participated in the interviews during my research. Unfortunately, due to the pandemic, it was not possible to conduct the interviews face to face and to meet the experts in real life.

Unfortunately, this year has not been particularly easy due to the Covid-19 pandemic. Personally, I had to find my way in this graduation process, which I had to start from home rather than being physically at the university. It is a pity that I could not share this memorable time with my fellow students by being on campus. Looking back, however, I am satisfied that the period went well and I managed to make the best of it. My gratitude goes out to my parents and my sister who supported me during this final stage of my studies. Moreover, I am thankful for my fellow graduates and friends. Together we were able to have some fun times during this weird period.

Lastly, I would like to take this moment to remember a dear friend, who is no longer with us. A tragic incident marked a dark beginning of this graduation period. May you rest in peace, Shashank.

M. Sliwinski
Delft, August 2021

Executive Summary

The Dutch economy is at present largely driven by fossil fuels, including the chemical industry. To achieve the goals set by the Paris Climate Agreement, the industry needs to decarbonise by switching to renewable sources. However, the industry faces many barriers in this climate transition. This research analyses the Dutch chemical site Chemelot, one of the largest sources of greenhouse gas emissions in the Netherlands. Chemelot uses primarily natural gas and naphtha as energy and feedstock resources. Currently, a debate is ongoing on Chemelot whether electricity or hydrogen should be the main focus of replacing fossil fuels and raw materials, as these are the most potential eco-innovation alternatives. These eco-innovations pose a technology battle for dominance. The site users on Chemelot need to make decisions now, which will have consequences for both society and firms in the future.

There are multiple types of factors that affect eco-innovation adoption. This study created a new framework that distinguishes Technological factors from Non-technological factors because it is desirable to gain early insight in both: Technological factors so that the decision can be based on what benefits best for the future industry and society; Non-technological factors to identify barriers and opportunities in time and how to deal with these. The Non-technological factors are distinguished between External and Internal factors, with External factors reflecting the environment in which a firm operates and Internal factors considering firm-specific characteristics. The objective of this study is therefore to identify relevant factors that affect the adoption of eco-innovations with the ultimate goal of decarbonising the Chemelot site. Hence, this research aims at answering the following research question: *What drives the technology battle for eco-innovation adoption on Chemelot?*

This exploratory and descriptive research investigated Chemelot as the main unit of analysis. It is a single and embedded case study design. This research started by reviewing the literature regarding the topics of technology battles, technology dominance, adoption, barriers in the chemical industry, and eco-innovations. Based on the literature review, a framework was made containing factors that affect eco-innovation adoption. Additionally, factors were added to the framework based on conversations with experts. The framework was then validated by interviewing experts and conducting a Best-Worst Method analysis. The Best-Worst Method is a suitable Multi-Criteria Decision-Making tool when evaluating multiple factors when objective metrics are lacking. Experts were asked to indicate the factors according to relevance with regard to eco-innovation adoption in the chemical industry. Additionally, the weights indicated by the participants were normalised using the Best-Worst Method to compare the factors. In total, 14 participants participated in the semi-structured interviews with questions to gain deeper knowledge about the technology battle between eco-innovations on Chemelot.

The site users on Chemelot have to make decisions for eco-innovations now, which will have consequences for future society and industry. Since the consequences of the eco-innovation choices are influenced by both Technological and Non-technological factors, this research created a new framework of factors affecting eco-innovation adoption. This research found that the sub-factor Regulatory Pressure is the most relevant in the set of Non-technological External factors. In the Non-technological Internal factors, Firm's Strategy is found to be the most relevant sub-factor, closely followed by Firm's Management. In the set of Technological factors, the sub-factor Capex is found to be the most relevant factor. The normalised weights of all the factors show that the Non-technological External factors are the most relevant factors for eco-innovation adoption for the Chemelot site. Furthermore, the Technological factors appear to be equally relevant as Non-technological Internal factors because they hardly rank higher.

The results from the conducted interviews show that experts define a successful energy & raw material transition when the environmental impact of greenhouse gasses is reduced while simultaneously maintaining employment, innovation, economic welfare, and adding value to society. The barriers the site users face on Chemelot to reduce environmental impact are: cross-sectoral collaboration among actors, sufficient availability of renewable energy and raw materials, lack of effective policy, high degree of integrated plants and processes, differently aligned strategies of the site users compared to Chemelot's, increasing pressure by lobbies and society, a failing market always that proposes fossil technologies as the cheapest option rather than providing sustainable eco-innovation alternatives making investment difficult, and the lacking or insufficient infrastructure. The opportunity Chemelot has are: the high degree of integrated plants because they offer synergies, advanced R&D facilities, the innovation and knowledge centre Brightlands Chemelot Campus, and highly experienced and knowledgeable experts.

The technology battle between eco-innovations on Chemelot is twofold. For the heat-generating application, the technology battle is fought between hydrogen and electricity. The direct use of electricity is much more efficient for this application, because energy losses during the initial conversion of electricity to hydrogen are avoided and because no flue gases are released that contain energy when generating heat from electricity. Nevertheless, hydrogen technology for this application is being pushed by the actors, despite the fact that it is a less favourable alternative. This could have serious consequences for Chemelot since this is a much more expensive alternative.

Furthermore, this research concluded that the technology battle for dominance is fought between the incumbent technologies and eco-innovations rather than between hydrogen and electrification. Both electrification and hydrogen are indispensable technologies required in this climate transition but will depend on the application. Moreover, site users continue to maintain their fossil assets while this is expensive and greenhouse gas emissions reduction is limited. They are reluctant to switch to disruptive eco-innovations because of the aforementioned barriers. Continuing the investments, in turn, raises the barrier for the site users to adopt eco-innovations due to the longer payback periods.

Delaying the adoption of eco-innovation can be explained by the lack of a positive business case. The business case is reflected by the Technological factors Capex, Opex, and Efficiency, and is indicated as a prerequisite. This affects the intrinsic motivation of the site users, which is reflected by the Non-technological Internal factors. However, site users are motivated by external pressures such as regulations, subsidies, market pressures, and rising emission taxes, which are reflected by Non-technological External factors.

Keywords: *Technology Battles for Dominance, Eco-innovation Adoption, Factors Technology Adoption, Chemical Industry, Best-Worst Method.*

Contents

1

Introduction

Since the Paris climate agreement in 2015, climate change has become more important than ever before. Countries and economic organisations signed the Paris Agreement which states the goal of keeping global warming under 2 degrees Celsius, and the desire to stay below 1.5 degrees Celsius compared to pre-industry levels [76]. Consequently, the Dutch government translated the international goals to national plans by presenting a National Climate Agreement and a Climate Law. The Act states that the Netherlands must reduce greenhouse gas (GHG) emissions by 49% in 2030 and by 95% in 2050 compared to 1990 levels [45]. The Climate Agreement describes how the government intends to achieve these goals. Currently, the Dutch economy is largely driven by fossil fuels, generating large amounts of GHG emissions [81]. Therefore, the Netherlands must decarbonise its economy in the coming decades by switching from fossil fuels and raw material sources to renewable sources. Although renewable energy resources will probably become increasingly available, they will only be available to a limited extent. The Netherlands can generate renewable energy, such as electricity or energy carriers such as hydrogen, itself or import it.

The use of newly available renewable electricity and energy carriers will ideally lead to the fastest possible reduction in CO_2 emissions, as well as to the lowest possible costs. The costs involve both current investments with regard to the future and the costs for the users in the future. The users of these sustainable technological solutions and the applications based on this have to be proposed now, for large-scale use later in the future. After all, this determines what the future energy system will look like for Dutch industry and society. However, the industry and society face barriers in this transition. The long investment cycles and long payback periods ensure the unfavourable investment climate. Due to high capital intensity and high volume, the industry has few opportunities to invest in disruptive technology, resulting in a lock-in [54]. Another barrier is that chemical industries operate in international markets where environmental incentives are lacking or differ from those in the Netherlands [54]. Therefore, it is difficult to sell more expensive products that are environmentally friendly. Moreover, the heterogeneity of the chemical industry can also be a barrier [10]. Because every chemical site is different, it is difficult for disruptive technologies to enter the market. Often these innovations are immature and not cost-effective [32].

Naturally, Chemelot also has to decarbonise its industry and switch from fossil sources to renewable energy sources. Currently, Chemelot's main energy sources are naphtha and natural gas, which together account for more than 200 PJ per year [70]. Seventy percent of this energy ends up in products produced by Chemelot such as in plastics that are flammable. This is referred to as non-energetic energy usage. The remaining thirty percent concerns the energetic consumption of fossil fuels such as the combustion of natural gas that provide the chemical processes with energy. To put this in perspective: the difference between non-energetic energy use at Chemelot (70%) and the Netherlands (20%) indicates a qualitative difference between the two systems, with the largest share of non-energetic consumption at Chemelot (over 150 PJ) out of the total consumption in the Netherlands (500 PJ) [70]. This perspective indicates that for Chemelot the raw material transition is even more important than the energy transition. Whereas the focus worldwide is primarily on energy transition, Chemelot and other chemical sites need to focus on both the energy and raw material transition.

1.1. Problem Statement

Chemelot is in the middle of a climate transition consisting of an energy and raw materials transition. Currently, a debate is ongoing at Chemelot whether and where renewable electricity or renewable hydrogen should be the focus in replacing the current fossil fuels and raw materials. The Chemelot site has expressed the ambition to be CO_2 neutral by 2050. The most important action point is to make both the raw materials and the energy sources used more sustainable so that the products and processes can become CO_2 neutral. Chemelot aims to become the most sustainable chemical site while simultaneously operating competitively with other industries [22]. Chemelot wants to achieve these goals by using sustainable raw materials by making these circular, and by using renewable energy [11]. It is important to note that Chemelot refers to a collection of companies like SABIC, OCI Nitrogen, and Arlanxeo that together make up the chemical site. These companies are the actors that make investment decisions and develop sustainability strategies. They are supported by Brightsite, an initiative that researches how to make the Chemelot site climate neutral by developing sustainability programmes.

Hydrogen is seen as a promising future energy source in the energy transition, and for the future economic system for Chemelot. Chemelot currently produces more than 200 kilotonnes of hydrogen per year through a process called steam methane reforming (SMR), which is used for fertiliser production. This process involves the catalytic conversion of methane and steam into hydrogen and carbon oxides [50]. Chemelot produces roughly 2000 kilotonnes CO_2 as a result of hydrogen production alone. There are various ways to produce decarbonised hydrogen [53]. Sustainable hydrogen can be produced with renewable electricity from the electrolysis of water [50]. Hydrogen can also be a co-product of technologies aimed at keeping the carbon within the cycle of the circular economy. Another option is to produce hydrogen from suitable waste streams. The latter can be energy-efficient and interesting where synergies between hydrogen production and carbon building blocks can be exploited for a sustainable industrial economy [53]. Importing sustainable hydrogen from other countries is also a possibility [53].

However, electrification of processes also helps Chemelot in decarbonising their plants, thus contributing to the efforts to become a sustainable chemical plant [11]. Electrification of processes means that no or less fossil fuels are used for heating processes by replacing fossil fuels with electricity. Like hydrogen, electricity can help Chemelot in reducing their CO_2 emissions, assuming that this electricity will ultimately be generated in a sustainable manner. If Chemelot wants to rely on this renewable electricity, then a sufficient supply is a precondition [22].

Sustainable alternatives like hydrogen and electricity also referred to as eco-innovations, pose a technology battle for dominance. Dominance can be defined as *”the distinctive way of providing a generic service or function that has achieved and maintained the highest level of market acceptance for a significant amount of time”* [38]. Eco-innovations are defined by the Organisation for Economic Co-operation and Development (OECD) as *“the development of products (goods and services), processes, marketing methods, organisational structure, and new or improved institutional arrangements, which, intentionally or not, contribute to a reduction of environmental impact in comparison with alternative practices”* [13]. However, this definition could also classify incremental technologies as eco-innovations. The climate transition could fail as a result of incremental eco-innovations, as they do not actively exclude fossil-driven technologies. This study, therefore, sharpens the definition by adding that the eco-innovations must be transparent and must aim for 100% fossil-free products and processes. The proposed eco-innovations both have advantages and disadvantages. As each process is different, there is no single solution that fits all applications. However, for some applications both electrification and hydrogen are possible options and are competitive throughout the entire energy chain, as this will be explained further in this thesis. Companies like Chemelot have to make decisions now in this transition, which will have consequences for the future due to technology inherent factors such as high investments costs and long lead times. Because of its sheer size and societal impact, Chemelot’s transition is also influenced by factors other than only technology. For example, politicians determine which policy and which initiatives are eligible for subsidy. The transition also requires collaboration with other parties in the market, especially upstream of Chemelot with the future energy and raw materials suppliers. These parties promote their own solutions, which are not necessarily in the interest of Chemelot parties. As a result, decision-making is strongly influenced by non-technical factors. In debates with stakeholders, non-technological arguments often dominate, for example, strategic priorities coloured by divergent interests, or societal acceptance (‘not in my backyard’).

When all the necessary factors are taken into account in the decision-making process, it is still necessary to distinguish the factors inherent to the technology of innovation from other, more non-technological factors. In other words, it is desirable to understand both types of factors at an early stage: technological factors so that when choosing between alternative pathways, the decision can also be based on benefits for future industry and society; non-technological factors, so that barriers and enablers can be identified in time and how to deal with them.

1.2. Research Objective

The problem Chemelot faces can be translated into the future raw material and energy supply, since both the raw materials and fuels will have to become renewable. This poses a technology battle of dominance between hydrogen and electrification that aims at replacing current fossil fuels and raw materials. Regarding the future energy supply, an overview of elaborated options is lacking that affect the adoption of eco-innovations. There is a need for categorisation of technological and non-technological factors that can guide the decision-making process and which will be researched in this study.

The aim of this research is therefore to identify relevant factors which affect the adoption of eco-innovations with the ultimate goal of decarbonising the chemical industry. This research starts with listing the elaborated options that Chemelot has to replace current technologies with sustainable technologies. Next, this research studies the current status of the technology battle and how it could evolve by interviewing experts. In doing so, this research contributes to the literature on technology dominance. This thorough analysis creates a clear comprehension of the importance of the factors and is based on experts opinions by conducting interviews. This is valuable for Chemelot and policymakers because they can better align actors by understanding the factors that affect adoption and therefore have the most potential to become the dominant technology. This is beneficial for the government and companies in achieving the emission reduction targets set out in the Climate Laws and Agreements. Ultimately, the insight into the factors is intended to investigate how non-technological factors can be approached, so that Chemelot can increase support and base its eco-innovation strategy on technological factors.

1.3. Research Questions

To make a well-advised decision on which type of sustainable eco-innovation is best for decarbonising certain industrial processes, factors affecting this decision-making need to be identified. Technology battles are fought and researched in a wide variety of environments, yet only a limited number of scholars have specifically researched a technology battle in the industry. Some scholars have identified a number of factors that affect the adoption of eco-innovations in industrial sectors [13], [17], [18], [29]. The literature distinguishes the non-technological factors between internal (firm-specific) and external (environmental) [13], [17], [29], [78], [73]. However, an overview of factors for the chemical industry is lacking. The question arising from the problem statement is based on the aforementioned view of multiple possibilities and preconditions. It concerns the characterisation of Chemelot's desire to affect the process of eco-innovation adoption by managing the non-technological factors in such a way that technological factors become prevalent. This characterisation leads to the following research question:

What drives the technology battle for eco-innovation adoption on Chemelot?

Additionally, sub-questions are posed that support the answer to the main research question. In this way, a more detailed final answer can be given. The first sub-question helps to create an overview of the current situation at Chemelot and which eco-innovations alternatives Chemelot is studying as a potential technology for implementation. The second sub-question focuses on finding factors in the literature that scholars have shown to influence eco-innovation adoption. Additionally, these factors are discussed with experts to see if any factors should be added. The third sub-question asks about the relative interest of the factors that affect the technology battle between the eco-innovations. It also ranks the sets of factors according to importance to find out which type of factors are considered most relevant and least relevant. The final sub-question addresses how the technology battle between the eco-innovations evolves on Chemelot.

- What are the eco-innovation alternatives for Chemelot?
- Which factors affect eco-innovation adoption?
- What is the relevance of the factors in the technology battle between the eco-innovations on Chemelot?
- How does the technology battle between eco-innovations evolve on Chemelot?

The first sub-question will be researched by means of literature research and by talking to experts at Chemelot. They are mostly chemical engineers and know the site well, and have therefore a good overview of potential eco-innovations for Chemelot. The answer to the second sub-question will also be researched by means of literature research. Based on the literature, this study will create a framework tailored to the problem presented. The third sub-question will validate the framework by asking experts to rank factors in the framework. Finally, an in-depth interview will be conducted to find how the technology battle on Chemelot between the eco-innovations will evolve. The answers to these sub-questions will determine the answer to the main research question. The details of the research methodology are explained in Chapter 2.

1.4. Study Scope

Due to the complexity and the magnitude of this problem, it is important to focus on primary issues. While this research studies the effects of factors on eco-innovation in the chemical industry, this study analyses the chemical site Chemelot as the focal unit of analysis. Since the definition of eco-innovations is quite extensive, various technologies fall under this definition. This research only focuses on hydrogen-powered and electrification innovations as eco-innovations. Of course, there are more possibilities to reduce emissions such as biomass and recycling of waste. However, the scope is limited to hydrogen and electrification because analysing more options is too time-consuming and Chemelot experts consider these two eco-innovations to be the most promising in the short term. Moreover, the scope of the assignment is limited to the cracking process controlled by SABIC, and the ammonia production process controlled by OCI. The reason for choosing these two processes is that they consume a lot of energy and cause more than 80% of Chemelot's Scope 1 CO_2 emissions [53]. They are both responsible for the emissions of approximately 2 Mt CO_2 [53]. It is therefore within these processes that the greatest gains can be achieved. Although there are more plants on the Chemelot site, it is too time-consuming and complicated for a non-chemical engineer to analyse them all because the plants are integrated and connected to each other. To understand this, more in-depth knowledge of the process and chemical technology is needed. Therefore, to simplify the research, the scope is limited to the cracking process and ammonia production process.

1.5. Thesis Outline

This concludes the introduction. The problem in this research is the lack of understanding of the factors that influence eco-innovation adoption for the chemical industry. Based on the research on the technology battle between hydrogen and electrification, this research aims to find the factors that influence eco-innovation adoption. First, the research methods used for the interviews and the Best-Worst Method are presented in Chapter 2 - Methodology. Then, literature and related work are discussed in Chapter 3 - Theory. This chapter also presents the framework containing the factors found in the literature that affect eco-innovation adoption. Chapter 4 creates provides insight into the Chemelot site, the processes, and how eco-innovations can play a role in the future. The results of the validation of the framework and the interviews are presented in Chapter 5. Finally, this work concludes with the conclusions and discussion in Chapter 6.

2

Methodology

This chapter describes the methodology used for this research. It introduces the methodological approach and describes the role of the literature in this research. Furthermore, the methods of data collection are presented, as well as the methods of analysis. Finally, the methodological choices made in this research are evaluated.

2.1. Research Approach

This thesis presents a research problem of the chemical industry that lacks a clear overview of factors influencing eco-innovation adoption. It is desirable for this industry to have this insight to base the decision for an eco-innovation alternative on empirical research. This research explores an under-researched topic that will be exploratory and descriptive in nature as it studies a battle between eco-innovations for Chemelot and how certain factors affect the adoption of eco-innovations. The eco-innovation alternatives for decarbonising the processes form multiple units of analysis, making this research a single and embedded case study design. A case study design is selected because it involves the collection of information regarding a specific organisation or event [69]. The purpose of a case study is to obtain a clear view of a real-life problem from multiple perspectives and using different data collection methods taking into account the rich qualitative intricacies. This case study requires qualitative data for the analysis and will present both qualitative and quantitative data. In a case study design, a researcher cannot manipulate core concepts and tries to answer why or how questions. The context is analysed in a case study design, whereas in other methods the context is controlled. Therefore, a case study design fits well for this study.

The first sub-question analyses the eco-innovation alternatives to see what the implications would be for Chemelot if it were to adopt one of these innovations. This will be based on literature review and internal communications with Chemelot employees. This secondary data information is needed to gain knowledge of the environment and processes on Chemelot before researching possible factors for adoption. Subsequently, the literature review will create a framework containing factors that are considered important in relation to eco-innovations. Based on this information, the third sub-question will validate the framework that affects eco-innovation adoption. Respondents will be asked to assess weights to the factors by ranking these according to the relevance to adoption. When a number of options need to be assessed regarding multiple factors to rank these alternatives, a multi-criteria decision-making (MCDM) method is a suitable tool. The method is further explained in section 2.3.2. The final sub-question will explore the technology battle on Chemelot between the eco-innovations by interviewing the same experts. This qualitative and exploratory research will create primary data. This will lead to broader usability of the obtained results, not only for Chemelot and the chemical industry but also for national policymakers. Figure 2.1 shows the research process schematically in a flow diagram that will be used in this study.

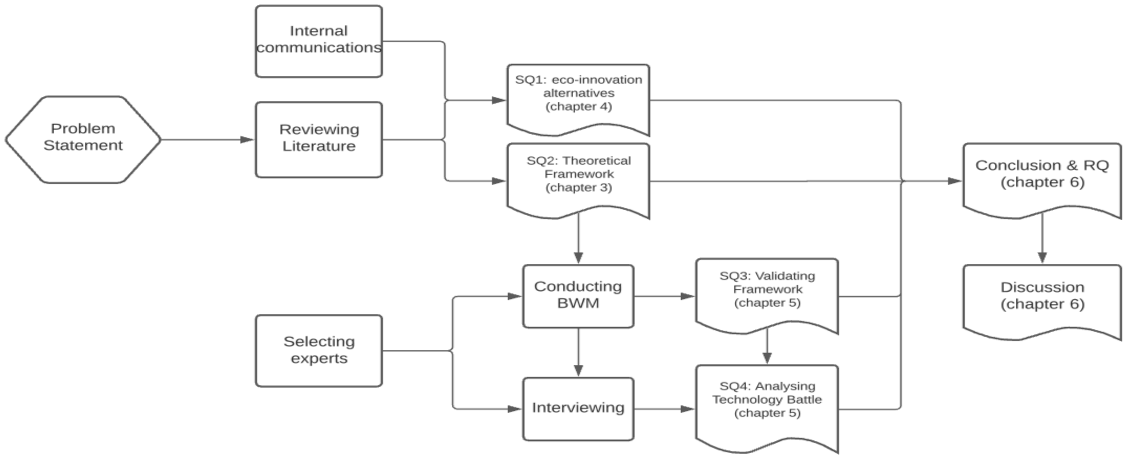


Figure 2.1: A research flow diagram of this study

2.2. The Role of Literature

A literature review is the analysis of available studies and theories on the desired topic, which provide information, data, and evidence from a certain viewpoint or theory [69]. It ensures that the new research builds on existing knowledge, as will be applied to this study. The literature aims to find what scholars have studied with respect to technology battles for dominance and technology adoption. Using the problem statement as a starting point, the literature research will lay the foundation of this research and therefore this study builds on that existing literature. This is a typical method of literature review. Additionally, in this study, the literature review will also be used as part of the research methodology as this study will create a new theoretical framework. The aim is to gain knowledge regarding the eco-innovations adoptions at a chemical site, as this is the main environment in which the technology battle is fought. The literature will begin by looking for scholars who have studied factors that affect technology battles. While these factors relate to the technology battles in general, the existing literature also looks at factors that specifically affect the adoption of eco-innovations. These factors will better fit the framework that this research aims to create. These factors are also based on fundamental literature of technology battles but are specified to eco-innovations and industrial battles. Thus, the role of the literature review in this study will be twofold: it will review the current literature which relates to the problem statement, and it will form the basis of the new theoretical framework.

The literature search will start by reviewing the fundamental papers regarding technology battles, technology dominance, adoption and selection. This is to grasp the idea of these concepts. Search terms used: Technology Dominance, Technology Battles, Adoption, Technology Selection, Factors and frameworks affecting technology battles. After establishing the fundamentals, this research will present a new theoretical framework also based on literature. Since the case study is about the chemical industry, the search in the literature will be specified towards the chemical industry or industry in general. Moreover, it will focus on the adoption of eco-innovations as it is used as the unit of analysis in this research. The literature will be reviewed to find frameworks and factors that affect eco-innovation adoption in the (chemical) industry. In this second search in the literature, the following search terms will be used: Eco-innovation Adoption, Frameworks and Factors affecting Adoption, Chemical Industry, Sustainable Innovation, Technology Battles for Dominance. The scientific databases Scopus and Google Scholar will be used primarily as literature search engines. Additionally, internal communications will also be consulted specifics regarding the Chemelot site are required. After finding useful papers in the databases, the tool Connected Papers tool will be used to find possible related papers on the same topic.

