Assessing industrial symbiosis opportunities for a selected industrial cluster under different decarbonisation options; towards a decision framework

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Preface

This report was written as fulfilment of my thesis project in order to obtain the MSc Management of Technology at Delft University of Technology (TU Delft). The host of the research project was The Netherlands Organisation for Applied Scientific Research (TNO). This graduation project was a great opportunity for me to combine my passion for sustainability and my chemical engineering background with the knowledge I acquired during my studies at TU Delft on new technologies and their implementation.

Firstly, I would like to thank my supervisors from the university. I would like to express my deepest appreciation to Rudi Hakvoort, my first supervisor, for motivating me to work on such an interesting topic and for being there whenever I needed his advice and guidance on the academic requirements. I am also grateful to Cees van Beers, for being the chairman of the committee.

I also want to express my regards to the people who work at TNO for hosting me as an intern the last months. I would like to express my sincere gratitude to Milkica Jovicic, the company's supervisor, for her daily guidance and extensive feedback throughout this project. I must also thank, Manoj Shinde and Arie Kalkman for their support during the project. The knowledge and information I obtained from all of them was vital for the completion of this project and for my future career.

Moreover, I feel the need to thank my family for their unconditional support throughout the years and for reminding me to keep my head up at times when I am struggling. I also wish to thank my flatmates for the last 2 years for being there through difficulties, but also sharing beautiful moments. Finally, I am thankful to my friends, either in close geographical proximity or not, who played a vital role in keeping a healthy work-life balance throughout the past two years.

I would like to conclude my preface with the following phrase that for me represents the true motivation for doing anything in life:

"The greatest glory in living is not in falling, but in rising every time we fall." - Nelson Mandela

Angeliki Anagnostou
Delft, January 2023

Executive Summary

This master's thesis, that was carried out on completion of the master's degree in Management of Technology. It focuses on decarbonisation options through industrial symbiosis opportunities within in a chemical cluster. In particular, it is being studied which would be the most suitable technologies that could be applied in order to reduce greenhouse gas (GHG) emissions in a cluster.

Background

According to the Paris agreement in 2015, global warming should be limited by applying new innovative technologies in the industry in order to keep the global temperature 2 degrees Celsius above pre-industrial levels. Human activities affect the environment and a large part is due to industry and the extensive use of fossil fuels. For this reason, the chemical industry is at the top of the list of GHG emitters. Governmental organisations, institutes and chemical manufacturing companies themselves are concerned about high emissions and all together are making efforts to find and apply more appropriate technologies to reduce GHG emissions.

Research objective

This research focuses on the chemical industry and specifically will be studied from the perspective of the chemical industrial cluster. The scope of the thesis is to study industrial clusters, focusing on the Netherlands, and to find a way to identify the most suitable technologies for decarbonisation. The concept of an industrial cluster has the view of interconnected companies located in industrial proximity and there is a perspective of cooperation in order to find a way to reduce emissions. This cooperation, however, creates complexity as the companies will have to cooperate on a financial, technical and social level. In order to define the research object of study, the main research question was formulated:

How to develop a decision framework for assessing industrial symbiosis opportunities for a selected industrial cluster under different decarbonisation options?

Methodology

In order to answer the question mentioned above, a key step is the design of the study. A comprehensive literature review is the first step in order to understand the terms industrial cluster and industrial symbiosis. In order to move to the topic analysis, a specific case study was chosen to study, which is the Port of Moerdijk industrial cluster. A key part of the analysis is the data collection, the cluster analysis and then the research and listing

of all available technologies that could be alternatives to the processes in order for them to become more sustainable and lower their emissions. Finally, using some criteria, the final scenario for the reduction of emissions in this case study will be proposed. Then, an attempt will be made to generalise this method and to design a decision framework.

Case study Moerdijk

Regarding the case study of the Moerdijk cluster, publicly available data was used and four companies were taken into account: Shell, Hexion, Lyondellbassel and Ardagh glass, which are in geographical proximity. The first three are chemical manufacturing companies and the last one is a glass packaging manufacturing company.

From the analysis of all energy and mass flows, it is observed that companies are already strongly interlinked by exchanging material streams and utilities, which is an example of existing industrial symbiosis. These products are used as an intermediate chemical for the production of other products by Shell, but also by Lyondellbasell and Hexion. The main raw material is naphtha, while energy is produced mainly by burning natural gas. This explains the high emissions of the cluster, around 2.8 Mt CO_{2e}/y, while the biggest emitter is the steam cracker unit (55% of the total emissions).

Based on the cluster analysis, various options for decarbonisation are identified, such as alternatives for feedstock, energy carriers and the alternative processes itself were analysed. Alternative feedstocks considered are bio-based sources like bionaphtha, bioethanol and waste plastic oil. As alternative energy carriers, electrification of gas-fired equipment and hydrogen as fuel are considered. Finally, as an alternative process to steam cracking, the methanol to olefins (MTO) route is studied together with carbon capture and storage (CCS). After all this research and taking into account qualitative and quantitative criteria, the final solution can be proposed.

Results

The solution proposed for the cluster of Moerdijk is to invest in the partial substitution of fossil-based naphtha feedstock with 10% co-feed of bionaphtha and 10% co-feed of waste plastic oil. Implementation of the electrification of the steam cracker, the steam boilers and the glass production processes and finally, Carbon Capture & Storage (CCS) technology is recommended. By implementing the recommended combination of decarbonisation options, it is estimated that by 2035 this will result in 45% of cluster emissions. After the proposal of the final scenario for the case study, an attempt is made to generalise this analysis, and thus a way towards a decision framework is presented. Essentially, a list of actions is presented, which someone could follow to find the appropriate solution for another chemical industrial cluster.

Conclusion & recommendations

This report is important as, in the literature, most of the studies on decarbonisation options and industrial symbiosis are mainly focused on a technical level. In this study, although technical characteristics of these technologies are also studied, all the social, environmental, economic and technical sectors are taken into account. Different alternatives are also studied in many processes, which are carried out in parallel (in an industrial cluster). This leads to a rather complex topic that should be solved or at least simplified. This study can be used by decision makers of a chemical manufacturing company, which is a part of an industrial cluster, as a tool in order to follow the right steps to conclude the most suitable option for decarbonisation. The advantage of studying this topic from an industrial cluster perspective is the decrease of individual investment costs by investing in a common solution with shared infrastructure. It can also provide input from the government who might be the owner of such an infrastructure, or to subsidize it through different programs and motivate decision makers to make action towards reducing GHG emissions.

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Chapter 1

Introduction

This report is the master's thesis with the title "Assessing industrial symbiosis opportunities for a selected industrial cluster under different decarbonisation options; towards a decision framework". It focuses on the chemical industry and its decarbonisation options. Therefore, in this thesis it will be studied how emissions can be reduced in the industry and the most suitable technology will be identified. This approach will be done with a focus on the chemical industry from an industrial cluster perspective. The interest is to study the decarbonisation of the chemical industry through industrial symbiosis.

The report begins with Chapter 1, which is the introduction and moving to the Chapter 2 the topic is introduced in more details, the questions to be answered are setting and the problem is presenting. In Chapter 3, a literature review is done which generally concerns the terms that will be discussed in this report. After this comprehensive research, the terms chemical industry and industrial clusters as well as industrial symbiosis are analysed. Moreover, the definition of industrial clusters is researched for the sake of listing the decarbonisation options of industrial symbiosis for an industrial cluster.

Before the analysis, it is necessary in Chapter 4 to describe and explain how the questions raised will be answered and what is the methodology for answering the research questions. In addition to a very good literature review,the methodology consists of a case study, through which a specific industrial cluster will be analysed and then, an attempt to generalise the analysis towards a decision framework.

Moving to the fifth chapter and after the selection of the industrial cluster Moerdijk as a case study, the cluster analysis is being held. After data collection, the data is analysed, the companies present in the cluster are analysed, as well as all the processes taking place, including products and mass and energy flows. Also, an important part is the estimation of the emissions from the different processes taking place at Moerdijk industrial site.

The existing and emerging technologies that could be a solution to the problem of high emissions are described (Chapter 6). Initially, a comprehensive literature review was done for all possible options for decarbonisation. These options are divided into categories based on which part of the process the technology will be applied. In addition to the detailed description, some basic technical characteristics are also presented for each case.

Thus far, a comprehensive analysis of the Moerdijk cluster's data has been done and all the technologies that could be applied for the solution to the problem have been listed. Chapter 7, constitutes the point at which the solution will be given. That is the final scenario that will be proposed. All the selection criteria used for the final decision will be analysed.

The previous sections are a process of finding the most suitable alternative for the Moerdijk cluster. However, the goal of this study is to design a framework that is more general. In Chapter 8, an attempt will be made to generalise all the procedures mentioned in the previous chapters. The decision framework is a flow of actions that should be followed for other industrial clusters to succeed in finding the suitable technology in any case. Although generalisation in this case faces challenges, these challenges are listed and analysed in the chapter.

Finally, the nineth chapter closes this report with the conclusion which basically constitutes the final answer to the research question. In this chapter the results are analysed and a comprehensive answer is given to how the problem raised at the beginning of the study was approached. Also, at this point all the recommendations regarding what could be improved and what is recommended for future research. This report ends with reflection, that is the impressions after the end of the study.

Chapter 2

Research objectives

2.1 Background

In recent years, the whole of world society has begun to be deeply concerned about the phenomenon of climate change. Human activities, the over-consumption of goods in the primary sector, but also natural resources have serious effects on the environment, such as its degradation. The World Meteorological Organization has warned of a significant and dangerous rise in temperature in the coming days. Cooperation between countries is therefore a global goal, to universally limit the rise in temperature. According to the Paris agreement (2015), the goal is to limit the rise of the temperature to 1.5°C, compared to the pre-industrial period [67].

An important factor that exacerbates this situation is the chemical industry. The chemical industry consists of companies that produce synthetics from natural resources [44]. The chemical industry is at the top of industrial greenhouse gas emissions, meaning it has a large share of responsibility for climate change. This happens because the production of chemicals is based mainly on fossil fuels, while at the same time high amounts of energy are required for the production process. Nevertheless, it is an industry that generates high profits and is very important for the economy of a country. It is also important that chemicals are now necessary to produce many other products, and this gives them a high value [16].

The high greenhouse gas emissions from the chemical industry, combined with the Paris Agreement, lead to the need to reduce CO_2 emissions in the chemical industry [67]. To do this, major gradual changes must be made to both raw materials and energy sources. Alternative energy sources and feedstocks such as biomass, hydrogen and other methods should be applied to reduce the impact on the environment. An important concept that precedes this endeavor is industrial symbiosis.

2.2 Problem Statement

Reducing CO_2 emissions in the chemical industry is not an easy task, especially when it comes to chemical industrial clusters. It involves assessing the potential of alternative sources of energy and feedstock such as biomass, green electricity, hydrogen, and waste streams. There are many different available technologies to achieve the reduction of CO_2 emissions, which makes it difficult to evaluate all possibilities.

The focus is on identifying and establishing integration possibilities where companies exchange materials and utilities. It is quite challenging for companies to establish how future technologies can be fitted into their current infrastructure. Especially, how to establish a collaboration/integration with their neighbours. There is a gap that should be overcome by providing the best solution considering the current situation. From the cluster perspective, the issue is to give the right future infrastructure but to avoid redundancies.

2.3 Research Objective

As it is mentioned above there are many available technologies that could be applied in order to make the production processes more sustainable. Especially, in a chemical industrial cluster, there are a lot of opportunities for both, to apply decarbonisation technologies and integrate collaboration between the companies, exchanging materials and/or heat. The challenging part is that the industrial sites inside a cluster are already established, and the companies work effectively; they have profit. To make changes there are difficulties, as there are many factors, which should be taken into account. The most important is the current infrastructure in combination with the production process.

These changes mean an investment, which usually costs a lot. Companies within an industrial cluster are large and can afford a large investment, but there are also smaller ones. The thing is, they also need reasons to invest and maintain their profitability. The main reason for a company to invest in solutions that will reduce the environmental footprint and get closer to the carbon neutrality that is the goal for 2050. At the same time, money will be saved from environmental taxes. The aim of this study is to find a methodology through which the appropriate technology for the reduction of CO_2 emissions in an industrial cluster will be applied. This means that the changes should be studied and evaluated in a way that the most appropriate solution can be given. Also, these changes may concern the production process of a product, all the products of a company, or a combination of products of various companies within the industrial cluster.

To achieve this goal, the following research sub-objectives should be completed.

- Determine the data needed so that cluster analysis can be done.
- Indicate the available decarbonisation options for the various chemical processes.
- Indicate the available ways for industrial symbiosis for an industrial cluster.
- Apply the methodology to a specific industrial cluster, which will constitute the case study.
- Evaluate the changes proposed for the specific case study, the economic feasibility and the CO_2 reduction

2.4 Research Questions

To achieve the objectives as described above, the research questions must be formulated. The main research question is:

How to develop a decision framework for assessing industrial symbiosis opportunities for a selected industrial cluster under different decarbonisation options?

The above research question must correspond to the research objections described above. According to the main question, this study sought an efficient way to find which are the appropriate technologies to achieve carbon neutrality in the coming years in a specific industrial cluster.

There are many technologies available in the literature and some of them are already applied in the industry. The aim is to find the specific technologies that will thrive in the industrial cluster taking into account the current situation. In order to answer the following research question, various decarbonisation options should be found as well as the opportunities for industrial symbiosis. It should therefore be evaluated whether the proposed changes are worth implementing and if so how big this investment will be. Therefore, the financial feasibility of this investment should be evaluated initially in combination with the percentage of CO_2 emissions that will be saved in the case of the implementation of the final proposal. There should therefore be appropriate indicators in the results for economic and environmental data. Finally, it is important to take into account other social factors such as whether the national and global policies allow such a change and also the social reactions.

In order to answer the main research question, it is needed to find the information. To this end, the following research sub- questions have been formulated.

1. *How to define industrial symbiosis?*

   The question above is intended to help answer the main research question. In order to find opportunities for industrial symbiosis, one must first study what the term industrial symbiosis is. This question helps the researcher to have a complete view of what it is and how it is applied. To answer this question, a literature review is necessary.

2. *How to identify the different decarbonisation options for a selected cluster?*

   The second research sub-question is perhaps the most important, as in order to answer it, a very good use of research methods is needed, which are going to be analysed in the fourth chapter. Through this sub-question, a very large part of the main question is answered. By initially removing the term industrial symbiosis, the cluster is first analysed and then the analysis is done, focusing only on the decarbonisation options. Through this question, the main question becomes less complicated and the study starts with fewer variables.

3. *How to identify opportunities for industrial symbiosis to create carbon neutrality?*

   The third sub-question concerns industrial symbiosis. For this question, the two sub-questions above have been a good basis. On the one hand, the analysis of the cluster has been done and has clarified what the most feasible decarbonisation options are and, on the other hand, a comprehensive study has been done on what industrial symbiosis is and what its applications are. This gives the opportunity to the researcher to observe the opportunity within the cluster.

4. *Which criteria should be taken into account for assessing the industrial symbiosis options?*

   The last sub-question is based on all the above and the answer will be the conclusion of the research. After the analysis for the specific cluster (case study) is done, the goal is to analyse the conclusions from the above process. Through this question the aim is to create a framework through which the process carried out above will be generalised and will now constitute steps and criteria that can be followed for any other cluster.

Chapter 3

Literature review

In order for one to start properly a literature review, one has to inquire about the availability of information on this chosen topic. This issue is a global problem, which in particular in recent years has occupied an increasing percentage of the world's population. Most of the keywords have a large volume of results on search platforms. This search was done mainly using Scopus and Google scholar.

More generally, it is the environment that concerns beyond the scientific community and society at large. For this reason, there is a lot of information in journalistic articles, which is not considered in a literature review but is a good incentive to start scientific research. Apart from the articles, however, basic information on the subject can be found on websites and in databases that are available to the public and are open to non-governmental organizations as well as to governmental organizations such as ministries of countries.

To determine the availability of information for our research, we must first define the keywords. Having defined the research question and sub-questions, the keywords are easy to find. The keywords are "industrial symbiosis" and "chemical industrial clusters". Both terms are very general and broad. For this reason, when searching, the results are many. In this work, however, a more specific analysis will be made concerning chemical industrial clusters and chemical products. For this reason, the word "chemical industrial clusters" was used as the key word, in order to limit the results and make the selection easier. Finally, it is important to have a keyword such as "decarbonisation options" and "carbon neutrality".

