Reducing CO_2 emissions of the Dutch refining industry towards 2050

Analysing CO_2 reducing alternatives by extending the traditional Technology Assessment so that it incorporates economic and institutional perspectives

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Cover photo: Refinery located in the Port of Rotterdam, Netherlands, via:
https://www.portofrotterdam.com/en/cargo-industry/refining-and-chemicals/oil-refineries

Preface

This thesis is the last step in completing my Master Systems Engineering, Policy Analysis and Management of the faculty Technology, Policy and Management at Delft University of Technology. My graduation project is conducted at the Clingendael International Energy Programme (CIEP). It went quite smoothly and overall I'm very pleased with the process and results. Of course this would not have been possible without the help and support of certain persons. Therefore, I would like to devote this section of my thesis to express my gratitude to these people.

First of all, I would like to thank Coby van der Linde for offering me the opportunity to do my graduation project at CIEP. The past six months were incredibly instructive and exciting for me. During the first two months of my graduation project you were of great help to me. Pointing me in the right direction and providing me with the necessary feedback and points of improvement. In a very short time I learned a lot about all different aspects of energy. Talking to my new colleagues, who all specialised in different aspects of energy, broadened my knowledge substantially. Pier, I especially enjoyed our conversations and discussions about all sorts of topics. You didn't get involved in the supervising of my thesis but our conversations provided me with very welcome distractions from time to time. A special note of gratitude to Maurits with whom I spend most of the time during my study and became my colleague again at CIEP. Thank you for keeping me in mind when the possibility of a new graduation topic came up at CIEP.

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On a more personal note I want to thank my parents for their unconditional support, you were always there for me. Not only during the writing of my thesis but also during my entire study period. We discussed my progress very often and you were always very interested in my findings. Last but not least I want to thank my girlfriend, Lisa. You supported me during my study and was always there when I needed you. When I choose to do a second Master you stood by me and I really appreciate that, you are the best.

Executive summary

The European Union aims to reduce greenhouse gas emissions by 80% to 95% below 1990 levels by 2050. For the Netherlands, a reduction of 80% implies that a limited amount of 30 Mton CO_2 per annum may be emitted in 2050. Such a reduction could especially affect the Dutch refining industry as it is a large emitter of CO_2 with a total of 11 Mton of CO_2 in 2015. Assuming that the CO_2 budget of the Dutch refining industry also decreases, investments are required that in alternatives that reduce CO_2 emissions. However, due to increasing competition, decreasing European oil demand and thin refining margins these investments cannot be taken for granted.

This research starts by analysing the processes present in Dutch refineries and their CO_2 emissions. Processes present within Dutch refineries are: atmospheric distillation, vacuum distillation, catalytic reforming, alkylation, fluid-bed catalytic cracker, hydrocracker, hydrotreater, thermal cracker, visbreaker and flexicoker. The Koch refinery has the simplest configuration while the Shell Pernis and ExxonMobil refineries are the most complex. Allocating CO_2 emissions to individual processes shows that the atmospheric distillation unit is most cases the largest emitter of CO_2. Besides atmospheric distillation, the Flexicocker, the FCC unit and hydrocracker also substantially contribute to the total CO_2 emissions of Dutch refineries.

Furthermore, a system analysis was performed to analyse the influence of the crude oil intake of Dutch refineries on their CO_2 emissions. Crude oil properties, such as API gravity and sulphur content, have a large influence on CO_2 emissions of refineries. The Netherlands imports light and medium crude oils with an API ranging from 31.3 to 43.6. These crude oils have a sulphur content ranging from 0.1 to 2.6. CO_2 emissions of refineries increase when crude oils with low API gravity (heavy) and high sulphur content (sour) are refined.

Factors influencing CO_2 emissions of refineries provide the basis for the overview of CO_2 reducing options. In general, refineries can reduce their CO_2 emissions by optimising their energy efficiency or their carbon efficiency. First of all, options are assessed that reduce CO_2 emissions of the most polluting processes within Dutch refineries. By improving the energy efficiency of the distillation column, FCC unit, hydrocracker and flexicoker, total CO_2 emissions of Dutch refineries are reduced. Secondly CO_2 reducing alternatives are discussed that relate to the possibilities of processing different crude types. Other CO_2 reducing options included within this research improve regional integration (heat/CO_2 exchange), alter the fuel usage (cogeneration and renewables), integrate biofuels or capture the CO_2 emitted by Dutch refineries (CCS/CCU).