2.3. Data Collection Methods

Research refers to an organised, data-based, systematic, objective, critical inquiry into a specific problem, conducted with the goals of finding answers [69]. In essence, research provides crucial information that helps researchers, policymakers or managers to make informed decisions. The latter is the purpose of this research: to collect the information that helps decision-making. The information may consist of primary data collected first-hand by the researcher or secondary data already available in databases, books, newspapers, etc [69]. This research will use two data collection methods: interviews and the Best-Worst Method. Both primary and secondary data will be consulted in this work. Secondary data will be consulted when reviewing the existing literature to gain knowledge on the eco-innovations, and on the fundamentals of technology battles for dominance and adoption. Primary data will be collected during the interviews with the participants to find the relevance of the factors and to find motivation for the ranking by the participants.

2.3.1. Interviews

Conducting interviews is an appropriate data collection method because it allows the researcher to collect a wide variety of different types of data from human participants [69]. The context of the interviews is the Dutch chemical industry, specifically the unit of analysis is the Chemelot site. Additionally, when assessing societal, political, and public opinions, the unit of analysis may be extended to the Dutch society. Several chemical plants and research facilities are located on Chemelot, which develop sustainability strategies. To find suitable participants, this study will look for researchers and managers who conduct research on topics related to climate change, emissions, sustainability, renewable energy sources, and innovations. The participants who will be selected are experts who have more than 10 years of experience in their expertise and are directly linked to the Chemelot site. A total of 14 experts have been selected and will participate in the interviews. A list of the experts is included at the end of this section. The participants are selected in collaboration with the project supervisors and are contacted by e-mail. The interviews are conducted online and last approximately 45 - 60 minutes.

Moreover, the interviewing process will consist of two rounds to create an iterative interviewing process. First, the researchers and Brightsite experts will be interviewed to give their opinions, which helps to obtain practical and technical knowledge that is not covered in the literature or is firm-specific. The Brightsite experts have a clear overview of the actors on the site, and usually have experience in working at one of the chemical companies. They are aware of the strategies, policies, and regulations. As sustainability agents from the site, they contribute to achieving the goals by creating road maps and collecting information that they present to the Dutch and European governments. They are assisted in their research by researchers from TNO (a Dutch Research Organisation). Together, they investigate alternative technologies to help the site achieve its sustainability goals. During the second round, company managers and directors of specific firms on-site will be approached to discuss their views from the stakeholder perspective as policymakers and firm strategists. This variety of participants allows for a broader perspective due to the different interests involved. After the interviews, the results will be discussed with the project supervisors and assessed whether they find the results logical.

Semi-structured interviews will be conducted for this research. Whereas structured interviews do not allow for diversion and ask a rigorous set of questions, a semi-structured interview is an open form of interviewing that allows new topics to be discussed according to the participant's input. The interview will consist of two parts. The first part will determine the participants' qualifications and insights on the energy and raw material transition. Moreover, experts will be asked to share their perception of a successful energy and raw material transition, and the barriers and opportunities that come with it. Additionally, the experts will be asked to share their perspective of the role of eco-innovation adoption, who influences these battles, how decisions are made with regard to eco-innovations. Moreover, the interviews will help to find additional information that is not covered in the literature. This will help in analysing the technology battle and its possible outcome. Before the interviews starts, a pilot interview will be conducted to receive feedback on the methodology and questions. The second part will be the validation by the participants of the framework proposed in this study. This step is explained after the BWM section.

The list of experts with their qualifications and experiences who will participate in the interviews:

1. Expert 1: works at TNO as a senior researcher and is specialised in the energy transition. Before TNO, he worked at ECN, which is a research organisation that specialised in sustainable energy. Furthermore, he holds a PhD in theoretical physics. Within Brightsite, he coordinates the transition paths and systems innovations to succeed with the transition.

2. Expert 2: has over 35 years of experience in the chemical industry both as a chemical engineer and manager. He holds a master degree in science. The expert works at Sitech and helps Chemelot to achieve its sustainability goals by setting out road maps, transition paths, and infrastructural issues while simultaneously keeping the synergies of Chemelot.

3. Expert 3: started her career with a PhD in Chemical Engineering. She started working on the Chemelot site as a chemical engineer, later as a manager of chemical and mechanical engineers. She also has experience as a lean six sigma consultant. After 20 years of experience, she switched to Maastricht University as an associate professor in circular chemical engineering. She is still involved in the programmes at Brightsite. She contributes to the energy and raw material transition not only at Chemelot but for the entire chemical industry. Chemelot plays a pilot case role from the university's perspective. She helps in developing transition paths, creating insight into social acceptance, and assists in digitising processes.

4. Expert 4: is a technology and innovation manager at Sitech. She has a PhD in Chemical Technology. Together with her team of experts, they help clients with operational and plant-related questions to ensure that the plants operate optimally and consistent. They also advise the plants on how to become sustainable, to decrease emissions and costs. Apart from sustainability, they assist the site users in innovations, digitisation, and automation of processes.

5. Expert 5: is the director of Brightsite and has over 12 years of experience in this type of function. He holds a degree in Law and Business Administration. He leads the Brightsite program where they create models of the energy and raw material transition. They make transition pathways and work out different scenario's. All the activities are conducted from a sustainability perspective.

6. Expert 6: works as a consultant at TNO and has 19 years of experience in working at DSM (predecessor of Chemelot). He holds a PhD in Chemistry. His role in the energy and raw material transition is that he is involved in the industry transformation towards a more sustainable industry both from a technological and business developer's perspective.

7. Expert 7: holds a degree in Chemical Engineering, and a PDEng in Process and Product design. He has over 10 years of experience in the oil and gas sector, TNO, DSM, and currently works at Vattenfall. Together with TNO, Sitech, and University Maastricht, he was involved in the Brightsite program to set a site-wide model through which they wanted to evaluate different transition pathways. The goal of this tool is to be able to compare the different pathways in terms of metrics like the abatement cost per ton of CO_2 for different measures.

8. Expert 8: works as a chemical technologist at OCI, and before this at DSM. She has more than 16 years of experience and is responsible for the sustainability programme for OCI. She researches alternatives on how OCI can reduce scope 1 and scope 2 emissions, which are imposed by the European Union. Moreover, she analyses technologies to achieve these emission reductions for acceptable costs.

9. Expert 9: is a senior manager of Technology and Sustainability at Utilities Support Group (USG) and is responsible for the technology, sustainability, and asset strategy projects. USG is a company that is responsible for the purchasing, sales, distribution, and production of electricity, steam, gasses, and water for the site users on Chemelot. He holds a degree in Chemical Engineering and has experience in both this direction as well as management experiences in the chemical industry.

10. Expert 10: she has over 20 years of experience on the Chemelot site in the area of process technology. She holds a PhD in Mechanical Engineering and currently works for Brightsite. Within Brightsite, she leads projects regarding process innovations that are aimed at reducing emissions. Her role contributes by increasing energy efficiency in processes.

11. Expert 11: holds an Engineering degree. Currently, she has the role of a senior consultant for Brightsite and has more than 10 years of experience in this area. She researches process safety and societal acceptance of the products and processes on the Chemelot site. Naturally, safety is a crucial aspect on an industrial site. Therefore, all plants and processes demand high safety standards now and in the future. Simultaneously, this links closely to the societal acceptance of the residents living near Chemelot, but also the (local) government.
12. Expert 12: studied organic chemistry, but gained experience in chemical engineering on the job. He has over 30 years of experience in the research and development area at DSM, where he specialised in process development for bulk chemicals. Now, he works for TNO and contributes to the recycling and circularity activities on Chemelot.
13. Expert 13: He holds a PhD in Chemical Engineering and now designs corporate strategies with the focus on sustainability for Arlanxeo. He has over 20 years of experience in the innovation and R&D departments in the rubber production industry. By designing the sustainability strategies, which are focused on reducing scope 1 and 2 emissions as well as finding alternative sources for raw materials, he contributes to the transition within Arlanxeo, and thus Chemelot.
14. Expert 14: holds a PhD in Chemical Engineering. In the corporate sustainability department for SABIC to advise on various sustainability issues and strategies for the company. He has over 30 years of experience in the chemical industry as a researcher and business analyst with a focus on energy efficiency, climate, and sustainability.

2.3.2. Best-Worst Method

Decision-making can be a complicated task as a wide variety of factors need to be considered. The decision-maker often bases his decision on evaluating capabilities and his own preference. However, in the absence of objective metrics, or when a wide variety of factors are involved, it can be difficult for the decision-maker to rely on experience and intuition. A multiple criteria decision-making tool can help decision-makers by reducing the degree of difficulty and increasing clarity. Creating insight into eco-innovation adoption is a multiple criteria decision-making problem. A given MCDM problem proposes X alternatives to be evaluated against Y criteria. The results are summarised in a performance matrix in which the MCDM methods rank the alternatives according to preference [46]. An MCDM method finds solutions to problems by first formulating the problem and identifying the goals and alternatives, evaluating alternatives regarding the factors, finding the importance of factors, and checking the reliability and validity. Several factors should be compared, as they affect the adoption of eco-innovations. It is desirable to find the most important factors faced by policymakers, hence this issue is characterised as an MCDM situation.

To determine the relevance of the factors, this research will use the Best-Worst Method as an analytical tool, a widely used type of MCDM research tool. This method is suitable when evaluating alternatives that consist of certain factors, especially when objective metrics are lacking. In this research, the framework will contain different types of factors with different units. Some factors will have no units and will be subjective. Moreover, it is used to find the weights of the factors that are used to find an outcome of a particular decision-making problem. When the goal is to rank factors among a set of alternatives, the BWM is an appropriate method [58].

This method uses two vectors of pairwise comparisons to find the weights of the factors [60]. First, the decision-maker determines the best (i.e. most relevant) factor and the worst (i.e. the least relevant) factor. Next, he compares the best factor to the others, and the others to the worst factor. The maximum absolute difference between the corresponding comparisons and the weight ratios is minimised by a non-linear min-max formula [60]. Since the decision-makers have no problem in indicating the direction of their preference, but rather in expressing the weight of the factors, this model is less complex than other MCDM tools [60]. The Analytic Hierarchy Process (AHP), which is also a method based on pairwise comparisons, is also widely used as an analytical tool. However, statistical results indicate that the BWM performs better compared to AHP. The BWM needs less comparison data and yields more consistent comparisons [59]. High consistency is beneficial because it leads to a high degree of reliability of a study. Because the BWM is a simpler model, it is also suitable for meetings that are not held in person. The BWM consists of five consecutive steps to find the factor weights [59]:

1. **Step 1**: Determines a set of decision factors $\{c_1, c_2, ..., c_n\}$. These factors have been determined by literature review and interviews with Brightsite experts and concern the adoption of eco-innovations.
2. **Step 2**: Determines the best (i.e. the most relevant) and the worst (i.e. the least relevant) factors. In this step, the experts are asked to indicate the most and least relevant factor with regard to eco-innovation adoption in their opinion.
3. **Step 3**: Determines the choice of the most relevant factor over all the other factors. The experts rank the factors according to relevance i.e. from most relevant to least relevant, resulting in a Best-to-Others vector:

   $A_B = (a_{B1}, a_{B2}, ..., a_{Bn})$

   where a_{Bj} shows the preference of factor *B* over factor *j*.
4. **Step 4**: Determines the choice of all the factors over the worst factor. Here, the factors are ranked from least relevant to most relevant, resulting in a Others-to-Worst vector:

   $A_W = (a_{1W}, a_{2W}, ..., a_{nW})^T$

   where a_{jW} indicates the relevance of factor *j* over the worst factor *W*.
5. **Step 5**: calculates the optimal weights $(\omega_1^*, \omega_2^*, ..., \omega_n^*)$.

   The goal is finding the optimal weights for the factors. When the maximum absolute differences $|\frac{\omega_B}{\omega_j} - a_{Bj}|$ and $|\frac{\omega_j}{\omega_W} - a_{jW}|$ for all *j* are minimised, then it translates into the following min max model:

   $$minmax_j\left\{\left|\frac{\omega_B}{\omega_j} - a_{Bj}\right|, \left|\frac{\omega_j}{\omega_W} - a_{jW}\right|\right\} \tag{2.1}$$

   such that

   $\sum_j \omega_j = 1$

   $\omega_j \geq 0$, for all *j*

   The equation 2.1 is equal to the following equation:

   min ξ

   such that

   $$\begin{aligned}\left|\frac{\omega_B}{\omega_j} - a_{Bj}\right| &\leq \xi, \text{for all j}\\ \left|\frac{\omega_j}{\omega_w} - a_{jW}\right| &\leq \xi, \text{for all j}\end{aligned} \tag{2.2}$$

   $\sum_j \omega_j = 1$

   $\omega_j \geq 0$, for all *j*

   Subsequently, by solving the following equation, the weights of the factors can be determined:

   $\omega_j^* = \frac{min\omega_j + max\omega_j}{2}$

   Moreover, the consistency ratio can be solving the following the comparison:

   $$\text{C}onsistencyRatio = \frac{\xi^*}{\text{C}onsistencyIndex} \tag{2.3}$$

The consistency index is presented by Rezaei [59] and in Table 2.1. The consistency ratio varies between 0 and 1, with ratios closer to 0 being more consistent and ratios closer to 1 being less consistent. However, the equation 2.2 can present multiple optimal outcomes. Therefore, the formula is reformulated to make it into a linear equation:

min ξ

such that

$$\begin{gathered} \left|\omega_B - a_{Bj} * \omega_j\right| \leq \xi^L, \text{for all j} \\ \left|\omega_j - a_{jW} * \omega_w\right| \leq \xi^L, \text{for all j} \end{gathered} \tag{2.4}$$

$\sum_j \omega_j = 1$

$\omega_j \geq 0$, for all j

A_{BW}	1	2	3	4	5	6	7	8	9
Consistency Index ($max\xi$)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Table 2.1: Consistency indices

The participants will be asked to assess the weights of the factors by ranking them and justifying this ranking. The aim is to find out the relevance of these factors by asking the participants to rank the factors. Participants will be asked to rank three sets of sub-factors and one set of factors. The sub-factors will explain the relevance of eco-innovation adoption in this particular factor. Next, to find the relevance on the meta-level, the participants will be asked to rank the main set of factors. The climate transition and eco-innovation adoption require a holistic approach. Therefore, the meta-level factors will explain the full dynamics of eco-innovation rather than just the sub-factors at the local level. To compare the weights with each other, the weights have to be normalised. By multiplying the weights of the sub-factors with the weights of the factors, we arrive at the normalised weights.

2.4. Section Summary

In summary, this research will first provide an overview of the literature in the field of technology battles, technology adoption, and eco-innovations. Together with experts and based on literature, the eco-innovation alternatives for Chemelot will be described. Next, this research will present a framework of factors that will emerge from the literature. Some additional factors will be added after discussion with the research supervisors. Subsequently, experts will be interviewed to find information about the energy and raw material transition, barriers, and opportunities involved, the technology battle between eco-innovations, and the adoption of eco-innovations. Moreover, this study will use the Best-Worst Method to validate the framework by finding the relevance of the factors. This method is suitable because it is less complex than other MCDM methods, requires less comparison data, produces more consistent comparisons, when objective metrics are lacking, when interviews are not held in person but online.

3

Theoretical Background

This chapter consists of two parts. The first part of the literature review discusses the fundamental theory of technology battles for dominance, technology emergence, and factors affecting these battles. The second part of this chapter reviews the literature on eco-innovation adoption and the factors affecting this adoption. This part is specified in the direction of the (chemical) industry. Moreover, barriers to the adoption of eco-innovations by the chemical industry are also presented.

3.1. Literature Review on Technology Battles

Usually, there are several technologies available, each with its own characteristics, but generally fulfil the same purpose. The different technologies compete in markets to gain dominance to achieve a competitive advantage. The dominant technology is eventually adopted by the market and reaps absolute benefits. The adoption rate follows a cyclical pattern, also known as the S-curve. A key aspect that influences the battle for dominance, is the adoption rate of innovations. Sequential adoption by individuals can quickly lead to the superiority of a single option, regardless of its technological superiority [66]. In the beginning, technologies are still being developed and only adopted in niche markets by early adopters. Later, the adoption rate increases as the dominant technology emerges in mass markets. The last phase represents saturated markets with this technology, only with incremental innovations. The performance of technologies also follows the trajectory of an S-curve. In the early stages of technology development, the performance improvement is slow because technologies are not understood sufficiently [67]. When the technologies are explored and firms start to comprehend the technologies, improvement starts to accelerate. Technology developers focus their attention on actors who understand the technology, thereby reaping the greatest improvement and causing the performance to increase rapidly. Eventually, the technology reaches its limits and the cost of incremental improvement increases. This causes diminishing returns and the S-curve flattens out, marking the end of the S-curve.

Technologies do not always reach their limits [67]. In the last phase of the S-curve, discontinuous technologies might enter the market and may render the current technologies obsolete. The economist Schumpeter referred to this as *”creative destruction”* where existing structures of industries are overturned, creating new winners and new losers [67]. When technology fulfils the same market need but does this on a new knowledge base, it is considered to be a discontinuous technology. When a discontinuous technology or innovation is brought to markets, this S-curve cycle starts again and makes the previous innovation obsolete. This can be seen in the shift from current fossil-fuelled technologies towards sustainable eco-innovations. At first, disruptive technologies may perform worse than incumbent technologies. Therefore, the returns are lower than the effort invested in the incumbent technology causing firmsto be reluctant to invest in disruptive technologies. For example, the first electric/hybrid cars or wind turbines were not efficient and expensive. They required subsidies to make it attractive. However, the S-curve of the disruptive technology might increase to a higher performance limit or the S-curve might be steeper. This means that returns of the innovative technology become higher compared to the investments in the incumbent technology. Now, the markets offer efficient electric cars and the first subsidy-free wind turbines parks are installed. Entrants in the industry presumably select the disruptive technologies while incumbent firms are facing difficulties to either extend the life cycle of their incumbent assets due to investments or to switch to the disruptive technologies [67]. When the performance potential of the disruptive technology turns out to be greater, it is likely to substitute the incumbent technology. However, limitations of the S-curve are that it is hard to predict the curve in advance [67]. Besides, firms can affect the curve by using complementary products, and markets can also change which influences the curve as well. Moreover, by overcoming barriers that limit technology improvement, firms can extend the lifetime of the incumbent technology. Therefore, it is not certain that substituting the incumbent technology with a disruptive one will be beneficial. It depends on the advantages offered by the disruptive technology, whether it fits the firm's capabilities or has acceptable switching costs, and depends on the expected diffusion rate of the disruptive technology.

The S-curve can be explained by the technology cycle. Anderson and Tushman noticed that technologies are passing through four phases. The first phase, the era of ferment, represents the discovery of a disruptive technology followed by its development [67]. It might provide breakthrough opportunities, but there is hardly any concession on how the technologies and complementary technologies should look like. Multiple firms will present their own design as a result of experimenting with different forms of technology, causing this phase to be turbulent and uncertain. This phase is followed by selecting the dominant design [67], [75]. Anderson and Tushman established that the dominant design emerged which is most supported by the majority of the market unless a discontinuous technology disrupted the cycle. Moreover, the dominant design is rarely in the same form as the original disruptive technology and is also not the leading edge of technology. The dominant design is not powered by technical or economic superiority, it rather encompasses a combination of elements that best meets the sociopolitical/institutional demand of the market majority [75]. Dominant designs are a key transition mark between the era of ferment and the era of incremental change. The latter emerges once a dominant design is selected by the market. Uncertainty regarding design choices vanished and firms focus on market penetration and efficiency. Moreover, cost efficiency is increased and production costs are lowered due to scale advantages and learning curves. Incremental changes continue in this period until the next technological discontinuity, which disrupts the cycle and substitutes the incumbent technology. Although disruptive technologies might provide significant advantages, successful firms still often resist substituting the incumbent technologies with disruptive ones. During the era of incremental change, stop investigating alternative designs or technologies. Instead, they focus to invest and refining their competencies related to the dominant design. This causes that firms capabilities continue to focus on one aspect, and thereby becoming less flexible to change to other innovations. When entire firms' structure and expertise are oriented towards the dominant design, it becomes a barrier to adopt disruptive technologies.

An important aspect of adoption, or specifically the degree of success of the adoption, is diffusion. Rogers [62] defined diffusion as: *"the process by which an innovation is communicated through certain channels over time among the members of a social system"*. The diffusion process is generally involved with mass media and personal communication channels. A person assesses an innovation and determines whether or not to adopt it based on conversations with other people who have already accepted or refused the innovation [62]. Although mass media usually creates awareness around innovations, it is the interpersonal communication between people to persuade most people to adopt a novel idea. The more people communicate about a particular innovation and try to persuade people to adopt it, the greater the chance that the innovation will be adopted. At some point in the diffusion process of innovation, the adoption rate suddenly increases at an inordinate rate. If the adoption rate is plotted against time, a diffusion curve emerges [62]. The key role of mass media communication in the diffusion process is to generate awareness regarding innovations. However, diffusion of innovations does not only focus on generating awareness, but also on decision-making, attitude change, and implementation of innovations. [62].

3.1.1. Perspectives on Technology Dominance

The problem addressed in this research can be categorised as a battle for technology dominance, or dominant design. The phenomenon of technology dominance is defined by Suarez [73] as: *"the emergence of a dominant technological trajectory among several competing ones"*. Within the energy transition, there are several battles between innovations and technologies that compete for dominance such as the battle between hydrogen-powered vehicles and battery-powered vehicles [36]. Currently, a debate is ongoing in the chemical industry and beyond whether electricity or hydrogen is the superior alternative to replace the current fossil fuels and feedstock. There are different perspectives on how such a battle should be fought.

The evolutionists view on technology dominance states that achieving dominance is the result of natural selection [1], [75]. Later, scholars refined this theory by stating that technologies evolve incrementally through periods of time until a major innovation, or technological discontinuity is presented. These discontinuities radically change markets or create new ones, creating the potential for a technology battle.

However, other actors focus on how market mechanisms affect the outcome of a technology battle [3], [37]. They argue that technology dominance is not actively chosen, but rather emerges from the environment influenced by market mechanisms such as network externalities [77]. Network economists focus on network and learning effects where technologies face increasing returns to adoption, meaning that the value of the technologies rises as they are applied. The number of users of the technology, or the installed base, therefore affect the result of the technology battle.

Tushman and Rosenkopf indicate, from the institutional economists view, that technology can prevail since socio-political and strategic behaviour influenced by actors have a major impact on technological evolution [48], [63]. Noble [48] demonstrated that powerful actors can collaborate to force the adoption of technology. Moreover, leading incumbents may strategically join forces to enlarge entry barriers to protect their environment and secure their competitive advantage. The environment in which firms and technologies find themselves is therefore not a product of independent natural forces, it is rather shaped by actors and their strategic actions. This clarifies that the technology that gets the most support is likely to become the dominant technology and not the most superior one.

Scholars in the technology management stream suggest that multiple firm-level factors influence the installed base, eventually leading to technology dominance [38], [66], [73]. The benefits of a technological network depend on the relative size of the installed base of two competing networks [73]. An example in the energy transition is the installed base of the electricity grid and products that run on electricity compared to the missing hydrogen infrastructure and products that are powered by hydrogen. This highlights the problem of the firm's installed base because a bias is created in favour of these technologies due to the advantages of the installed base. Moreover, the role of expectations created by brand reputation, strong financial resources, or technological superiority can also influence the result of a technology battle. Technologies that are superior to their competitors are more likely to become dominant because more users will adopt them [77]. Although this is the preferred outcome, in reality, this is not always the case. Lee et al. [38] share this view by confirming that innovations often become dominant regardless of technological superiority. The emergence process of dominant technologies is often seen as a black box in which technological and non-technological factors interact. Although Lee et al. [38] found the interaction between technological and non-technological factors, they did not specify any factors. Moreover, their study focused on non-technological factors, as it suggests that technology dominance does not emerge from technological superiority. However, Lee et al. [38] argue that firms have the power to strategically affect the emergence process by managing technological and non-technological factors in the pursuit of competitive advantage from innovation processes.

Suarez [73] suggests that the battle for dominance for complex technologies, such as those in the chemical industries, does not change. However, the process does change. More complex products require more actors to align for technological design to become dominant. A complex system requires more attention to multiple interfaces and communicating with all kinds of users of complementary products. The boundary of the technological field widens as it moves from simple technological artefacts to more complex ones. Suarez [73] distinguished two groups of factors that affect the result of a technology battle: firm-level factors i.e. factors that can be managed by firms, and environmental factors i.e. factors that can barely be influenced by firms. The latter category does not directly affect the outcome of a technology battle for dominance, but it paves the way for technology and thereby increasing the likelihood of reaching dominance.