3.1 Industrial clusters

Another very important term in the chemical industry is industrial clusters, or clusters. The term cluster is commonly known as industrial cluster, competitive cluster, Porterian cluster. According to Michel Porter (2003), cluster is a "Geographically proximate group of interconnected companies, suppliers, service providers and associated institutions in a particular field, linked by externalities of various types" [51]. Michael E. Porter is recognized as the founder of industrial cluster concept [4]. Many different definitions have been given for industrial clusters, but all describe the industrial clusters as interconnected production chains [55].

One of the most important advantages of the industrial cluster is that through the collaboration of the companies inside the cluster they can be competitive in the market. According to Michael Porter, industrial clusters have the potential to affect competition in following three ways:

- By increasing the productivity of the companies in the cluster
- By driving innovation in the field
- By stimulating new businesses in the field [4].

Industrial clusters began in the second half of the 20th century when members who were small and medium enterprises had the opportunity through clusters to be competitive locally and internationally. Large companies risked losing in specific part of business such as product design, research and development. They find it difficult to compete with geographically close businesses that operate with a common goal. Therefore, lately some of these big companies are choosing to join specific industrial clusters as they are interested in the opportunities that may exist in terms of innovation [41].

Morosini (2004) studied industrial clusters in two dimensions the social and the economic [41]. Specifically, the first part concerns the physical and social characteristics of a cluster through which it explains who the others are to create innovation. On the other hand, the economic activity that exists within a cluster significantly increases the competition of all the companies, which gives us to understanding of the potential of the industrial clusters. By understanding both dimensions it is possible to design and implement important strategies that will lead the company globally. The practical characteristics of a cluster are easy to understand if we answer the question of what conditions contribute to the creation of an industrial cluster. It usually starts from a good system of facilities and from a geographical point that gives easy access to raw materials as well as energy, water and fuels. Logistics also plays an important role in the industry. A good freight system can help the economy grow quickly and efficiently. Also at this point, a geographical location plays an important role, since in the field of logistics a cluster located near a large airport, an important port or even in an area surrounded by a good road network and infrastructure, can increase the economic performance and increase its competitiveness beyond the local in the international and perhaps global economy [72].

Finally, in order to understand how the geographical clustering of industry became important and interesting for researchers, it is enough to look at when and how the concept of the industrial cluster was observed. An interesting example is the electronics industry in California - the technology and innovation cluster, Silicon Valley - as well as the clothing industry cluster in northern Italy. These are two general examples of the most famous that are important analytical material for the research, development and evolution of new models for industrial clusters. So, it seems that in some sectors there is a specific business activity. It usually starts from the raw materials in the area or from the good communication of the knowledge of specific technology of the area. Through the development of innovative collaboration products between institutions and universities as well as company collaboration, it has been observed that technology can evolve quickly in a limited space [33].

3.2 Industrial symbiosis

In order to understand what industrial symbiosis is and why it is important, the definitions and specific characteristics of this term are the initial priorities. Firstly, the term symbiosis generally describes "the symbiosis of different individuals or units from which all members can receive mutual benefit". With the term industrial symbiosis, the units are the companies or the industries which coexist in a way that benefits all the members, financially, environmentally and in all the other sectors. "Industrial symbiosis engages traditionally separate industries in a collective approach to a competitive advantage involving physical exchange of materials, energy, water, and by-products" [18]. This is of great interest to the business and research community as it is an important opportunity for eco-innovation [42].

In recent years, the field of industrial symbiosis has grown significantly since the Paris Agreement in 2005, as everyone aims to tackle global warming and in particular a low-carbon economy. The European Union has also already begun to build a strategy as well as to impose a reduction in CO_2 in the industry of all the member countries. All this has led to investment in research and the implementation of industrial symbiosis tools [48].

According to the European Commission (2018) "Industrial symbiosis is the process by which wastes, or by-products of industry or industrial processes become the raw materials for another." It is a more sustainable way of using products, by-products, and waste in an industrial environment. Apart from products and raw materials, energy management is also very important. An example is generating energy from industrial waste; this is a way to reduce CO_2 emissions [21].

Industrial symbiosis is a subset of industrial ecology. Industrial ecology is an industrial system that has sought to optimize the total materials cycle, from the raw material to the product to the final disposal of the product. Industrial ecology has three levels and industrial symbiosis occurs at the inter-firm level since there is the interaction between several organizations [18].

A key factor related to the industrial symbiosis between companies and industries is geographical location. In particular, the transfer of by-products and waste products from one industry to another for the purpose of their exploitation, use, and recycling is greatly facilitated when companies, synergies, and factories are within walking distance. Geographical proximity is therefore an opportunity for industrial symbiosis and is an important factor in reducing transportation costs over time and environmental impact [42].

For this reason, the term industrial symbiosis is often associated with industrial parks or industrial clusters that have the advantage of geographical proximity and their characteristics are associated with those of industrial symbiosis. Apart from this, the industrial parks have other characteristics such as the use of renewable energy sources, green building, and smart growth, within them [42].

Thus, by implementing industrial symbiosis within the companies of an industrial cluster it is possible there are significant economic, environmental and social benefits.

3.3 Chemical industry & chemical industrial clusters

The term industrial cluster is a board term. A cluster can be a chemical cluster, energy cluster, technology cluster, financial cluster and various other categories. In this literature review, the goal is to study how in the environment of an industrial cluster, industrial symbiosis technologies can be applied, and which are the opportunities to achieve the goal of reducing or even minimizing carbon dioxide emissions can be achieved. Therefore, in order to reduce the issue and to analyse more specifically the industrial symbiosis in industrial clusters, this study will focus on the chemical industry and therefore on chemical industrial clusters. The chemical industry consists of companies that produce industrial chemicals. Nowadays, raw materials such as oil, gas, air, water, metals and minerals can be converted into a wide range of chemicals, more than 70,000 different products. One of the dominant industries contained in the chemical industry is the plastics industry since plastics are produced 100% from chemicals.

There are many different types of chemicals. Most of these resources are based on fossil fuels. The most common raw material for the chemical industry is crude oil but also for their production large quantities of fossil fuels are used, such as natural gas. In recent years, due to the depletion of fossil fuels and considering the environmental conditions they have in global warming, a process of search for alternative energy sources has begun, as well as raw materials that could replace the raw material [65].

The chemical platform I have encountered chemicals that can be used as a substrate to produce many high-value products. In 2004 the Department of Energy identified 12 building blocks as potential platform chemicals, which can be retained from biomass. This list was updated in 2010 and other chemicals were added [69].

There are different categories of chemical industrial clusters, which are based on the type of the products oil & gas, Plastics, Biopharmaceuticals, etc.. Despite of the categories the companies or firms which are in a chemical cluster have some common characteristics:

- The companies have common suppliers of raw materials, so they share feedstock
- The companies are sharing and nurturing a common stock of product
- The companies target on the same market
- The companies share energy resources
- The companies invest in common research for innovation
- Some companies share infrastructure, in case they have common processes.

3.4 Chemical industrial clusters in the EU

In the European Union, chemical industrial clusters as a concept are quite a given as there are areas that have a quite strong economy in the field of chemicals. Specifically, Germany results in the country with the most industrial clusters in Europe. According to the literature, the growth of the countries in the field of industrial clusters shows that the policies implemented by each country significantly affect the development of industrial clusters.

According to a European Union Study conducted in 2002, policies should promote and encourage business development among local businesses. Government policies should also strengthen the local economy with the aim of corporate competitiveness and consequently national competitiveness in the international community. It is also important that institutes and universities are not funded to help research the development of new technologies and strategies for the development of chemical industrial clusters [38].

In recent years, in addition to economic growth, the European Union has largely focused on green growth and sustainability strategies. In particular, the European Commission has approved, EU Chemicals Strategy for Sustainability with a view to zero pollution for the environment. Chemicals are a key part of the daily lives of all citizens and applying innovative solutions to chemicals enhances green growth. This strategy is about strengthening innovation for sustainable and safe chemicals in terms of human health and environmental protection [20].

3.5 Industrial symbiosis opportunities & decarbonisation options

The industrial can be applied in a variety of ways to a chemical industrial cluster. One of the basic principles of industrial symbiosis is the utilization of the by-products of one chemical process by another. The first opportunity is to map the input and output flows from all companies and identify which of them can be utilized in a process. In practice, this means that the by-product of a process within the industrial cluster is used as a raw material for another process and the production of another product. The above process has the benefit of minimizing transport and consequently reducing environmental emissions and cost, as well as contributing to the circular economy, though the immediate reuse of by-products instead of disposing of them [61].

The next opportunity is related to the fact that companies in an industrial cluster usually share the raw materials. They usually have a common supplier of raw materials and common energy supplies. To approach the goal of carbon neutrality, it is better to make joint decisions and change raw materials and even suppliers en masse. Sustainable raw materials can be substituted for crude oil, but also fossil-based chemicals derived from bio-based resources. In other words, the supplier could change en masse and some material that enters the production chain can no longer be based on mineral raw materials. Thus, the footprint of the industrial cluster is significantly reduced and the companies follow the recommendations for compliance with the green development.

The last opportunity is related to the first, where it is proposed that the by-products be used as raw materials in another process within the industrial cluster in order to reduce transportation costs. This case concerns the outputs of a process and their exploitation. Many times, from various processes in addition to the products there are residual flows, which have no chemical value and cannot be used as raw materials. These flows can be either residual gases or direct CO_2 emissions. These heroes can be exploited in such a way as to generate energy that will be used internally in the cluster and replace other energy sources [18].

Chapter 4

Methodology

4.1 Research strategies

The research methods that will be followed are a very important part of the study. They are essentially the methods followed to answer the main question. The methods that will be used are a literature study, a case study, the method of Multi-Criteria Decision Making and the method of observation, while the goal of this research is the composition of a framework. This chapter will follow a detailed explanation of the methods by which the research sub-questions of chapter 2 will be answered, which will lead to the answer to the main research question.

4.1.1 Literature study

The first research sub-question is the following: *"How to define industrial symbiosis?"*. To answer this sub-question, it should first be analysed what industrial symbiosis is and its applications should be given. This process is part of a thorough literature study, through which the term will be fully understood. To this end, a search will be made on the internet, in scientific articles and books. The way to do it is to first search, read, and analyse the most relevant sources and then evaluate how this information could help to the research. However, this research can be enriched by looking for cases, such as companies and organizations and their reports where industrial symbiosis has already been applied and in this way, the feasibility of the process can be evaluated. Finally, research into industry legislation concerning the industry would help to better understand the situation.

In order to answer the second research sub-question a case study will be done. The question is: *"How to identify the different decarbonisation options for a selected cluster?"*. To have a comprehensive answer to this question and to find which of the decarbonisation options are the best for an industrial cluster the available ones must first be found. So, the first step is to do a literature study of the available options and list them.

4.1.2 Case study

Case study methodology

The second research question is not going to be answered only through a literature study, as a specific industrial cluster should be considered. The research method that could be chosen, then, is case study research. "Case study research is said to allow for an in-depth review of new or unclear phenomena whilst 'retaining the holistic and meaningful characteristics of real-life events" [22]. In order to do a case study successfully there are some specific steps that must be followed which make up the case study protocol [14].

The protocol case study consists of the following steps:

- The first step is the selection of the specific case. In order to make the choice of the case to be studied, there should be specific criteria. For the case of this study, the first step is to find the criteria for the selection of the specific industrial cluster that will be analysed.

- The next step is the research questions. In this step the researcher asks the questions which should be answered to provide the results and conclusions of the study and also determines what information is needed in order to answer these questions. For this study the questions have been given in section 2.4.

- The third step is data collection. In this stage, the organization of data collection takes place, it is checked whether there is access to the elements and permissions required for the use of the data, as well as the types of data collection.

  For this specific research, this point is one of the most demanding. The companies in the cluster should be identified, as well as other details such as the products they produce, some basic economic data, and environmental data such as emissions. The above information is usually hard to find as the companies do not share the details of the production processes and the individual environmental and economic data, but only some aggregate data, such as some profitability indicators.

- The following step is the analysis and interpretation of the data. At this stage, the analysis of the selected cluster will be done so that there is an overview of the industrial cluster with the most relevant production processes and their material and energy flows within the chemical industrial cluster. Then, the analysis of the implementation of the decarbonisation options is following, as well as the observation of possible industrial symbiosis opportunities.

- The final step in the case study is writing a case study report. The task itself is good to organize from the beginning, i.e. to identify the audience and to decide the structure of the report early so that there is a flow in the telling of the storytelling [63]; [58].

Case study: Moerdijk

Considering all the steps of the case study protocol in the previous section, at this point the reason and the criteria that led to the selection of the port of Moerdijk as a case study will be mentioned. First of all, the options were limited to the ARRA region (Antwerp - Rotterdam - Rhine - Ruhr - Area), as the 40% of the chemicals in the European Union are produced in this area [56]. The Netherlands is a place with quite competitive chemical industry in the European market, so the research will be limited to the Dutch chemical industrial clusters. According to Hydrocarbon Processing (2021) approximately 20 - 25% of the total ghg emissions of the European chemical industry come from steam cracking units [52]. According to Amghizar et al. (2020) these high emissions are mainly due to the high energy consumption of the steam cracker [7]. In the Netherlands there are three companies that operate steam cracker units; they are Shell, Sabic and Dow Chemicals (Table 4.1) [25]. So, the industrial site will be one of those three industrial sites and finally Moerdijk was chosen.

Table 4.1: Steam crackers in the Netherlands [25].

Location	**Operator**	**Capacity in kt ethylene/year (2021)**
Geleen	Sabic Europe	1.310
Moerdijk	Shell	910
Terneuzen	Dow	565
Terneuzen	Dow	580
Terneuzen	Dow	680

4.1.3 Multi Criteria Decision Analysis

After the industrial cluster is selected and analysed, it should be found which are the most suitable options for decarbonisation and which of the processes taking place in the industrial cluster would be best applied. Considering the current situation of the cluster, a Multi-Criteria Decision Analysis will be done on which of the options is the most appropriate to apply within the cluster. Practically, this can be done by using a table. The rows of the table would constitute the production processes that were taken into account during the analysis of the previous cluster. In the section 4.1.1, it was mentioned that the second sub-question needs a literature study, through which the possible decarbonisation options will be listed. These will form the columns of the table.

Multiple criteria will therefore be set for the evaluation in order to determine the best feasible solution among multiple alternatives, with the desired outcome [35]. In this case, some of the criteria that are going to be considered, are the reduction of CO_2 emissions, the abatement cost, the effect on the process and productivity. Finally, a detailed analysis will be done on selected options that are believed to have the biggest impact. These options will be considered as sub-cases for the selected cluster chosen as the initial case study. For those sub-cases, it is important to do the analysis of the cluster after the implementation of these options, in order to have a comprehensive overview of the cluster in the new situation.

4.1.4 Observation

In order to answer the third research sub-question which is *"How to identify opportunities for industrial symbiosis to create carbon neutrality?"* the observation method will be used.

The goal is to reduce CO_2 emissions and get one step closer to carbon neutrality. Industrial symbiosis can contribute to achieve this goal as the companies could share the cost of the infrastructure. That is why there should be a good overview of the cluster and observe where there could be an opportunity for industrial symbiosis and in what way. To achieve this, it is important to analyse the cluster in its current situation, listing the production processes and their energy and material flows considered within the cluster. Also, the cluster analysis should be done after applying the decarbonisation options chosen, which are the sub-case studies in sub-question 2. Having all this information and presenting it in a block diagram, it is possible to observe where the field is to apply industrial symbiosis. The literature study of the first sub-question will also contribute to having a better understanding of what could be an opportunity for this specific cluster.

4.1.5 Decision Framework

The fourth and last sub-question concerns the framework that will be composed at the end of this study. The question is the following: *"Which criteria should be taken into account for assessing the industrial symbiosis options?"*.

The aim is to find which are the appropriate methods for the carbon neutralization of an industrial cluster. To do this, the best solution should be found that will help reduce emissions but not reduce the profitability of companies. Answering the previous sub-questions, a series of steps will be followed in order to analyse the impact of one or more options on CO_2 reduction for a specific cluster. From this process, all the criteria that must be taken into account to assess industrial symbiosis and decarbonisation can be derived and the final framework can be developed.

4.2 Data Collection

For the analysis of an industrial cluster, information is needed and therefore, data collection, as mentioned in the case study protocol, is an important part of the Moerdijk case study. The data needed for the cluster analysis is detailed. These are the companies that are involved in industrial clusters, which are the specific processes, the details of their mass and energy balances and the GHG emissions.