A Technology Assessment (TA) is used to assess the wide variety of CO_2 reducing options. TA along with a multi-criteria analysis is most suitable for this research, as criteria from both technical and societal perspectives are used. For this research TA is extended with criteria from both economic and institutional perspectives. Figure A shows the evaluative criteria from the four perspectives used to determine the most promising CO_2 reducing alternatives.

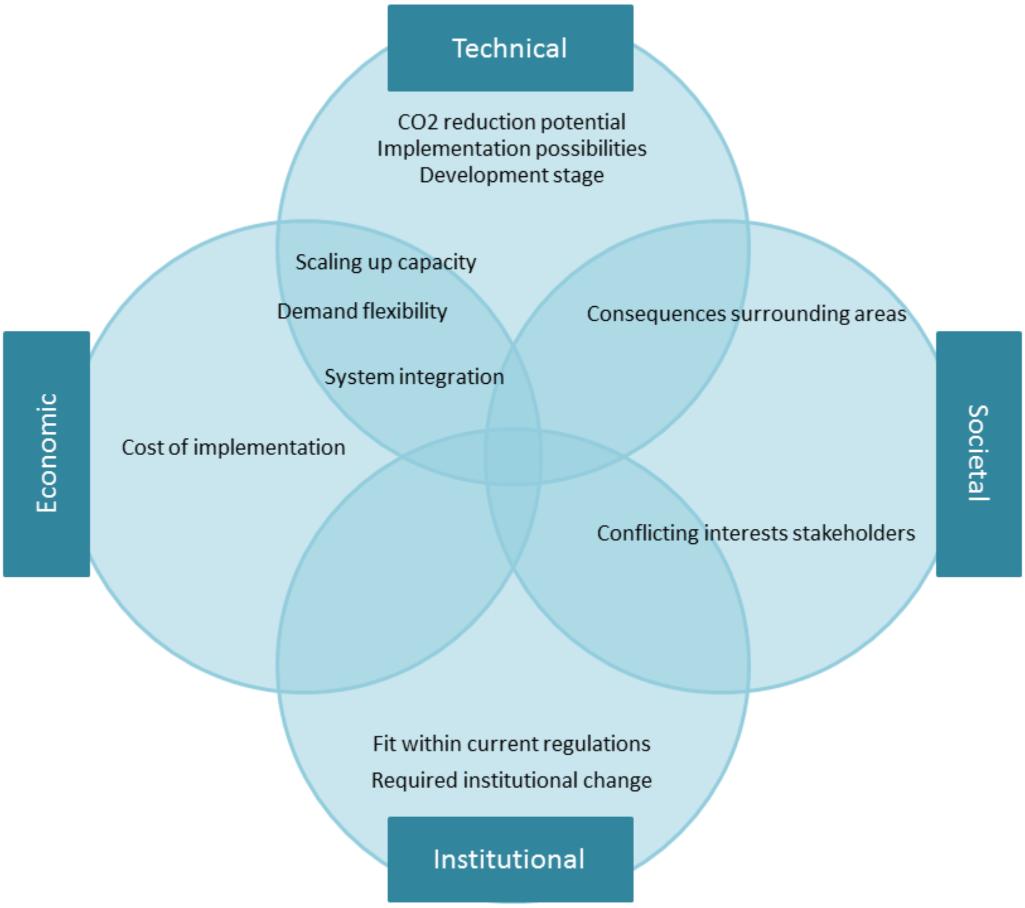

Figure A - Evaluative criteria deducted from the extended TA framework

A multi-criteria analysis is used to determine the most promising CO_2 reducing alternatives. Weights of the evaluative criteria are a crucial factor and dependent on the interests of the different actors involved. As a result, a multi-actor perspective is incorporated in the analysis. Four important actors are: 1) the Dutch government, 2) highly complex/integrated refineries, 3) less complex/non-integrated refineries and 4) Dutch citizens. Consequentially, the most promising CO_2 reducing alternatives are dependent on the various actor perspectives. Table A shows that on average for all actor perspectives heat exchange, optimizing the distillation unit, processing a variety of lighter and sweeter types of crude oil and CCU are the most promising CO_2 reducing alternatives for the Dutch refining industry.