Schilling confirms that the direction of the development of technology is highly path-dependent [66]. Therefore, the technology that emerges as the winner from the battle is not necessarily the superior technology. The technology battle is characterised by complexity and non-linearity, as indicated by path dependency, making prediction difficult. Nevertheless, idiosyncratic effects such as policy and politics primarily exert their influence by impacting factors that have a predictable and reliable effect on technology adoption. This applies also to Chemelot since lobby groups and politicians promote hydrogen for energetic applications. If hydrogen eventually dominates the markets, Chemelot has no choice but to go with the market developments because it cannot select another eco-innovation. Therefore, Chemelot would rather use a technocratic approach than succumb to path dependency. Schilling [66] further indicates that technology standards are not only driven by network externalities such as complementary goods and the installed base (i.e. the example of electricity vs hydrogen infrastructure and complementary goods), but also by the firm's timing of market entry and learning orientation. Although Schilling [66] views the battle of technology dominance from the perspective of the technology producer rather than from the perspective of the technology user, her research contributes to creating an understanding of the status of technologies. As a result, her research helps policymakers to base a decision on technological and non-technological factors, increasing the chances of success.

When all the necessary factors in the struggle for dominance are taken into account, it remains necessary to distinguish the factors inherent in the technology of innovation from other, more environmental factors. The chemical industry wants to gain early insight into both types of factors: in technological factors so that when choosing between alternative pathways the decision can also be based on benefits for future industry and society; in non-technological factors to identify barriers and enablers in time and how to deal with them. The chemical industry wants to increase the chances that in the case of eco-innovations, the technologically superior alternative will be the dominant technology this time. Although Lee et al. [38] made the distinction between technological and non-technological factors, they did not specify the factors within these categories. However, this study also uses the categorisation but does specify the factors within these categories.

Another approach to achieving technology dominance is through the standardisation process. The standardisation stream, part of the technology management literature, presents selection as a stage of the process. There are two approaches of standardisation: committee-based and market-based [78]. Market-based standardisation is achieved as a result of competition between technologies in the market. Committee-based standardisation is based on an agreement made in a committee. However, the latter does not necessarily mean that it is accepted by the market. Besides, even when policymakers and the chemical industry would agree on a decision regarding an industry-standard technology, other stakeholders such as lobby groups, regulatory institutions, and competitors can influence the decision [78].

3.1.2. Distinguishing Internal and External factors

The effects of firm-level and environmental factors, or internal and external factors, can be explained from a theoretical perspective. Several scholars [13], [17], [29], [78], [73] distinguished between these two categories.

The effect of the internal factors can be explained from the Resource-based View theory [19]. This theory explains that a firm's resources are limited and therefore critical elements that determine its strategy and success. A firm makes certain choices because it considers its availability and limited resources. Firms operating in the chemical industry struggle to adopt eco-innovations for various reasons [35]. However, Barney and Hesterly argue that resource-based factors support the firm to achieve competitive advantage [8]. These resources encompass financial, human, physical, and organisational resources [7]. The lack of these resources complicates the challenge of eco-innovation adoption. While corporate environmental management may not provide short-term gains, it is likely to provide long-term economic gains [16]. firms can improve their environmental competitiveness by incorporating environmental management into their policies and thus be the first to reap benefits. Moreover, if a firm is able to manage its resources such that they are heterogeneous, immobile, and have properties that are valuable, rare, inimitable, and non-substitutable, then these resources offer the firm a competitive advantage [7].

The effect of external factors can be explained from the Contingency theory. Essentially, the Contingency theory poses that good management depends on situational or environmental variables [47].

Variables such as job design, participation in decision-making, style of leadership, and organisational structure influence the overall managerial outcome, strategy, and performance. Multiple scholars have studied the effects of Contingency theory with regard to the adoption of practices within management. Chauhan et al. [19] state that the actions of a firm are contingent upon factors that fall outside a firm's control. Prajogo [55] concluded in his study that a firm's innovative activities are driven by external factors. From a strategic management perspective, Ortt [52] approves the Contingency theory as a suitable alternative to one-size-fits-all management perspectives since there *"is no optimal strategy for all organisations and poses that the most desirable choice of strategy variables alters to certain factors"*.

3.2. Building a new Theoretical Framework

This second part of the theoretical background is about building a new theoretical framework. This framework contains factors that affect eco-innovation adoption. It starts by presenting some of the major barriers for the chemical industry to adopt eco-innovations. Furthermore, the literature is consulted to find what scholars have found regarding eco-innovation adoption.

3.2.1. Barriers for Eco-innovations Adoption

The chemical industry supports nearly all economic activity and is an energy-intensive production industry. This industry produces 15% of the direct annual carbon emissions of the global industry [27]. Now that the Dutch government has increased its goal up to 55% reduction of GHG emissions [61], the Dutch chemical sector also has to increase its effort to decarbonise its processes. Decreasing greenhouse gasses (GHG) emissions and bettering the environmental sustainability in this industry involves decarbonisation and clean energy investments. Nevertheless, progress in GHG emission abatement has been slow and if the industry continues to emit according to the ongoing trend, the GHG emissions could rise by roughly 80% by 2050 (compared to 2007) [54]. Despite proven means of environmental improvement, the chemical industry, especially energy-intensive processing industries, face barriers that make it harder for these organisations to switch to eco-innovations.

The first barriers are the long investment cycles. Due to high capital intensity and large volumes, the industry has few opportunities to invest in disruptive technology, which results in a lock-in [35], [54]. The second barrier is the international business markets in which chemical industries operate and where environmental incentives are lacking. Therefore, it is difficult to sell more expensive products [35], [54]. A third barrier is the heterogeneity of the chemical industry [10]. Because almost every chemical site consists of different integrated plants, it is difficult for disruptive technologies to enter the market. Often these eco-innovations are immature and not cost-effective [32]. Another barrier that chemical industries face in adopting eco-innovations is the lack of customer demand for eco-friendly products because of its B2B character of industry products. Lastly, the insufficiency of adequate prioritisation and inaccurate policy effort is also seen as a delay in the process of eco-innovation adoption [35].

3.2.2. Literature on Eco-innovation Adoption

While the literature so far has focused on the fundamentals of innovations, technology battles, and adoption in general, it now dives deeper into environmental innovations or eco-innovations. Normally, firms consider environmental strategy as something that limits a firm's growth, competitiveness, and profitability [13]. Economic growth is directly linked to innovation, though simultaneously, it is affiliated with environmental damage [13]. Governmental and societal pressure rises on firms to reduce their environmental impact. Therefore, to be strategically and economically successful, firms should take into account social and environmental aspects when developing products. In this context, the concept of eco-innovation emerges. As defined in chapter 1, eco-innovations must have a beneficial impact on organisational operations and consumer behaviour, while incorporating economic, social, and environmental characteristics in their adoption to succeed in sustainable development [13].

Bossle et al. [13] are interested in the factors that motivate firms to adopt eco-innovations. Firms should approach environmental challenges to limit climate change and uphold a good reputation. The complexity of these challenges depends on the firm's activity (external factors) and the firm's strategy (internal factors). Therefore, empirically identifying the factors of eco-innovation adoption is the main task. Eco-innovation is perceived as an outcome, which can be demanded by society, accomplished by firms, and stimulated by the government as a means of advancing sustainable development [13]. Bossle et al. [13] found the following external factors affecting eco-innovation adoption: *”Regulatory pressures, Normative pressures, Cooperation, Expanding market, Technology, The role of governments”*. Also, they found the following internal factors: *”Efficiency, Adoption of certifications, Environmental managerial concerns, Environmental leadership, Environmental culture, Environmental capability, Human resources, Performance”*.

Another research by Fu et al. [29] that researched the effect of factors on sustainable process technology adoption concluded that the following factors found in the literature are important: *technology capability, market pressure, coercive pressure, adoption experience, certified systems, internal support, and cooperation*. However, this study did not distinguish between internal and external factors, or between technological and non-technological factors. Furthermore, Fu et al. [29] found that technology characteristics are seldom researched because the majority of researchers focus on firm characteristics and coercive pressures. Moreover, some factors did not receive sufficient attention, like the infrastructural factors. The lack of technical characteristics and infrastructure factors is among others an incentive to research what the influence of these factors is in the chemical industry.

The most recent study by Chappin et al. [17] researched factors that overlap with the factors found by Bossle et al. [13]. Specifically, they reviewed the literature to establish factors for the adoption of energy-efficient eco-innovations in the chemical industry. Chappin et al. [17] developed its own framework containing internal and external factors. The 6 internal factors are: *”Awareness of the high CO_2 emissions by constantly reporting, High resources and production costs, Ethical responsibility, Management promoting CO_2 reduction initiatives, Corporate culture encouraging initiatives from employees, Clear objectives and plans in terms of CO_2 reductions”*. The 6 external factors are: *”Regulatory pressure on CO_2 emissions, Threat of new regulation on CO_2 emissions, Subsidies on CO_2 reductions, Stakeholders’ expectations, Business opportunities, Competitive advantage*”.

3.2.3. Defining the Theoretical Framework

This section presents a framework of factors that affect the adoption of eco-innovations. Since Lee et al. [38] recommended further research into various factors, this study builds on that framework and identifies technological factors rather than using technological factors as a generic force. It is necessary to make this distinction between technological and non-technological factors to avoid systemic bias, which represents the inherent tendency of processes to support preferred outcomes. As stated by scholars, technology battles are often won not by technological factors, but by non-technological factors such as politics or profits [38], [66], [73]. If society prefers one technology over another due to aesthetics, for example, this technology gains popularity and is in turn likely to become the dominant technology. Looking at the energy transition, we see that the technology battle contains uncertainties such as the absence of consensus over which technology is most desirable from a future point of view, lacking regulations, and an unfavourable investment climate. During this energy transition debate, we see arguments such as ’not in my backyard’ or investments that are not profitable, often subjectively motivated. This short-term thinking can be explained by the fact that the government’s term of office is no longer than 4 years, and managerial positions are also not long enough to be intrinsically motivated to achieve long-term goals and divergent interests of the various parties involved (or excluded).

However, the decisions that firmsand institutions have to take now have immense consequences for the future. Brandts [53], a Chemelot expert, argues that it is desirable to gain early insight in technological factors so that when choosing between alternative pathways, the decision can also be based on scientific factors that are relevant for the future society which, after all, will use the eco-innovations that are being put forward now. Brandts [53] believes that future societal interests benefit more from long-term thinking and science-based factors. Technological factors encompass the inherent characteristics of the eco-innovation and are based on science and technology such as the efficiency of consumption of (for the next decades) scarce renewable resources (energy, non-fossil feedstock); scalability, i.e. the impact relative to the climate problems to be solved (e.g. a niche market innovation is not going to save the climate); CO_2 abatement efficiency of the combination ‘application and make technology (CO_2 reduction achieved per kWh or per kg renewable feedstock), costs for investors and consumers. These characteristics are numerically demonstrable and at least in principle, verifiable and replicable. One can think of technological factors as arguments from a technocratic perspective.

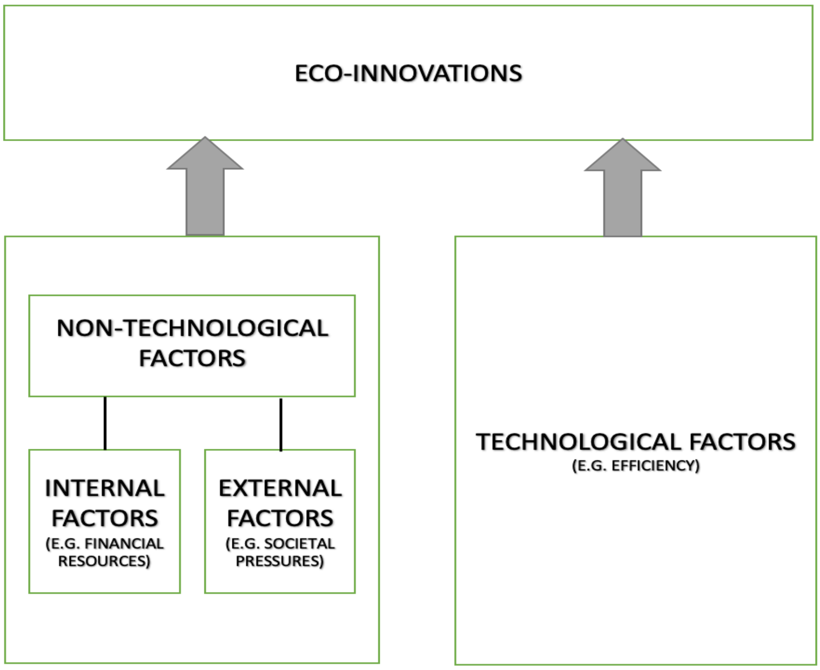


Figure 3.1: Framework with Technological and Non-technological factors affecting eco-innovation adoption

Furthermore, this research aims at finding which non-technological factors affect the adoption of eco-innovations. Like technological factors, non-technological factors are factors that affect the adoption of eco-innovations. However, whereas technological factors concern the characteristics of an eco-innovation, non-technological factors do not. These are factors concerning society, environment, firm-specific characteristics, and human resources. This research distinguishes the non-technological factors between internal and external factors. This categorisation is often a common approach in literature [13], [17], [19]. External factors reflect the effect of the environment a firm operates in i.e. market pressures or governmental policy. For example, a certain product can be classified as toxic which means that a specialised mode of transport is required. This affects the chemical industry as it has to adapt to new regulations. Internal factors consider the firm-specific characteristics such as financial and human resources. For example, it is desirable for a chemical plant to employ chemical engineers that have sufficient knowledge regarding the processes. A firm has direct control over its internal factors but has no or little control over its external factors.

Consequently, this framework has two sets of factors with (1) the technological factors covering the inherent characteristics of the eco-innovation like pricing and efficiency, and (2) the non-technological factors covering all the other factors like firm-specific and environmental factors. The non-technological factors are categorised into internal and external factors. Figure 3.1 illustrates the sets of factors. The following example demonstrates the difference between the technological and non-technological factors. Wind turbines are good innovations for emission-free power generation. From a technological perspective, it is desirable to install many wind turbines because this contributes to achieving the goal of decarbonising energy generation. However, these wind turbines have some limitations that are illustrated by non-technological factors. For example, local residents resist the installation of these eco-innovations because these wind turbines are placed close to their homes due to noise complaints. Both technological and non-technological factors, therefore, influence the application of eco-innovations. Both perspectives should be taken into account when making an informed decision.

Introducing Technological factors

As mentioned earlier in this chapter, Lee et al. [38] mentioned this categorisation but did not specify any factors. In this study, factors are categorised to find the effect on the adoption of eco-innovations. Although the technological factors are analysed separately in the literature, no framework has been found in the literature that discusses these technological factors. This is partly due to the fact that these factors are technology-specific and differ per chemical cluster. Therefore, these technological factors are identified in cooperation with the management of Brightsite.

1. Capital Expenses (Capex): Investment is often referred to as capital expenditures. This is a type of expenditure a firm makes when acquiring, maintaining, or upgrading physical assets like plants, buildings, technologies, property, or equipment. The switch from fossil fuel-based energy to renewable sources of energy requires new types of installations. Disruptive technologies in the chemical industry are cost-intensive because the entire process has to be changed. Since the Chemelot site is so integrated and clustered, every change affects the process which adds to the investments costs.

2. Operating Expenses (Opex): These are expenses a firm has during regular business operations. Examples are rent, payrolls, insurance, marketing, funds for R&D, and inventory. The transition from fossil fuels towards renewables has an effect on Opex. For example, switching from methane to electricity for the cracking furnaces has an impact on the operational costs of this process. However, not only does the energy source needs to be considered, but also the raw materials need to be included in the Opex because these change as well. In the future, Opex may well become the most important driver, as Opex will be largely determined by the price of renewable electricity and renewable hydrogen. The prices of energy and raw materials might fluctuate and depend on the method of generation and transportation. Therefore, Chemelot needs insight into Opex to make a decision.

3. Efficiency of technology: all technologies have an operating efficiency, meaning how much energy technology can use usefully from the total energy it consumes. There are various eco-innovations, all of which work differently and have their own characteristics. Since renewable energy will be scarce for a long time, the overall efficiency of eco-innovations from source, transport and use have to be closely researched. Moreover, the efficiency throughout the chain must be examined, i.e. from the energy source, conversion, transport and other efficiency losses. The network operators pass these costs on to the end-users.

4. Lead time: The time needed to carry out a project. It takes a long time to implement and install new infrastructure and new technologies. This has to be planned carefully because resources are limited. The electricity grid is quite advanced, but for the electrification of chemical processes, the grid has to be extended on a large scale. The same applies to hydrogen, for which a hydrogen network is completely lacking. Any project has to take into account the lead time, especially when sustainability goals are taken into account.

5. Technological feasibility: there are several eco-innovations with each their advantages and disadvantages. Eco-innovations should be technologically feasible for it to be successful. Characteristics like superiority (i.e. eco-innovation must be perceived superior compared to the incumbent technology), integrability (i.e. the degree of integration of energy generation on-site), stability (i.e. a constant supply of energy), and scalability (i.e. sufficient supply of feedstock) are important to know when considering multiple alternatives.

6. Recyclability and circularity: some eco-innovations may still produce some waste or emissions. Recycling or circularity is a desirable option to limit the use of resources. Moreover, Chemelot has the desire to become a circular hub. Therefore, it needs recycled raw materials, but also the ability to recycle the residual products or waste. Thus, finding suitable options for recycling is paramount. A part of this is CO_2 abatement. In the future, Chemelot will continue to produce CO_2 from its processes. However, there are multiple CO_2 abatement options like CCS, using biomass, or using recycled plastics for plastic production. The adaptability for an end situation on the Chemelot site for zero-emission in 2050 plays an important role.

Introducing Non-technological factors

A stream of literature dealing with the adoption of eco-innovations presents factors regarding this topic [13], [17], [29], [39]. Due to overlapping factors, this study presents a new framework that reduces overlap and introduces new factors. This new framework distinguished between Internal and External factors, where Internal factors are within a firm's own control and External factors are outside a firm's control.

Internal factors

1. Financial Resources: firms with solid financial resources face a higher probability of adopting eco-innovations. firms are continuously looking for options to reduce costs and improve efficiency. By reducing energy costs, investing in environmental improvements, and upgrading equipment, firms can operate more efficiently and save on costs [13], [17].
2. Human Resources: employees of a firm play a crucial role in adopting eco-innovations. When firms can rely on high quality and educated staff, they are more motivated to adopt eco-innovations [13].
3. Firm's commitment: the top management of a firm plays a key part in the decision-making for eco-innovation adoption. The top management guides the firm towards its goals and according to its firm values. They show commitment and motivate employees to work from a sustainable perspective. The managers create, manage, and integrate the strategy for sustainable innovations for the firm [13].
4. Technological knowledge: the firm's technological capabilities such as R&D, experts, or specialised departments with broad innovative capabilities are desirable for eco-innovation adoption [29]. Firms with their own R&D departments or joint ventures that develop eco-innovations are more likely to adopt eco-innovations. It allows a firm to be at the leading edge of eco-innovations.
5. Corporate culture: by motivating its employees and by creating a corporate culture that stimulates ideas that can flow between lower and higher departments, a firm can achieve a greater human capital intensity. This ensures a corporate culture which enhances the probability of adopting eco-innovations [17], [29].
6. Strategy: Firms with both clear strategies and integrated action plans are motivated to innovate [17]. It is paramount to incorporate sustainability as an explicit objective in firm processes to adopt eco-innovation, as this increases the likelihood of eco-innovation adoption [13].
7. Responsibility: Firms with social and ethical responsibility are conscious of their firm's operations, risks, opportunities and encompass a responsible role towards society and future generations. Despite the higher risks, higher investments, lack of returns which are barriers for eco-innovation adoption, a firm can pursue energy savings, emission reduction and adoption of eco-innovations from a corporate social responsibility perspective [17], [29].
8. Awareness of environmental damage: firms are more motivated to adopt eco-innovations when they are faced with the facts of emissions they produce. By continuously measuring and reporting emissions, firms are aware of the environmental damage they cause and are therefore triggered to reduce emissions. In turn, this increases the likelihood of eco-innovation adoption [17].

External factors

1. Regulatory pressure: regulators can increase pressure on firms who emit large quantities of CO_2 emissions from their processes to invest in emissions abatement. Local, national, and international governments can issue new regulations on CO_2 emissions. Research shows that firms are likely to adopt eco-innovations when environmental regulations require these practices [17].
2. Financial incentives: higher prices and low return on investments for environmental products are often a barrier to enter these markets. Government subsidies help to reduce these barriers and are often a positive incentive for firms to adopt eco-innovations. Moreover, higher taxation on emissions, for example, also encourages firms to adopt eco-innovations [13], [29].
3. Market pressures: firms face market demand from stakeholders such as clients, suppliers, competition. Stakeholders have expectations and can demand eco-friendly products which can influence the motivation in selecting eco-innovations. The approval, support and market pull of stakeholders are crucial for firms[17]. For example, corporate sustainable responsibility programmes

motivate firms to adopt eco-innovations [13]. firms are compared with the competition and try to operate according to standards and norms which apply in a certain sector [13].

4. Business opportunities: firms scan markets for opportunities that can be linked to eco-innovations. This increases the chance for firms to adopt eco-innovations [17]. Firms can be first to market which may be advantageous, especially when innovations have momentum created by market demand, pressure, or regulations. Firms are continuously looking to create a competitive advantage by pushing technology to markets. Competitive firms are part of the market environment and they are able to create a competitive advantage when they realise a cost advantage by implementing eco-innovations. This motivates firms to reduce emissions and save energy to sustain their competitive advantage.

5. Infrastructure: the adoption of eco-innovation depends on infrastructural factors. The better the infrastructure supports the innovation, the higher the rate of eco-innovation adoption. Infrastructure can be perceived as a form of network externalities. For example, a battery-powered car becomes more successful when the charging infrastructure is expanded. Fu et al. [29] stated that this fact has not yet been widely studied in the literature. Since the infrastructural development is important in this case, this factor is added. Experts agreed and explained that the type of infrastructure most likely has an effect on the adoption of eco-innovations.

6. Availability of energy: the energy transition creates a large demand for renewable energy. The factor Availability of Energy is added because the experts have serious concerns regarding this factor [53]. The certainty of enough renewable energy supply plays a crucial role in the energy and raw material transition. For example, it is technologically possible to produce hydrogen from biomass, woodchips, or municipal waste. However, the vast amount of material required for this process to produce hydrogen make that this path is not likely to provide enough supply. This factor has not been included in other studies that presented factors that affected adoption. Therefore, this factor is added to find other experts opinions.

7. Societal awareness: this suggests that firms take the public into consideration when making decisions [33]. The factor Societal Awareness is added because the experts stated that the chemical industry suffers from a bad reputation among society [53]. They indicate that the gap between society and the chemical industry is large and that does not help the transition. Moreover, they indicate that strong lobbies and political opinions have also a major effect on society. This makes it difficult to choose for technologically the most suitable option because the public opinion desired otherwise. Residents living close to chemical plants can also exert influence on the decision-making of eco-innovations by addressing concerns regarding the environment, safety, risks, contamination, and trust [56]. For example, residents opposing to the installation of wind turbines in the area due to noise and landscape pollution, also known as 'not in my backyard' phenomenon. This factor has not been included by other studies and is therefore added to this framework.

3.3. Section Summary

This literature review identified barriers that the chemical industry faces to adopt eco-innovations. Furthermore, it created insight into the process of technology emergence, and shed light on theoretical perspectives on battles for technology dominance, adoption, and diffusion. The evolutionists, network economists, institutional economists, and technology management streams are discussed as well as the role of standardisation in technology dominance. Subsequently, this theory section funnelled papers on these topics in the direction of chemical plants and environmental studies. At this point, multiple frameworks of factors that affect the adoption of eco-innovations emerged from the literature. This chapter presented a novel framework with new distinctions: technological factors versus non-technological factors and non-technological internal versus non-technological external factors. In addition, this research creates a better understanding of the sustainability strategies, each with its own characteristics and sets of factors that are competing for technology dominance.

4

Eco-innovations on Chemelot

This chapter presents an overview of how the current situation on Chemelot looks like, based on open information sources. It presents schematic energy and material flows and introduces the two largest plants and their processes. Moreover, it shows which roles the eco-innovations might play in making the processes more sustainable. It describes the possible roles of hydrogen and electrification in the ammonia production and cracking processes. Moreover, it shows a road map of sustainable hydrogen production.

4.1. Current Situation

Chemelot is a large chemical site in the Netherlands, home to 150 multinationals such as Arlanxeo, AnQore, Fibrant, SABIC, and OCI Nitrogen [21]. This industrial site contains 60 plants that are tightly integrated, offering high levels of synergies. Two firms dominate: SABIC and OCI are the key processors of fossil raw materials naphtha and natural gas respectively. Appendix A.1 shows a simplified illustration of the largest plants on Chemelot and their main processes and products. The plants on Chemelot produce chemicals, raw materials for other plants on the site, and end products for a very broad number of applications and markets. Moreover, the industrial park is supported by Brightlands Chemelot Campus and is connected to universities. The high degree of integration and synergies makes Chemelot one of the most sustainable industrial parks in Europe because less energy is wasted and more recycling is possible. Naturally, to maintain this position, the industrial park needs to continue with emissions abatement.