Searching for public data online, two major databases were found, from which most of the data is provided. In particular, the first database that deals with the overall national emitters and their production processes is the MIDDEN (Manufacturing Industry Decarbonisation Data Exchange Network) database. The database of the MIDDEN project contains detailed information regarding the energy and materials consumed by manufacturing industries in the Netherlands [5]. Nevertheless, some of the processes are not included in this database. More information is found on the company's website, but it is not that detailed.

Another important aspect of the analysis is GHG emissions for each major emitter within the Moerdijk cluster. Also, companies are obliged to share their emissions either with national emission authorities or with ETS. So, it was difficult to find consistent data on emissions, which usually includes either only direct emissions, or direct and indirect, while the difference between the two is not clearly stated. For this reason, it was difficult to harmonize the type of data collected. This information can, also, be calculated using emission indicators, but for most of the processes considered there is data from the Dutch Emission Authority (Nederlandse Emissieautoriteit, NEa) [2]. In this database, information about the annual CO_2 emissions is reported for the years 2013 - 2018.

Chapter 5

Industrial Cluster Analysis: Moerdijk

5.1 Cluster overview: Moerdijk

Moerdijk industrial cluster is an important industrial zone for the Netherlands and Europe, considering the location and business activity in the area. Regarding the chemical industry, important companies produce their products, mainly polyolefins and glass materials in the port of Moerdijk area [39].

5.1.1 Location and infrastructure

The port of Moerdijk is located in West Holland, southern of the port of Rotterdam, which is the largest port in Europe, and has an open connection to the North Sea. Moerdijk has a strategic geographical location and is the fourth largest seaport in the Netherlands, while the area of the industrial area is more than 2500 thousand hectares [45]

Moerdijk cluster is located in the wider area of the ARRRA cluster (Antwerp - Rotterdam - Rhine - Ruhr - Area). [56]. ARRRA region is an important industrial area in Europe as it concerns the petrochemical industry, Germany, the Netherlands and Belgium. The industrial activity of this region is important as it constitutes 40% of the petrochemical production of the European Union. The reason that the productivity in this area is efficient and highly profitable is the significant location, the interconnected network of pipelines, the advanced transportation system, large ports, such as the Port of Rotterdam and the Port of Antwerp, inland waterway, roads, railways and airports (Figure 5.1). There is also a high-quality of knowledge, research and innovation. The area is globally competitive in the production of various chemical product groups.

The strategic location of the Moerdijk is of particular importance for the transport of products and feedstock used for the production of various chemicals and mainly petrochemicals. It is a fact that the largest percentage of materials used and produced in the industrial part is transported through the pipeline network. The remaining materials are mainly transported through the port via ships [70].

Figure 5.1: Pipelines network in ARRRA (Antwerp-Rotterdam-Rhine-Ruhr-Area) [24].

The port of Rotterdam and the port of Antwerp have important refineries which can supply Moerdijk [59], since they are geographically close. The geographical proximity to the port of Rotterdam in addition to material exchanges has led to it being considered Moerdijk, as sub-cluster of the Port of Rotterdam or the so-called Rotterdam-Moerdijk cluster. Nonetheless, the chemical production in Moerdijk is significant enough to analyse Moerdijk as an independent industrial cluster.

5.1.2 Companies

As mentioned in the chapter 4 this particular study focuses on the port of Moerdijk and the companies operating in the area. One of the main reasons that this area was selected is that it is one of the three companies which operate steam crackers in the Netherlands, namely that of Shell Chemie BV. Steam Crackers are responsible for a significant proportion of the environmental impact in the chemical industry. Shell also produces other important chemical products in the region. Apart from Shell, other important chemical companies have their production sites in the port of Moerdijk.

In the area of the port of Moerdijk, many businesses of various kinds are active, mainly related to trade and logistics. At the same time a port with such available space and infrastructure is the suitable location for industries to be developed. This industrial site hosts a lot of manufacturing companies as well. So, in addition to businesses related to trade, there is significant activity in the construction sector as well as in the manufacture of chemicals and materials (such as metals and packaging materials).

This study will consider the chemical industry as well as the production industry of some materials. Besides Shell, there are other chemical companies in the industrial site of the Moerdijk. These chemical industries are presented below:

- Shell Nederland Chemie B.V.
- Hexion B.V.
- Basell Benelux B.V. (Part of LyodellBasell)
- Air Liquide Nederland B.V
- Ardagh Glass Moerdijk B.V.
- Omya Netherlands B.V.

In the section 4.2 on data collection, it was mentioned that not all the companies will be taken into account, but only the processes of some specific companies, in particular Shell, Ardagh glass, Hexion and Lyondellbassell.

Although these companies are a small sample of the cluster, these processes result in high CO_2 emissions and they have high energy demand, which nowadays is based on fossil resources. The aim of this study is to tackle the problem of high emissions in the chemical industry and, therefore, it is essential to study processes that require high energy demand and products based on fossil feedstock.

An important part of this study is the collection and availability of data and to do this analysis. The chemical industry usually consists of complex processes that we need to know in order to be able to do the analysis required to arrive at the proposed solution. The processes and products for each company will be analysed in the following chapter.

5.1.3 Products & Processes

Shell Chemie B.V.

Shell is an international world's leading company in the chemiclal industry with expertise in the exploration, production, refining and marketing of chemicals. Shell supplies industrial customers over 17 million tonnes of petrochemicals per year [59]. Although the headquarters are located in Europe and specifically in the Netherlands, and the United Kingdom, there are many industrial sites on all continents. In Europe there are chemical production sites, refineries, and administrative departments, mainly in the Netherlands, Germany and the United Kingdom. In the Netherlands there are two industrial sites. In Pernis (Shell Netherlands Raffinaderij BV), there is an oil refinery and chemicals are also manufactured. The second industrial site is Moerdijk which has been considered the case study of this study [59].

Shell is the largest chemical manufacturer in Moerdijk. Its main products are chemicals, mainly olefins, which are supplied to other companies to make their final products. Shell's main process is the steam cracker which is naphtha based and produces high value chemicals line ethylene, propylene and benzane which are of high importance for the production of other intermediate chemicals and products. Some of the chemicals produced are processed by the company itself other companies that manufacture final products [59].

The block diagram (figure 5.2) shows all the products that are manufactured by the shell company in the industrial site of Moerdijk and through this figure, someone could easily understand the whole value chain of chemicals and how they are connected to each other. With the letter P, the production processes that take place are represented.

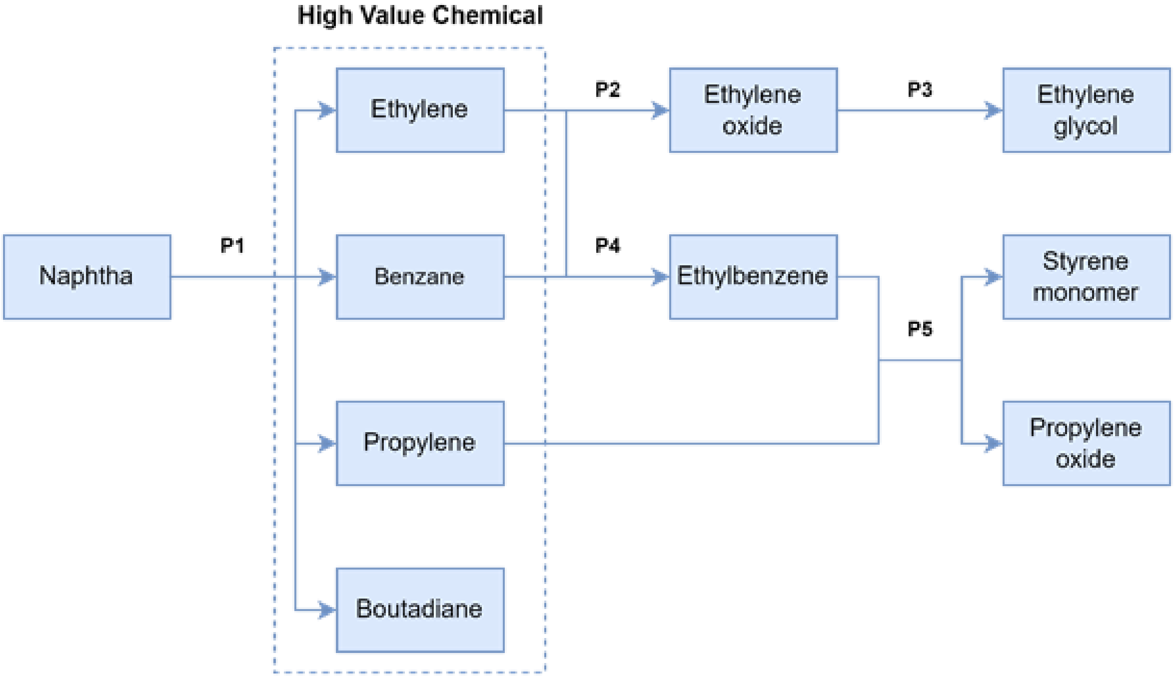


Figure 5.2: Product value chain of of Shell Chemie B.V.

The list of the production processes that are illustrated in the figure 5.2 are explained bellow:

- P1: Steam cracker: Naphtha based - ethylene
- P2: Ethylene oxide production
- P3: Ethylene glycol production
- P4: Ethylbenzane production
- P5: Styrene monomer & propylene oxide production

Ardagh Glass Moerdijk B.V.

Ardagh group is a manufacturing company which produces metal and glass packaging; materials which are sustainable and recyclable. It is a leading company with 65 production sites worldwide, in 16 countries [8]. At Moerdijk industrial site, Ardagh group has a production site in which glass packaging is produced through two production processes. The list of the production processes is illustrated in the figure 5.3 and they are described below:

- P6: Container glass melting process
- P7: Post-melting process CG

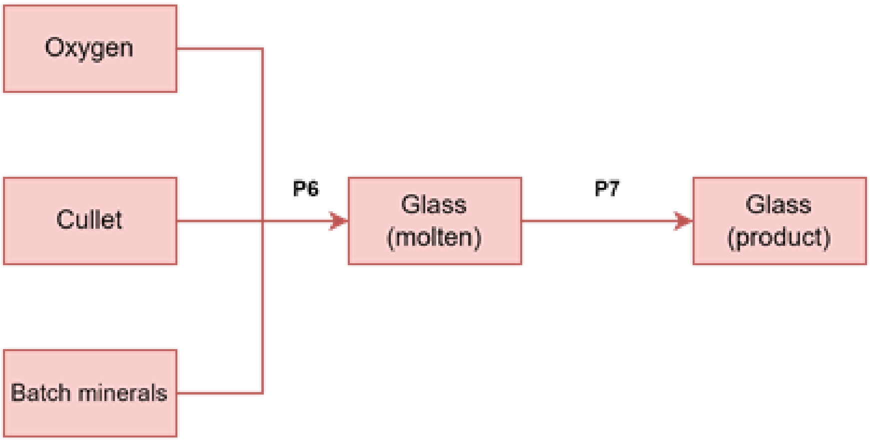


Figure 5.3: Product value chain of Ardagh Glass Moerdijk B.V.

Hexion B.V.

Hexion B.V. is a chemical manufacturing company with manufacturing plants around the world. The European headquarters are located in the Netherlands, where there is also production of products in three different locations, in Pernis, Botlek and Moerdijk. At Hexion Moerdijk production plant, ethylene oxide is produced. For the production of ethylene oxide, the basic raw material (figure 5.4) is ethylene, which is produced in Moerdijk by Shell. Also, the production plant is located right next to Shell's.

Figure 5.4: Production in Hexion B.V.

Basell Benelux B.V.

Lyondellbasell is a global chemical manufacturing company that produces chemicals, polymers and fuels. According to the company's website, it is a company that is environmentally conscious of the circular economy and invests in plastic recycling and decarbonisation. In the Moerdijk cluster, Lyondellbasell has a Cataloy plant (Besell Benelux B.V.). Catalloy is a polymer which has a wide range of applications for the manufacture of final products, while this production technology is considered the most advanced and this production plant is the largest plant of catalloy in the world. As shown in figure 5.5, the feedstock of the process is ethylene, propylene and a butane; the first two are supplied by Shell.

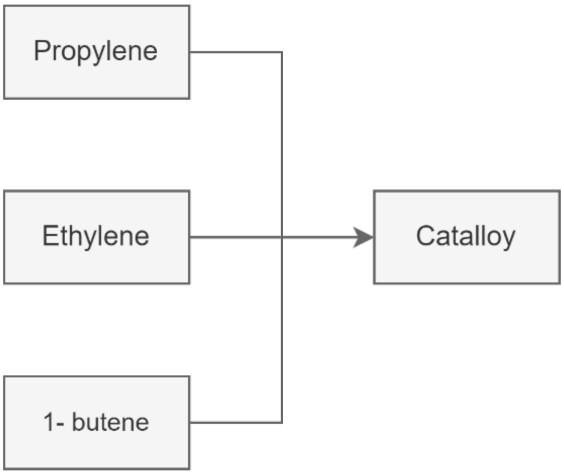


Figure 5.5: Production in Basell Benelux B.V.

The figure 5.6 presents the Production Process of Catalloy as described by the company's official technical sheet. This is a polymerization process for which there is no publicly available information on production capacity.

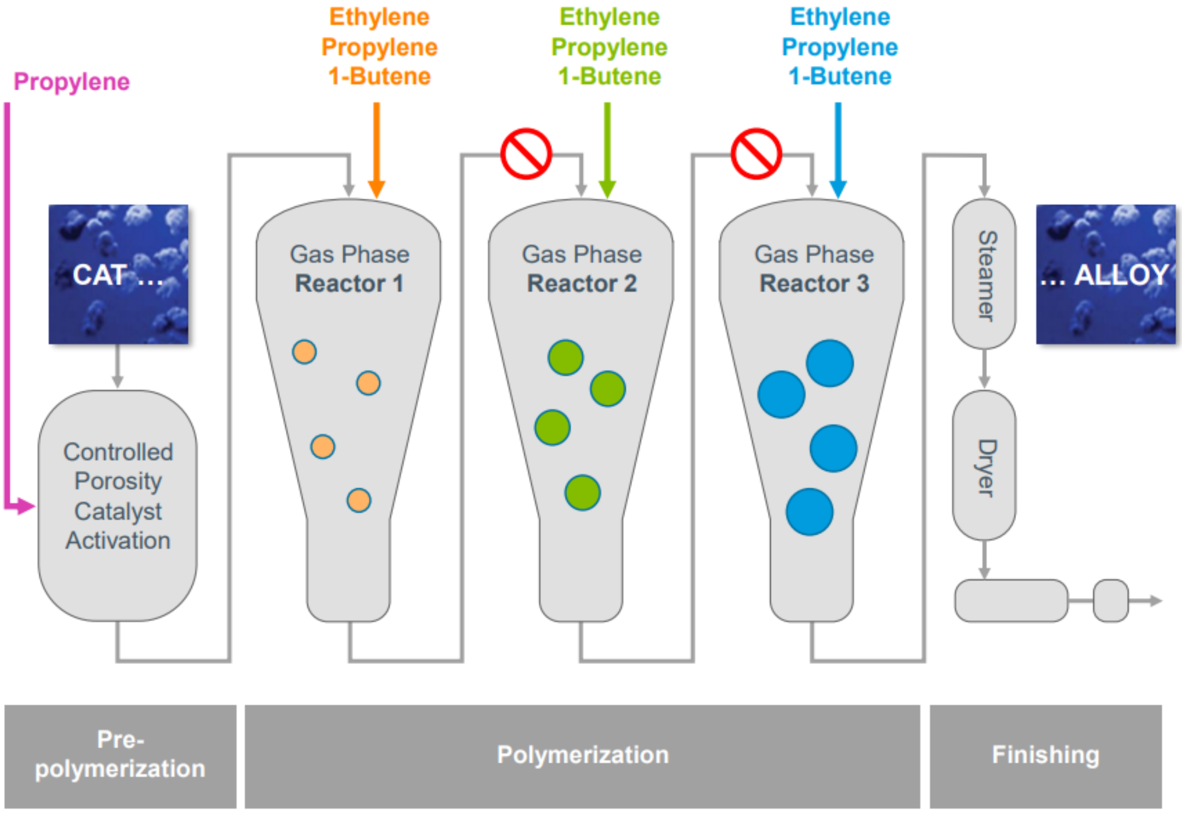


Figure 5.6: Catalloy production process in Basell Benelux B.V.[11]

5.1.4 Scope & Boundaries of the analysis

In the previous section, all the companies that were taken into account were described, as well as all the products with their production processes in this case study. The figure 5.7 shows an overview of the products that were considered for the scope of the study. In this figure, each company is represented by a different color, as well as products and raw materials are placed according to the category, depending on whether they are a source, a commodity, an intermediate chemical or a product that is used directly as an application. The companies considered are Shell, Ardagh glass, Hexion and Lyondellbassell.