Table A - Three most promising CO_2 reducing alternatives for each of the four actor perspectives

Perspective	1st Alternative	2nd Alternative	3rd Alternative
Dutch government	Heat exchange	Distillation unit	Lighter and sweeter crude oil
Highly complex and integrated refineries	Heat exchange	Distillation unit	CCU
Less complex and non-integrated refineries	Heat exchange	Lighter and sweeter crude oil	Distillation unit
Dutch citizens	Heat exchange	Distillation unit	CCU

Exchanging heat to nearby residential areas or industries is the most promising alternative for all actor perspectives. Another promising alternative for all actor perspectives is the optimisation of the distillation unit. This is not a surprise since it only affects refineries, leads to significant CO_2 reductions and is relatively cheap. Processing lighter and sweeter types of crude oil is especially interesting for the less complex/non-integrated refineries since they can substantially reduce their CO_2 emissions with this alternative, although these crudes usually trade at a premium. This alternative is less interesting for the highly complex/integrated refineries since the processing of lighter and sweeter crudes will lower the utilisation of their complex configuration. CCU is an interesting alternative but has not yet reached a mature phase within the Netherlands and is a large cost for the highly competitive industry. Nevertheless, this alternative shows great potential towards 2050.

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List of abbreviations

United Nations Framework Convention on Climate Change	(UNFCCC)
European Union	(EU)
carbon dioxide	(CO_2)
International Energy Agency	(IEA)
International Oil Companies	(IOCs)
the Industrial Emissions Directive	(IED)
Reference document on Best Available Technologies	(BREF)
National Emission Ceiling	(NEC)
sulphur dioxide	(SO_2)
mono-nitrogen oxides	(NOx)
Particulate Matters with a maximum size of 10 micrometre	(PM10)
Emission Trading System	(ETS)
Basic Plant Scenario	(BPS)
Stringent Plant Scenario	(SPS)
Light Tight Oil	(LTO)
the United States	(US)
Greenhouse Gas Emissions	(GHG emissions)
North-West European	(NWE)
Technology Assessment	(TA)
Fluid Catalytic Cracking	(FCC)
Liquefied Petroleum Gas	(LPG)
CO_2 Weighted Ton	(CWT)
American Petroleum Institute gravity	(API gravity)
Crude Distillation Unit	(CDU)
Carbon Capture and Storage	(CCS)
Carbon Capture and Utilisation	(CCU)
Multi-Criteria Analysis	(MCA)

Kiloton	Kton
Megaton	Mton
thousand barrels a day	kb/d
degrees Celsius	°C.
Petajoule	PJ
Terajoule	TJ
Megawatt	MW

Part I – The challenges for the Dutch refining industry

1. Introduction

Today Dutch policy-makers are more and more focussed on the transition towards a low-carbon economy (RLI, 2015 ; EZ, 2016a ; EZ, 2016b). This transition is mainly driven by global climate agreements. The first major global agreement concerning climate change was the Kyoto-protocol in 1997 (UN, 1997). In 2015 a new agreement was reached during the COP 21 in Paris. All parties of the United Nations Framework Convention on Climate Change (UNFCCC) agreed to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future (UNFCCC, 2015). The central aim of this agreement is to not let global temperatures rise by more than 2 degrees Celsius above pre-industrial levels. From these global agreements the European Union (EU) derives her own policies for the reduction of greenhouse gasses (GHG). Towards 2030 the EU already aims at a reduction of greenhouse gas emissions of 40% below 1990 levels. However, the underlying goal of these European policies is to reduce greenhouse gas emissions by 80% to 95% below 1990 levels by 2050 (EFC, 2010).