OCI is one of the largest global fertiliser manufacturers and the largest melamine manufacturer [51]. Fertiliser is used in large quantities in agriculture to sustain the globally rising demand for nourishment. Melamine is a raw material that is used for resins and adhesives in many applications such as laminate flooring, furniture, plastic tableware, and coatings. Ammonia is for both products a necessary raw material and has to be produced [41]. Ammonia production is the most energy-intensive process in the fertiliser industry [41]. Methane is both used as feedstock to produce hydrogen and as an energy source for heat generation in the ammonia production process [70]. This process is visualised in Appendix B.1.

SABIC produces intermediates for the production of numerous plastics which are made from naphtha [65]. SABIC imports its naphtha from the Port of Rotterdam via pipelines [53]. SABIC owns two naphtha crackers which produce ethylene and propylene and other high-value chemicals, the main components for plastics [15]. Cracking is a chemical process where oil-based feedstock like naphtha is heated so that complex organic molecules are broken down into smaller molecules [65]. The heat required is generated by burning methane, one of the products of the cracking process, which produces emissions [70]. Other plants subsequently process intermediates into polymers and more complex intermediate products. The cracking process is schematically visualised in Appendix C.1.

To illustrate the current situation of energy and raw material consumption, this section presents a simplified roadmap. This roadmap approaches a value chain to create a better understanding of the processes, energy and material use, and products that the plants on Chemelot produce. Figure 4.1

shows the current situation on Chemelot [14]. Here, the source represents a type of origin of the used energy or feedstock. The T stands for one or multiple technologies to convert materials from the source into a commodity, for example pumping oil or gas from the earth. The commodity represents a product that a plant acquires to process. Some of the commodities need to be converted again to be suitable for use in chemical processes. For example, refinery technology is used to convert oil into naphtha. Subsequently, the chemical plants process commodities to produce intermediates which are one or more basic molecules like melamine or to produce materials like polyethylene.

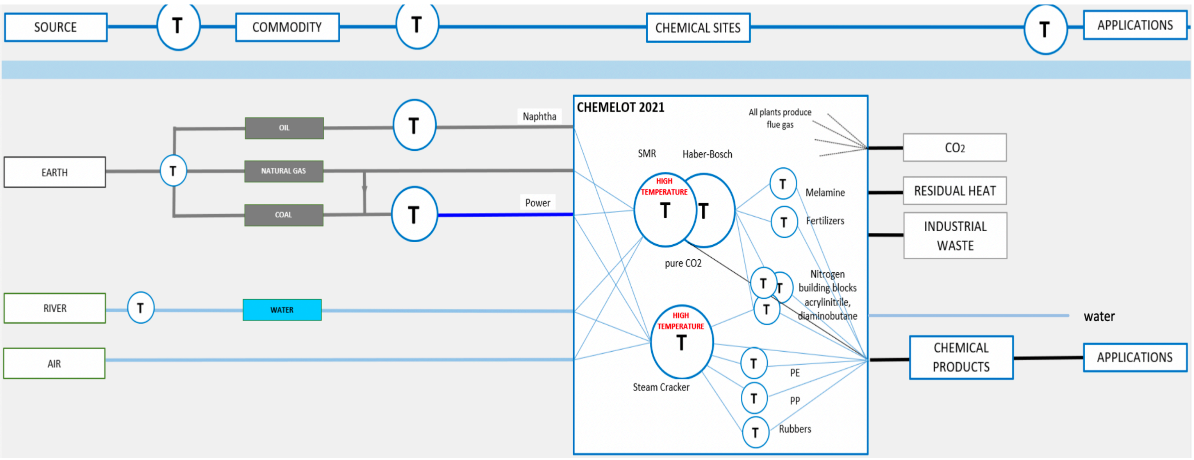


Figure 4.1: Simplified visualisation of current energy and raw material consumption on Chemelot (Source: Brightsite)

Chemelot's primary energy usage mainly concerns naphtha and natural gas (methane) and amounts to more than 200 PJ per year [70]. Approximately 70% hereof ends up in products like plastics and is therefore referred to as non-energetic use. The remaining 30% is used as energetic use of fossil fuels: the combustion of natural gas and cracker methane which fuels the chemical processes. This distribution is different compared to the Dutch energy usage where around 10% is used as non-energetic and 90% is used as energetic use [70]. Chemelot imports natural gas and naphtha via pipelines. These forms of commodities are refined and processed by technologies of third parties outside Chemelot. The plants on Chemelot subsequently use it in their processes and to produce materials. The consumed energy leaves the site as unused heat which means efficiency loss in flue gas or water vapour such as CO_2. The products made are used as feedstock on the Chemelot site or sold to customers.

The processes on Chemelot produce large amounts of emissions. Figure A.2 shows that the emissions arise during the production processes, heating of the processes (fuel burning), power generation, and flaring [70]. The emissions are divided in direct emissions which are produced by the firm, and indirect emissions are a result of activities of the firm but occur at locations not owned by the firm. Moreover, the emissions are divided into 3 scopes, as visualised in Appendix A.3. Scope 1 are direct GHG emissions from on-site combustion such as production in owned chemical processes like combustion from boilers, furnaces, vehicles [57]. Furthermore, because scope 2 emissions actually occur at the electricity generation location, scope 2 emissions are indirect GHG emissions from acquired electricity or electricity that brought otherwise inside the boundaries of the organisation [57]. Lastly, scope 3 encompasses indirect GHG emissions as a result of the firm's activities but happen on locations not owned by the firm [57]. Scope 3 emissions are furthermore split into upstream and downstream activities. Scope 3 upstream activities encompass emissions due to the winning of natural gas (methane), oil winning and refinery, naphtha production. Scope 3 downstream activities include end-of-life emissions, arising from the slow decay of plastics in the environment, the burning of waste, the interaction of fertilisers with soil and microbes producing N_2O, and waste treatment of sold products.

4.2. Desired Situation

The current processes on Chemelot produce large quantities of GHG emissions that are harmful to the global climate. Like other sectors, the chemical industry needs to decarbonise. The Dutch government accepted the Climate Act which legally establishes the target of 49% reduction in 2030 and 95% reduction in 2050 compared to 1990 [44]. To achieve the 2030 goals, Chemelot plans to reduce nitrous oxide emissions, store carbon dioxide, and use energy more efficiently [11]. However, to realise the 2050 goals, Chemelot requires a different approach which exists of two main angles. First, the electrification of processes, for which the demand for green electricity will increase [11]. Second, renewable carbon becomes important, and circularity is one of the ways to achieve that [11]. The transition to sustainable feedstock ensures that carbon-based molecules can still be used. After all, carbon is needed to produce plastics. Due to better design for recyclability and end-of-life treatment of products, the carbon stays within the chain, making it a sustainable process. It is technically possible today to switch from fossil resources to renewable energy for the energy transition and ultimately eliminate the associated GHG emissions. It is also theoretically possible to switch to renewable resources for the products that we produce today. The challenge, however, lies in (1) developing the technologies to commercial scale, (2) the availability of abundant renewable energy and most importantly, (3) the sustainable sourcing of large volumes of renewable carbon [11]. The latter poses the larger challenge since Chemelot needs 4000 kilotonnes of naphtha and one billion cubic meters of natural gas. Chemelot is facing this challenge soon, as Chemelot uses ca. 75% of its fossil fuels as raw material, while the Netherlands uses roughly only 10% for raw materials and 90% for energy. Worldwide, the demand for renewable raw materials will be ever larger. The ultimate reward is that a multitude of GHG emissions can be eliminated and the creation of positions and options for the Dutch chemical industry in the climate transition.

Chemelot presented two strategies for emissions abatement by 2050: making raw materials more sustainable and electrification [23]. When sustainable raw materials enter the plant, sustainable products also leave the plant. The substitution of fossil materials with sustainable materials is, therefore, a priority [23]. However, this poses a challenge for individual firms. Chemelot director Radix adds that Chemelot offers opportunities for new firms to join the site in the challenge to support the transition to sustainable materials [11]. Apart from making raw materials more sustainable, the electrification of processes with renewable energy is required. The sourcing and availability of sustainable energy carriers are crucial for making the site more sustainable.

Parallel to these two strategies, three additional approaches are important for a successful transition: process innovation, hydrogen, and circularity [22]. For making the raw materials sustainable, serious process changes are required. Simultaneously, making the processes more energy efficient is also included. Figure 4.2 presents a possible future energy and raw materials flow on Chemelot [14]. Here, the demand for renewable hydrogen and electricity is visualised. Currently, Chemelot produces large quantities of grey hydrogen (based on fossil fuels) and uses it as feedstock. There are multiple options for sustainable hydrogen. At first, the focus will be on blue hydrogen production in combination with carbon capture and storage (CCS) [22]. Later, additional technologies will be used such as green hydrogen production (based on renewable electricity) or by gasification of household waste [22]. Sustainable alternatives for hydrogen production and electrification are presented later in this chapter.

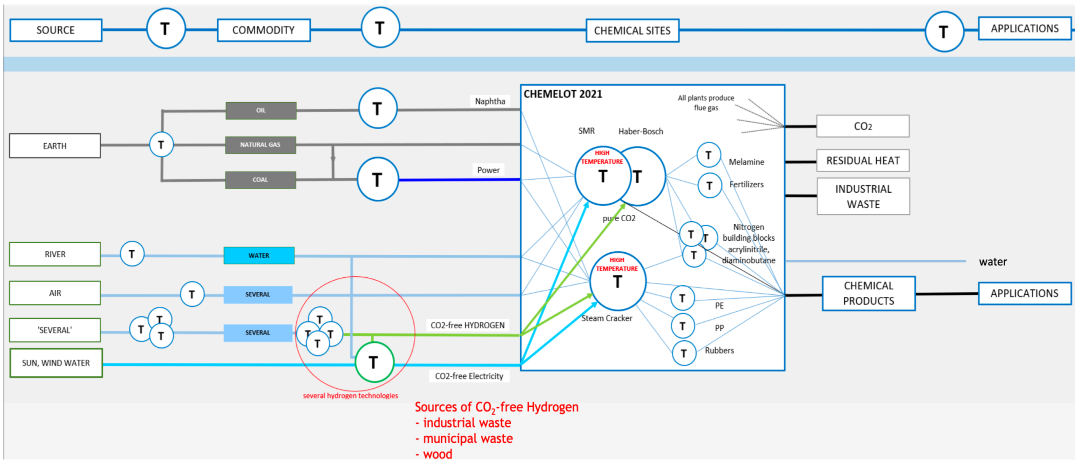


Figure 4.2: Simplified visualisation of future energy and material consumption on Chemelot (Source: Brightsite)

Apart from process efficiency and hydrogen, circularity is crucial for a successful raw material transition. Chemelot will gradually replace the fossil raw materials (naphtha and natural gas) with renewable raw materials [22]. The future circular economy of Chemelot is visualised in Appendix A.4. In addition to a reduction of the scope 1 emissions, Chemelot is also able to contribute in other ways of CO_2 reduction in other sectors and thus to the sustainability of the Netherlands. By supplying heat, Chemelot can contribute to the heating of homes and businesses by meeting the heat demand. In addition, there is a possibility for the supply of CO_2 to greenhouse horticulture and Chemelot can, for example, generate energy by means of manure fermentation. Moreover, greening at Chemelot can reduce CO_2 emissions further down the chain. The latter point is essential and it is important in the long-term to build in the right incentives for this. Apart from a technical or economic problem, circularity is also an important societal issue [22]. It requires a different view of raw materials, products, waste, and logistics processes. In the future, for example, raw materials will sometimes still have to be pre-processed at the Chemelot site or elsewhere and they will not always be supplied via underground pipes, but by trucks or vessels. This requires an intensive dialogue with the society and environment about what circularity and the recycling of waste means in reality.

4.3. The Role of Hydrogen

The hydrogen targets in Europe are ambitious. The Netherlands has also assigned hydrogen an indispensable role for green hydrogen in its government vision [25]. Green hydrogen is a crucial link in the future climate-neutral energy and raw materials supply to achieve the goal of operating CO_2 neutrally in 2050. However, there is no consensus among experts on the vision on the role of hydrogen and hydrogen-powered applications in decarbonising our economy [15], [41]. Some state that green hydrogen has great potential to decarbonise the chemical industry and society [2], [49]. It is a promising alternative for heavy-duty vehicles, industrial processes, and to heat buildings as other applications. While others agree that hydrogen has great potential in the chemical industry, but discard the role of hydrogen as a fuel for transportation due to the inefficiency [4], [12], [31], [42]. But also the application of green hydrogen in the built environment is estimated to be too expensive, uncertain, and less efficient than using electricity. For a number of applications, electricity competes directly with hydrogen [15], therefore resulting in a technology battle for market dominance. Currently, this battle is active for the cracking process on Chemelot. Much remains to be done before there is a mature hydrogen market with sufficient demand and affordable supply. For example, hydrogen infrastructure is required for the supply of sustainable hydrogen to industrial users on Chemelot. In addition to technical, infrastructural and regulatory challenges, the price of sustainable hydrogen is an important factor in balancing supply and demand [22]. Although many national and international studies provide a positive perspective on future price developments, there are currently too many uncertainties for profitable business cases that depend on green hydrogen. The industry requires subsidies to compensate for the unprofitable top margin losses the industry faces when adopting hydrogen innovations.

4.3.1. Ammonia Production Process

Hydrogen has been a crucial building block on Chemelot for the production of ammonia. Currently, hydrogen is produced from natural gas in the reformer, which is visualised in the production of ammonia in Appendix B.1. Hydrogen can play a role in decarbonising this process by stopping the production of hydrogen on-site for ammonia production [53]. This means that the process will exist only of ammonia synthesis, as is visualised in the box in Appendix B.2. Two conditions are required for this alternation in the process namely (1) a purification plant to deliver pure N_2 for the air, and (2) a stable supply of renewable hydrogen. The latter condition poses a challenge since renewable hydrogen will be scarce.

4.3.2. Cracking Process

The role of hydrogen is less forthcoming in the cracking process compared to the ammonia production process. Hydrogen could be used to replace methane as a fuel to heat the cracker [15]. No CO_2 would be emitted, under the assumption that renewable hydrogen is used. However, renewable hydrogen is scarce and will be for the coming years. Moreover, hydrogen has to be produced with electricity in an electrolyser. If one wants to use hydrogen as a fuel, the hydrogen has to be converted using a fuel cell. Although both an electrolyser as well as a fuel cell have efficiency losses, the efficiency loss of using hydrogen as a fuel is greater. This makes using hydrogen as a fuel less suitable and more expensive than electricity. Despite the fact that hydrogen is less suitable for this process, it is still proposed as a viable solution by lobby groups and governments. If hydrogen will dominate, this will have severe consequences for Chemelot as it cannot choose other eco-innovations but has to go along with the market developments. This means that the cracking process will become much more expensive.

4.3.3. Hydrogen Solutions

This section presents hydrogen alternatives for Chemelot, see Figure 4.3. Some of the alternatives are more suitable for import while others are more suitable to be produced on-site. Chemelot's current estimate is that in the future 50% of the total hydrogen requirement can be supplied from local, sustainable production at Chemelot. The rest will have to be supplied from outside the site, for example from Rotterdam [22]. The way of hydrogen production is important including the amounts of CO_2 emitted. The most promising options are presented in the road maps, which visualise the routes and processes from the source till the end station Chemelot. Additionally, the limitations of the alternatives are described. First, the current situation of hydrogen production is presented after which the alternatives are presented.

Current hydrogen production process: Steam Methane Reforming. Today, about 95% of the hydrogen the chemical industry uses is produced with natural gas (SMR without CCS) [30], resulting in GHG emissions of 70 to 100 million tonnes CO_2 yearly in the EU [26]. This type of hydrogen production where CO_2 is emitted is referred to as grey hydrogen. SMR is nowadays the most regular method to produce hydrogen [26]. In this process, natural gas reacts with steam to produce hydrogen and carbon emissions. For Chemelot, this means that their current demand of 200 kt hydrogen emits roughly 2000 kt CO_2 during production [53]. Current benefits of natural gas steam reforming are the existing infrastructure, low costs, and viability [79]. However, the large quantities of carbon dioxides emissions are problematic if Chemelot wants to reach the climate goals. Moreover, the methane often has to be imported from countries that are not always politically stable.

Option 1: SMR/ATR with CCS. Steam methane reforming and autothermal reforming with carbon capture and storage can be promising hydrogen production alternatives in the short-term energy transition [30]. If carbon emissions are captured and stored, then this type of hydrogen is referred to as blue hydrogen [24]. SMR is currently the most affordable and mature large-scale hydrogen production method. Combined with CCS, it can become a feasible alternative in this transition [30]. Autothermal reforming (ATR) is another way of producing hydrogen. First, it produces syngas which exists of hydrogen and carbon monoxide. Then, it splits the syngas into hydrogen and carbon oxides [30]. Both ATR and SMR need to be provided with CCS to remain operable, in case of tight emission regulations [30]. The hydrogen backbone and the CO_2 pipeline are required measures for Chemelot to make CCS and the hydrogen supply viable [22]. Since a large quantity of the produced CO_2 during the ammonia production is of pure quality, CCS would be a relatively low-cost option. An international pipeline enables cost-sharing but could increase the complexity among actors. If such a pipeline will not be installed, the price for CCS for Chemelot will increase because another method of CO_2 transport is required via vessels.

Option 2: Electrolyser Technology. This is a promising method that is still being developed worldwide. An electrolyser splits water molecules into hydrogen and oxygen by using an electrical current [34]. The working principle of an electrolyser is visualised in Appendix D.1. Currently, alkaline electrolysis is a more mature process. While proton exchange membrane (PEM) electrolysis is more efficient and has greater possibilities for future developments [34], it is more expensive as well because it uses noble metals [34]. There are also novel, high potential electrolysis technologies such as Anion Exchange Membrane (AEM) and Solid Oxide, but these are less mature technologies [34]. If electrolysis is used with renewable electricity, it is defined as green hydrogen where no emissions are emitted [24]. That makes electrolysis combined with solar or wind power a suitable innovation to drive decarbonisation in the chemical industry. In areas where CCS is not viable, water electrolysis is likely to be the only low-carbon hydrogen production alternative [34]. Since water is the only feedstock electrolysers use to make hydrogen, the Opex of electrolysis decreases when the costs of renewable power decrease. However, the current forecast is that the electricity costs will not decrease sufficiently and that Capex is still high. Therefore, electrolysis is only economically viable in sun abundant countries. However, hydrogen transportation is costly and energy-intensive. The electrolysis of steam is a more efficient method which, due to low-grade steam available, is suitable for Chemelot [22]. Unfortunately, this technology is not yet ready for commercial use.

Option 3: Pyrolysis. During this thermochemical process, methane is heated but not burned so that it decomposes into the elements hydrogen and carbon [74]. The produced hydrogen is referred to as turquoise hydrogen because it still uses fossil fuels as source [6]. One major benefit is that pyrolysis consumes less energy compared to the traditional SMR process [50]. Compared to other emission-free hydrogen production processes, it requires 20% less electrical energy [5]. The used power should be renewable for this process to be sustainable. Another benefit of this process is that carbon is not combusted, meaning that neither CO or CO_2 is emitted [50]. Instead, the solid carbon can be used as a raw material for additives in steel or graphite, thereby contributing to climate mitigation. Moreover, an appropriate market for solid carbon as a byproduct results in a reduction of the production costs [6]. The thermochemical pyrolysis is an economically feasible approach providing a great potential to become competitive in future industries [50].

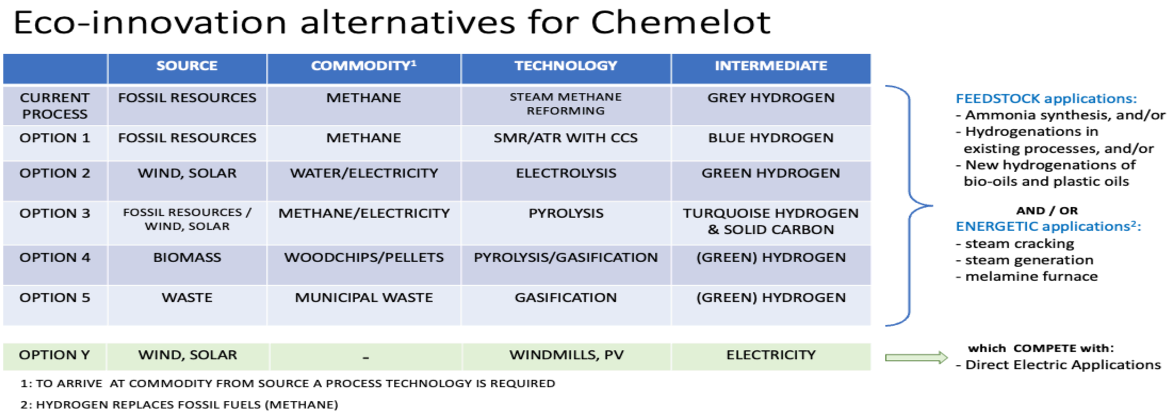
Option 4: Biomass-based thermochemical methods. Currently, the main feedstock used for hydrogen production are hydrocarbons. Nevertheless, the demand for sustainable technologies is becoming inevitable as fossil fuels are finite and GHG emissions are harming climate change. Therefore, the share of biomass is likely to increase in the future and to replace incumbent fossil-fuelled technologies [50]. Biomass is a sustainable energy source that comes from natural materials like wood, grass, crops, industrial residues, animal and municipal waste [6]. Although CO_2 is emitted during hydrogen production with biomass as feedstock, this quantity of CO_2 emission equals the quantity that was absorbed by the plants when they were alive [6]. Biomass can be processed via thermochemical and biological methods to produce hydrogen [50]. Where biological methods are less energy-intensive and hence more sustainable, they provide low yields of hydrogen [50]. Meanwhile, thermochemical methods are faster and provide higher yields of hydrogen, and mainly involve pyrolysis and gasification [50]. A disadvantage, however, is the vast amount of biomass required to fulfil the enormous demand for renewable hydrogen.

Option 5: Gasification of Municipal Waste. There are multiple actors that have an interest in producing hydrogen near Chemelot, partly due to the high degree of integrated plants. Recently, RWE announced the FUREC project which aims at developing a waste-to-hydrogen plant at Chemelot [64]. This plant will process regional municipal waste and convert it to circular and green hydrogen for the chemical sector. In the process of gasification, the municipal waste, which consists of approximately 50% of biomass, is converted into biofuel [72]. Subsequently, the process is similar to biomass gasification [72]. By using municipal waste from households as a commodity, over 200 million m3 of natural gas could be saved every year. This corresponds to a CO_2 reduction of 380 kilotonnes per year [20]. However, the supply of municipal waste has to be guaranteed. Also, upgrading the power grid around Chemelot and the connection to the backbone are paramount for this method to be viable [22].

Future Option: Plasma Technology. Currently, Brightsite researches and develops plasma technology. This technology is able to produce sustainable hydrogen and acetylene from bio-methane using sustainable electricity [22] and is researched for ethylene production as well. This technology creates the possibility to produce polyethylene (PE) and polypropylene (PP) without GHG emissions. Nevertheless, this technology is not a mature technology yet and therefore little concrete information regarding energy consumption, efficiency, and CO_2 abatement is known [22].

4.4. The Role of Electrification

The electrification of processes is a promising method for the industry to achieve CO_2 reduction because it eliminates unavoidable heat losses through flue gasses resulting from fuel burning. It is also much more efficient to perform work compared with steam-driven machinery. This section presents the role of electrification as an alternative to hydrogen-powered options. Possible projects are currently being researched and depend on the technical and economic feasibility. The availability of both transport capacity and sufficient green electricity is an important condition for Chemelot for the actual continuation of large electrification projects. Electricity needs to be generated by wind, solar, hydro, or nuclear power, or other CO_2 free alternatives like waste and biomass. Electricity can be used to generate heat which is required for processes. Partly, this involves existing technologies such as electric boilers



Eco-innovation alternatives for Chemelot

	SOURCE	COMMODITY[1]	TECHNOLOGY	INTERMEDIATE
CURRENT PROCESS	FOSSIL RESOURCES	METHANE	STEAM METHANE REFORMING	GREY HYDROGEN
OPTION 1	FOSSIL RESOURCES	METHANE	SMR/ATR WITH CCS	BLUE HYDROGEN
OPTION 2	WIND, SOLAR	WATER/ELECTRICITY	ELECTROLYSIS	GREEN HYDROGEN
OPTION 3	FOSSIL RESOURCES / WIND, SOLAR	METHANE/ELECTRICITY	PYROLYSIS	TURQUOISE HYDROGEN & SOLID CARBON
OPTION 4	BIOMASS	WOODCHIPS/PELLETS	PYROLYSIS/GASIFICATION	(GREEN) HYDROGEN
OPTION 5	WASTE	MUNICIPAL WASTE	GASIFICATION	(GREEN) HYDROGEN
OPTION Y	WIND, SOLAR	-	WINDMILLS, PV	ELECTRICITY

FEEDSTOCK applications:
- Ammonia synthesis, and/or
- Hydrogenations in existing processes, and/or
- New hydrogenations of bio-oils and plastic oils

AND / OR

ENERGETIC applications[2]:
- steam cracking
- steam generation
- melamine furnace

which COMPETE with:
- Direct Electric Applications

1: TO ARRIVE AT COMMODITY FROM SOURCE A PROCESS TECHNOLOGY IS REQUIRED

2: HYDROGEN REPLACES FOSSIL FUELS (METHANE)

Figure 4.3: Hydrogen and Electricity production alternatives for Chemelot. (Source: altered from Brightsite)

and replacing steam turbines with electric propulsion. Additionally, it concerns new technologies that still need to be developed and require technological up-scaling like the electrification of furnaces and plasma technology [22].