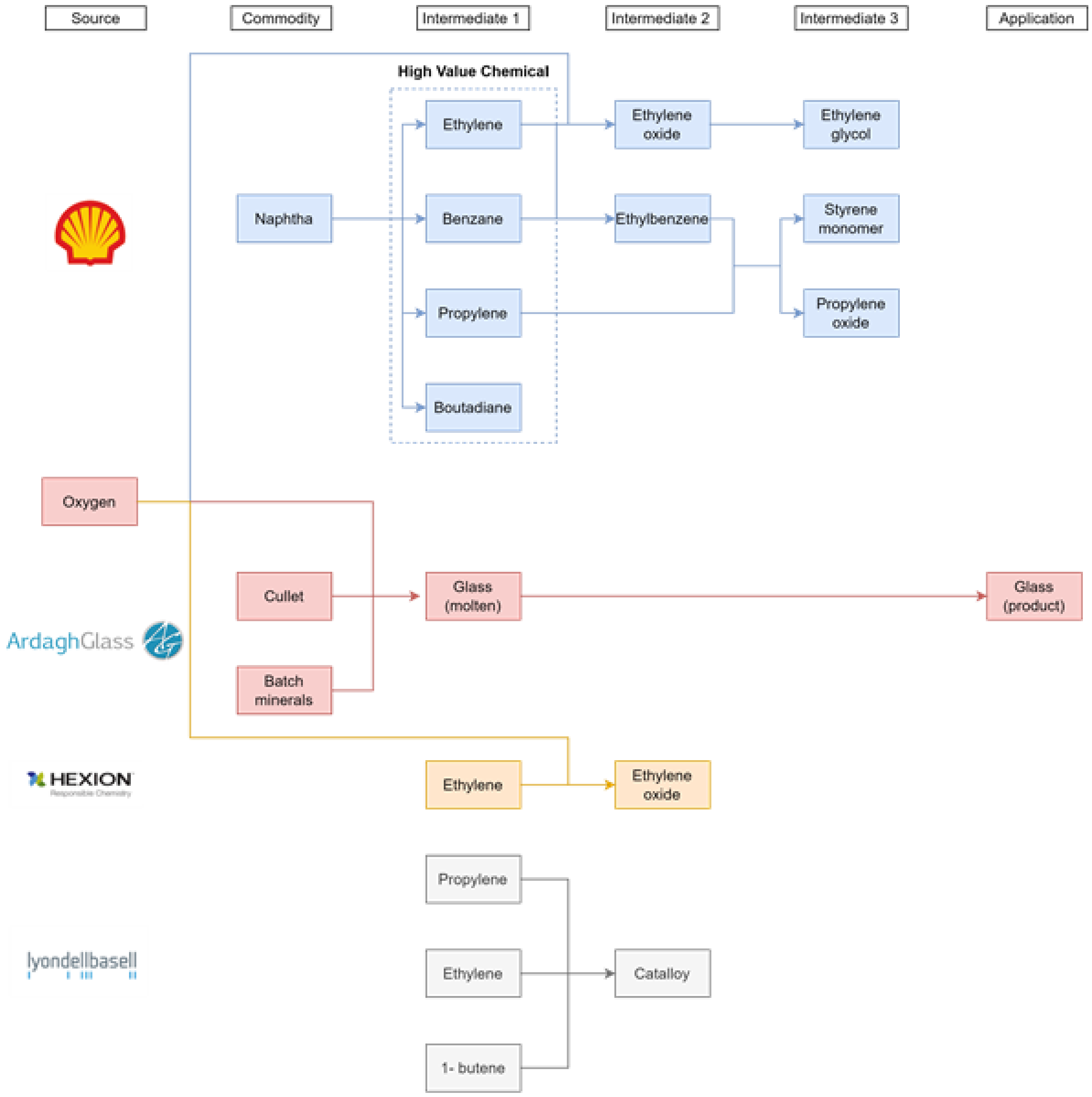


Figure 5.7: Cluster overview: Scope & Boundaries of the analysis

5.1.5 Mass & Energy flows

In this section the flows that have been considered (section 5.1.3) of this analysis will be quantified. It is important to know the flow of materials in the cluster in order to know which are the feedstocks that are used, but also what is the output. The output of a process could be the product, but also byproducts and residual streams. In the chemical industry there is a high demand for energy, which is usually originating from fossil sources. That is the reason that in this section the energy flows will be analysed. Also, the residual streams are, in many cases, energy streams, like steam of residuals that will be used as a fuel.

Plants Capacities

The processes and the products are already described in the section 5.1.3. The production capacity of the plants that are considered on the figure 5.7 are show on the following tables. In the table 5.1 all the products with their capacities that are produced by Shell Chemie Moerdijk BV are listed.

Table 5.1: Plants production capacity from Shell Chemie Moerdijk B.V.

Technology Description	**Main Product**	**Production Capacity**	**Unit**
Steam cracker: naphtha based	Ethylene	900	kt/y
	Propylene	500	kt/y
	Benzene	500	kt/y
	Boutadiene	115	kt/y
	Total: High value chemical (HVC)	2180	kt/y
Ethylene oxide production	Ethylene oxide	305	kt/y
Ethylene glycol production	Ethylene glycol	155	kt/y
Ethylbenzene production	Ethylbenzene	640	kt/y
Styrene monomer & propylene oxide production	Styrene monomer	450	kt/y
	Propylene oxide	207	kt/y
Styrene monomer & propylene oxide production	Styrene monomer	550	kt/y
	Propylene oxide	253	kt/y
Steam boilers and CHP	Steam (high pressure)	1060	MWTh

In the table 5.2 the products with their capacities that are produced in Ardagh Glass Moerdijk are listed. To be more specific, in this case, the product "Glass (molten)" is an intermediate product for the production of the final one, "Glass product". The reason that this information is mentioned is because the whole amount of the intermediate product is used in the next process, so this "main product"is not an output in the end.

Table 5.2: Plants production capacity from Ardagh Glass Moerdijk

Technology Description	**Main Product**	**Production capacity**	**Unit**
Oxy/fuel furnace with bubblers and electricity generation	Glass (molten)	222	kt/y
Post-melting process CG	Glass product	200	kt/y

Feedstocks

Feedstock is a raw material which is supplied in a processing plant [12]. In the industry, the energy that is used is fossil fuels. In the chemical industry though the feedstocks are usually fossil sources. Specifically, natural gas and crude oil represented 87% of feedstocks in the carbon-based chemical industry, in 2016 [1].

The table 5.3 shows the raw materials used in Moerdijk for Shell and Ardagh. It can be seen that the main building block in Moerdijk cluster is naphtha as from it many other commodities are derived. These commodities are often used as feedstock in other processes on the site [59].

Table 5.3: Fedstocks (material input) in the industrial site of Moerdijk

Company	**Feedstock**	**Value**	**Unit**
Shell Nederland Chemie B.V.	Oxygen	63	kt/y
	Naptha	2812	kt/y
Ardagh Glass Moerdijk	Oxygen	276	kt/y
	Cullet	169	kt/y
	Batch minerals	54	kt/y

Energy carriers

In the chemical industry, the energy required to obtain the final product requires a high energy demand, as in order to produce the final product, high temperatures and special conditions are required. Also, many times additional processes are needed in order to separate the products. The table 5.4 shows the overview of the energy flows input into the system by type of fuel and by company. In the table 5.5 all the energy inputs are presented in detail. It is shown what the energy demand is per production process in the cluster and what type of energy is used.

Table 5.4: Summary of energy demand in Moerdijk cluster

Company	**Natural gas (PJ/y)**	**Fuel gas (PJ/y)**	**Electricity (PJ/y)**	**Steam (PJ/y)**
Shell	19,66	2,60	2,00	16,20
Ardagh	0,90		0,11	
Total	20,61	2,60	2,11	16,20

Table 5.5: Energy input streams in Moerdijk cluster by production process

Process	**Natural gas (PJ/y)**	**Fuel gas (PJ/y)**	**Electricity (PJ/y)**	**Steam (PJ/y)**
Steam cracker (High value chemical production)	18,05		1,28	9,40
Ethylene oxide production			0,37	
Ethylene glycol production		0,10	0,04	0,70
Ethylbenzene production	1,61		0,04	2,10
Styrene monomer & propylene oxide production		1,13	0,12	1,80
Styrene monomer & propylene oxide production		1,38	0,15	2,21
Container glass melting	0,79		0,01	
Post-melting	0,11		0,10	

Residual streams

In this section, all the information about the mass and energy flows and, all mass and energy balances, sould be presented. In addition to energy inputs, some of the processes also have energy outputs, which are usually what we call residual streams. These flows are important since they could be used as input in other processes and thus the energy efficiency would be higher and this is an opportunity for industrial symbiosis. These residual streams for the Moerdijk cluster are presented in table 5.6.

Table 5.6: Energy output streams in Moerdijk cluster by production process

Process	**Natural gas (PJ/y)**	**Fuel gas (PJ/y)**	**Steam (PJ/y)**
Steam cracker (High value chemical production)			
Ethylene oxide production			1,50
Ethylene glycol production			
Ethylbenzene production			2,00
Styrene monomer and propylene oxide production		1,71	
Styrene monomer and propylene oxide production		2,09	
Container glass melting	0,04		
Post-melting			

5.2 Emission Analysis

Since all the details concerning the production at the Moerdijk industrial site are known, the next step is to analyse the emissions these productions cause. The goal of the study is to reduce GHG emissions which are responsible for global warming. All the emissions from all the processes taking place in the Moerdijk cluster will be estimated.

5.2.1 Estimation of CO_2 emissions in Moerdijk cluster

There are two ways to estimate emissions. The first is to calculate; in the literature there are "emission factors" by which the footprint of a process or product can be calculated. The second is the data extraction from a reliable database, which was done in this case study. Specifically, for the Netherlands there is an organization NEa, Netherladse Emissieautoriteit (Dutch Emissions Authorities) [2], where it is publicly available information about the CO_{2e} that is emitted from companies' activities, with detailed emissions for each of their production plants. In the table 5.7, the GHG emissions are presented in detail, which are expressed as CO_2 equivalent per year for each process was taken into account, and also the total emissions of the cluster are also calculated. The total emissions are 2.8 Mt CO_{2e}/y. Also, taking into account that the total Dutch emissions in 2018 were 151 Mt CO_{2e}/y, the scope of the study is about 1.7% of the total emissions of the Netherlands.

Table 5.7: Moerdijk cluster: CO_2 Emissions in 2018 (Dutch Emission Authorities)

Company	**Process**	**Emissions 2018 (kt CO_{2e}/y)**	**Emissions Share (%)**
Shell Nederland Chemie B.V.	Steam cracker: naphtha based - ethylene	1545	55%
	Ethylene oxide ethylene glycol production unit	90	3%
	Ethylbenzene production	172	3%
	Styrene monomer and propylene oxide production unit 1		
		44	2%
	Styrene monomer and propylene oxide production unit 2	221	8%
		20	1%
	Steam boilers and CHP	662	24%
Ardagh Glass Moerdijk B.V.	Glass production unit	62	2%
Total Emissions		2817	100%

5.2.2 Analyse the CO_2 emissions in Moerdijk cluster per production unit

In the table 5.7 it the percentage of emissions are also calculated for each of the processes. This emission share is expressed in percentages and in table 5.8. The emission share serves to make visible and understandable which of the processes taking place in the Moerdijk cluster is the most harmful to the environment.

Table 5.8: Moerdijk cluster CO_2 Emissions share

Production Unit	**Emissions share (%)**
Steam cracker	55%
Ethylene Oxide Ethylene glycol production unit	3%
Styrene monomer Propylene oxide unit	16%
Steam boilers and CHP	24%
Glass production unit	2%

The emission share is presented in the figure 5.8 in pie chart form and thus, the percentage of emissions can be visualised. According to the results, it is obvious that the cracker operated by Shell is clearly the bigger emitter and in fact is responsible for more than half of the emissions considered in the scope of the study (55%), while the steam boilers and CHP system (utilities production unit) follows with a percentage of 24%.

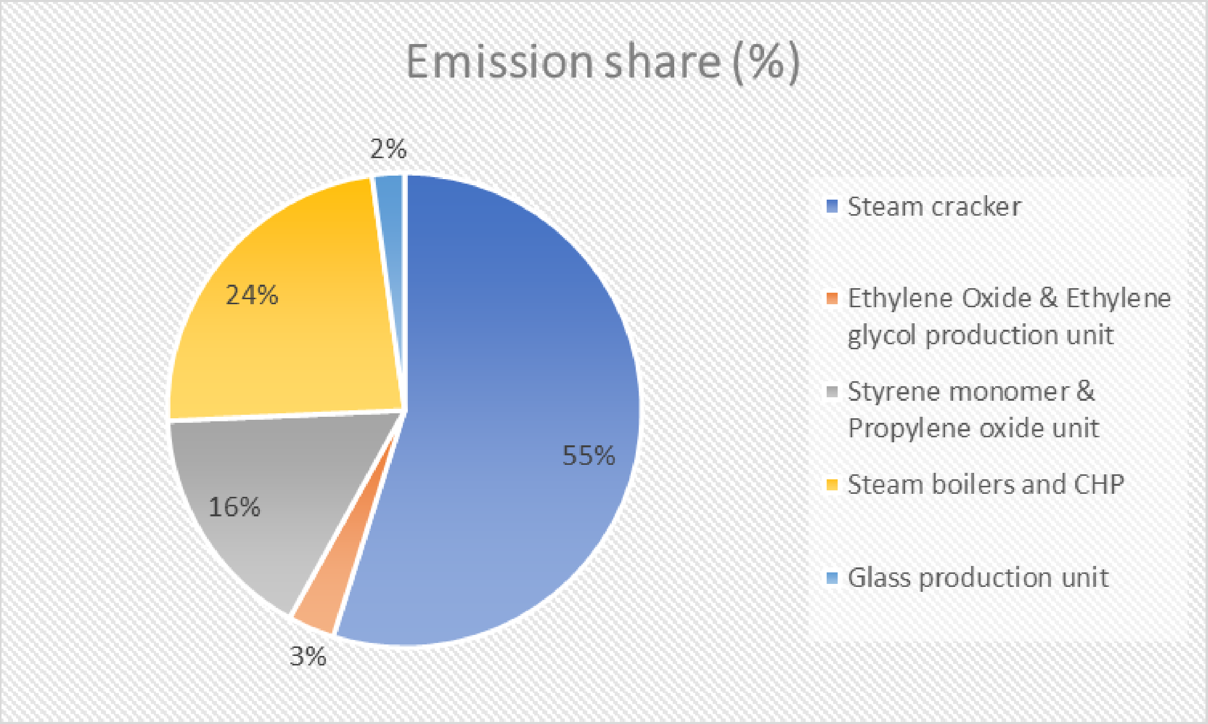


Figure 5.8: Moerdijk cluster - Visualisation of CO_2 Emissions share

Chapter 6

Decarbonisation Options

In this chapter, a literature study will be done on what are generally the options for decarbonisation in the chemical industry. After approaching the topic with a general view, it will be narrowed down to those technologies that are suitable for the processes and products mentioned in chapter 5. An attempt will be made as well to find the main characteristics of these new technologies, in order to facilitate the choice of the final scenario in which a specific case study will end up.

6.1 Decarbonisation options by category

The problem to be solved is how to achieve the reduction of high CO_2 emissions in the chemical industry. First, it is very important to know where these emissions are due. A chemical process mainly affects material flows and energy flows. Specifically, a process consists of four main parts. Initially, the feedstocks are used as inputs and processed to produce the final chemical. Also, in order to carry out each process, energy is required. The second part is the energy carries; the source and the type of the energy input usually affect the process' emission output. However, the output streams need to be considered. Output streams are the final product itself, as well as the by-products and residual streams. It could be assumed that apart from the product, the rest of the output streams are not useful in the analysis. However, there is a distinction whereby output streams that can be used directly as products are considered by-products. Regarding residual streams, their life cycle is of great importance for the process.