For the Netherlands, a reduction of 80% implies that a limited amount of 30 Mton CO_2 may still be emitted in 2050 (RLI, 2015). Such a reduction especially affects the Dutch refining industry since it an energy intensive industry with a total of 11 Mton of carbon dioxide (CO_2)emissions in 2015. Table 1 shows that this adds up to 20% of the Dutch energy sector's CO_2 emissions (Emissieregistratie, 2016). The sector emits such large quantities of CO_2 since its core function is the production of useful products from crude oil (Treese et al., 2015). Among these products are transport fuels, such as gasoline, diesel, kerosene, LPG, and gas oil (Speight, 2009). Refineries also produce naphtha which can serve as feedstock for the petrochemical industry or for gasoline manufacturing (Parkash, 2003). The processes that convert crude oil into all these different products are highly energy intensive and cause refineries to emit vast amounts of CO_2 and other polluting particles (Johansson et al., 2013).

Table 1 - CO_2 emissions of the Netherlands, its energy sector and refineries. (Emissieregistratie, 2016)

		CO_2 emissions in Mton	
	Dutch refineries (processes)	Dutch energy sector	The Netherlands
1990	11,04	41,74	163,2
1995	11,59	49,63	173,7
2000	12,38	50,2	172,4
2005	12,36	54,03	177,8
2010	10,61	53,84	182,8
2015	11,04	54,92	166,7
EU Target 2050 for the Netherlands 80% reduction to 30 Mton per annum (RLI, 2015)			

As a result of their high CO_2 emissions the Dutch refining industry is affected by the increasingly stringent environmental legislation (ECN,2015). Since CO_2 emissions of Dutch refineries account for 20% of the total energy sector's emissions, they also need to be part of the 20% emission reduction. In order for the Dutch refining industry to meet the CO_2 targets, investments are required for the implementation of technologies and alternatives that reduce their CO_2 emissions. A wide variety of these options exist, ranging from highly experimental to already proven. To reach the 2030 CO_2 targets, CO_2 reducing alternatives have to be implemented that are currently available or in a far developed phase. With regard to the 2050 CO_2 targets more experimental alternatives can be taken into account.

To get better understanding of the Dutch refining industry, it is important to place the sector in perspective of European and global developments. These developments are essential for assessing the Dutch refining industry towards 2050. Since the refining sector processes crude oil into useful products, future oil demand determines the output and therefore the emissions of the refineries. The IEA (2015) expects that demand for oil will reach a peak or even decline towards 2050. Despite stagnating growth of oil demand, oil will remain the main energy source for the transport sector (Eliasson & Proost, 2015). It is therefore likely that demand for most transport fuels will keep increasing (ExxonMobil, 2016). This increase in demand appears to be good news for the refining industry. Worldwide refining capacity has increased substantially the past couple of years and it is forecasted that this growth continues towards 2040 (IEA, 2015). However, this increase in capacity is for the most part caused by non-European regions. From 2005 till 2015 Europe experienced a decrease in refining capacity of 4.3% while worldwide refining capacity increased by 11.0% (BP, 2016). FuelsEurope (2015) even reports that the EU refining capacity has dropped 10% since 2008. Figure 1 shows the refining capacity over a longer period of time comparing different regions and the Netherlands. It shows that the Asia pacific region experienced the largest increases in capacity while the Dutch and Europe's capacity decreased (BP, 2016).