By replacing fossil fuel materials with electricity, processes are decarbonised regarding Scope 1 emissions. Substantial growth in electricity demand is anticipated in every possible scenario. Eventually, the electricity demand of the Chemelot site is estimated to grow from 250 MW in 2020 to 700 - 1700 MW in 2050 [22]. Based on this, it can be concluded that the current transport capacity of the power grid is insufficient and that the grid needs updating. An electricity grid with a higher capacity is not only beneficial and necessary for Chemelot, but also for other plants and firms in the rest of the Netherlands. The power grid, therefore, requires upgrading to a high-voltage grid of 380 kV. However, it is estimated that this upgrade will take 7-10 years [68]. This might cause a threat in realising the climate goals of 2030. Apart from the lead time, upgrading the electricity grid is capital intensive. The process of upgrading the grid is being discussed in collaboration with grid operators, the local government, and the firms.

Another aspect in which Chemelot wants to gain experience is in freely adjustable and flexible power demand and supply. The current factories and processes at Chemelot are designed for continuous process operations and are less suitable for flexible process operations. However, new processes and factories are expected to be designed to respond more flexibly to current developments in the electricity market. Extensive electrification is therefore expected to lead to more flexibility in the electricity demand, as a result of which Chemelot will make a contribution to national and regional grid stability in the future.

4.4.1. Ammonia Production Process

The hydrogen section presented an alternative to decarbonise the ammonia production process by OCI Nitrogen. Electricity can also play a role to make this process more sustainable since yearly 1000 kilotonnes of ammonia are produced [41], [53]. Now, natural gas is used as feedstock and as fuel to heat the steam reformer, as is shown in Appendix B.3. By switching from natural gas to electricity, the reformer can still be heated. Under the assumption the electricity is renewable, no CO_2 is emitted in this heating process.

4.4.2. Cracking Process

Electricity can also be used to make SABIC's cracking process more sustainable [15]. Currently, the furnace is heated by burning methane, which emits CO_2. By replacing methane with electricity to heat the furnace, CO_2 emissions decrease, as is visualised in Appendix C.2. However, electric furnaces are a new technology that has not yet been practised on a large scale and where high investment costs are foreseen. Other parts like compressors and pumps in his process can also be electrified. Naturally, the electricity has to be renewable electricity for the process to be sustainable. Cracking naphtha, however, produces methane among other materials. Therefore, this produced methane has to be processed in a sustainable way to prevent CO_2 emissions. The methane can be used as feedstock in the ammonia production process, or as feedstock in the hydrogen production process via pyrolysis, SMR/ATR with CCS, or via plasma technology. In these processes, CO_2 is not released in the atmosphere.

4.4.3. Electrification Solutions

As mentioned earlier, electrification of processes is inevitable in this energy transition. Therefore, electrification is included in Figure 4.3. There are various strategies in electrification and electricity generation. Chemelot could install a wind turbine park to generate its own power. However, since the firms on Chemelot are production facilities, Chemelot does not have the resources such as capital and place to generate its own electrical power. Chemelot relies on the availability of the national electricity grid because they know that the Netherlands face the energy transition just like Chemelot. However, the hydrogen industry receives more attention from the Dutch government, lobby groups, and other actors, thereby pressuring the society and industry towards hydrogen while leaving electrification aside [28], [40], [80]. Therefore, Chemelot is forced to investigate hydrogen production alternatives, as can be seen in Figure 4.3.

Currently, the electricity on Chemelot is supplied either via the national grid or via its own gas-fuelled heat and power plant (Swentibold). However, the future of this power plant is uncertain and it is unknown how long it will remain in operation in the current setting (baseload operation with a gas turbine). When the plant closes, the demanded electricity needs to be imported entirely from the national power grid. However, the supply of renewable electricity is limited. Although Chemelot generates approximately 3.4 MWh of sustainable electricity annually via solar panels and additional panels are planned, this generation is insufficient for Chemelot's total demand.

Furthermore, replacing electricity with hydrogen is only feasible to a limited extent. The conversion of electricity into heat or hydrogen into heat for the cracking process is for both processes the same and about 95%. The heat generated by hydrogen is in flue gas which consists of water vapour and nitrogen. During this process, approximately 50% is used useful. The rest of this energy is used to produce steam which is used for preheating or other processes on the site, which has an efficiency of 70%. The heat generated by electricity is not in flue gas which means that it can be used entirely. That is why using hydrogen for heating purposes is less efficient than electricity.

Both electricity and hydrogen will probably play a future role on the Chemelot site, though it is not entirely clear how these roles will look like. The roles will differ per application, and since most of the site is integrated, every change has consequences on the processes which makes the energy and raw material transition rather complex.

4.5. Section Summary

This chapter created insight in the possible roles of the eco-innovations electrification and hydrogen, as defined in this research. It started by describing the current situation on Chemelot, and how the ammonia production and cracking process are currently being executed. It concludes that the current processes on Chemelot cause many emissions. Next, it showed the desired situation on Chemelot by explaining what changes are required. Strategies for Chemelot to achieve this are electrification of processes and sustainable raw materials. As the scope of this research is limited to ammonia production and the cracking process, these two processes are analysed to see how hydrogen or electrification can make these more sustainable by limiting emissions. An overview of the eco-innovation alternatives is provided in this chapter. Both electrification and hydrogen are suitable options for making the ammonia production process more sustainable. For the cracking process, electrification seems to be the only viable option since using hydrogen for heating the crackers will be too expensive.

5

Results

This chapter presents the results of the research. The new framework is presented as the first result of this research. Secondly, the results from the BWM analysis are presented. These include the weights of the factors per set and the normalised weights of all factors together. Then, the findings of the interviews are presented. These include the perception of the participants on the climate transition and the technology battle on the Chemelot site.

5.1. Selection of factors

This research presented a clear categorisation of environmental factors and firm-level factors, both which affect the technology battles for dominance [13], [17], [73]. In this research, these factors are referred to as non-technological internal factors and non-technological external factors and are ranked by experts. Additionally, the experts addressed the topic of technological factors. The choice for eco-innovation also depends on technological factors, apart from non-technological factors. Therefore, the set of technological factors is added to the framework to find out how experts think how these factors affect the adoption of eco-innovations. Beneficial of introducing technological factors is that a comparative analysis can be made which may reveal fact-based reasons for the inferiority of certain technology-pushed solutions. Experts state that it is desirable to create insight into which type of factors - technological, non-technological internal, and non-technological external - are most relevant in affecting the adoption of eco-innovations. Therefore, the new framework presented in this thesis is the first result. In total, this section starts with presenting the weights of the category sub-factors. Second, the weights of the category factors are presented. Lastly, all factors are compared with each other by normalising the weights of the factors.

5.2. Technological factors

Experts have ranked the Technological sub-factors. Figure 5.1 shows that the most relevant sub-factors are Capex and Technical feasibility. The results reveal two perspectives used by the participants. On one side, experts state that Capex and Opex can change due to subsidies or CO_2 taxes. If the technology is not feasible or scalable, it will never be successful. Therefore, Technical Feasibility is considered by some to be a prerequisite. On the other side, experts take a more economic perspective by claiming if technology has no potential business case i.e. cannot generate any profits, a firm will not develop such technologies. Factors that are paramount in a successful business case are Capex, Opex, and Efficiency. The consistency ratio of this analysis is 0,06.

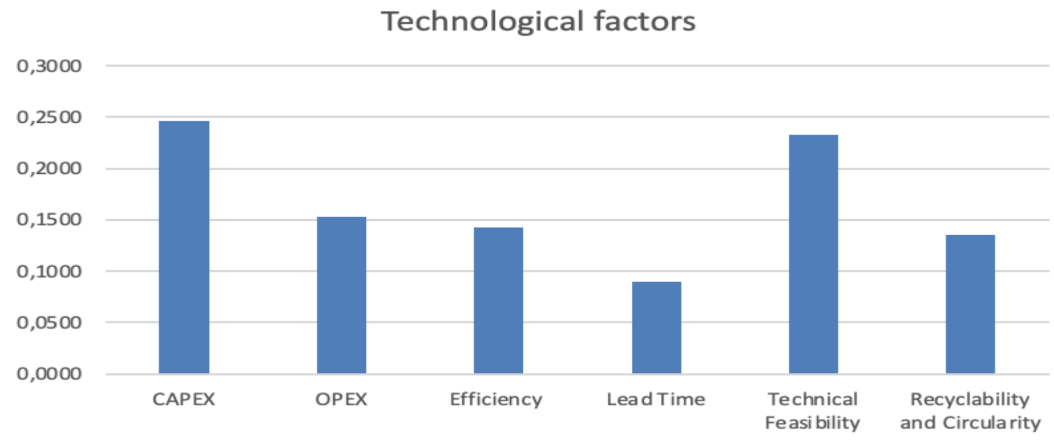


Figure 5.1: BWM Results of the Technological sub-factors

Figure 5.1 shows that Opex, Efficiency, and Recyclability and Circularity are approximately equally important. Chemelot experts barely make a distinction in relevance between these factors after they find either the Capex or Technical Feasibility the most relevant factor. Opex and Efficiency are required for the business case whereas Recyclability and Circularity, as well as Technical Feasibility, are often indicated as prerequisites. Experts state that if an eco-innovation is not recyclable, circular, or feasible, it has little chance of success.

Lastly, the results show that Lead Time is least relevant because it is only important if one wants to take a leading position in a certain market segment or if one wants to avoid a penalty. Moreover, it is claimed that Lead Time is not a construct of technology, but is determined by the business itself. If technology is required for a certain business case, it is argued that lead time is not a limiting factor. In fact, the construction or implementation of technology can often be accelerated.

5.3. Non-technological Internal factors

Experts have ranked the Non-technological Internal factors. In figure 5.2, we can see a clear distinction between factors that state something regarding the Firm's Management, Corporate Culture, and Firm's Strategy. These factors are all closely interrelated. If a firm has a certain strategy, the management is aimed at that realising strategy. The corporate culture can be reshaped to realise the new strategy. The experts state that, as an Internal factor, the firm or working culture should intrinsically be motivated to adopt eco-innovations. If that is missing or not given the right priority, it will not succeed. The firm's management should therefore set a clear strategy and motivate its employees accordingly. The consistency ratio of this analysis is 0,07.

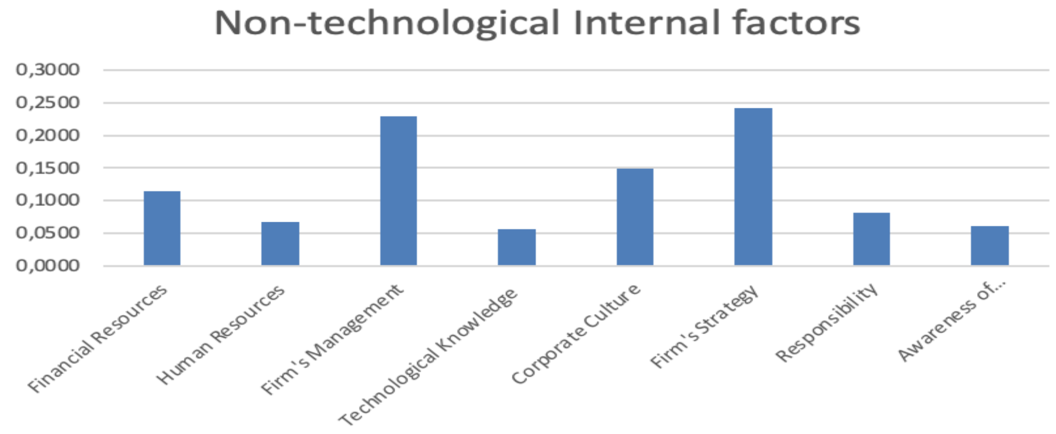


Figure 5.2: BMW Results of Non-technological Internal sub-factors

Furthermore, because the firms located at Chemelot have their headquarters outside the Netherlands or outside the European Union, they have a different view on sustainability, processes, and investment decisions because these firms operate globally. The headquarters are therefore always hesitating whether they should move the plants and processes to another location with fewer regulations. Obviously, this would be disastrous for the Chemelot site and the Dutch economy. It is a difficult task for the Chemelot site users to convince the headquarters of the firm to invest in an eco-innovation.

Among the remaining factors, no clear difference can be perceived. Some believe that firms with a good strategy can get loans easily. Others claim that firms have excellent financial resources themselves and that it is their strategy that is keeping them from withholding to adopt eco-innovations. Technological Knowledge is explained by experts as easy to achieve or acquire, so that is never a limiting factor. Awareness of Environmental Damage is found to be less relevant because firms are already obliged to measure their emissions, and because a firm looks at what the regulations prescribe in terms of how much it can emit. Firms hardly consider this as an intrinsic factor but rather as a rule they must adhere to. The degree to which material is toxic or polluted will always be a matter of debate between regulators and firms. Again, a firm should be intrinsically motivated to aim at zero emissions instead of complying with the law. Therefore, the factors Firm's Management, Firm's Strategy, and Corporate Culture are prevalent.

5.4. Non-technological External factors

Experts have ranked the Non-technological External factors. Figure 5.3 clearly shows that Regulatory Pressure is the most relevant factor when it comes to adopting eco-innovations. Experts say that unless the regulatory bodies take action, in other words, oblige firms to make the change, the adoption of eco-innovations will not succeed. An explanation is that the economy always looks for the cheapest options. Currently, these are always fossil-fuelled alternatives. Therefore, regulations have to be implemented to motivate firms. There is now a movement in the industry that, because of the Regulatory Pressure, that firms are starting to act because targets have been set for 2030 and 2050.

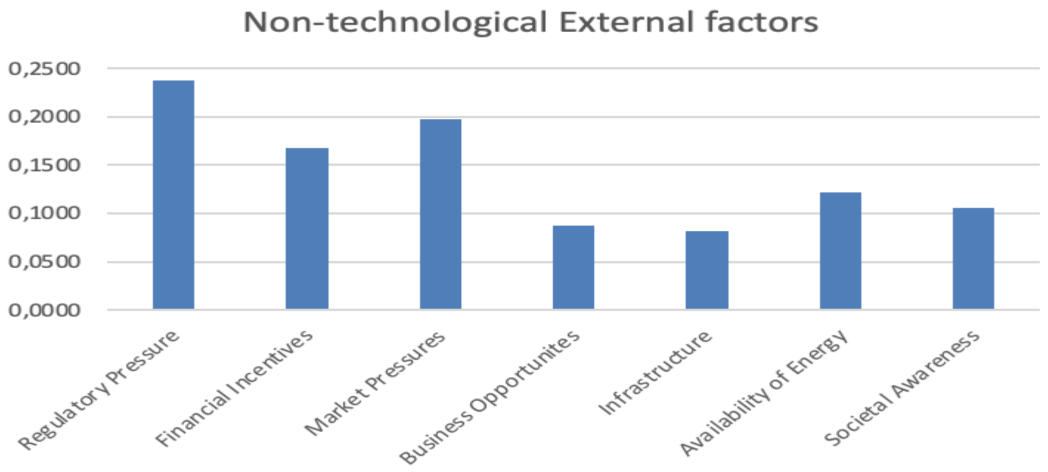


Figure 5.3: BMW Results of the Non-technological External sub-factors

Followed by the Regulatory Pressure are the Financial Incentives. Logically, these are a product of the regulations and indispensable in helping the firms in the transition. Eco-innovations are often not profitable. The difference between the market price and the investment is known as inevitable losses, which can be temporary due to i.e. gradually increasing carbon taxes. Therefore, subsidies are available to liquidate these temporarily inevitable losses. The consistency ratio of this analysis is 0,07.

Experts say that Societal Awareness receives too little attention and should be much more important. Now, the industry undertakes too little action to explain to society and policymakers how they operate or will operate and why that is important for society. In the Netherlands, the chemical industry suffers from a bad reputation and causes a gap between the industry and society. In reality, experts argue, societal awareness should be given more attention as this is an influential factor.

Another problem identified by experts is a lack of customer demand for sustainable products. Even when technologies are available to produce sustainable products, the firms cannot sell these because there is no demand or customers do not want to pay higher prices. This issue is raised by the chemical industry with the policymakers, who should encourage society more to buy sustainable products. For the chemical industry, it is more attractive to invest in eco-innovations when there is demand for sustainable products instead of preventing a penalty for their emissions.

Availability of Energy is about guaranteeing that firms will supply enough renewable energy. If a power plant runs on biomass but not enough biomass can be supplied, that creates a problem. Chemelot faces two concerns: a sufficient supply of energy and a sufficient supply of raw materials. Relatively, Chemelot uses a small amount of energy compared to their raw materials. Naturally, there are technologies and processes to produce sustainable products from recycled materials. However, the sheer amount of feedstock required is what makes this issue so complicated. Experts are convinced that for energy consumption this problem is easier to solve because of wind or solar energy. For Chemelot, the challenge is to receive a sufficient supply of renewable feedstock. Experts add, however, that their estimation is that in the long-term this problem can be solved. This estimation applies also to the factor Infrastructure. If there is the desire to act, these factors will not be problematic. Additionally, experts note that a firm's effort to keep or improve its current processes as much as possible instead of searching for disruptive business opportunities. The chemical industry is a conservative industry that makes it difficult to be innovative.

5.5. Sets of factors

The experts have ranked the sets of factors i.e. the Technological, Non-technological Internal, and Non-technological External factors to determine which set of factors they consider most relevant in affecting the eco-innovation adoption. It is important to note that these factors do not consist of the sub-factors, but rather explain the degree of relevance in the total dynamics of the climate transition on Chemelot which exists of Technological, Internal, and External factors. Whereas in previous rankings the sub-factors are analysed, this analysis takes place at the meta-level. Figure 5.4 clearly indicates that experts convincingly agree upon the fact that the External factors have the largest impact in affecting the adoption of eco-innovations. They believe that technology already exists, or they are confident that technological alternatives will be available when we need them. External factors play the most important role in the climate transition and thus the adoption of eco-innovations. These factors cause firms to switch to a more sustainable way of working or to move the production to other parts of the world, primarily due to regulatory pressure. Internal factors play a less important role. This represents the intrinsic motivation of a firm with regard to the climate transition. Currently, this motivation is not always aligned or is lacking. If this internal pressure is lacking, pressure can be exerted via External factors. This phenomenon is confirmed by the experts. Interestingly, there is no significant difference in relevance between Technological and Internal factors. The consistency ratio of this analysis is 0,04.

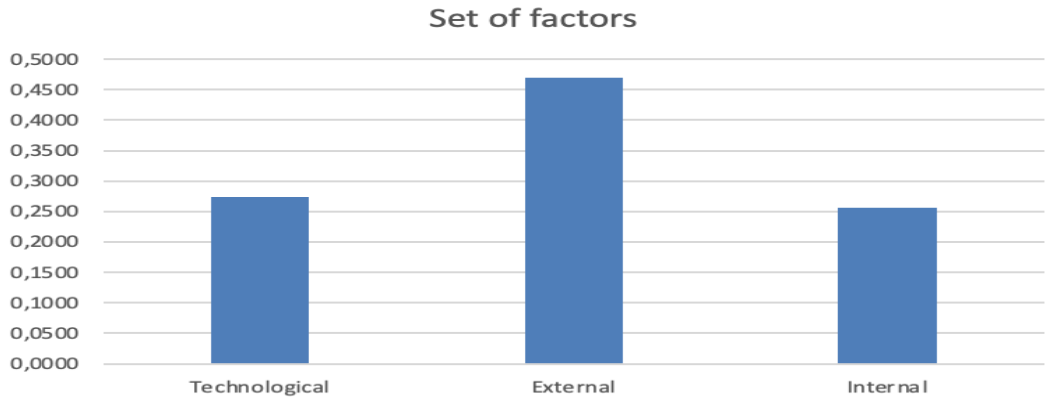


Figure 5.4: BWM Results of main Sets of Factors

5.6. Comparing the Results

This section presents the results of the normalised weights. Since the sub-factors only explain the relevance within the specific factors, these weights are normalised with the weights of the set of factors found in section 5.5. This creates the possibility to compare the factors with each other. Figure 6.1 shows the normalised weights of the factors ranked from most relevant to least relevant. We see that the weights of the first three factors combined is about 28% and are all External factors. Moreover, 50% of the weights are determined by 7 sub-factors out of the total 21 sub-factors, in which all three factors are represented.

EXT	Regulatory Pressure	0,112
EXT	Market pressure	0,093
EXT	Financial Incentives	0,079
TECH	Capex	0,068
TECH	Technical Feasibility	0,064
INT	Firm's Strategy	0,062
INT	Firm's Management	0,059
EXT	Availability of Energy	0,058
EXT	Societal Awareness	0,050
TECH	Opex	0,042
EXT	Business Opportunity	0,041
TECH	Efficiency	0,039
EXT	Infrastructure	0,038
INT	Corporate Culture	0,038
TECH	Recyclability	0,037
INT	Financial Resources	0,029
TECH	Lead time	0,025
INT	Responsibility	0,021
INT	Human Resources	0,017
INT	Awareness of Environm	0,016
INT	Technological Knowled	0,015

Figure 5.5: Normalised weights of the factors

5.7. Results of Interviews

The interviews consist of two parts, the BWM and questions to gather additional information on the technology battle. Although the BWM ranking provides numerical insight, the motivation behind this ranking is more important as it describes the participants' perceptions of the climate transition, the technology battle and the ranking of the factors. This section shows the answers to the questions from the interview.

How would you define a 'successful' energy & raw material transition?

This question aims at finding out if experts share their views on how to achieve the goals of becoming one of the most sustainable chemical sites in Europe. All experts unanimously state that a successful energy and raw material transition starts with reducing environmental impact, and more specifically, reducing CO_2 emissions. Chemelot already has the ambition to be climate neutral in 2050. If we are talking about success, experts state, it would be a great step forwards if all the energy supplied in the Netherlands would be CO_2 free. Living up to the Paris Climate Agreement, or to possible new agreements, is also mentioned as a driver for reducing environmental damage.

Interestingly, after mentioning the unanimous goal of reducing emissions, experts substantiate how to achieve this. Here, experts refer to the system as a whole where the system stands for the sum of scope 1, 2, and 3 emission reduction of greenhouse gasses in CO_2 equivalents in the chemical industry, generated by the use of fossil raw materials. It is not necessarily the urge to reduce emissions on Chemelot but within the system. In fact, if emissions decrease in the system but increase on Chemelot, this could also be satisfying. It is stressed that the focus should not only be on reducing scope 1 emissions, but also on reducing scope 3 emissions. Reducing emissions in the system is by experts mentioned as the ultimate goal of success. Since this is not limited to solely energy as a fuel, a strong need to improve recycling and circularity is also seen to reduce emissions in the raw materials. An expert specified substituting the incumbent with sustainable technologies, specifically the electrification of processes. Without electrification and CO_2-free electricity, the expert stresses, it is impossible to achieve the environmental goals. The policy regarding emission reduction does not help.

Another factor that indicates a successful transition often mentioned by experts, is maintaining economic benefit. One can simply reduce impact by closing the Chemelot site. This would have a detrimental effect on the welfare in The Netherlands, and more specifically, in the area of Chemelot since thousands of jobs, directly and indirectly, rely on the economic activity in the area. Currently, Chemelot is growing which is beneficial for Chemelot and the region. Via this way, it aims at attracting new firms and start-ups to increase economic activity and staying competitive. Maintaining this economic growth is paramount and should not be affected by achieving the climate goals. Moreover, closing plants or the entire site would also not be beneficial for the environment at all. Since the worldwide demand for products would not decrease, the plants would open elsewhere with fewer environmental laws. As a consequence, the efficient and relative clean processes on Chemelot would close and emissions would just be emitted elsewhere in the world. Keeping the plants and processes here is paramount, but possibly with completely new substituting processes or technologies. It is about taking the step of supplying Chemelot with renewable energy and raw materials without an economic dip. Generally, a successful transition is defined as reducing the environmental impact of greenhouse gasses and emissions while simultaneously maintaining employment, innovation, economic welfare, and making new products that add value to society.

What barriers does Chemelot face to achieve its sustainability goals?