Taking into account these four parameters, the decarbonisation options can be separated more easily and their investigation is facilitated. The figure 6.1 is a nice illustration of all the decarbonisation categories as they are studied by MIDDEN project. In this figure it appears that there are seven different categories [46]. These categories are:

1. Fuel substitution
2. Feedstock substitution
3. Process design
4. Recycling
5. Product design

6. Use of residual energy
7. CO_2 capture and storage or re-use

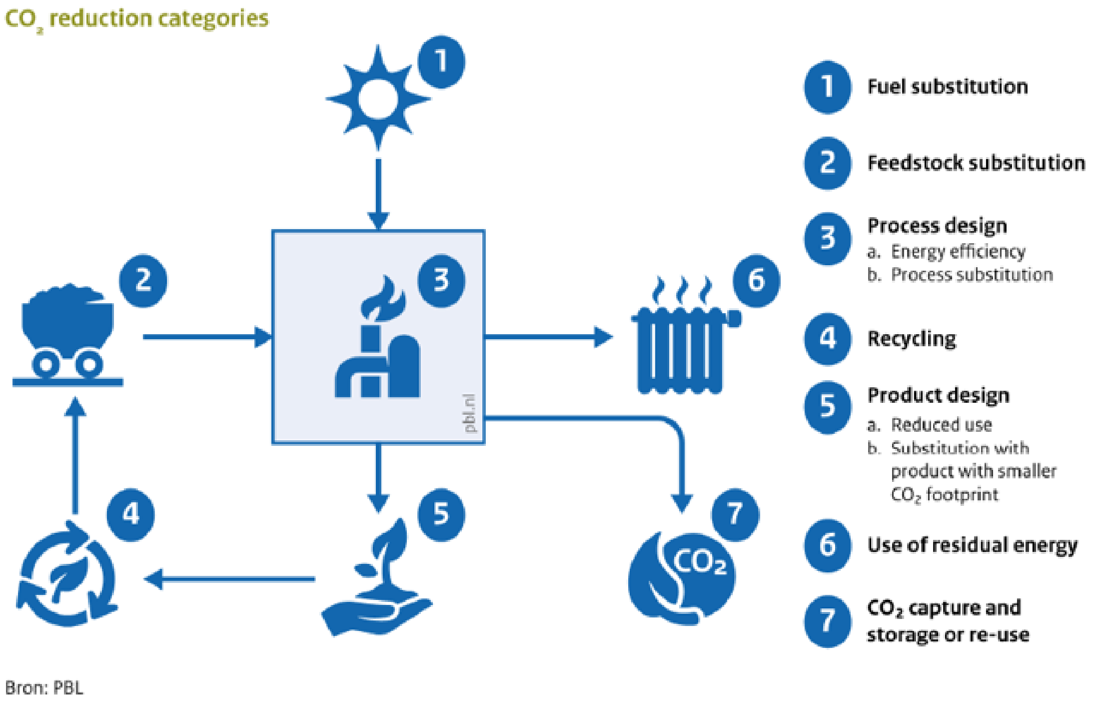


Figure 6.1: Visualisation of the decaronisation options categories [46]

It is observed that in addition to the four parameters mentioned, raw materials, energy carriers, residues and the product itself, an important area is the capture of CO_2 in order to store or re-use it in other processes where a significant amount of carbon dioxide may be needed. Also, recycling where possible plays an important role in reducing carbon dioxide. Finally, something that can change and significantly affect CO_2 emissions is the process itself. Replacing the processes or changing the way a product is produced automatically could affect all four factors mentioned at the beginning of this section.

6.2 Analysis of the decarbonisation options for Moerdijk cluster

In this section, the study will follow in the manner before mentioned. Specifically, the decarbonisation categories as defined by the MIDDEN project will be used in order to find the most suitable technologies for the specific cluster. In addition, the fact that in chapter 5 have been analysed all the processes that take place in Moerdijk cluster and the detailed quantitative information are known.

6.2.1 Fuel Substitution

As shown in figure 6.1, the first category to be studied is fuel substitution. Specifically, taking into account the fact that energy flows in the chemical industry are an important part of the production processes, a change in the type of energy used could reduce GHG emissions. Fossil energy sources are mainly used, as they are more efficient, but also cheaper. This is also evident in the Moerdijk cluster, as according to the table 5.4 the main source of energy is natural gas. However, in recent years, alternative lower carbon fuels, such as hydrogen or electric heating have shown promise.

Electrification

In the chemical industry, in order to process some materials and obtain the final product, special temperature and pressure conditions are usually required, which require high energy, mainly for heating. In order to produce heat amounts of fossil fuels are used, which are responsible for the high carbon footprint of the chemical industry.

Electrification seems to be an emerging technology nowadays. Electrification is the process of replacing a fossil energy carrier with electricity[3]. A nice example is electric cars, where more and more cars run on electricity instead of gasoline or diesel. This particular case is a form of direct electrification [68]. However, there is also indirect electrification which concerns the use of electricity in industrial production [17].

Electricity in the chemical industry is supported by many scientists and experts as the solution to tackle climate change. There are two ways of applying electricity in the chemical industry, which are either electric heating or the intervention of electricity in the process itself, the so-called electrochemistry [10]. At this point, the route of electric heating will be analysed. As from the analysis made in chapter 5, it is observed that the largest amounts of energy are used in steam cracking and for the production of steam. Fuel substitution is also studied in this subsection.

Although electrification is considered a promising solution to net-zero emissions, there are some challenges that do not allow the immediate implementation of this technology, while Technology Readiness level (TRL) is 6-7 [70]. The first point is how "green" is the electricity that will be used. In order to reduce greenhouse gas (GHG) emissions, fossil fuels should be replaced with green energy, which means that electricity is produced from low-carbon energy sources. Then, the implementation of electrification in a specific location will result in the reduction of emissions only if the electricity grid has a large percentage of renewables.

Another reason is that the chemical industry is one of the most complex industries and the products are produced on a large scale. This means there is no flexibility to change the process of chemicals are produced. Probably, the production has to switch off for a while and this is unpleasant for the manufacturers. Finally, although chemical production is a fairly profitable industry, technologies such as electrification require very high investments and therefore the CAPEX is high [32].

Generally, electrification can be applied either as an alternative energy for boilers for the production of steam or as alternative energy for furnaces [70] ; [57]. In the industrial cluster of Moerdijk, this technology can be applied in specific processes. These processes are the steam boiler system and the steam cracker. It is important to mention that these two processes are those that have the largest carbon footprint in terms of emissions. Through this technology, part of these emissions can be reduced [26].

Steam cracking is currently a process that uses gas-fired equipment (natural gas) to produce heat; gas-fired equipment can be replaced with electricity (Figure 6.2). According to the European Union research results (CORDIS), using green electricity can reduce the emissions of a cracker by 30% [26].

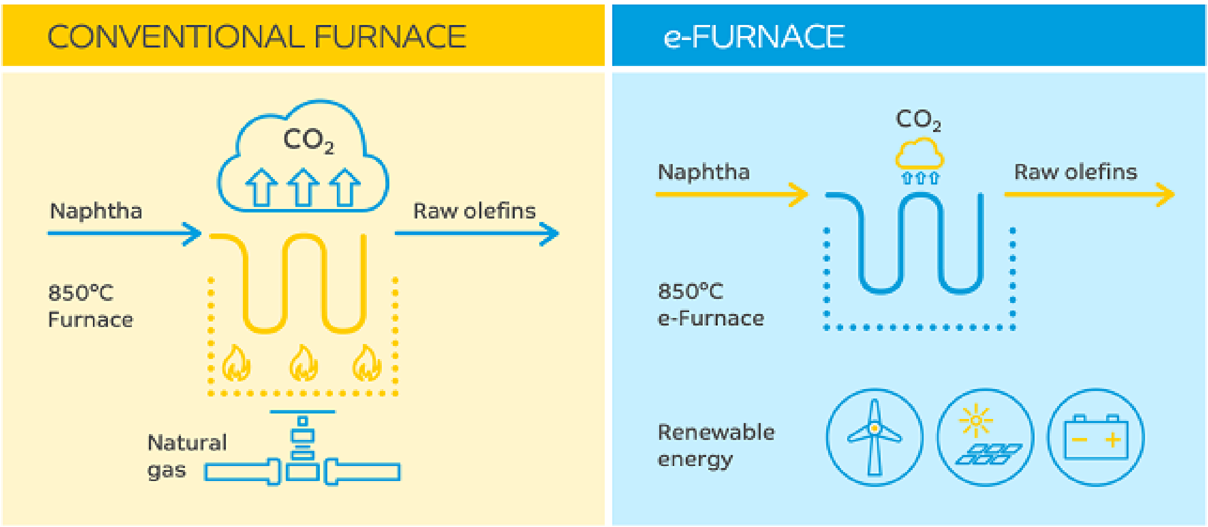


Figure 6.2: Replacement of gas-fired furnaces with e-furnaces (electricity) [57]

In Moerdijk, high amounts of steam are used in various processes. Steam production, as shown in the previous chapter, is carring a large part of the emissions. Steam is also used in other processes, such as the co-production of styrene monomer and propylene oxide, which means that if the steam production process is decarbonised, indirectly other processes which are carried out in the cluster will be affected. So, the implementation of an e-boiler in the Steam boilers and CHP system in the cluster could play an important role in the goal of net-zero emissions by 2050.

Hydrogen

Hydrogen is an important part of the chemical industry as it is used and produced in various ways, for example as a raw material for the production of chemicals such as ammonia and its other derivatives [62]. It is also obtained as a by-product from various chemical processes such as the chlorine production process and - more relevant to the case study - it is one of the products of the steam cracker [37]. However, hydrogen can also be used as an energy carrier. [6].

Hydrogen, when it is burned, produces heat and water as a by-product. This heat can be used as energy in many processes. Hydrogen as an energy carrier has some advantages that make it an emerging decarbonisation alternative, since it is a form of energy that can be stored, transported, and delivered in many ways. Although it is considered a promising form of energy, it does not mean that it is necessarily renewable. It is important for the study, since the goal is the decarbonisation of the cluster and the reduction of fossil energy sources[46]. How "renewable" hydrogen is depends on how it is produced [62].

Hydrogen is the first and simplest element that exists on the planet, and it can be extracted from many sources such as fossil sources, biomass and water[37]. Fossil fuels can, for example, be produced from natural gas or coal. However, producing hydrogen from these sources is not considered as a solution to the problem, because these are non-renewable sources of energy.

Regarding the other routes of hydrogen production, hydrogen can also be produced using biomass as a raw material through thermal and biological processes. The thermal processes are pyrolysis or gasification, while the biological ones can be through fermentation and biophotolysis [43]. It should be taken into account how renewable its production method is. Currently, hydrogen as a fuel is divided into categories. The main ones are green, gray and blue hydrogen [46].

Green hydrogen is produced by splitting water (H_20) into its components hydrogen (H_2) and oxygen (O_2) with the help of electrolysis. When the electricity used comes from renewable energy sources, then it is called green hydrogen. Although green hydrogen is considered a truly renewable energy source and sustainable option, there are some challenges that are being faced and prevent green hydrogen from being commercialized as an alternative fuel. Also, electrolytes needed for its production have a high cost [66]. Because of these, the TRL of this technology is around 4 and it is estimated that green hydrogen will become widely commercialized in 2050 [49].

Another type of hydrogen is gray hydrogen, which is essentially the production of hydrogen using natural gas (CH_4) and steam (H_20), the process of steam methane reforming. In this case, these two elements are divided into hydrogen and carbon dioxide. However, during the production of hydrogen, quantities of carbon dioxide are released into the air, which would be good to avoid. The idea is to capture the CO_2 produced and store it underground [66].

Therefore, combining the production of gray hydrogen and the collection of carbon dioxide, makes the process carbon neutral. This is blue hydrogen. It is considered to be a cheaper solution than green hydrogen, more direct and might be used faster. The use of residual gases instead of natural gas is also an option that is studied, and it is a way to enhance industrial symbiosis, especially in the case of an industrial cluster [46].

6.2.2 Feedstock substitution

The second category that will be studied is the substitution of the feedstock. The aim of this specific study is to address the high carbon dioxide emitted by the processes that take part in the cluster. The process itself is responsible for a large percentage of the emissions, but it is very important what is used as a feedstock. Feedstock is not really calculated in direct emissions, but it should be considered as part of the system. An example is the steam cracking process. According to Ren et al., about 30% of CO_2 emissions come from the feedstock, which in this particular case is naphtha (Figure 6.3). Naphtha is one of the main commodities for production of various chemicals, out of which many are intermediates in the value chain, leading to an even bigger number of final products (Figure 5.7). In the case of replacement of this feedstock with a more sustainable one, a reduction of up to 30% in emissions can be achieved [47].

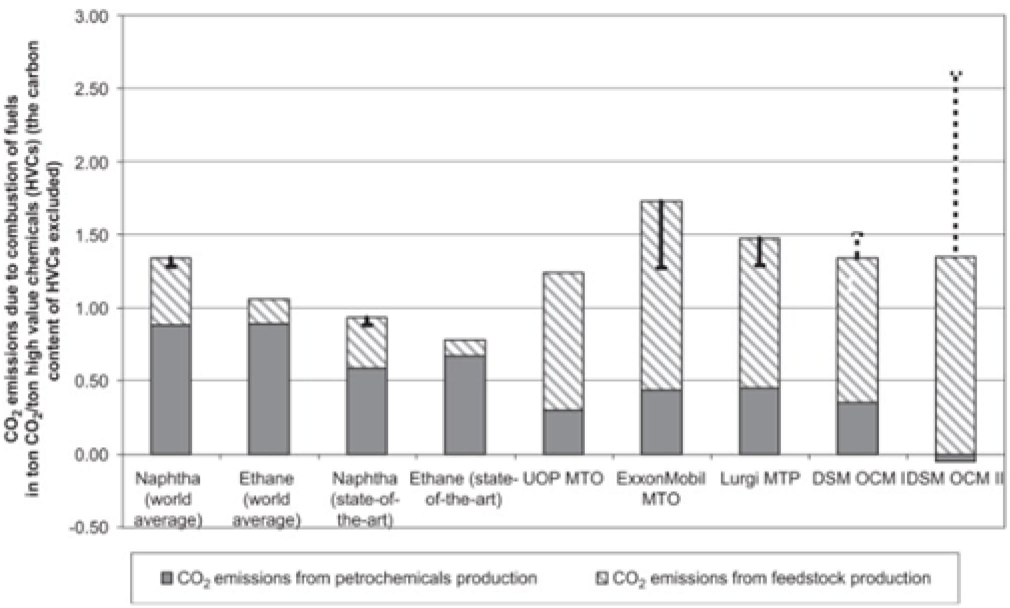


Figure 6.3: CO_2 emissions in steam cracking [54].

Use Bionaphtha as Feedstock

One of the two main sources that can be used as a substitute feedstock for steam cracker is the use of bionaphtha. Naphtha is the basic feed in the steam cracker and it is originally a product of crude oil refining. A way to replace naphtha is the production of bionaphtha, which is quite challenging, because bionaphtha demand can't be met easily. Bionaphtha can be produced in various ways and the categories are two; production through upgrading (vegetable) oil and production through biomass gasification followed by the Fischer Tropsch process. It is, also, important to note that this alternative cannot replace 100% naphtha. In this particular case study, the co-feed of 10% bionaphtha (the rest-90% fossil based naphtha) in the steam cracker will be studied [70] ; [47]. Therefore, from the emissions of this process, the goal is to reduce 10% from the 30% of emissions that correspond to the feedstock (Figure 6.3) [54].

Use waste Plastic Oil

Another feedstock substitute for naphtha could be waste plastic oil. Generally, industrial symbiosis is something that has been of concern in recent years as it can contribute to the reduction of CO_{2e} emissions. Thus, various residual streams are studied for how they can be utilized in order to achieve this goal. Plastic production has a large share in the market as plastics are produced for a wide variety of applications as in transport sector, civil engineering, for home appliances, electronics, etc. Packaging is a really small percentage to be mentioned here, and yet - many of these other plastics can be recovered as well. From these processes, however, there are large amounts of residues, of which only a small part, around 29%, is recycled [36]. Recycling of waste streams is an issue of concern to the plastics manufacturing industry.

Waste plastic oil is a case that has been studied. If it is processed appropriately, it could be feedstock for steam cracker and olefin production. Firstly, not all plastic waste is suitable to be treated with technologies such as pyrolysis. Polyolefins residues are definitely suitable and after upgrading processes they could meet the steam cracker specifications and be used as co-feed. The pyrolysis process, essentially thermal cracking, is needed. This process is followed by the separation of the solids and then the separation of the pyrolysis plastic oil product and the gases that are not considered suitable for steam cracking [27]. This process is illustrated in figure 6.4. It is important to note that the yield of pyrolysis plastic oil to waste plastic oil is 0.86. This value is useful for calculating the cost of this technology [46].