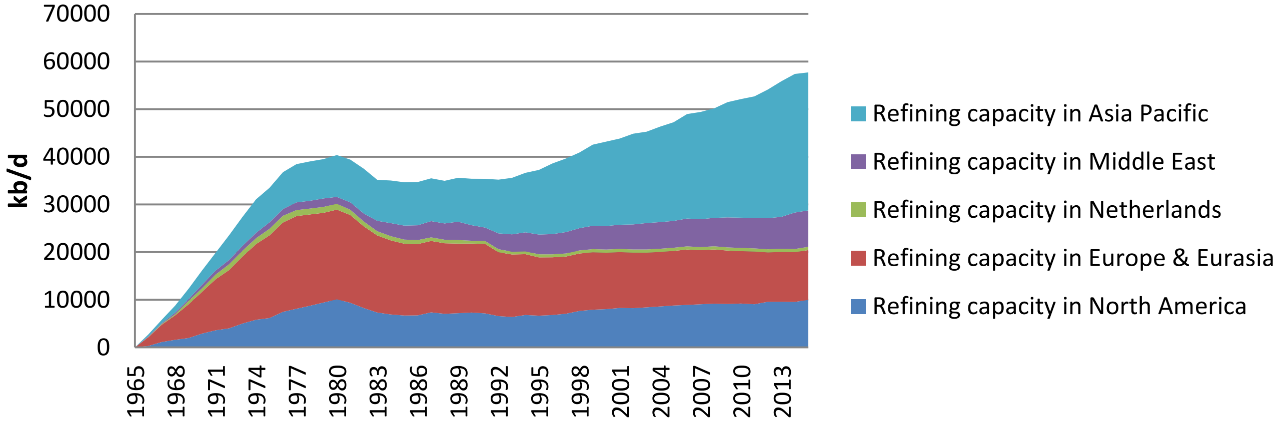

Figure 1 - Refining Capacity of different regions (BP,2016)

Complying with increasingly stringent environmental regulations is not the only challenge for the European refining industry. Crude oil and product trade flows have been facing a long term transition since the end of refining's golden age in 2009 (van den Bergh et al., 2016). A main driver behind this transition is the foreseen structural decline in European oil product demand (IEA, 2015). Together with expanding export-orientated refining capacity in the Middle East a change in demand and supply patterns can be observed within the regional market (FuelsEurope, 2015). This already sheds some light on the second driver which is a severely intensified competition within the global refining industry. Refining margins are crucial for the competitiveness of refineries. Despite high refining margins in 2015 as result of low oil prices, European refineries experienced periods of extremely thin margins after 2009 (Meijknecht et al., 2012). When these margins are compared with the margins of non-European refineries the difference is large. This is partly caused by high energy and labour costs for European refineries.

European and global developments have a large impact on the Dutch refining industry. The global demand for transport fuels keeps increasing toward 2050 which implies that the refining industry keeps its prominent role. As a result of the increasingly stringent environmental regulations, technologies or alternatives have to be implemented that reduce the CO_2 emissions of refineries. However, due to the decreasing European oil demand, increasing competition and thin refining margins, investments within the Dutch refining industry cannot be taken for granted (Purvin & Gertz, 2008).

1.1 Research problem

The introduction briefly introduced the challenges that the Dutch refining industry currently faces. To further explore the situation in which the Dutch refining industry finds itself and derive the research problem of this thesis, a more detailed analysis of current and future environmental legislation along with the increasing competition is required. The following section discusses existing dilemma's in depth using state-of-the-art literature.

1.1.1 Challenges within the Dutch refining industry

The Dutch refining industry faces increasingly stringent environmental legislation ever since policy-makers are more focussed on the transition to a low carbon economy. This legislation can be divided into two main categories namely, reducing CO_2 emissions from burning fossil fuel and lowering sulphur levels in crude oil products (ECF, 2012 ; Purvin & Gertz, 2009). The IMO Marpol legislation is on a global level and addresses the standards for the sulphur content in bunker fuels (ECN, 2015). For the reduction of CO_2 emissions multiple international policies exist or are designed. First the EU Fuels Quality Directive (EC, 2009) which addresses certain crude oil qualities with their own standard greenhouse gas values. As a result heavy and sour crudes will be heavier taxed than the light and sweet ones. Emission standards for the different combustion installations within a refinery are set by the Industrial Emissions Directive (IED) (EC, 2013). For emissions with regard to the units of a refinery the Reference document on Best Available Technologies (BREF) exists (EC, 2015). Finally the National Emission Ceiling (NEC) regulates the maximum emissions for NOx, SO_2, NMVOC and PM (EC, 2010).