A major barrier is a cross-sectoral collaboration among actors. First, the government has to take well-thought actions and create good policies. They rely, however, on information that comes from the chemical industry, the network operators, and society. All actors involved should cooperate but this is happening insufficiently. Current policies are wrongly aligned for Chemelot. Serious progress has been made with initiatives like the Paris Climate agreement, but also on a national level with the Cluster Energy Strategy (CES) and the Meerjaren Infrastructuurprogramma Energie Klimaatakkoord (MIEK). These initiatives create insight among the actors to structure the process that should lead to an effective, efficient, and timely available infrastructure. Here, we see improvement in information sharing with the governments, clusters, and network operators. However, the government should do a better job in taking the lead. In addition to this point, which addresses cross-sectoral collaboration, are other actors that help create a chain. It is difficult to align actors like the agriculture, waste recycling plans, or power plants with the chemical industry to for example supply the chemical industry with renewable raw materials. These actors face internal barriers like financial and process-related barriers to producing renewable raw materials. In turn, for the chemical industry, the quantities they produce are negligible. Therefore, there are large barriers to overcome in forming good supply chains and aligning the actors.

Another barrier is the availability of renewable energy and raw materials. Chemelot uses huge amounts of naphtha as raw material and natural gas as both raw material and energy source. In the future, Chemelot will need lots of renewable electricity. However, Chemelot is not going to generate that, since it does not have the space or the resources for it. The supply hereof, and the infrastructural issues are challenges to be solved. However, the raw materials transition is relatively much more important because the raw materials and energy transition at Chemelot are intertwined. Almost all of the products we use on a daily basis like the ink in our pen, coating of wires, plastic cases of our computers and telephones, packaging etc. is made from oil. If we no longer want to use any fossil raw materials, which is something else compared to we want no more CO_2 emissions, these raw materials have to be replaced with alternatives. These alternatives are technically available, but the industry requires enormous quantities of these renewable alternative feedstock. So the sourcing of these sustainable raw materials is an immense challenge, not only for Chemelot but also for the entire industry. Simultaneously, the policy-makers and governments focus on renewable energy rather than renewable raw materials. This is not wrong, but for Chemelot the energy usage is only responsible for a fraction of the emissions. The emissions caused by the raw materials is way greater. The policy is not focused enough on the raw materials, which for the chemical industry is of great importance to reduce emissions.

In addition to the previous barrier, policy, in general, is also perceived as a barrier. The current national and European policy does not encourage circularity, there are no incentives for operating circular. There are large funds available for different projects, but it is incredibly difficult for governments to find their way in creating helpful incentives. The governments mainly stimulate the fuel energy transition and have proper instruments like subsidies to stimulate this. In the chemical industry, however, scope 3 emissions and raw materials are way more important and until now, there was no attention for this. The industry has eventually managed to convince the government of this issue, and it seems that awareness is created. However, there is still no concrete policy or plan. Apart from subsidies, other incentives are required as well. Subsidies alone will not be sufficient.

Furthermore, the high degree of integration of firms forms a barrier. Because the processes are so integrated and a firm decides to take action to become more sustainable, this means that it has - often disadvantageous - consequences for the other firm that relies on the process. Therefore, this action is cancelled. Because of the linkages between plants and processes, the actions towards sustainability are held back. Because there are so many diverse site users with different parent companies, which are dependent on each other, this high degree of integration on Chemelot creates a huge competitive advantage that no one wants to lose. For a successful transition, these site users, and more specifically the parent firms, should cooperate with each other. In reality, however, this is difficult due to the different interests of the firms.

A barrier that experts foresee is that not all companies will be able to go along with their mother companies or want to go along with the climate transition. So a barrier is that the interest that Chemelot wants to achieve is not in line with the interest of the parent company, so there is no financial space and motivation to do that.

Another concern is the increasing societal pressure on the chemical industry. Society has little understanding and sees a dirty and possibly hazardous site. The chemical industry needs to work on its appearance and educate the residents about the risks. Society has also little awareness of the employment opportunities a chemical site offers. Closing Chemelot would be disastrous for the area. Also, the municipalities are taking some unwise decisions like permitting the construction of a hotel within 500 meters of Chemelot. There should be a joint vision, preferably one institution that handles issues like these instead of separate municipalities. Sometimes, governors from local municipalities think naive and tend to copy policies that work in other municipalities because they were successful. Chemelot is a unique site that requires tailored policies and decisions. One can only achieve this by discarding small-scale governance and giving the responsibility to a national institution that can run Chemelot. Also, there should be groups with local governors, Chemelot spokespersons, and residents where they can discuss developments in the region. They can create a better understanding among all the parties involved. Residents can stress their perceptions and worries. In turn, Chemelot can explain all the processes on Chemelot and its risks and dangers. In the past, everyone in the region was very proud of mines, which were originally at the Chemelot site. It provided employment to many people, which meant that something was accepted by the residents if something happened. It seems that society has lost this acceptance and think of the chemical site as a bad and dirty site and that it should change or be moved. That while people have every need for all products which come from Chemelot. For Chemelot lies the challenge to build that connection again with society. The local governments should be aware of this. Moreover, experts point out that Chemelot should have a larger and more successful lobby, both in the region and in The Hague. Lobbying from Chemelot should take place in all kinds of areas. Experts conclude that the information streams are not sufficient enough to inform the governments what Chemelot needs for the transition.

Furthermore, there is a huge valley of death, a market failure. One might think if we collectively want to address climate change, that corporate entrepreneurship would arise. However, this is not happening because the industry suffers from fossil efficiency. Oil and gas technologies are so efficient and cheap that alternatives are way too expensive. In the European Union, we created an ETS system that charges the emissions of CO_2. However, if a firm is faced with an investment decision for new technology and needs a loan, banks are not very willing to grant that loan due to the risks, unfavourable business cases, and difficult payback times, even with rising CO_2 prices. The market, therefore, fails to provide us with sustainable technologies because the markets always look for the most (cost)efficient alternatives which are still gas and oil-powered technologies. Large projects are subsidised or receive favourable loans when the government gives guarantees. Firms are reluctant to start projects like Plastic Energy by SABIC. This project is not profitable but is still continued due to pressures to invest strategically. Financially, it is not feasible, especially without incentives like subsidies, for sustainable technologies to become successful. This barrier is also seen as a vicious barrier. Firms are investing in their current assets to make these more sustainable and less emitting. This means that firms need the investment to be profitable, which means that the assets and investment need to operate for several years. This increases the barrier to investing in disruptive innovations because a firm would need to depreciate its assets. Simultaneously, investing in current assets making these more sustainable is often relatively cheap, and 'quick fixes' to reduce emissions. For firms, this dilemma is difficult to deal with and means that investments for disruptive innovation stay behind.

The last barrier that completes this list, is the infrastructural combined with financial barriers. Infrastructural issues are already mentioned previously, but they are also self-contained barriers. If one looks at even for partial electrification at Chemelot i.e. electrifying one of the two naphtha crackers, the electricity demand is so enormous which means that the current power connections to the site do not have sufficient capacity for this supply. Therefore, additional infrastructural electricity capacity would have to be installed, which is a complex project that is costly and takes several years. The question here arises who is going to bear the costs? Similarly, for hydrogen to be economically feasible, most likely it should be delivered from a faraway source where electricity is cheap, like Spain or North Africa by pipelines or imported by vessels. However, many experts question the attractiveness of this way of hydrogen to reduce CO_2 emissions due to the complex situations and costly operations. So, either way, one has infrastructural issues for these two options.

What opportunities does Chemelot have to achieve its sustainability goals?

The first significant opportunity for Chemelot is the high degree of integration of plants and processes. Chemelot offers a very good platform to introduce novel technologies with many by-products. An industrial site like Chemelot can use these by-products which means that one can achieve many synergies. This is hardly possible with a stand-alone plant. Therefore, it is attractive for start-ups and scale-ups to a position at Chemelot. In turn, Chemelot benefits because start-ups are likely to add to becoming more sustainable. Chemelot has the opportunity to attract start-ups that enable disruptive innovations, something which is quite difficult in the incumbent dynamics of business operations. Instead of plants leaving Chemelot, the site grows, which is also beneficial for the local area because it offers job employment. Therefore, Chemelot invests in educating people to ensure that they will be employed directly or indirectly in the future. The opportunities also have to do with the history of the site. The whole Chemelot complex was invented by the people who worked here. The firms on Chemelot hold numerous patents on these types of factories and these types of processes all over the world. The skilled experts on Chemelot are very capable of developing new processes and designing these on a large scale. Because of Chemelot's structure, nature, and thinking of Chemelot as an entire system is a great strength to become more sustainable in the future.

Another great opportunity for Chemelot is the existence of Brightlands Chemelot Campus, an innovation and R&D facility for material and process technology. The experts at Brightlands, but also at Chemelot in general, are very skilled and knowledgeable. As mentioned in the previous opportunity, the firms at Chemelot hold many patents and are very experienced in the process technology, many of which are unique for Chemelot. This powerful connection ensures many novel activities and technologies, which in turn causes firms to choose Chemelot as a location to settle. Also, Chemelot offers this experience and skills when a new actor wants to place a pilot plant to research processes. The combination of scale efficiency, knowledge, and experience makes Chemelot a suitable location. Besides, Chemelot is one of the few places where the heavy (chemical) industry may take place, so this fact should therefore be utilised. Having a research facility, and a private fire brigade makes Chemelot an attractive location.

How do you see the battle between hydrogen and electrification evolve on Chemelot?

This research has established that the two most potential alternatives for decarbonising the chemical industry are electrification of processes and hydrogen-powered technologies. Currently, hydrogen is already produced on-site because it is used as feedstock for ammonia production. This hydrogen is made with natural gas (grey hydrogen) and emits large quantities of CO_2. Green hydrogen is desirable to reduce emissions. In the coming years, hydrogen production will remain on-site, only the CO_2 will be captured and stored. Firms have to depreciate assets gradually, and therefore current production methods will be exploited for several years. Green hydrogen production is possible with for example electrolysers. Although the electrolyser is a no-regret technology, Chemelot does not have the resources and the space on site to exploit an electrolyser.

Chemelot could import green hydrogen, but there are many uncertainties with regard to when this is available, the quantity, the costs, and the transportation method. Later, hydrogen might be produced with biomass and waste recycling. Hydrogen import is also an option, but transporting hydrogen via vessels or pipelines will be expensive, which remains a very large uncertainty. Hydrogen might be converted into either methanol or ammonia, two substances that are much easier to transport. Although stakeholders in the gas industry are positive regarding hydrogen, which is logical due to their bias towards gas products, there are barely subsidies available for this technology because it is still too expensive. Also, the fact that hydrogen is often mentioned in the plans of political parties, concrete plans are missing. Firms are more likely to opt for alternatives that they can test for example in pilot plants and find how to cut costs before applying it on a larger scale. The enthusiasm for hydrogen is perhaps correct for the long run, but in the short term technologies like electrification and CCS are more viable. Many people are hyped regarding hydrogen and think it is the solution to many problems. Until they do some calculations and find out that it will not be feasible anytime soon. Using hydrogen in transportation or heating applications is simply unwise.

The battle will mostly evolve on a national level rather than on Chemelot. Each application should be investigated to find the best option - either renewable electricity or renewable hydrogen. Due to the losses, it is not favourable to use renewable electricity to produce renewable hydrogen. One could only do this efficiently when there is a surplus of renewable energy. This is not happening anytime soon. It is more efficient to directly use the electricity for many applications, for example in cars or heating the built environment. Using renewable electricity to produce hydrogen, to use this in for example transport, is senseless due to the efficiency losses compared with the direct use of electricity in battery cars. The business case for hydrogen remains uncertain and unclear, probably for several years. For now, hydrogen is perceived as a long-term solution due to the many barriers it still faces, one of which is the large costs of green hydrogen. However, the expectation, in the long run, is that renewable hydrogen will be produced in places where electricity is very cheap, such as Africa or the Middle East. Moreover, expectations are that the hydrogen could be converted into ammonia or methanol, substances that are better transportable.

CO_2-free electricity, on the other hand, has more potential for short-term decarbonising the chemical industry. Especially in energetic applications, electricity is more efficient than hydrogen, although this depends on the availability of electricity. As mentioned previously, it is often not favourable to produce hydrogen to use it in an energetic application due to efficiency losses if the direct application of electricity could be possible as well. Furthermore, many off-shore windmills are installed, which indicate that this technology is further developed than hydrogen. Moreover, the plans for large-scale wind park deployment is broadly mentioned in the plans of political parties. The wind parks are developing at a rapid pace. Some of these projects require subsidies, but there are already parks that do not require subsidies. For SABIC, electrification of the crackers is an attractive solution that receives more attention. Therefore, SABIC is researching electric crackers. Electrification is becoming increasingly important and is an indispensable technology. The current crackers have to be electrified to prevent fully depreciation in a short period of time. Also, it is impossible to do without these crackers because the demand has to be fulfilled. If the crackers in Geleen cannot meet the demand then somewhere else in the world the production is increased. The climate does not benefit from this. Although electrification is the most potential eco-innovation, there is uncertainty regarding the costs of renewable electricity and its availability.

A disruptive form of electrification is plasma technology. The maximum potential electricity has to offer can be used with this technology, and very high temperatures can be achieved. This disruptive technology can help the entire transition because practically all the solutions are based on fossil fuels. All the technologies which aim at making the current way of production more efficient, are add-ons or bypasses to reduce some emissions. Disruptive technologies however are indispensable in this transition because of their potential to keep carbon within the cycle. For example, plasma can convert the future methane (which is then considered to be waste) of an electric cracker into hydrogen and new carbon building blocks for plastics [20]. Unfortunately, plasma technology still requires several years of development. However, disruptive technologies are the most potential ones in the ultimate technology battle. Firms typically tend to be very reluctant to implement new technologies and certainly to be the first ones to experiment. It is great for publicity but in reality, nobody wants to experiment too much because of the possible consequences and the risks involved. A firm may lose large sums of money invested or may be too late to select other innovations because they were occupied with developing their own.

In addition, the site users cannot switch immediately to disruptive eco-innovations. They have no other option than to exploit the current assets as long as possible. The investments are so immense, that it is simply impossible to depreciate the current assets. This is an order from the parent firms. Therefore, sites will rather make incremental improvements than going for disruptive changes. This makes disruptive technologies a lower priority. They do know, however, that they have to research these disruptive technologies because the processes will change in the future. A trend is that these disruptive technologies are developed by universities or start-ups which are supported by venture capital funds or philanthropists. They have the freedom to develop a technology in a protected environment because they are not directly competing with incumbents on international markets. They do so when they are fully developed. Disruptive technologies, in addition, will also not be available and meet the immense demand required. Disruptive technology is not scalable enough. It will need protection in a niche of some sort where this technology needs to prove itself.

Furthermore, it is not expected that Chemelot can influence the technology battle significantly. Since the site users do not develop such technologies, they are largely dependent on which technologies the market offers. Chemelot is a collection of firms located on a site named Chemelot. Chemelot has a legal structure with only limited property and capital. Therefore, Chemelot cannot choose eco-innovations. The firms on Chemelot however, can select eco-innovations. The phrase of the chicken and the egg is often heard. The firms base their decisions for eco-innovations on the availability of energy and infrastructure. They expect the network operators to supply the energy demand the firms need. Currently, expanding the infrastructure is behind because the network operators demand a guarantee that a firm will consume a certain amount. The firms, in turn, cannot give these guarantees due to uncertainties when the infrastructure is ready, and what the costs of the energy will be. Furthermore, the firms will always base their decision at a certain time when it is required and most desirable for themselves. Synergies and scale advantages are taken into account, but they cannot make a collective decision for eco-innovations. What adds to the complexity is that the decisions are seldom taken at the same moment. For example, OCI needs to investigate whether to opt for green hydrogen or to proceed with hydrogen production on-site and to capture and store the CO_2. This decision is based on whether the infrastructure is available at the time being, and if enough green hydrogen can be supplied. Otherwise, OCI will exploit the option of CCS. When the decision is made, they will ideally stick to this method for as long as desirable. Other plants on Chemelot have no vote in this decision. The same applies the other way around. If SABIC decides to electrify their crackers, a plan that they might conduct over 10 years, then OCI already had to make their decision for green hydrogen or CCS. Also, OCI has no say in which choice SABIC eventually will make. A reason for this is technology readiness. CCS is already technologically possible while the electrification of crackers is not yet 100% developed. Additionally, the CO_2 tax caused by the ETS plays a role. This determines the costs a firm has to pay if they proceed with the current processes. This CO_2 tax price can be a decisive factor. Lastly, the firm's commitment plays a role. If a firm is very committed to achieving sustainability goals, it might take a decision earlier compared to other firms. From this perspective that plants base their decisions separately, no synergies can be achieved.

Conclusively, the variety of plants, processes, and products is extensive. For all applications, a different and most suitable source of energy will be used. Hydrogen and electrification are interchangeable in the energy transition, but these are not interchangeable for Chemelot. On Chemelot, both hydrogen and electrification will be necessary. Hydrogen and electricity are both part of the solutions for the successes at Chemelot. In the future, green hydrogen will most likely be used as feedstock, not as energy. Applying electricity directly is always better than using hydrogen made with electricity.

It is more efficient to use hydrogen as feedstock to make products than to transport power or to burn it to generate heat. Until then, the CO_2 which is emitted during the current hydrogen production, will be captured and stored. Renewable electricity has more potential in energetic applications, such as electrifying the crackers. It will be highly application dependent whether hydrogen or electricity will be the better solution. Multiple scenarios are continuously developed with regard to costs, timing, availability, resources, feasibility, investments. Hence, it is not a technology battle between electrification and hydrogen, but rather between eco-innovations and incumbent technologies.

5.8. Section Summary

This section presented the results of this research. It started by showing the new aspects of the developed framework. Subsequently, the results of the BWM analysis were visualised, categorised per set of factors. Moreover, the normalised results of the rankings were shown to compare the results. Lastly, this section contains the participants' responses to the questions asked during the interviews. These responses show the motivation of the participants' rankings of the sub-factors and factors.

6

Conclusion and Discussion

This section starts by answering the research questions asked in this study and presenting the conclusions. Subsequently, the results from this study are interpreted and discussed in relation to the literature. Furthermore, the contribution of this study to the literature is presented, including the implications.

6.1. Conclusions

The goal of this study is to establish how factors affect the adoption of eco-innovations and thereby substituting the incumbent technologies at the Chemelot site. Since the Paris Climate Agreement in 2015, regulations require firms to reduce their emissions. As one of the largest polluters in the Netherlands, Chemelot faces a difficult and complex task to make its processes and products more sustainable. Naturally, multiple factors play a role in complex decision-making processes such as those currently facing the chemical industry. Therefore, this study creates insight by posing the main research question: *What drives the technology battle for eco-innovation adoption on Chemelot?* To answer this question, it is split up into sub-questions so that a more comprehensive answer can be given. The answers to the sub-questions provide the information to answer the main research question. The first sub-question is:

SQ1: What are the eco-innovation alternatives for Chemelot?

There are many eco-innovations that help decarbonise chemical plants. A temporary solution is carbon capture and storage where CO_2 is captured and stored in an empty gas field. In this way, no CO_2 is emitted into the air. Other examples of renewables are solar power and biogas. However, this study focuses on electrification and hydrogen-powered technologies as these are the technologies with the greatest potential for large-scale applications. The amount of energy and raw materials needed on Chemelot are enormous, so not all eco-innovations are suitable. In addition, electrification and direct combustion with hydrogen to reach high temperatures are alternative solutions on Chemelot. Moreover, hydrogen is needed as feedstock and is already produced on site. Replacing this with renewable hydrogen is, therefore, a suitable way to decarbonise the process of fertiliser production. Electrification, including CO_2-free electricity, is considered a potential eco-innovation due to better efficiencies and especially on short-term, a cheaper solution. This is because energy losses during the initial conversion of electricity to hydrogen are avoided and because no flue gases are released when generating heat from electricity.

SQ2: Which factors affect eco-innovation adoption?

To establish a framework of factors that affect eco-innovation adoption, the literature has been reviewed. The literature distinguishes firm-level factors from environmental factors. In this study, these are referred to as non-technological internal factors and non-technological external factors. While most factors are found in the literature, the factors Infrastructure and Social Acceptance were added after discussions with Chemelot experts because of the importance of the possible role these factors have

	Technological factors	**Internal factors**	**External factors**	**Sets of factors**
1	Capex	Firm's Strategy	Regulatory Pressure	External factors
2	Technical Feasibility	Firm's Management	Market Pressure	Technological factors
3	Opex	Corporate Culture	Financial Incentives	Internal factors
4	Efficiency of Technology	Financial Resources	Availability of Energy	
5	Recyclability and Circularity	Responsibility	Societal Awareness	
6	Lead Time	Human Resources	Business Opportunities	
7		Awareness of Environmental Damage	Infrastructure	
8		Technological Knowledge		

Table 6.1: The factors from the framework ranked from most relevant to least relevant

in the adoption of eco-innovations. Additionally, there is the need to compare these factors with factors inherent to eco-innovations, referred to as technological factors. This addition is desirable to find whether the type of eco-innovation plays a role in the decision-making. Ultimately, this study presents the following framework:

Technological factors: Capex, Opex, Efficiency of Technology, Lead time, Technical Feasibility, Recyclability and Circularity. **Non-Technological Internal factors**: Financial Resources, Resources, Firm's Management, Technological Knowledge, Corporate Culture, Firm's Strategy, Responsibility, Awareness of Environmental Damage. **Non-Technological External factors**: Regulatory Pressure, Financial Incentives, Market Pressures, Business Opportunities, Infrastructure, Availability of Energy, Societal Awareness.

SQ3: What is the relevance of the factors in the technology battle between the eco-innovations on Chemelot?

To validate the factors from the framework and to find their relevance, we have interviewed experts and requested them to rank these factors according to their own perception of factor relevance. The Best-Worst Method is used as a tool to research the factor relevance. In total, 14 experts have been interviewed from categories such as managers, (chemical) engineers, consultants, and researchers. The experts ranked the factors that they thought were most relevant to the adoption of eco-innovation. The ranking of the factors from the framework is presented in table 6.1 within their own category. The normalised weights of all the factors combined are shown in figure 6.1.

SQ4: How does the technology battle between eco-innovations evolve on Chemelot?

This research has found that the technology battle for dominance is fought between the incumbent technologies and the eco-innovations rather than between electrification and hydrogen. Chemelot needs both electricity and hydrogen for their processes. While hydrogen and electricity are interchangeable in the energy transition, they are not interchangeable on Chemelot. So, both hydrogen and electricity will have a dominant role but that will depend on the type of application. For energetic purposes, it is likely that electricity will be selected due to efficiency and costs reasons. For some other applications, however, renewable hydrogen will be a suitable option. However, there is one technology battle active namely the technology battle between hydrogen and electricity for heat generation. There is a technology push of hydrogen by lobby groups for heat generation applications. An application in which electricity is more efficient. Yet, Chemelot is largely dependent on market pressures as it cannot choose the eco-innovation itself. If hydrogen will be selected for this application and the infrastructure will be installed, Chemelot is likely to use this process as well. It seems that the hydrogen lobby has the upper hand while the general public interest is insufficiently heard in the discussion. Apart from this, the technology battle seems to be fought between eco-innovations and the incumbent technologies. Some site users are still investing in the current fossil-driven technologies, while this is expensive and the emission gains are limited. This, in turn, raises the barrier for the site users to adopt eco-innovations because their old investment is not paid back yet.

EXT	Regulatory Pressure	0,112
EXT	Market pressure	0,093
EXT	Financial Incentives	0,079
TECH	Capex	0,068
TECH	Technical Feasibility	0,064
INT	Firm's Strategy	0,062
INT	Firm's Management	0,059
EXT	Availability of Energy	0,058
EXT	Societal Awareness	0,050
TECH	Opex	0,042
EXT	Business Opportunity	0,041
TECH	Efficiency	0,039
EXT	Infrastructure	0,038
INT	Corporate Culture	0,038
TECH	Recyclability	0,037
INT	Financial Resources	0,029
TECH	Lead time	0,025
INT	Responsibility	0,021
INT	Human Resources	0,017
INT	Awareness of Environm	0,016
INT	Technological Knowled	0,015

Figure 6.1: Normalised weights of the factors

With the sub-questions answered, we can now answer the main research question: *What drives the technology battle for eco-innovation adoption on Chemelot?*

The conclusion on the technology battle for eco-innovation adoption in this thesis is twofold. For the energetic application, there is a technology battle between electricity and hydrogen, where hydrogen is posed as the solution while it is the less efficient alternative compared to electricity. However, for other applications, this research concludes that there is no technology battle between electrification and hydrogen on Chemelot, but rather a technology battle between the eco-innovations and the incumbent technologies. Firms continue to maintain their fossil assets rather than adopt eco-innovations. All eco-innovations are necessary to achieve sustainability goals and to reduce emissions. The choice for an eco-innovation will depend on and be determined based on the business case. At the moment, business cases are far from favourable. Regulatory Pressure (i.e. increasing ETS prices), Market Pressure (i.e. demand for eco-friendly products) and Financial Incentives (i.e. providing subsidies) are the most relevant factors in the category of external factors because they motivate the firm to adopt eco-innovations despite the unfavourable business case.