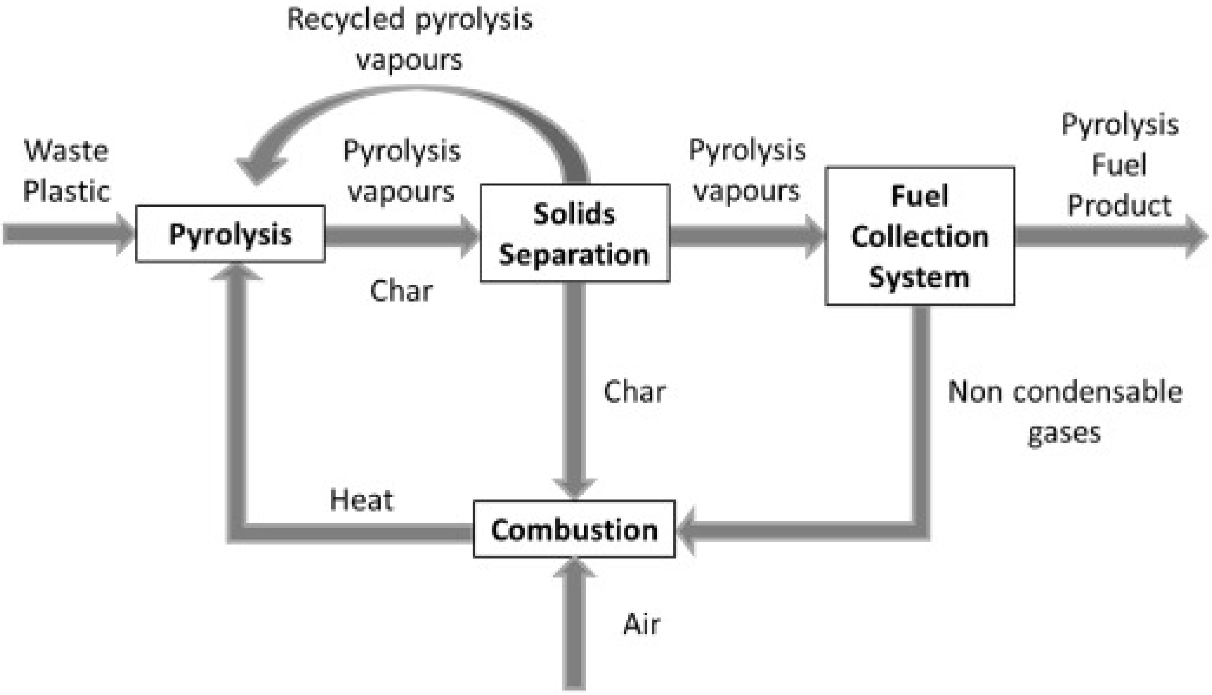


Figure 6.4: Pyrolysis of waste plastic oil [27].

Finally, this alternative will be studied is a 10% pyrolysis plastic oil product co-feed in the cracker. At the same time, the utilization of residual streams is worth studying in the cluster case. Especially, if there are plastic manufacturing companies with notable amounts of residual streams. Then, with direct waste recycling inside the cluster, industrial symbiosis is achieved [21].

6.2.3 Process substitution

The third category as studied in the MIDDEN project is the process substitution. This can be done in two ways, either by changing a part of the process to achieve a more efficient production, or by completely replacing it with an alternative. However, this may also mean changing other parts of the process such as the feedstock, the energy carriers and all the infrastructure[46].

Two different process substitution alternatives will be studied. The first alternative to be studied is the use of bio-ethanol for the production of ethylene, while the second is the production of olefins via methanol. Both these pathways have many different options for producing the final product. Also, there are some challenges that need to be considered, as in this case the entire process is replaced and the products can differ in terms of quantity and quality. For a company, the risk of switching off the production plant and building a new one is considered high, as base chemical production is quite a profitable business. These challenges will be discussed for both alternatives.

Use bio-ethanol to produce bio-ethylene

The chemical industry is mainly based on fossil sources and this has ranked it as one of the most polluting industries. In order to replace petrochemical production, much research has been done on how biotechnological processes could be used. The biotechnological processes are emerging technologies and some of them are already mature. Biotechnological process is the use of renewable raw materials for producing bio-based chemicals through fermentation of biocatalysts or other metabolic products, as well as enzymatic processes [31].

Bio-ethanol is one of the most notable bio-based chemicals. In particular, bio ethanol can be produced from many renewable sources, mainly from agricultural ones, through microbial fermentation, but its applications are also interesting. It is an alcohol that can be used as a renewable and highly competitive biofuel, but also for the production of other bio-based chemicals [60]. Although it is considered one of the most promising bio-fuels, in this case the focus will be on bio-ethanol as a feedstock for the production of bio-ethylene. The raw materials for the production of bio-ethanol from the agricultural field,can be sugars from sugar beet, sugar cane, corn, various types of grain (as they contain high percentages of carbohydrates) as well as starch and lignocellulosic biomass. The production of bio-ethanol using some of these sources is already widely commercialized; for example, the production of bio-ethanol from sugarcane in Brazil. This is also considered one of the most competitive and cheapest bio-ethanol production processes[71].

It is a fact that in the cluster of Moerdijk that is being studied, there are several production plants that require ethylene for the production of other chemicals. These are the production of ethylene oxide, which is produced by both Shell and also by Hexion, the production of ethylbenzane by Shell, and ethylene is one of the main feedstocks of the catalloy plant of LyondellBasell (Section 5.1.3). This means that if it becomes possible to produce ethylene from bio ethanol, it will be possible to replace the ethylene that is currently produced through the steam cracker and all the productions mentioned above will use a renewable feedstock (bio-ethylene) [40].

However, there are some challenges that need to be addressed. Initially, in case the steam cracker is replaced, a solution should be found for how the other products, such as propylene and benzene, will be produced. Then, either the steam cracker will continue working partially, or an entire bio-refinery with all the base chemicals that are required for the other processes in the cluster will need to be built. Apart from that, it is important to study whether this process is feasible since the amount of ethylene needed is high. Whether bio-ethanol is imported from abroad or produced using local cultivated products, it is really difficult to achieve such high amounts of bio-ethanol. In the first case, the main reason is the cost, as bio-ethanol has a high price and limited supply quantity, while in the second case, the land is needed to cultivate the crops for the sugars that will be used for the biotechnological production of bio-ethanol. Finally, even though renewable sources are used, the process of catalytic dehydration of bio-ethanol to bio-ethylene has high energy requirements and, therefore, this reduces the potential saving of greenhouse gases [29].

Methanol to Olefins (MTO)

In the effort to find ways to replace fossil fuels and minimize the use of resources in general, methanol (CH_4) has been introduced as an alternative. In recent years, how methanol can be converted into hydrocarbons or the route of methanol to olefins has been studied. Resulting is a new concept called the "methanol economy" [13].

Methanol to Olefins (MTO) reaction is quite important as it allows base chemicals to be produced from sources other than petroleum/naphtha. The conversion of methanol into olefins is quite specific. What matters and will make the difference is how sustainable the process of producing methanol is. Methanol can be produced in many ways, but in this study the renewable pathways of producing methanol will be analysed, which in recent years has been a high priority for researchers. These pathways are divided into two categories; there is the bio-based route and the e-based route [23].

Regarding the bio-based route, the first option is the production of methanol via biogas. In this case, biogas is produced from biomass, then syngas is produced from biogas, which is finally converted into methanol. The second is methanol through gasification. This pathway is the gasification of biomass to syngas and then, syngas is converted into methanol [23].

Regarding the e-based route, methanol is produced via electrolysis, using green electricity. In the first pathway, water is electrolysed into Hydrogen and then, water combined with Carbon Dioxide is converted into methanol. The second pathway is the co-electrolysis of water and carbon dioxide to syngas. Finally, as in the bio-based method, the syngas is converted to methanol. It is worth noting that carbon dioxide may come from capture in another process [23].

6.2.4 Carbon capute & Storage (CCS)

In an effort to reduce CO_2 emissions in industry, an idea that has emerged in recent years is the Capture & Storage (CCS), or even the Capture & Use of Carbon (CCU).

Essentially, if part of the emissions or even all of them are stored and not released into the environment, then the problem of gas emissions is solved. This solution sounds ideal as it is possible to continue the use of fossil fuels in the chemical industry and combine it with Carbon Capture & Storage (CCS). The idea of using the captured carbon is, for example, to produce "green" hydrogen [30]. Nevertheless, the energy consumed for the use of captured CO_2 is much greater than that of storage. In this study, we will focus on the CCS route.

It will be possible to capture the carbon dioxide produced by the steam cracker furnaces, the steam boilers and CHP systems, as well as in the glass production processes. The challenging part is where it will be stored [70]. Also, there are many plans in the Netherlands to capture and store the CO_2 in the North Sea and this is considered to be applicable to Moerdijk, because of the location of the port and the direct connection with the North Sea [46]. This technology is expected to be commercialized around 2035 [49].

6.2.5 Overveiw of decarbonisation options

In section 6.2 the analysis of all decarbonisation options concerning the processes taking place in the Moerdijk cluster was made. This analysis was done based on the categories as defined by the MIDDEN project. However, the most important part is to determine how they can be applied to the Moerdijk cluster. The details concerning the processes and the characteristics of these options were analysed in the previous sections. The table 6.1 shows an overview of all decarbinisation options and a brief description of the potential implementation of the processes.

Table 6.1: Overview of decarbonisation options [46]

Alternative	**Category**	**Relevant to process**
Electrification	Fuel substitution (1)	Applicable to processes using gas-fired equipment (e.g. steam cracking)
Blue or Green Hydrogen as fuel	Fuel substitution (1)	Applicable to processes using gas-fired equipment (e.g. steam cracking)
Use bio-Naphtha	Feedstock substitution (2)	Co-feed for steam cracker
Use waste plastic oil as feedstock	Feedstock substitution (2) Recycling (4)	Co-feed for steam cracker
Use bio-ethanol to produce bio-ethylene	Process substitution (3) Feedstock substitution (2)	Alternative route for ethylene production (replace the steam cracker) Alternative feedstock (ethylene) for 3 processes
Methanol to olefins	Process substitution (3)	Use Methanol to Olefins route (replace the steam cracker)
Methene to methanol methanol to olefins	Use residual streams (5)	Use the methane-rich gas
CO_2 capture storage (CCS)	Carbon capture storage reuse (7)	

6.3 Technical characteristics of the decarbonisation options

In this chapter, all the decarbonisation options for the Moerdijk cluster are analysed. In section 6.2, all these options were described in detail. In this section the technical characteristics or otherwise quantitative characteristics will be presented. These quantitative characteristics are listed in the tables below.

The first two basic characteristics for most alternatives have already been mentioned in the previous section, they are the Technology Readiness Level (TRL) and the year of entry into the market. Technology Readiness Levels (TRL) is a system that is used to estimate the maturity of a new technology towards full economic operation [53]. These two specific values are important as some of the technologies considered in this study are not ready to be implemented yet, either because the technology is not mature enough or because they need to be improved and overcome the challenges that prevent these technologies from being commercialized. It is important when trying to find a solution to know exactly when a technology could be implemented. So, these two characteristics may influence the final decision for the solution that will be proposed to deal with high GHG emissions.

Also, important quantitative data that will help in the analysis is how much the company should invest in order to implement the proposed alternative. For this, the value of the Capital Expenditure (CAPEX) for the implementation of the alternatives mentioned in millions of Euros (2019) was searched and also estimated based on the references from the literature.

Finally, an important factor that must be studied is the GHG emission savings. In order to choose the most appropriate alternative, apart from the economic aspect, it should be studied which is the most appropriate alterantive environmentally. For this, the potential of GHG savings was calculated for each alternative in CO_{2e} per year. Thus, the possibility of finding which of the alternatives has a greater chance of reducing GHG emissions. All these values are listed for each alternative in tables 6.2 and 6.3.

Table 6.2: Quantitative characteristics for the decarbonisation options considering the chemical production process [47] ; [46].

Decarbonisation option		**TRL**	**Market entry**	**CAPEX ($MEUR_{2019}$)**	**GHG emission savings (kt CO_{2e}/y)**
Electrification	30%	6 - 7	2030 (full)	330,77	108,9
	50%			460,87	181,5
	70%			587,48	254,1
	100%			777,71	363
Blue/ Green Hydrogen as fuel		4	2030 - 2050		
Use bio-Naphtha			present	152,74	36,3
Use waste plastic oil as a feedstock			present	124,61	36,3
Use bio-ethanol			present	191,23	484
Methanol to olefins		8 - 9	2025	862,25	
Carbon capture storage (CCS)		5 - 7	2035	114,21	726

Table 6.3: Quantitative characteristics for the decarbonisation options considering the glass production process [49].

Decarbonisation option	**TRL**	**Market entry**	**CAPEX ($\mathbf{MEUR_{2019}}$)**	**GHG emission savings (kt $\mathbf{CO_{2e}/y}$)**
Electrification	6 - 7	2030 (full)	100	62
Blue/ Green Hydrogen as fuel	4	-		47
Carbon capture storage (CCS)	5 - 7	2035	10000	47

In table 6.2, the characteristics of each alternative concerning the production of chemicals are illustrated. In particular, all the alternatives described in the previous chapter are mentioned as they can all be applied to chemical production processes (mainly in steam cracking). Table 6.3 lists the possible alternatives for glass production, where only three out of the seven alternatives mentioned in section 6.2 are applicable.

Finally, it is worth noting that the data was found in the literature and calculated specifically for the chemical production processes in TNO report by Oliveira et. al (2020) [47], while for the glass production processes the PBL report of Papadogeorgios & Schure (2019) [49] was used. The final values were calculated using the above references and adjusted to the capacities of the processes taking place in Moerdijk.

Chapter 7

Analysis of the Decarbonisation options for Moerdijk cluster

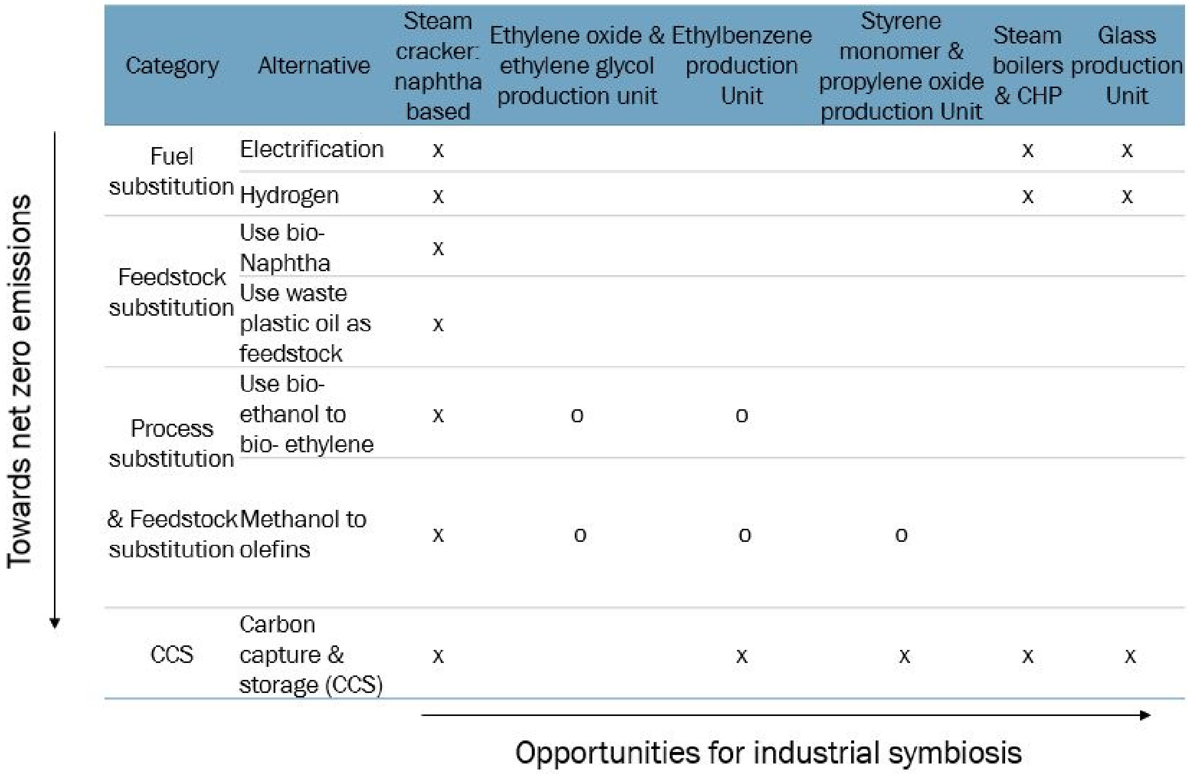
In this chapter, the decarbonisation options will be analysed, but this time the analysis will be more specific to the Moerdijk cluster. First a decision table will be filled in and then all the criteria for selecting the final solution will be listed. Finally, taking into account all the criteria, the final scenario that will be proposed will be presented.