One of the most important policies with regard to CO_2 emissions is the Emission Trading System (ETS). The ETS is a EU policy designed to reduce GHG emissions in a cost-effective manner. It works via a 'cap and trade' principle and is the world's first and largest carbon market. The cap is the total amount of GHG that can be emitted and is reduced over time so that total emissions will decrease. Companies receive or by emissions allowances and trading arises when certain companies have an excess or shortage of emission allowances. The cap ensures the value of the allowances. However the ETS is not working as it should be, low carbon prices, an inflexible system and carbon leakage are all examples of negative externalities (liang et al., 2013 ; Salant, 2016). With regard to the refining industry the most important negative externality is the risk of carbon leakage. Since the EU is the only region that has such a system, competitors do not face similar costs. Because refineries produce products that are subject to competition they might optimise their refining capacity outside the EU. Since the worldwide refining capacity is more than sufficient it can result in competitive closures. In this case the CO_2 emission do not decrease but are emitted somewhere else (Clò, 2010).

Future environmental regulation is uncertain and it is therefore better to work with possible scenarios. ECN (2015) comes up with two scenario's for the Dutch refining industry, namely the Basic Plant Scenario (BPS) and the Stringent Plant Scenario (SPS). The BPS assumes highest future emissions limit values as is interpreted by the Dutch refining sector from current legislation. This would mean that under IED, RED, EU ETS and IMO Marpol should be taken into account for the BPS. However the SPS assumes more stringent emission limit values and also includes the BREF and NEC regulations. The quantity of emissions that the Dutch refining industry is allowed to emit in the future therefore strongly depends on future policy choices.

In order to comply to the increasingly stringent environmental regulation, Dutch refineries need to invest in options that reduce their CO_2 emissions. However, this is problematic because increasing competition upsets the current market structures making the business case for Dutch refineries increasingly difficult (van den Bergh et al., 2016). As a result, the willingness to invest in the implementation of CO_2 reducing alternatives is negatively influenced. Both global and regional factors affect the competitiveness of the Dutch refining industry.

On a global level the first trend that can be observed which increases the competition for Dutch refineries is the shift towards source refining. Source refining means that the refining industry is located very close to the source of crude oil and their products are then exported to the different regional markets. This is of course disadvantageous for the Dutch refining industry since the Netherlands has no large source of crude oil. The shift towards source refining resulted in a decrease of North-West European refining capacity and large increases of refining capacity in for example the Middle-East, Russia and China. However, most of the increased refining capacity in China is first used to meet the demand of the domestic market before they become export-orientated (Gaffney et al., 2014). Since these refineries are closer to the source of crude oil this automatically means their energy costs will be lower compared to European refineries. Low energy costs and direct access to feedstock means that new investments will most likely take place within the source refining industry and not within the Dutch refinery sector.

The second global cause for the disruption of current market structures is the United States (US) light tight oil (LTO) abundance (Meijknecht et al., 2012). Until not so long ago the United States were largely dependent on refinery exports from the European market to fulfil their demand of transport fuels. However, the emergence of LTO had a significant impact on the global energy market. This LTO developments made the US a source refining country with cheap domestic feedstock, making the US refineries more and more competitive (Sen, 2013 ; Six, 2013). Currently they are among the most competitive in the World with significantly higher refining margins then Europe and Asia (ECN, 2015). Instead of exporting products to the US, Dutch refineries are now also facing increased competition from the US.

Besides global influences the Dutch refining industry also faces regional challenges that have an important effect on changing market dynamics. The first changes are related to the changing EU oil demand which only shows marginal future growth. Since the European oil market is considered a mature market the expectation is that demand growth will follow the general economic development (Meijknecht et al., 2012). This means that emerging regions such as the Asia Pacific, Africa, Middle-East and Latin America which have a higher economic growth are expected to report a larger increase in oil demand (Exxonmobil, 2016).

The increased competition for the Dutch refining industry is also related to the economic performance of the refineries. Profitability of a refinery is largely determined by the difference in value between feedstock and finished product (ECN, 2015). Therefore costs (fixed and variable) play a crucial role in the profitability of a refinery. Besides profitability, complexity and location are also important factors for a refinery's performance (Lukach et al., 2015). However, it becomes obvious why Dutch refineries are facing fierce competition when taking a closer look at refinery costs and margins. When the costs of Dutch refineries are compared with source refineries the biggest difference is the cost of energy. Energy costs amount to 40-60% of total costs for Dutch and European refineries (FuelsEurope, 2015). Alongside the high energy costs Dutch refineries also face strict environmental regulation which increases the costs even further. Figure 2 shows the differences in costs between a generic Dutch refinery and a generic refinery from the Middle East. European refineries have an competitive disadvantage of $4.4 per barrel without the additional costs for regulation.