This study shows that the external factors are the most relevant factors for adopting eco-innovations. The study finds that external factors are necessary to motivate firms to take action. It shows that external factors are a key driver for a firm's motivation to take action. In turn, this translates into the Firm's Strategy, the Firm's Management, and the Corporate Culture. Furthermore, according to Chemelot experts, this study shows that internal factors are subordinate to external factors. Within this category, it can be concluded that a firm's intrinsic motivation is the most important driver for adopting eco-innovations, as the factors Firm's Management, Firm's Strategy, and Corporate Culture rank the highest.

Moreover, the experts stated that they consider the category Technological factors as preconditional. A firm will not take any action without a solid business case. If the business case is positive, a firm will usually take action automatically. However, there are barely positive business cases for eco-innovation adoption to achieve climate objectives. External factors such as Regulatory Pressure and Financial Incentives, and the predictions for future markets such as Market Pressure and high taxation for carbon emissions, motivate firms to adopt eco-innovations anyway. Intrinsic motivation can also be a driver if a firm believes it can get a strategic or competitive advantage by adopting eco-innovations.

6.2. Discussion

This discussion section is divided into three parts: a discussion on literature, methods, and results.

6.2.1. Discussion on Literature

This study found many barriers for the chemical industry to adopt eco-innovations. These barriers are similar to those found by Prado [54] and Janipour [35]. The barriers related to the huge initial investments and failing markets, firms operating in internationally competitive markets with different regulations, high degree of plant integration and heterogeneity, and lack of market incentive, and demand for sustainable products appear to be the most important barriers. This study confirms these barriers and shows that, as a result of these barriers, the incumbent technologies can be considered locked in. In addition to the locked-in incumbent technologies, this lock-in effect is reinforced by another argument, which relates to investment barriers. In line with Schilling's [67], research shows that firms continue to invest in fossil-fuelled technologies due to large assets positions and strategic commitment because there is a better business case and higher profitability compared to eco-innovations. In the case of eco-innovation, firms face very high investment costs and long payback cycles As a result, firms are reluctant to actively maintain the incumbent technologies, which leads to the lock-in of incumbent technologies.

As these are the major barriers mentioned both in this study and literature, the list of barriers is extended in this study. A factor often mentioned is actor alignment, due to the complexity of the transition. This is in line with the suggestion of Suarez [73] that a more complex process requires a greater amount of actors to be aligned for a design to achieve dominance. In the energy and raw materials transition, one can imagine the vast amount of actors ranging from firms, governments, clients, network operators, energy suppliers. These actors all have desires and different interests which cause the complexity of this transition. Other factors that this study found are the limited availability of renewable energy and raw materials, failing policy, societal pressures, and infrastructural barriers. The latter factor has been added to the framework in this research. Fu et al. [29] stated that prior research has not included these factors and that the effect of Infrastructure on eco-innovation adoption should be included. However, it is noteworthy that this factor scores low in the framework of external sub-factors. It has been indicated that this factor is seen as a prerequisite and that it is a matter of time for the infrastructure to be available. Experts are more worried about the other external factors, hence the low ranking of Infrastructure.

Moreover, contrary to prior expectations, this study did not necessarily establish a technology battle between the alternatives electrification and hydrogen, but rather a battle of eco-innovations substituting incumbent technologies. The selection of eco-innovations will be highly application dependent when electrification and hydrogen will fulfil different needs. In this case, it is not about a technology winning ground relative to the other, since all efforts are required to decarbonise the industry. Hydrogen can be used both as feedstock and as an energy carrier. For hydrogen as feedstock, there is no technology battle. In a technology battle where alternatives generally fulfil the same purpose, they compete in markets to gain dominance and to achieve competitive advantage relative to each other, which ultimately results in adoption by markets. The energetic application of generating high temperatures with either electricity or hydrogen, a technology battle is active and affected by various external factors and different costs. As mentioned earlier, the use of electricity for heating purposes is much more efficient. If the hydrogen lobby succeeds by pushing their technology, for example by comparing the investments for the infrastructure of hydrogen versus electricity in favour of hydrogen, this could result in that third parties not investing in upgrading the electricity grid. The technology battle for dominance for the heat generation application is fought outside Chemelot but could have bad consequences for Chemelot as it will be burdened with a more expensive way of generating heat by using hydrogen as a fuel.

It can be argued that electrification enjoys a steeper learning curve than hydrogen since this technology is broader integrated into society. People might be sceptical towards hydrogen tanks in their cars or near their houses, but they are very well used to using electricity. Schilling [66] argued that the development of technology might benefit due to learning curve effects, which in turn increases a greater installed base and causes other technologies to be locked out. As already indicated, it is unlikely that hydrogen will be locked out entirely because it is required as a raw material for some applications in the chemical industry. Nevertheless, one might state that electrification will be first to market, thereby reaping the first-mover advantage. Another indication for a technology battle between eco-innovations and incumbent technologies rather than a battle for dominance is that the site users do not develop the technologies themselves, but rather aim to adopt these eco-innovations. The technology that is developed by other parties is pushed by powerful lobbies. These lobbies influence politicians that are sensitive because they often lack engineering backgrounds. However, it is these politicians that are making the decisions regarding the eco-innovations, policy, subsidies, and investments that are paid by taxpayers and have huge consequences for the future society.

Disruptive technologies, in this case, eco-innovations aimed at gaining market dominance, are likely to follow an S-curve [67]. They are likely to substitute the incumbent technology when it offers better performance. However, it is hard to predict the S-curve. Firms can influence the curve and, as already mentioned, face barriers to adopting innovations. The S-curve can be further explained by the technology cycle [67]. The emergence of the dominant design, which is usually a mix of elements that best meets the requirements of the majority of the markets, is an important transition point between the era of ferment and the era of incremental change [75]. We can establish that the incumbent fossil-fuelled technologies are in the era of incremental change. These technologies have been exploited for decades, and incremental efficiency improvements and add-ons have been developed to improve (cost)efficiency and reduce emissions. This is supported by the study conducted by Schilling [67] in which she plotted the performance of fossil-fuelled technologies against investment and found that fossil-fuelled technologies do not seem to benefit from performance improvements due to research and development investment. Actually, its performance is decreasing despite significant investment. Nevertheless, Schilling's study [67] also shows that fossil fuels, despite their declining performance, are still significantly more affordable compared to eco-innovations. Therefore, it is not surprising that fossil-fuelled technologies are used in the chemical, bulk, and energy industries. This is also confirmed by the results of this study. Now, we can see eco-innovations advancing which disrupts the cycle and introduces the era of ferment. This phase represents the discovery of eco-innovations and their development. One can observe the developments in the hydrogen markets regarding the electrolysers and infrastructure. Additionally, we see technology-based on electrification developing, e.g. electric crackers, electric boilers etc. However, no dominant design has yet emerged because there is no agreement on how technologies and complementary technologies should look like. Firms are still experimenting with different designs, causing this phase to be turbulent. It can be concluded, that the eco-innovations for the chemical industry are in the era of ferment. Eventually, a dominant design of all these eco-innovations will emerge, and incremental changes will mark the beginning of the era of incremental changes.

In agreement with earlier literature [13], [17], [29], [73], [78], this research distinguished between firm-level and environmental factors, which are referred to in this study as non-technological internal and non-technological external factors. In line with the findings of Fu et al. [29], external factors are considered to be most important for eco-innovations to be adopted. That study also recommended researching technological characteristics as this would help policymakers determine which eco-innovations are suitable to promote. While technological characteristics are undoubtedly relevant, this study found no substantial evidence to support that Technological factors of eco-innovations are more important than External factors.

Contrarily, the study by Chappin [17], which also distinguished between external and internal factors, found that internal factors were the most relevant. That study argued that their findings contradicted the literature, as external factors could have a greater effect on disruptive eco-innovations than on energy-efficient eco-innovations. This could be clarified by the fact that firms are reluctant to switch to disruptive eco-innovations due to the investment cycles and financial barriers, and instead opt to adopt energy-efficient technologies due to more favourable conditions. That study focused on the paper and brewing industry while this study focused on the chemical industry. The fact that these industries have different positions in the production/supply chain and consequently different types of customers could explain this difference in factor relevance. Especially the brewing industry is closer to the end customer, which has an impact on the motivation of a firm to choose for eco-innovation. The chemical firms on the Chemelot site have their headquarters outside the Netherlands and mostly outside Europe. This combined with the fact that the chemical industry is the first link in the production chain and therefore has less to do with pressure from the end customer could explain the difference in motivation for eco-innovation adoption.

Furthermore, this study supports the idea that to increase eco-innovation adoption [13], high long-term commitment by firm's strategy and management is necessary. A clear strategy developed by a firm is a solid basis for eco-innovation adoption. Eco-innovation adoption is not likely to succeed with lacking commitment and strategy. This is supported by the results of the internal factors in this study, which show that intrinsic motivation is paramount. This research is insightful because the pressure from governments and society for decarbonised products is rising. Moreover, the demand to use renewables is increasing among clients who rely on firms to provide eco-innovation alternatives. Firms can either react or act proactively to this pressure by managing their internal factors which encompass the requirement for cleaner products and processes by adopting eco-innovations. However, the results indicate the external factors as the most important type of factors. Within this classification, the regulations emerge as the most relevant driver, which is in line with Bossle's indication [13], followed by financial incentives. This implies that regulation and financial incentives are needed to accelerate the adoption of eco-innovations. Without external pressure, firms are not motivated enough (internal factors are not invoked) and eco-innovations are not adopted.

Looking at the S-curve, we can argue that the eco-innovations are located at the beginning of the curve due to their low performance. Interestingly, this study found that technological factors are less relevant in the adoption of eco-innovations. Experts are convinced that the technological factors do not have a hindering effect and that if regulations and incentives are urgent enough, the technologies will become available. This implies that the technology battle is not led by inherent factors of the technology, but rather by other factors. This is also mentioned by Schilling [66] and Lee [38], where it is stated that technology dominance is achieved regardless of technological superiority.

The pressure and attitude from society regarding eco-innovations have increased significantly. People are getting more and more articulate, accepting things less easy and starting to protest more often. Society is becoming a more powerful actor, demanding a safe and clean living environment. Firms can react to this by adopting eco-innovations, or by offering sustainable products for clients that want to contribute to a better environment. An important aspect of adoption, is diffusion [62]. Mass media, for example, create awareness among people, which in turn can persuade others to opt for an eco-innovation or sustainable product. However, the chemical industry suffers from being a bulk industry and is positioned at the beginning of the production chain. These firms operate with very low margins. Offering an eco-product means raising the price. However, other businesses which use these products are reluctant to pay a premium. A firm could only do that when it can pass the costs to its customers. It is possible that diffusion in B2B markets is more difficult and has less influence from societal pressure. On the contrary, lobby groups are becoming more successful in achieving their goals, sometimes by going to court [43], [71]. This causes firms to create strategies and advance towards adopting eco-innovations. However, this study has found that the influence of Societal Awareness to be the fifth most relevant factor out of seven. It is stressed, however, that society plays a greater role than ever before. Apparently, it is less important than Regulatory Pressure and Financial Incentives, as it is indicated that firms need external motivations to adopt eco-innovations. It is not surprising that governments can have a more pressing effect on the chemical industry. Besides, society, in turn, can motivate the government to take action, as these actions have led to lawsuits in the past. Moreover, from a business perspective, it can be explained that the financial factors outweigh the societal influences until the tipping point when society is willing to pay a higher price for eco-products. The industry is then pressured by markets, which increases the motivation for firms to adopt eco-innovations. It can be stated with certainty, that the factors found in this study are highly interrelated.

6.2.2. Discussion on Methods

The energy and raw material transitions are closely linked to each other and it is almost impossible to separate these two. This thesis considered the climate transition as both the energy and raw material transition. However, since the participants were not confronted with a clear definition, the question remains which view the participants used when ranking the factors. Participants can use several perspectives to look at things, which makes this climate transition so complex. The External factors and their corresponding actors with their interests interact with the Internal factors and their corresponding actors with their interests. The possible future scenarios for Chemelot are influenced by both External as well as Internal factors. This creates the complexity of the environment and the dual causality. From the energy transition perspective, Chemelot needs to be ready to fulfil the needs of the External factors, but Chemelot can simultaneously affect these needs. From this perspective, Chemelot must fulfil the demands from external actors because otherwise, it will go bankrupt. From the raw material perspective, Chemelot is leading in these developments. If the site users on Chemelot decide to not act in the raw material transition, they can electrify processes and reduce Scope 1 emissions to meet the demands set out by external actors while not investing any resources in the raw material transition. Both the use of fossil energy and fossil raw materials in the chemical industry affects the climate negatively, although current policy focuses on scope 1 only to reduce emissions originating from energy use. This puts Chemelot in a rather unfavourable situation.

The Technological factors are objective or can be made objective and determine the feasibility of the future eco-innovation alternatives. The Technological factors represent possible future decisions. There can be a future A which consists of electrification, a future B which consists of hydrogen, a future C which consists of a hybrid model, etc. Each of these future scenarios is defined by the Technological factors i.e. Capex is different for each scenario. The scenario and the corresponding Capex is yet unknown but will be in the future. This applies to all the factors. The External factors try to steer towards one of the possible future alternatives. The hydrogen lobby, for example, tries to push the industry towards hydrogen as a solution because the lobby would benefit from such an outcome. The same applies to the electricity market, which consists of other actors. These External factors largely determine a technology's chances of being chosen. These actors can ignore the objectivity of the Technological factors and push their own interests forward. The Internal factors can be directly linked to the participants and represent the perception of interests of Chemelot. It represents the site users who are analysing both the Technological as well as External factors. Adding to this is their own vision, strategy, and decision-making policy which in almost all cases is located outside the Netherlands and outside Europe. The site users have to respond to both factors simultaneously. Considering all actors and factors means that there is an order in the decision-making process. The goal is the objectivity of the future eco-innovation alternative. The External factors promote a certain type of eco-innovation alternative, and the Internal factors look at the connection between the Technological, External, and Internal factors.

Moreover, the used ranking method is a linear method where participants can rank certain factors. The problem posed in this thesis revealed an environment with Technological, External, and Internal factors. The External factors affect the Internal factors. However, the Internal factors, represented by the participants, also influence the External factors. Both these factors affect the decision on a future eco-alternative scenario which is represented by the Technological factors. This environment of interactions cannot be translated into a linear model, because all factors interact. Although the weights of the factors indicate a sequence, the strength and significance are not indicated in this study. It is desirable to research the interactions between these factors to see how they behave and to increase the transparency in this field of actors and factors.

However, the normalised weights do indicate the relevance of the factors. The sub-factors only explain the relevance of eco-innovation adoption within the specific factor whereas the set of factors explains the relevance of these factors in the dynamics of the entire eco-innovation adoption. All factors - Technological, Internal, and External - exert influence on the decision on eco-innovations on meta-level. This means, for example, that the participants indicate the degree to which Technological factors are relevant in the dynamics of eco-innovation adoption. This does not mean that Technological factors include the six sub-factors. The factor Technological factors is not defined by these sub-factors, but by the perception of the participants that is subjective. To able compare the sub-factors with each other, these weights have been normalised. By multiplying the weights of the sub-factors with the weights of the factors, one can find the normalised weights.

The subjectivity of the perceptions of the participants should also be mentioned, as this could lower the validity of the study. Moreover, besides that semi-structured interviews were conducted, interviews were not all the same. The same applies to the BWM method. One participant elaborated more on Technological factors, for example, while another elaborated more on External factors. The researcher's bias also plays a role. If the participants were asked different questions or the same questions differently, this research would probably present other findings. For instance, if all the sub-factors were asked in one list of 21 factors instead of three sets of factors, the list would probably look different than it does now.

Although participants are asked to rank the factors from their own point of view, it is not always clear whether they answered from today's perspective or a future perspective. Or participants can rank differently from a coercion situation i.e. the site must be climate neutral in 2050, or from a voluntary situation. The latter situation is reflected by a business case in which site users can base their decisions freely. In a coerced situation, an actor needs to settle for an outcome that is probably not desirable. In addition, the participants indicated that they had difficulties with using this method. This is because some participants perceived certain factors as prerequisites rather than factors. This implies that this method is less suitable for conducting this analysis. Moreover, participants found it hard to rank the factors because they found all factors very important. Some stressed that the outcome should not create the perception that the low factors are in reality less important. They are all important but in a different way.

6.2.3. Discussion on Results

The research objective of this thesis was to create an overview of factors that affect the decision for adopting eco-innovations. This thesis introduced the categorisation of Technological and Non-technological factors since both affect this decision-making. It is argued that Technological factors should be the prevalent force when a decision has to be made that will be most beneficial for the future industry and society. The Non-technological factors identify internal and external barriers or enablers and show us how to deal with these in time. The results in this thesis show, however, that External factors are the most relevant in adopting eco-innovations in this climate transition. This can be explained by the fact that integral transparency, which indicates how certain eco-innovation alternatives are related to each other and to the future consequences, is lacking. The industry receives much influence from various actors which all have their own interests. The choices for eco-innovation alternatives the industry has to make now have consequences for society in the future. To be able to make an informed decision, one should see the climate transition as a holistic system. This way of thinking in terms of systems can be very difficult for policymakers and politicians because different actors try to influence it by pushing their own interests. Moreover, it is difficult to oversee the future consequences of a decision that has to be taken today. These consequences should be given more attention when making decisions for eco-innovations. A measuring instrument that analyses and compares future impacts is desirable in the decision-making process.

From the set of technological factors, Capex emerges as the most relevant indicator. This can be explained from a business perspective as eco-innovations require a huge investment. However, the role of Capex could become less important in the future if the European Union could guarantee the investment costs in the field of eco-innovations. A large part of investments is needed for the infrastructure, something that most governments are responsible for. Interestingly, the factor Infrastructure seems to be the least relevant in the set of External factors. Experts indicate that the infrastructural challenges will not be a bottleneck. In this case, the industry is inclined to look at governments and network operators because in the view of the industry these actors are responsible. Moreover, Capex is also closely related to Opex. The Capex applies more to the investor or the decision-maker, while the Opex applies more to the site-user or the operations department. Both Capex and Opex score high in the Technological Factor set, but this is not reflected in the normalised weights. It could be explained by the factor Technical Feasibility and its high score. This is often indicated by experts as a prerequisite rather than a factor. This might cause an inconsistency in the analysed results.

The efficiency factor can be interpreted from different perspectives. A network operator might have a different definition of Efficiency than an end-user. A government might be interested in the most efficient lowering of CO_2 emissions, given the availability of a certain amount of CO_2-free energy. This will create different interests of the actors involved. Naturally, this factor is also included in the business case. Most of the participants found it hard to rank these factors separately and mostly referred to the business case as a factor. It is argued that when the business case is positive, then eco-innovation adoption is not a problem. However, many barriers are indicated that the business case is not positive due to infrastructure, financial situation, technological issues, etc. The business case is seen as a prerequisite, while the rest of the sub-factors are seen as factors. This makes the comparison of Technological sub-factors with External and Internal sub-factors somewhat less meaningful.

As mentioned earlier, the business case, which largely consists of Capex, Opex, and Technical Feasibility, reflects a free choice in the strategy of a firm. In a coerced situation, site users are pressured to make a decision, or a decision is made for them in order for the firm to stay alive. The participants stated that such coercion is often encompassed by External factors such as Regulatory Pressure, Financial Incentives, and Market Pressure. Interestingly, the normalised weights show that these sub-factors score the highest, followed by Capex and Technical Feasibility. This could mean that participants used different perspectives in ranking the sub-factors. The position of the Firm's Strategy and Firm's Management might reveal the uncomfortable situation where the site users find themselves. Although the business cases are important and must add up, the firm's intrinsic motivation is subordinate to the business case and external pressure. One could argue that if a firm is intrinsically motivated, eco-innovation adoption might be faster. But since the decision-making units of the site users are located in countries outside of Europe, it is hard for the site users to convince these units to invest heavily in the European site without profits. The problem is the level playing field of the multinationals and the international competition that is limiting eco-innovation adoption. Therefore, site users can have the attitude that until it is not mandatory to limit GHG emissions, they will not adopt eco-innovations.

Furthermore, it is interesting to interpret the meta-level by looking at the sets of factors. Looking back in the past few years, some minor incentives helped the industry. But participants indicate that with incentives such as the ETS, the industry started to act rapidly. This shows that intrinsic motivation that consists of the Firm's Strategy and the Firm's Management, is paramount, but perhaps needs encouragement from External factors. This encouragement is also needed for the lacking positive business case for eco-innovation adoption. The positive business case translates into the intrinsic motivation, which makes the positive business case so self-evident for most experts on Chemelot that a negative business case is not even considered, as could be indicated by the ranking of the meta-level set of factors. Nevertheless, the experts should start taking the negative business into consideration because a negative business case today could turn positive in the future. Moreover, the adoption of eco-innovation could be enforced due to Regulatory Pressure. The External factors have the highest weights, which fits the profile of a manufacturing plant that Chemelot represents. These are enormous plants that produce bulk goods and are located at the beginning of the production chain, and therefore face little consumer pressure. They behave differently compared to an entrepreneurial firm that is continuously looking for Business Opportunities.

Another issue that arises is whether the participants ranked the factors, keeping in mind the possible consequences. A lower ranking of certain factors can have a major impact on the realisation of certain decisions. Lead time has been given the lowest weighting indicated by the participants. For a governmental institution, for instance, this might be an important factor and could cause friction between both parties. The low score of Lead Time could be explained by the fact that a few years ago regulations and obligations were lacking. Now, however, Lead Time is much more important. The prices of the Emission Trading System (ETS), which allow a firm to emit CO_2, are rising rapidly. If Chemelot does not reduce its emissions, at the current ETS prices it will go bankrupt within a few years. Or customers may no longer order products from Chemelot because they want more sustainable products. So if Chemelot does not realise its sustainable strategy on time, the consequences will be enormous. These consequences are not reflected in the results, because Lead Time scores low.

The results show many different perspectives and some inconsistencies caused by differences between the reference frames of the participants. The vision on the climate transition and eco-innovation adoption should be approached from a system perspective with an integrated value chain and the entire energy chain from energy generation until the end-user. Only this approach creates good insight and allows comparisons between eco-innovation alternatives and their impacts.

6.3. Contributions

This research has various contributions to the literature. First, this research contributes to the literature eco-innovation adoption in the chemical industry. Scholars have researched the barriers to become more sustainable in this industry, but factors affecting eco-innovation adoption have not been investigated. As defined in Chapter 1, eco-innovations are a broad concept. Some studies research a specific technology battle for dominance between two technologies. This study focuses on the substitution of incumbent technologies with eco-innovations as well as the technology battle between hydrogen and electricity for energetic applications. Furthermore, this study specifies the eco-innovations to electrification and hydrogen-based technologies because these are the most promising technologies. In the chemical industry, both technologies are paramount and will play a prominent role in becoming more sustainable. This is because the choice for eco-innovation is highly application dependent due to different required resources, consequences, and integrated methods. Therefore, this research has aimed at both a general view of eco-innovation adoption and a specific technology battle between the eco-innovations.

Moreover, considered the potential market for eco-innovations in the chemical industry, understanding the effect of factors on adopting eco-innovations is critical. Looking at the plans from governments such as Paris Agreement and the European Green Deal, and incentives like the Emission Trading System, firms are investigating ways to increase efficiency through adopting disruptive eco-innovations. After interviewing the participants and analysing the interviews, the study aims to develop a novel framework with factors that affect eco-innovation adoption. Several scholars developed frameworks before, and distinguished Internal and External factors, also referred to as firm-level factors and environmental factors [13], [17], [73], [78]. In this study, these are referred to as Non-technological Internal factors and Non-technological External factors. Although Lee et al. [38] developed a framework containing technological and non-technological forces, no studies created insight in comparing a set of Technological factors with a set of Non-technological factors.

By creating insight into the drivers and motivation of adopting eco-innovations divided per set of factors, this study builds on existing frameworks and adds additional factors and thereby contributes to the literature. This framework suggests that through understanding the interaction between Technological and Non-technological factors, firms and policy-makers can better understand the dynamics of adopting eco-innovations. Because firms face trade-offs and uncertainties due to investing in new markets, this framework can serve as a guide to evaluate what the focus of a certain strategy should be. It does so by showing that firms can manage internal factors to adopt eco-innovations. Although firms have little control over the external factors, they are able to adjust their Internal factors to adapt to the External factors. Moreover, it can guide policy-makers and governments in making new regulations, tools, or incentives. As the framework does not provide concrete answers, it helps to remind to evaluate Technological, Internal, and External factors which may be vital to the successful adoption of eco-innovations.