7.1 Assembling decision matrix

Chapter 6 is thorough research and analysis of alternatives for cluster decarbonisation. Initially, all the different alternatives have been described and technical characteristics have been given. Having, also, analysed the industrial cluster of Moerdijk and, knowing all the quantitative and qualitative details, in this section, a table will be made, which will help to make the final decision and finally the proposal of the scenario.

In order to design this decision matrix, all the decarbonisation options studied in this chapter were initially listed on the y-axis. Then, on the x-axis are listed all the production units that have been considered in this case study as mentioned in chapter 5. Then, this table is filled in. An "x" is placed where the decarbonisation alternative could be implemented. At the same time, there are some production processes which, although they will not directly be affected - there is no change in the process - they will be indirectly affected. In this case, the product of the process which is decarbonised,is used as a raw material for this production process; then, an "o" is placed on the matrix. In this way, once the table is completed, there is an overview of whether one of the alternative technologies is suitable for implementation in more than one process and the industrial symbiosis opportunities can be identified. In conclusion, the x-axis is the pathway to net-zero emissions, while the y-axis is the opportunities for industrial symbiosis. The table 7.1 is the final decision matrix for the cluster of Moerdijk.

Table 7.1: Decision matrix for the Moerdijk cluster



Category	Alternative	Steam cracker: naphtha based	Ethylene oxide & ethylene glycol production unit	Ethylbenzene production Unit	Styrene monomer & propylene oxide production Unit	Steam boilers & CHP	Glass production Unit
Fuel substitution	Electrification	x				x	x
	Hydrogen	x				x	x
Feedstock substitution	Use bio-Naphtha	x					
	Use waste plastic oil as feedstock	x					
Process substitution & Feedstock substitution	Use bio-ethanol to bio- ethylene	x	o	o			
	Methanol to olefins	x	o	o	o		
CCS	Carbon capture & storage (CCS)	x		x	x	x	x

7.2 Criteria for selection the final solution

Most of the decarbonisation options in the cluster are technologies that could be implemented in more than one process. From the matrix (table 7.1), it could be said that the alternative technology that will be implemented will be the one that finds the most applications in the cluster. However, there are many criteria that will lead to the final proposal. These criteria are studied from 4 different aspects: environmental, economic, technical and social. Also, the criteria are divided into qualitative and quantitative.

Regarding the environmental aspect, which is perhaps the most important, the quantitative criteria mainly concern the current emissions and the potential emissions that will be saved. This means that initially the biggest emitter should be identified; where the most GHG emissions come from. It is also important to know the demand for heat and steam that is consumed in the initial situation, since these two sectors significantly affect the environmental footprint of the industrial site. At the same time, the potential savings of GHG emissions for each alternative should be taken into account. In this way, an alternative can be chosen precisely, if it has the potential to tackle a higher percentage of emissions.

Moving to the qualitative criteria, electricity seems to be very useful in the future, but it is also a complicated source of energy. Electricity is currently produced mainly from fossil resources. Most of the alternatives for decarbonisation need the use of green energy in order to achieve the goal of net zero emissions. Therefore, the quality of the electricity grid in the specific area should be studied. From a quantitative view, the percentage of the renewable sources for electricity production in the grid should be considered [34].

The following aspect is the financial one. The study concerns already existing processes that are profitable and operated by companies. These companies are following a specific technology that brings high profits. So, it is important to investigate which of the available alternatives is the most economically advantageous. For this reason, important criteria are considered the investment cost, as well as if the production cost whether with the new alternative will differ from the production cost in the current process and in what degree.

Table 7.2: Criteria for selection the final solution

Aspect	**Qualitative Criteria**	**Quantitative Criteria**
Environmental	(Renewable) electricity in the grid	CO_2 emissions per current process unit
		CO_2 emissions savings
		Heat & steam consumption
Economic		Production cost
		Investment cost
Technical	Space availability (infrastructure)	TRL
	Scalability	Market entry
	Reliability	Efficiency of main product per input
Social	Stakeholder's opinion	
	Social acceptance	

All the criteria for choosing the appropriate scenario are summarized in the table 7.2. At the same time, there is another criterion or method, through which an accurate evaluation can be made and takes into account both the economic and environmental factors. It is about the Levelised Cost of Carbon Abatement (LCCA). It is a new tool with which investors and decision-makers can compare various technologies related to the reduction of CO_2 emissions [64]. This tool was recommended by Columbia University's center on international energy policy. Levelised Cost of Carbon Abatement (LCCA) is, essentially, how much CO_2 can be avoided by a specific investment cost. It is measured in euros per tonne of CO_2 that is avoided. This tool will also be used in this case study and will help to conclude the final scenario that will be proposed [9] ; [28].

7.3 Final scenario

Taking into account the criteria mentioned in the previous section, as well as the extended analysis that has been done so far for the Moerdijk cluster, it is now possible to choose and propose the final scenario.

Firstly, the main criterion you choose is the fact that the steam cracker is responsible for more than 50% of the emissions of the whole cluster, so the choice will be based on this production unit. Also, as is visible in figure 7.1, the olefins (ethylene, propylene etc.) that are produced via steam cracking are used as feedstock in other production units. The steam cracker is owned by Shell and the olefins are used in other production plants of Shell, but other companies are supplied olefins by Shell's steam cracker [59]. Beyond that, it is known that the seven alternative technologies are all relevant to the steam cracker.

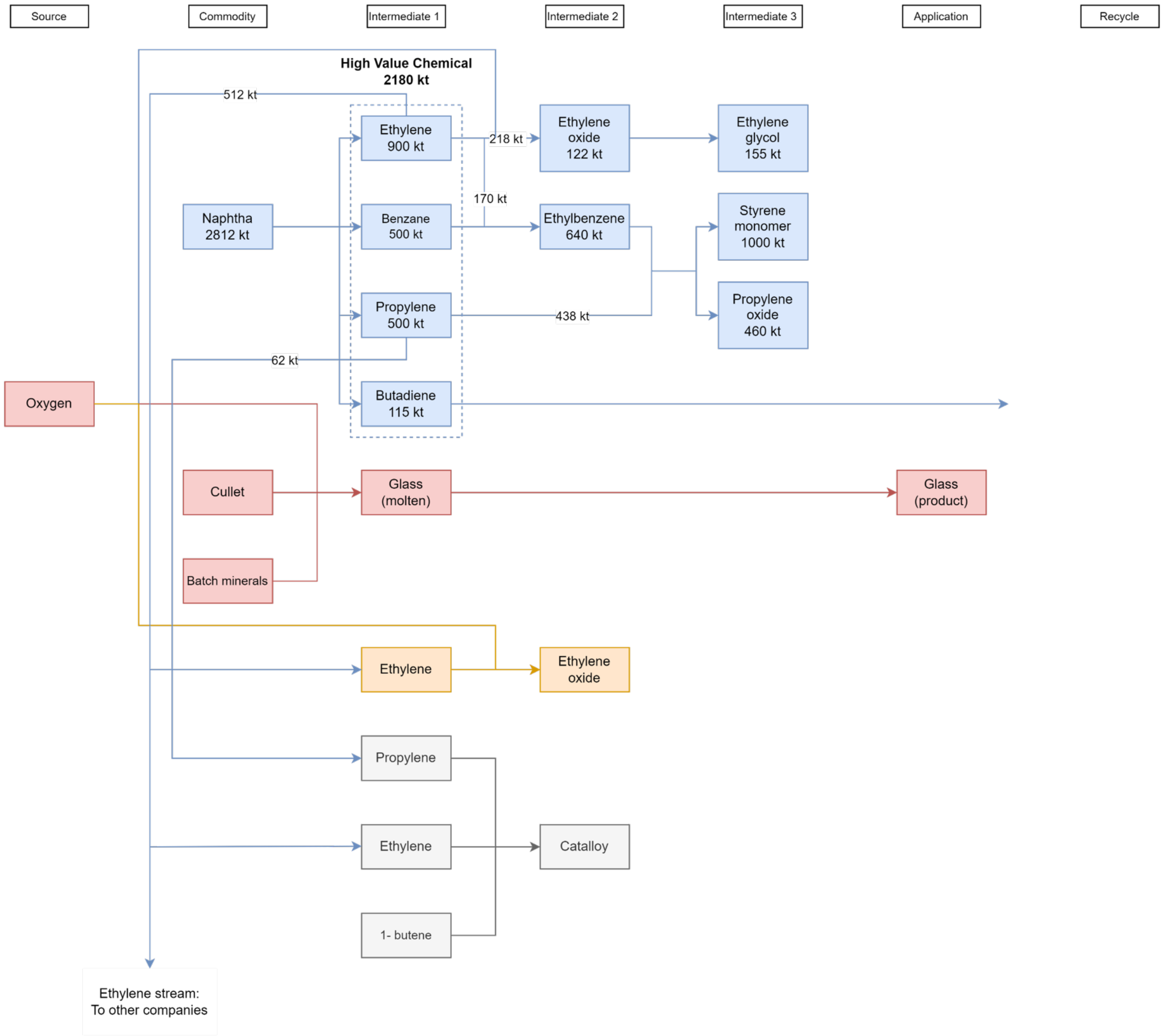


Figure 7.1: Olefins supply from the Shell's steam cracker to other production processes in Moerdijk (industrial symbiosis).

In order to conclude the proposed scenario, other criteria must be taken into account. An important role is played by the TRL of each technology, but mainly in the year of market entry. Therefore, based on the maturity of the technologies, the use of hydrogen is not considered in the scenario because of the low TRL of the technology and, also, the non-existing infrastructure in the area. It will be possible to apply it to Moerdijk after 2050 and only if a large blue hydrogen plant is installed in the Rotterdam industrial area [70].

Then, it is investigated whether its steam cracker could be switched off and olefins could be produced through other means. However, the production capacity of all of the olefins is high (900 kt ethylene/year) [70]. In both cases, it will be challenging to convince the companies that they should shift to another production route. In particular, in the use of bio-ethanol there is also the problem of scalability, since it is difficult to supply such a large amount of bio-ethanol in order to produce bio-ethylene.

The rest of the alternatives will be taken into account and the results from their application will be presented. In particular, initially the use of bio naphtha as a co-feed to the steam cracker (10%) is proposed and use of waste plastic oil in the same way, because these technologies are already in the market. However, the potential GHG emission savings is low. The next, and most important, step is to electrify. At the moment, this particular alternative is not mature enough to apply full electrification. For this reason, electrification is analysed initially at a rate of 30% and then 50%, 70% and then full electrification. According to the pbl report, full electrification will be available in 2030 [47].

According to the European Commission, (CORDIS: EU scientific results), by the electrification of the steam cracker, a reduction of GHG emissions up to 30% could be achieved using green electricity. If Carbon Capture & Storage is implemented, then a 90% reduction in GHG emissions could be achieved [26]. The CCS technology will not be commercialized before 2035 [49]. In conclusion, the proposed scenario is a long-term scenario of investments which may be implemented by 2035.

Table 7.3: Levelised Cost of Carbon Abatement for the final scenario

Decaebonisation option		**CAPEX ($\mathbf{MEUR_{2019}}$)**	**GHG emission savings (kt $\mathbf{CO_2}$/y)**	**LCCA (MEUR/kt avoided)**
Bio-Naphtha		124,6	36,3	3,4
Waste plastic oil		152,7	36,3	4,2
Electrification	30%	330,8	108,9	3,0
	50%	460,9	72,6	6,3
	70%	587,5	72,6	8,1
	100%	777,7	108,9	7,1
Carbon capture storage (CCS)		114,2	726,0	0,2

Chapter 8

Discussion & Development

After the case study of Moerdijk has been completed and after the final scenario has been proposed, in this chapter the topic will be discussed from a more general point of view. In the section 8.2 there is an attempt to generalise the analysis. The analysis that was done in previous chapters for the case study of Moerdijk towards designing a Decision Framework in the section.

8.1 Discussion on the analysis

In chapter 2 and specifically in section 2.4 the main research question was formulated. In order to facilitate the analysis, the research sub-questions were formulated as well. After the case study of Moerdijk cluster and the data analysis, an attempt will be made to answer these questions.

The first research sub question is "*How to define industrial symbiosis?*". This question is answered by the literature study that was done in chapter 3. The term industrial symbiosis is between different companies that cooperate in order to evolve and at the same time become competitive by exchanging materials, energy and by-products. Industrial symbiosis could be applied in an industrial cluster, due to the geographical proximity that by definition exists in a cluster. By deeply understanding what this term means, the researcher should be able to identify industrial symbiosis in the specific case of study. Thus, it can focus on finding the commonalities between the processes running in the cluster.

The second research sub question is "*How to identify the different decarbonisation options for a selected cluster?*". This question indicates a specific cluster and, for this reason, Moerdijk' s cluster was studied. In order to find the different decarbonisation options, a literature review should be done. However, the general search for alternatives in the literature should be limited to those that can be applied to the particular cluster. An important step is cluster analysis, which results in finding all the processes taking place in the cluster, the products and by-products, and the mass and energy flows. The alternative technologies concern the feedstock, the energy carriers and the process itself. Knowing all those details can make a more targeted search for available technologies in the literature. In this particular case, the alternative feedstocks considered are bio-based sources including bionaphtha, bioethanol and waste plastic oil. As alternative energy carriers, it was found that electrification and hydrogen as fuel for gas-fired equipment for steam crackers, for example. Finally, as an alternative process to steam cracking, the methanol to olefins (MTO) route is discussed as an emerging technology in the literature together with carbon capture and storage (CCS).

The third research sub question is "*How to identify opportunities for industrial symbiosis to create carbon neutrality?*". This question is more related to the first question and mainly concerns industrial symbiosis. After the cluster analysis and the analysis of decarbonisation options have been done, the aim is to propose the final scenario. This issue is complicated because the appropriate decarbonisation alternative should be found, not only for a specific process, but for multiple processes located in geographical proximity (cluster perspective). The industrial symbiosis is related with the fact that some of the products, mass and energy flows in the cluster are common and some of the alternatives can be applied in more than one process. Thus, the implementation of a solution can be done with a shared infrastructure at a lower investment cost since the cost will be shared among the involved companies. The way to find common solutions is described in the previous chapter and visualised in the table 7.1.

The last research sub question is "*Which criteria should be taken into account for assessing the industrial symbiosis options?*". The last question is about the criteria that must be taken into account in order to conclude to the final solution. These criteria for the case study of the Moerdijk cluster were analysed in section 7.2. The aim of the thesis is to present all these criteria in a more general approach in order to create a tool that can be used for other chemical industrial clusters. Each case could be different. In this chapter a generalization of the analysis will be carried out, using the knowledge and experience gained from the case study.

8.2 Generalisation of the analysis

The aim of this section is to study whether the analysis that has been done in the previous Chapters can be generalised to the specific case study of Moerdijk. In order to conclude the final scenario, the steps that were taken into account are very precise, and in fact that is evident from the structure of the report. Parts of the analysis have already been approached from a general view and then targeting to find a solution for Moerdijk.

In order to generalise, there are some limitations which should be considered. It is, therefore, important to evaluate whether the analysis that has been done is generalisable. According to Polit & Beck (2010), there are three models for generalisation; the statistical, the analytical and the case to case translation model. The latter is the model to be used in this case and is commonly referred to as "transferability" [50]. More specifically, in 1986 the methodologist Donald Campbell instead of external validity, considered that an expansion of the research could be made in the case where there is proximal similarity. This term was coined by him and what it means is that the results can be transferred when the research topic is similar. In this particular case, it could be transferred and generalised to other chemical industrial clusters through the proximal similarity model [15].

Although the model generalises with a limitation of considering the chemical industry and the perspective of the cluster, there are also many factors that could influence the result and differ, such as the location, the country, the production scale and the economy in which the cluster is located. It is certainly risky to assume that from a single case study a complete Decision Framework could be designed. For this result, it would make more sense if other cases of chemical industrial clusters were considered, so that the similarities could be observed. However, addressing all the limitations, an attempt will be made to show the flow the thoughts and steps of analysis carried out for the Moerdijk industrial cluster in a more general context.