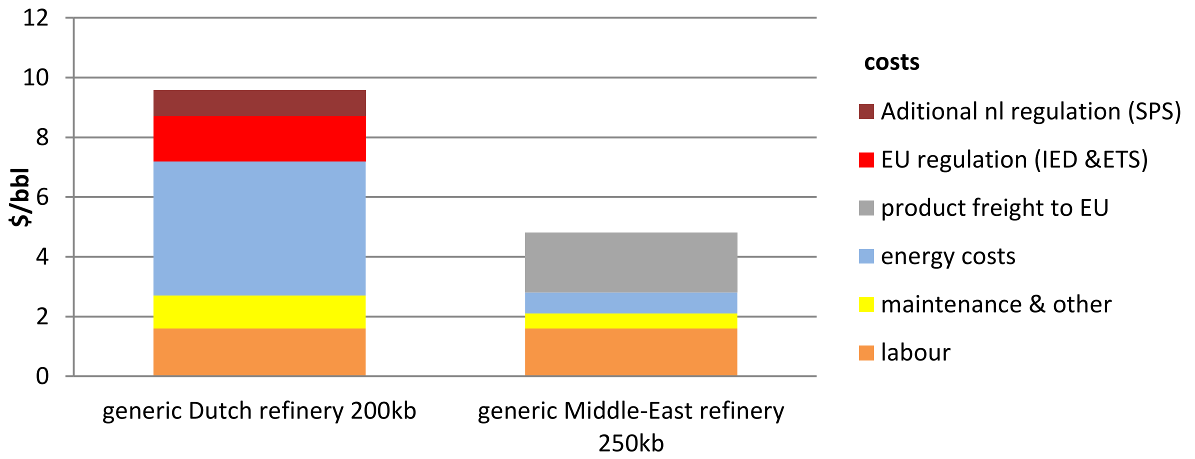

Figure 2 - Refining cost comparison between generic Dutch and Middle-East refinery (FuelsEurope, 2015)

The shift towards source refining, the US LTO abundance, the EU oil demand contraction, increasing regulation and low refinery margins makes investing in Dutch and European refineries less attractive. A lack of investments tips the table even further because it in turn also negatively influences the competitiveness of Dutch refineries. After the financial crisis in 2008 refinery investments for the large part took place in high growth regions only (Purvin & Gertz, 2008 ; 2011). If investments remain absence the danger of refinery closures becomes more and more realistic. This would have large consequences because the Dutch and European sector will still have to deal with the external costs (carbon leakage, GHG emissions) of the fossil fuel economy while the benefits (GDP, jobs) of a large refining industry disappear (van den Bergh et al, 2016). Since domestic refineries cover 90% of the overall oil demand in the region, security of supply becomes an issue when the refining industry faces closure due to a lack of investments. The greatest threat for the Dutch sector is external competition and therefore it can be concluded that investments within the refining industry are required to ensure a long-term future.

1.1.2 Problem statement

It can be concluded that the European Union, driven by global agreements such as the Paris agreement (UNFCCC, 2015), aims to reduce the emission of greenhouse gasses. The underlying objective of these policies is to reduce CO_2 emissions by 80% to 95% below 1990 levels by 2050 (EFC, 2010). Within the Netherlands this especially affects the refining industry since they are one of the largest emitters of the energy sector (Emissieregistratie, 2016). To comply to stricter regulations, the Dutch refining industry has to invest in alternatives that reduce their CO_2 emissions. However, due to increasing competition, decreasing European oil demand and thin refining margins the business case for Dutch refineries is not very strong (Van den Bergh et al., 2016). Investments in the Netherlands cannot be taken for granted and the implementation of these CO_2 reducing alternatives will be difficult to achieve. Therefore the problem statement of this research is:

The Dutch refining industry faces increasingly stringent environmental regulations. In order to comply to this legislation and achieve the objectives, investments are needed for the implementation of alternatives that reduce CO_2 emissions of refineries.