Finally, this research provides an insight into how the experts at Chemelot view the climate transition and how they visualise an approach. This research brings Chemelot closer to developing a measuring instrument that can compare the consequences of a particular decision. The knowledge generated will arm Chemelot in this technological battle against uninformed decision-makers or lobby groups. Ultimately, this ensures that the most favourable decisions are taken for future industry and society.

6.4. Limitations

One limitation of this research is that the scope is limited to the Chemelot site. The opinions of experts are not compared with other chemical sites in the Netherlands or Europe. This single and embedded case study, therefore, is less suitable to compare these findings to other industries. That is also difficult because Chemelot is a unique site. However, the findings of this study are compared to the literature, of which a few have research eco-innovation adoption in other industries in the Netherlands.

Another limitation is that the participants are limited to experts which are directly involved with Chemelot. These are employees of site users, researchers which study and develop site related technologies and processes, and managers who manage the strategy and policy of the firms on-site. No policy-makers from the local or national level are taken into consideration.

Lastly, it is important to be aware that the framework this study delivers, is largely based on factors from existing literature. Naturally, there might be other factors that are not included in this framework. In addition, the definitions of external and internal factors are often static. In reality, motivations for these factors might be dynamic and might overlap in different ways from different perspectives. Eco-innovation adoption is a complex process for a firm and experts experienced difficulties with ranking the factors in this study due to possible overlapping. In addition, some factors are seen as a prerequisite by experts, making it hard to rank the factors.

6.5. Implications

The results have some implications for policymakers since they can affect the process of eco-innovation adoption. It is relevant for policymakers to realise that regulatory pressure motivates firms, and is in fact necessary for firms to adopt eco-innovations. To compensate firms for the not functioning business cases, financial incentives are required as well. Policymakers should use this insight to develop new regulations and policies.

The diffusion theory of Rogers [62] states that communication media are paramount for the diffusion process. More comparative studies between eco-innovations and incumbent technologies are desirable in different industries. It is insightful to see how the eco-innovations diffuse among firms and among society compared to the diffusion of incumbent technology. Moreover, since eco-innovation adoption requires more stimulation by governments, society, and markets, interactions between these types of actors are more complex than with incumbent technologies. Therefore, it is recommended to study the relationships between these actors to find the reinforcing and conflicting areas in decision-making for eco-innovation adoption.

Eco-innovation adoption in countries where electricity is expected to be cheap and to increase awareness should be researched since the Dutch industry will rely largely on energy from these countries. We will depend on these countries, their possibilities, and their affordable energy. That information is required to be able to compare alternatives to make informed decisions.

6.6. Reflection

This part reflects on the content and process of the master thesis and ends with a reflection on the Management of Technology curriculum.

This research is conducted at the Delft University of Technology and Sitech Services, a subsidiary of the Chemelot chemical site. It has been a great experience, both on academic and corporate levels. I was very enthusiastic and eager to dive deep into the topics I wanted to research. Although I scoped the boundaries to two processes - the cracking process and the ammonia production process - I might have lost too much time. Not in the sense that it was useless because I learned very much. But more in the sense that it was too extensively explained. I found it very interesting and I wanted to prepare myself well for the interviews with extensive background knowledge. In hindsight, however, it turned out that the interviews barely touched upon specifics of the eco-innovations. Additionally, during the thesis, I came across some side paths that were interesting to investigate. Naturally, I needed to stay focused on the main research question of the topic. Some of these subjects may be suitable for another master thesis research. For example, to compare the results of this study with a chemical site in Asia, the US, or the Middle East because they have different regulatory bodies and different climate goals. Or to conduct research on how to create a successful lobby, or how to align residents around the chemical industry to reduce societal pressure. Furthermore, I am glad that I noticed a shift in the technology battle just in time. Actually, there are two technology battles - (1) the technology battle for heat generation by either hydrogen or electricity where the hydrogen lobby is pushing its desired solution with all its consequences, and (2) the battle of eco-innovations substituting the incumbent technologies. This created confusion in the beginning but added extra depth to this work.

Another point is that with studies like these, it is hard to predict an outcome. Since one cannot look in the future, these types of studies are mostly done looking back in the past. Currently, it is too early to analyse a design of an eco-innovation because there are too many, some of which are still in the early development phase. But it sure is an interesting topic to be researching in a few years. One can then look from a firm's perspective which are developing the eco-innovations. One aspect which I did not think of in the beginning, and for which I did not have the time, was to include interviews with people for (local) governments, and perhaps with residents. Naturally, I selected the participants to be experts. But it is desirable to also create a perspective from other actor groups. Conclusively, my first major research which I had to conduct completely independently posed some typical issues. Together with some assistance from my company supervisors and my first supervisor Geerten van de Kaa, I managed to deal with these issues accordingly. Content-wise it has been an informative experience to base decisions that you, as a researcher, have to be able to justify.

As mentioned in the previous paragraph, the process of diving deep into the specifics of the eco-innovations consumed a lot of valuable time. Although it was very insightful to gain some extensive knowledge, it was less valuable from the academic perspective for this thesis. It also caused a delay in starting the interviews. At the beginning of the thesis, I made a plan for certain parts. Apart from the delay with the interviews, I mostly worked according to the planning. Moreover, since I had barely any experience with interviewing participants for research, I needed to accustom myself to this type of research. Sometimes, I had difficulties with explaining some definitions or concepts to participants, whereas other participants immediately understood me. Also, some participants said that they cannot rank the factors as they are all equally important. Then, I stressed that for the sake of my research, it is important and valuable to rank the factors. Moreover, some participants used a completely different point of view of which I did not think of prior to the interviews. The process of interviewing has been a valuable and educational experience, but still offers some points of improvement. Naturally, the COVID-19 pandemic has not made the process of graduating much easier. Due to the pandemic, I was unable to work at the company or conduct the interviews face-to-face. Also, in the beginning, it was not possible for students to study at the faculty. In the last month or two, some of the limitations were cancelled, which meant that I could study at the faculty again with some fellow master thesis students. It is valuable to help each other as students with the process of writing a master thesis because you both benefit from this. Unfortunately, for one fellow MoT student and dear friend, it all became too much. He is no longer with us. This sad and unfortunate happening has caused the beginning of the thesis period to be difficult for all of the fellow MoT students and friends. Naturally, this had an impact on motivation sometimes. Luckily, I received good support and understanding from my supervisors, fellow students, family, and friends which helped me through this period. I can conclude, despite this incident, that the process of researching and writing my master thesis is a worthy, educational, and insightful moment to end the master's programme.

When I was searching for a master thesis topic and thought of the courses which I enjoyed the most. My bachelor Mechanical Engineering has taught me that I am more interested in the corporate side of complex problems where multiple aspects are combined. I especially enjoyed the first-year courses Technology, Strategy, and Entrepreneurship (TSE) and Emerging and Breakthrough Technologies (EBT). This motivated me to study the specialisation of Emerging Technology-based Innovation & Entrepreneurship. In this specialisation, I had the course Technology Battles, which is one of my favourite courses in the master's programme. However, I did not specifically choose this topic because of that course. I wanted to study something hydrogen-related since I wrote several papers about hydrogen (in the automotive industry). Therefore, I contacted some firms in the hydrogen industry, and eventually, I came in touch with Chemelot. Together with my company supervisors, and with some proposals from my side, we defined the topic of this thesis. I enjoyed this topic greatly, although it was sometimes hard to combine the corporate perspective, goals, and ambitions with the academic guidelines. After all, I think that this thesis topic fits perfectly well in the MoT curriculum because it combines how technologies can be used to develop solutions that maximise customer satisfaction while maximising corporate productivity, competitiveness, and profitability. Moreover, the competencies the MoT programme has taught me were useful in writing the thesis. The several papers I had to write definitely improved my writing skills. In addition, the knowledge provided by TSE, EBT, and the specialisation, turned out to be a solid basis of insights. A course in the specialisation - Sustainable Innovation Transitions - helped me better understand the complexity and perspectives because I conducted an actor analysis, which proved to be helpful in my thesis. The course Research Methods also helped to structure the master thesis better and to select the correct research method. Lastly, I would like to make a suggestion for the course Preparation for Master Thesis. I am convinced that if that course is better integrated into the programme, students can conduct a better literature review that is more elaborate and extensive. This ensures a better motivation of the student and therefore improves the quality of the literature review, and thus the thesis.

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A

Additional information Chemelot

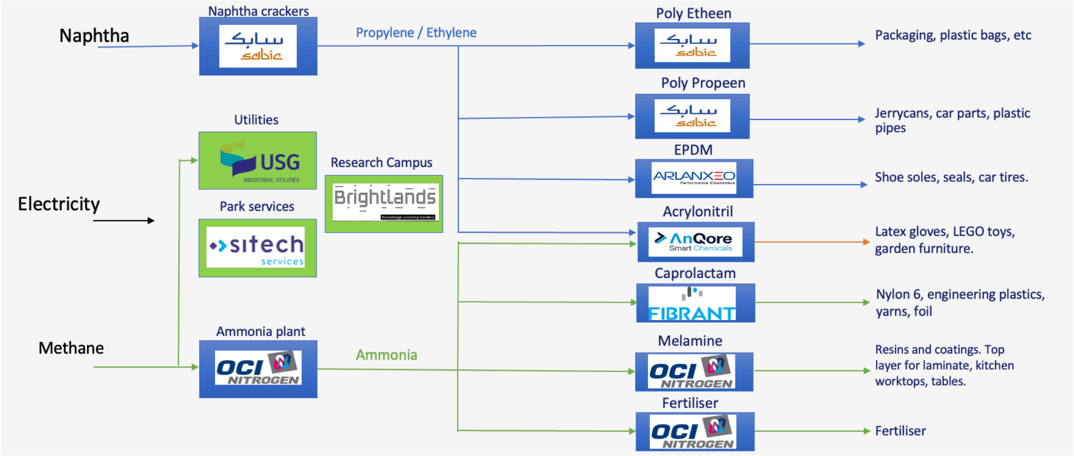

Figure A.1: Simplified visualisation of the plants and products on Chemelot (Source: Brightsite, [70])

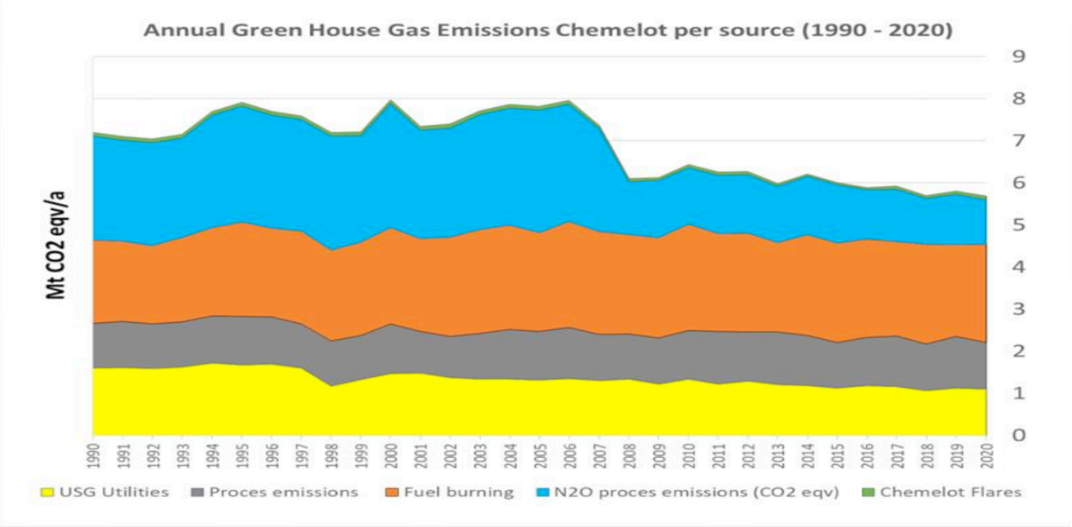

Figure A.2: Annual GHG Emissions on Chemelot per source (1990-2020) (Source: Brightsite, [70])

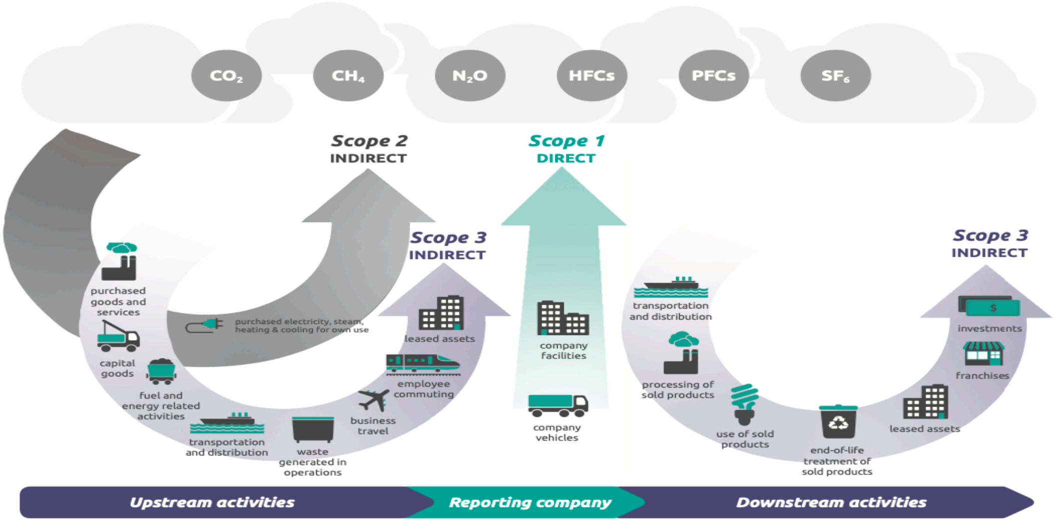

Figure A.3: Visualisation of GHG scopes definition (Source: GHG Protocol [9])

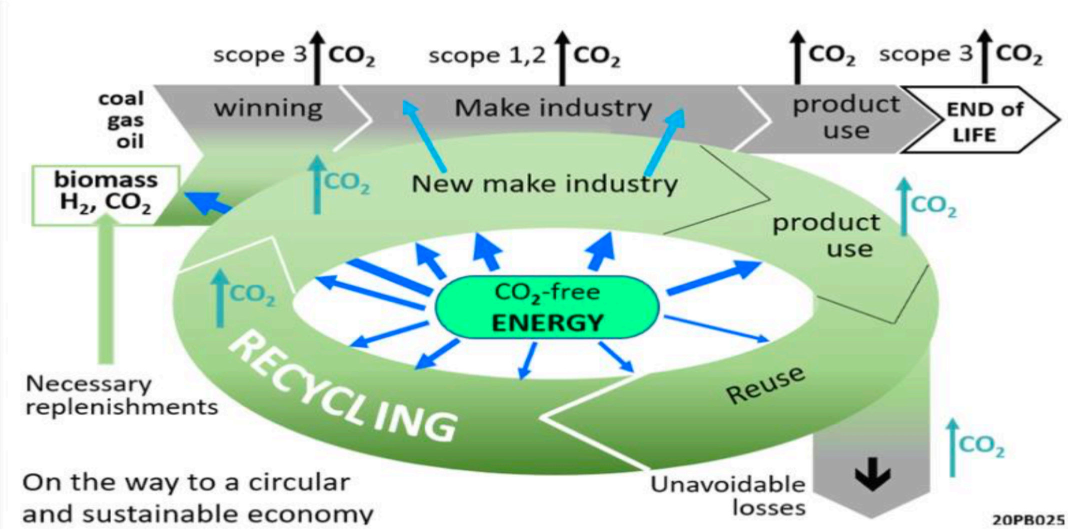

Figure A.4: Future Circular Economy of Chemelot (Source: P. Brandts, Brightsite, [53])

B

Ammonia Production Process

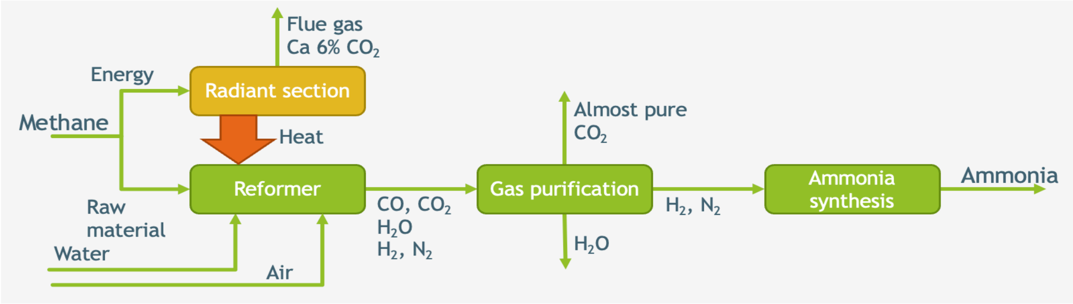

Figure B.1: Simplified ammonia synthesis process (Source: Brightsite, [70])

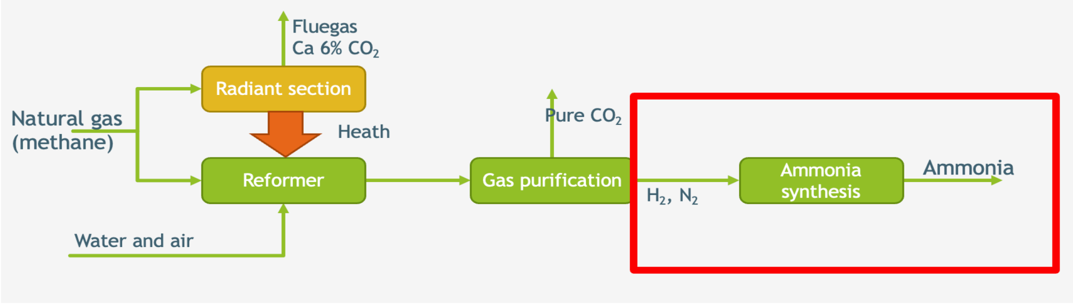

Figure B.2: Ammonia production process based on imported renewable hydrogen (Source: Brightsite, [70])

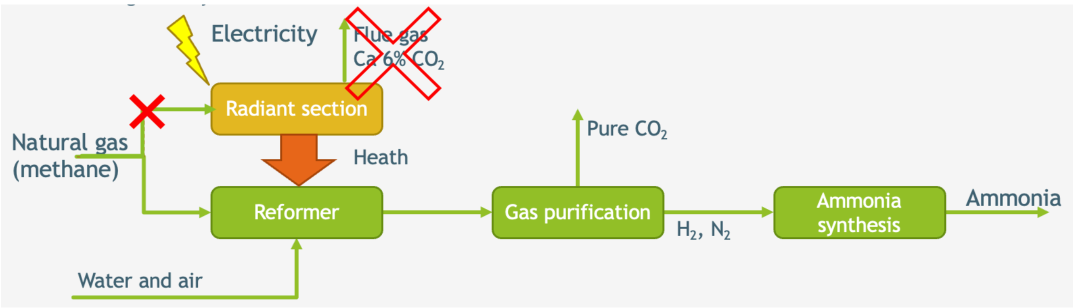

Figure B.3: Ammonia production process heated by electricity instead of natural gas. (Source: Brightsite, [70])

C

Cracking Process

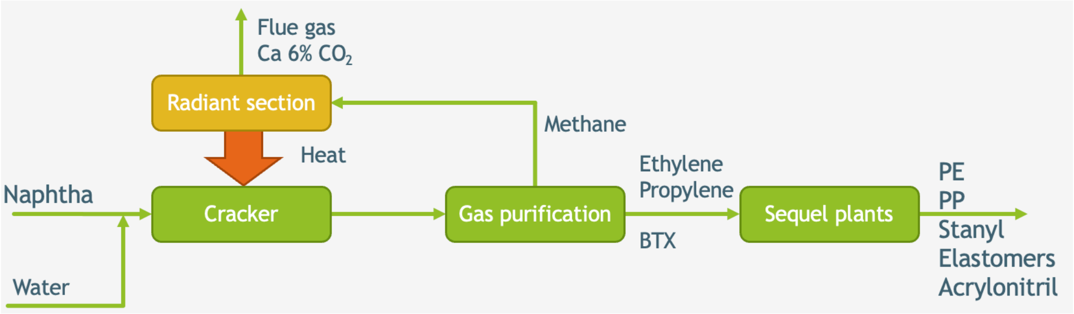

Figure C.1: Simplified cracking process (Source: Brightsite, [70])

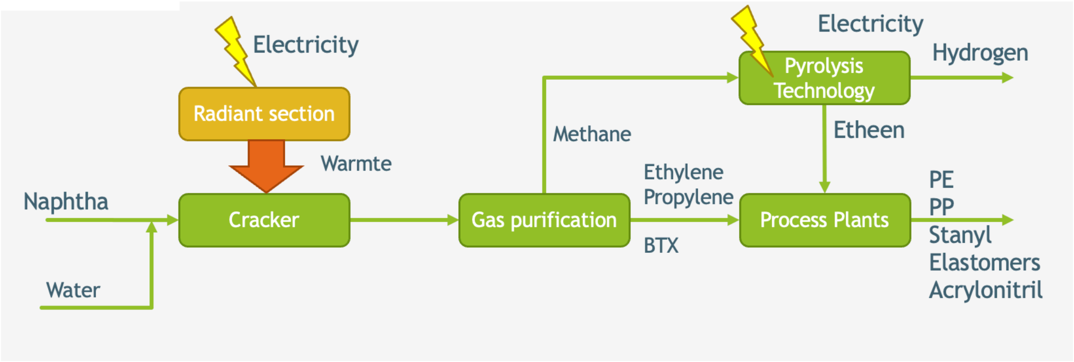

Figure C.2: Cracking process heated by electricity instead of natural gas. (Source: Brightsite, [70])

D

Electrolyser

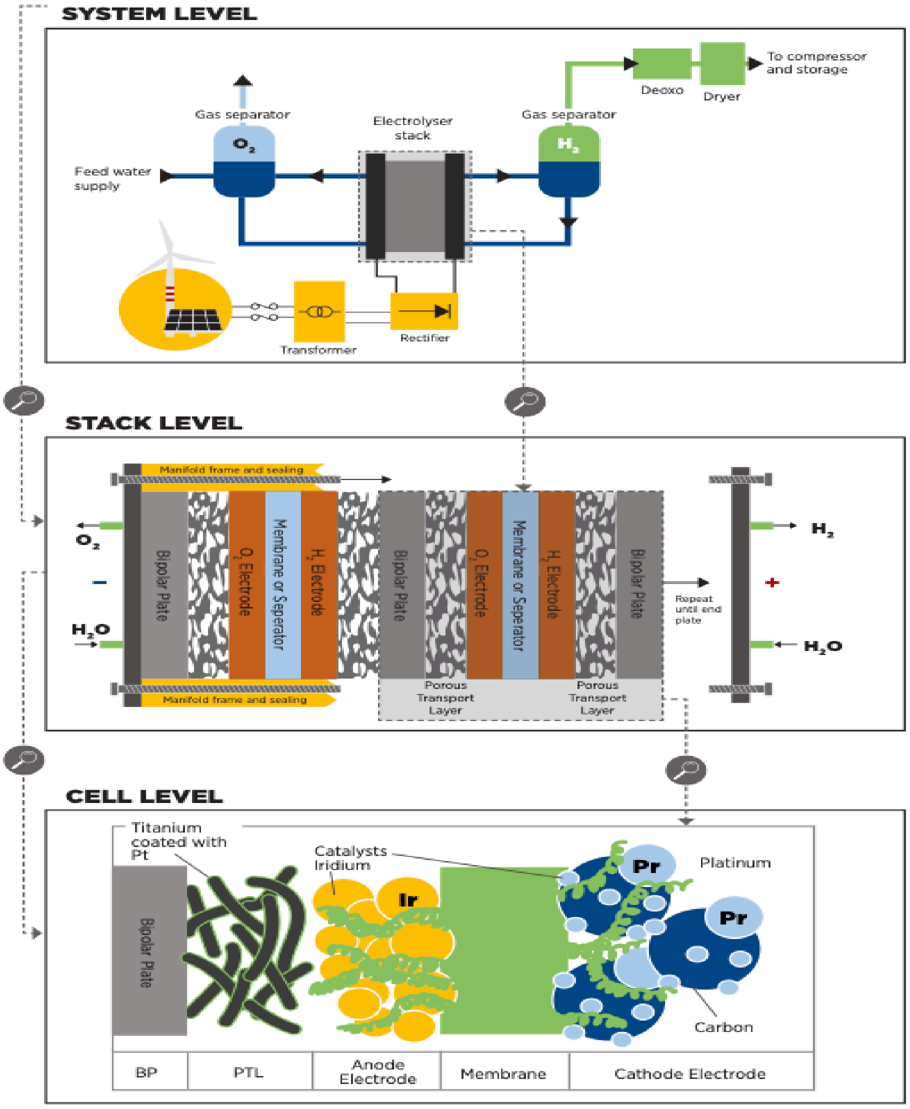

Figure D.1: Components of an electrolyser on different levels (Source: IRENA, [34])