8.3 Towards a decision framework

Taking into account all the limitations mentioned in the section, as well as the challenges faced in analysing the case study in the figure 8.3 all the steps followed for the Moerdijk cluster are depicted with a more general aspect. It can be seen that the first input is the data collection and their evaluation. Even before starting the first step, it is notable to know the availability of the data for the cluster to be studied and how accurate the information is. The more information, the easier it is to analyse the cluster.

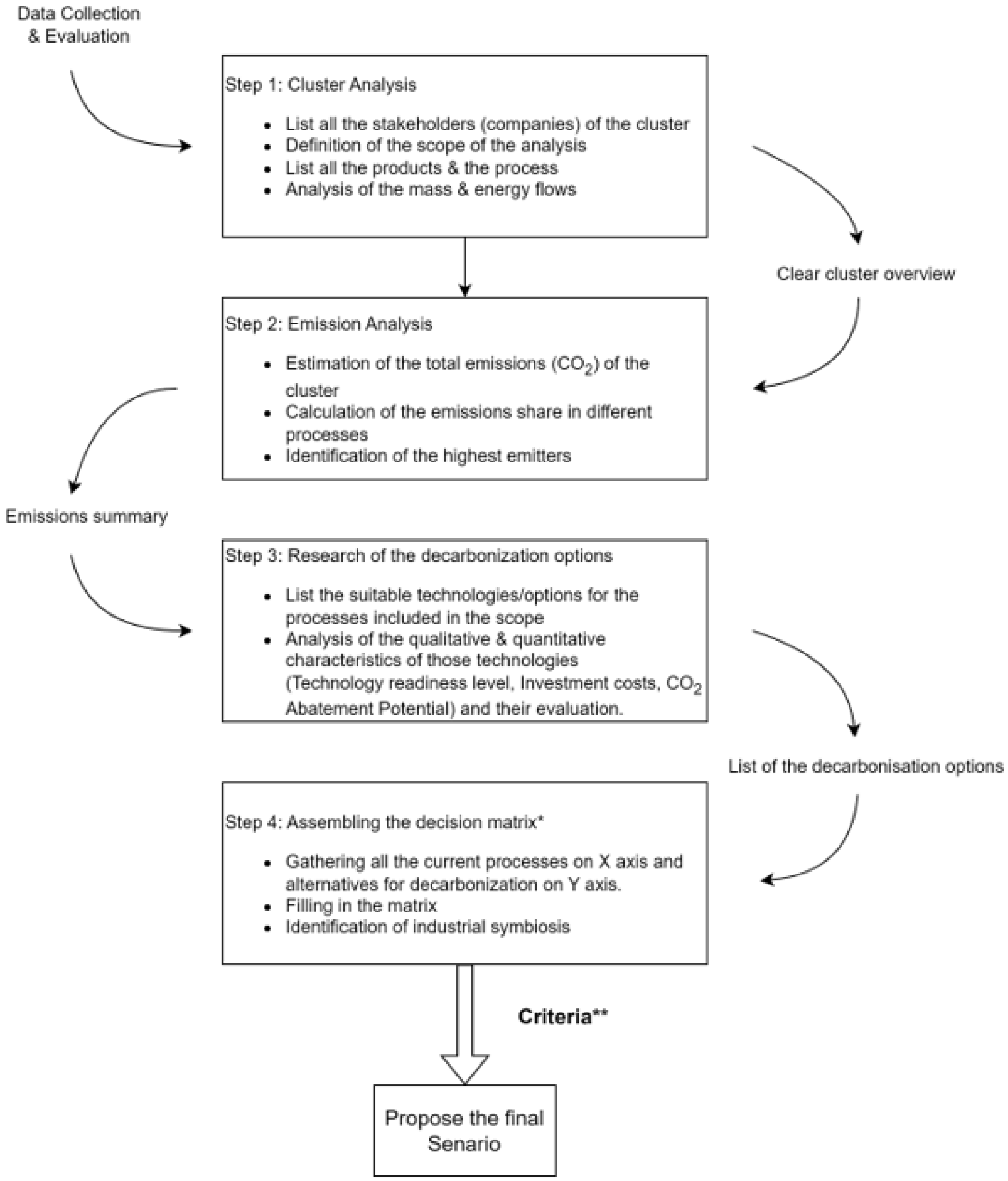


Figure 8.1: Towards designing a decision framework

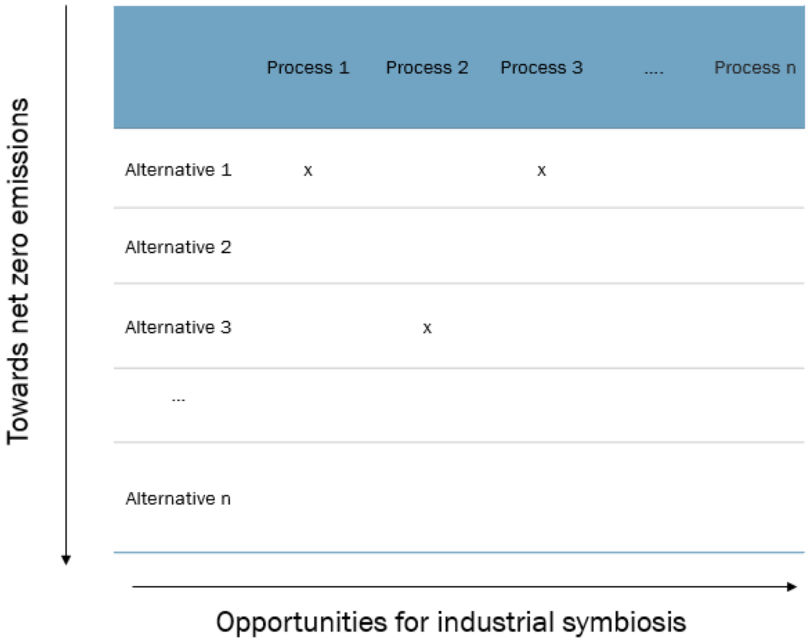


Figure 8.2: * Template for the decision matrix

The cluster analysis is the first step to be carried out, which includes the scope of the analysis and list of companies, their processes, products as well as energy and mass flows. After the first step, there is a clear overview of the cluster. The second step is Emission Analysis. Essentially, the goal is to find a way to reduce emissions, so in order to select an appropriate solution, the current emissions must be known and, also, from where are they coming from. After the end of the second step, an Emission Summary is also available.

In the third step, research should be done on what are the decarbonisation options, by a literature study and then by analysing all the qualitative and the quantitative characteristics of the alternatives. At the end of this step, a list of all the decarbonisation options will be available. The fourth step is to assemble the decision matrix. The way of filling out this table is described in detail for the Moerdijk cluster in the section 7.1 Nevertheless, in order to have a more general description of the matrix, the figure 8.2 presents a generalised template for the decision matrix. After the fourth step there is all the data so that the final decision can be made and using the criteria described in the table 8.1 a final scenario can finally be proposed.

Table 8.1: General criteria for selection the final scenario

Aspect	**Criteria**
Environmental	CO_2 emissions savings
Economic	Investment cost
	Production cost
Technical	Technology Reediness Level (TRL)
	Year of market entry
Social	Social acceptance
	Stakeholder's opinion

The criteria are divided into four different aspects: environmental, economic, technical and social. An important criterion is whether a technology can be applied to more than one process in the cluster. Since the problem that is trying to be solved is environmental, it is important to study the environmental aspects, mainly the potential for GHG emission savings for each alternative. Economic factors play an important role as the decision makers have a great interest in the cost, both the investment and the production cost. Also, there are technical characteristics that are the Technology Readiness level (TRL), which indicates whether each technology is ready to be implemented. Finally, the social factors are of great importance, as they concern the social acceptance of each alternative and the various reasons that a stakeholder may choose an alternative.

Chapter 9

Conclusion

9.1 Answer to the research question

Through this research, key points of the chemical industry were analysed in a general context but also more specifically for the Netherlands and an in-depth study of decarbonisation options to deal with the high GHG emissions that have led to the climate crisis has been done. This is a topic that worries scientists and policy-makers since climate change in recent years is increasingly evident. Considering this problem, the following research question was formulated:

How to develop a decision framework for assessing industrial symbiosis opportunities for a selected industrial cluster under different decarbonisation options?

Initially, the terms industrial clusters, industrial symbiosis and decarbonisation options were analysed in the literature review. Having a clear overview of what is being studied and after the research question has been formulated, it is now clear what the goal is, so there is an idea about what the desired outcome will be. Since the goal has been defined, the main point is to formulate the methodology to be followed.

As the main study case, Moerdijk industrial cluster is selected after which all relevant data for it was collected. It is important to set the scope and boundaries of the case study, as it depends, significantly, on data availability. The more accurate is the data, the more precisely the subject can be studied. For this research, only publicly available data was used.

The aim of the study is, initially, to provide a proposed solution for the specific industrial cluster being studied. The proposed scenario that is expected to be given is a proposed change in order to deal with high emissions and so, the reduction of CO_2 emissions. For this case, four companies were studied; three chemical manufacturing companies and one glass manufacturing company. They provide a sample of processes that are carried out in geographical proximity and thus, it is possible to study the topic from the perspective of a cluster. When the data is sufficient and accurate, it is possible to facilitate a cluster analysis for Moerdijk, as was done in chapter 5, where finally an overview of the cluster and a summary of the emissions are made. Moving on to chapter 6, the analysis of decarbonisation options is done in the literature and their qualitative and quantitative characteristics are presented.

An attempt was made to combine the knowledge gained from these two analysis. The research for the specific case study was completed taking into account the data and considering some criteria, all the alternatives that could be applied to the Moerdijk industrial cluster were evaluated. Finally, the proposed scenario is based on a series of alternative technologies; changes that, if made, will reduce the environmental footprint of the industrial site.

Initially, it is proposed to replace a small percentage of naphtha, which is the feedstock of the steam cracker with two alternative feedstocks, considering a co-feed of 10% and the use of waste plastic oil, also considering a co-feed of 10%. The rest 80% of the feedstock will still be fossil-based naphtha. With the supply of renewable feedstock, a reduction of approximately 72 kt CO_2 per year can be achieved. This percentage is very small compared to the total of 2.8 Mt CO_2 per year.

It is proposed to apply these readily available technologies first and then start the investment in implementing the electrification of the steam cracker. A high investment is needed and it is a fact that technology is now 100% mature. It is predicted that full electrification can be implemented by 2030. At the same time, it is important to notice how "green" the electricity grid is currently and what are the predictions for the future. Implementing full electrification of the steam cracking process could make a saving of 363 kt per year. If electrification is applied to other parts of the cluster, more emissions can be saved. Overall, with the co-feed of the two alternative feedstocks and electrification to the time tracker and glass production processes, an annual reduction 25% GHG emissions can be achieved.

Finally, the technology that is going to significantly reduce emissions is the Carbon Capture & Storage (CCS), which may be commercialised as a technology in 2035. If CCS is implemented to the steam cracker, it is going to save a total of 1224 kt CO_2 per year, which corresponds to around 50% annual reduction in CO_2 emissions by 2035.

While in this research a specific cluster is studied, the aim is to approach the topic on its most general basis. Taking into account the detailed analysis made of the Moerdijk cluster, an attempt was made to generalise the model followed for the Moerdijk study case. Considering the low generalisability, the final result is towards a decision framework. This framework consists of four steps and then, taking into account the quantitative and qualitative criteria that were analysed in the previous chapters, is an approach to the topic from a more general view. By following these steps (Figure 8.3) and applying them to other clusters, the study may achieve a remarkable result.

9.2 Recommendations

In this section all recommendations for improvement for the research will be mentioned. Initially, for the Moerdijk cluster case study, four companies were considered out of which detailed data was available for only two. Although Shell operates a steam cracker and also other production units for which there is data available, for some of the companies there was no data on the production capacities, so they were studied at a theoretical level. Even though there were processes to analyse, it would be difficult to find a way to get the data in all its detail in a reasonable time.

Regarding the companies, in addition to the quantitative details, there are also some qualitative details that could add value to this study. In the chapter that studied the criteria for selecting the final scenario, it was mentioned that the criteria concern four different aspects. social aspect was one of the criteria, considering public opinion on certain technologies and their implementation. Therefore, the company's opinion on how willing they are to implement an alternative for decarbonisation is one of the criteria that could be taken into account and it is suggested in future research to interview the companies in order to take into account their opinion and their willingness to change.

The following recommendation concerns the generalisation attempt made in chapter 8. To be more specific, in this thesis, a case study was held for an industrial cluster and then an attempt was made to generalise, in order to design a decision framework. It was mentioned that there is low generalisability and thus, the generalisation would be more valid if more clusters were taken into account, which means more case studies. Finally, a more accurate result would come out. Within a given time frame for this research, only one study case was executed. In order to make a more representable result, it is recommended to make more cluster studies by implementing the approach suggested within this work and, if necessary, to adapt it based on new.

Moreover, it is important to mention that this study has a high dependence on timeline. Initially, time is related to the final solution proposed in each case. In this case, the proposed scenario is intended to be implemented from 2025 to 2035. This timeline considered arbitrarily since there wasn't specific guidance. If the study was carried out, for example for a consulting project, this time frame would have been given by the final recipient of the study. Therefore, in another case, there would be restrictions, such as, for example, giving the goal for a plan until 2050. Some of the technologies that have lower TRLs could also be taken into account in that case. Regarding TRLs, they show that technologies are highly related to the time. In particular, the TRL of a technology shows how mature technology is for commercialisation in the market. Most of the technologies studied in this thesis have a TRL of less than nine and are therefore not quite ready. These are extremely emerging technologies and scientists are intensively studying their evolution. This means that if this thesis is carried out two years later, we might reach a different result.

9.3 Reflection

This thesis is part of the postgraduate program Management of Technology at TU Delft and was carried out in collaboration with the Sustainable Processes and Energy Systems (SPES) department of TNO. Initially, the inspiration for this particular subject came from a personal interest in sustainability, the environment and the chemical industry. Doing an internship at TNO and studying this master's, an interest is developed for new technologies and especially in how they can be integrated into society and become a stepping stone for development.

9.3.1 MOT relevance

The objective of this master's degree is to teach students to manage technology, and to be able to analyse existing and emerging technologies and contribute to their commercialization and integration into industry. The problem of industry and high emissions is important and it is truth that many companies and institutes are concerned on how to reduce their environmental impact. For this reason, the companies themselves, and government agents are trying to find solutions to decrease emissions in the shortest time frame. Through this study an attempt is made to explore and understand all available technologies as well as an attempt to assess how they could be applied in the chemical industry. This study takes into account very different sectors; technologies are not analysed only from the technological aspect, but an attempt is made to evaluate all these new technologies from an economic, environmental and social perspective. The fact that such a technical topic as chemical or material production processes is not only approached from the technical side gives a wider view to the subject and thus the specific study becomes even more relevant to the master's curriculum.

9.3.2 Academic relevance

In terms of the scientific approach to the topic, the research question asked is a rather complex problem. Although the problem of the chemical industry on the environmental impact seems to be an environmental problem, it is actually a multifaceted issue. This happens because the industry is essential for human activities and, beyond that, it is a highly profitable industry. The chemical industry is based on fossil fuels not only through high energy demand, but also because the raw material for the production of processes is fossil-based. In addition to companies and institutes, governmental organizations have a key role in this, which have already introduced policies and legislation according to which emissions should be limited. Considering the rapid increase of climate change, the problem is becoming more and more important. It is understood that technologies are not mature enough to solve the problem, there is a need for companies to invest in the energy transition and thus the scientific community (researchers) accelerates the processes for the development of these technologies.

All the aspects above show the complexity and multifaceted nature of the problem. In this study, in order to provide a solution, a key part is to define and understand all the terms concerning the problem and, specifically, do a comprehensive literature review. Although the topic was very general in the beginning, an attempt was made to move it into an industrial field and give an approach through which this complex topic will be simplified.

Also, in order to give a realistic approach to the topic, a case study was held. Taking into account data from a specific industrial cluster allows the study to take into account the actual situation and the problem escapes from the theoretical perspective. The goal of this study was to design a decision framework. Considering that there was a given time frame for a master's thesis, this project was quite ambitious. The attempt that was made to generalise the analysis based on only one case study. Thus, the most important recommendation for further research is to make more case studies by implementing the approach suggested within this work.

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