1.2 Knowledge gaps

The Dutch refining industry is a complex industry that has to reduce its CO_2 emissions in order to meet increasingly stringent environmental regulation. Investments are required for the implementation of technologies that reduce these CO_2 emissions. Before an overview of CO_2 reducing options can be provided it is essential to describe the CO_2 profile of refineries. The first knowledge gap concerns the contribution of individual processes to the total CO_2 emissions of Dutch refineries. Within the Dutch refining industry it is unclear which processes emit the most CO_2. Furthermore it remains unclear what the effect of the crude oil intake and product slate of Dutch refineries is on their CO_2 emissions. To provide a comprehensive overview of the complete CO_2 profile of Dutch refineries these effects need to be analysed.

After the CO_2 profile of Dutch refineries is constructed another knowledge gap arises. This knowledge gap relates to the possible options that can reduce the CO_2 emissions of the Dutch refining industry. There is some literature that discusses possible options for the reduction of CO_2 emissions within the Dutch refining industry. However, in most cases literature either only discusses options that improve the energy efficiency or explores options that improve the carbon efficiency. No complete overview of all CO2 reducing options for the Dutch refining industry is currently present. This literature is furthermore dated and CO_2 reduction technologies are developing rapidly. therefore an updated overview of CO_2 reducing alternatives for the Dutch refining industry is needed.

Finally it remains unclear which technology has the greatest potential to reduce the CO_2 emissions of Dutch refineries. Existing literature in most cases only focusses on exploring and identifying possible CO2 reducing options. In some cases the CO2 reduction potential, technical and economic, is included within the analysis. However, to fully analyse the potential of CO2 reducing alternatives more criteria are important. A Technology Assessment is applied and criteria are deducted from this framework. Via a multi-criteria analysis it is possible to identify the most promising CO2 reducing alternatives based on a wide variety of evaluative criteria. Such an analysis is not yet performed.

1.2.1 Research questions

With the help of the identified knowledge gaps, the main research goal can be identified:

To explore the Dutch refining industry, determine the different factors that contribute to their CO_2 emissions and assess which CO_2 reducing alternatives are the most promising for achieving the goals set by increasing stringent environmental regulation.

In order to achieve the main research goal, five research questions are identified that will result in achieving the main objective. The approaches and corresponding methodologies used to answer these research questions are elaborated on in Chapter 2.

1. **Which processes take place within the Dutch refining industry and how do they contribute to the CO_2 profile of the refineries?**
2. **In what way is the CO_2 profile of Dutch refineries affected by their crude oil intake and product slate?**
3. **What are possible options that can be used to reduce the CO_2 emissions of Dutch refineries?**
4. **In which way can Technology Assessment be applied within this research and what criteria can be deducted from this framework?**
5. **What are the most promising alternatives that reduce the CO_2 emissions of Dutch refineries based on the criteria deducted from the designed framework?**

1.3 Research scope

The Dutch refining industry finds itself in a complex situation. Within the scope of this research the main focus lies on assessing a wide variety of options that enable refineries to meet the increasingly stringent environmental regulation. Key within this research is the reduction of CO_2 emissions by 85% to 90% below 1990 levels in the year 2050. Refineries also emit other pollutants, such as sulphur dioxide (SO_2), mono-nitrogen oxides (NOx) and Particulate Matters with a maximum size of 10 micrometre (PM10), but these fall outside the scope of this research. This is mainly due to the fact that the Dutch refining industry already reduced these emissions quite substantially (Emissieregistratie, 2016).

Moreover, this research solely focusses on CO_2 emissions directly related to refineries. Options that influence emissions in processes outside the refining industry are therefore not taken into account. Therefore emissions related to crude oil recovery and usage of refined products lie outside the scope of this research. While CO_2 emissions related to crude oil recovery fall outside the research scope, crude oil characteristics like the API gravity do influence CO_2 emissions of refineries and therefore crude qualities fall within the scope of the research. The demand for crude oil and oil products, fall outside the research scope as well. The scope of this research is visualized in Figure 3.

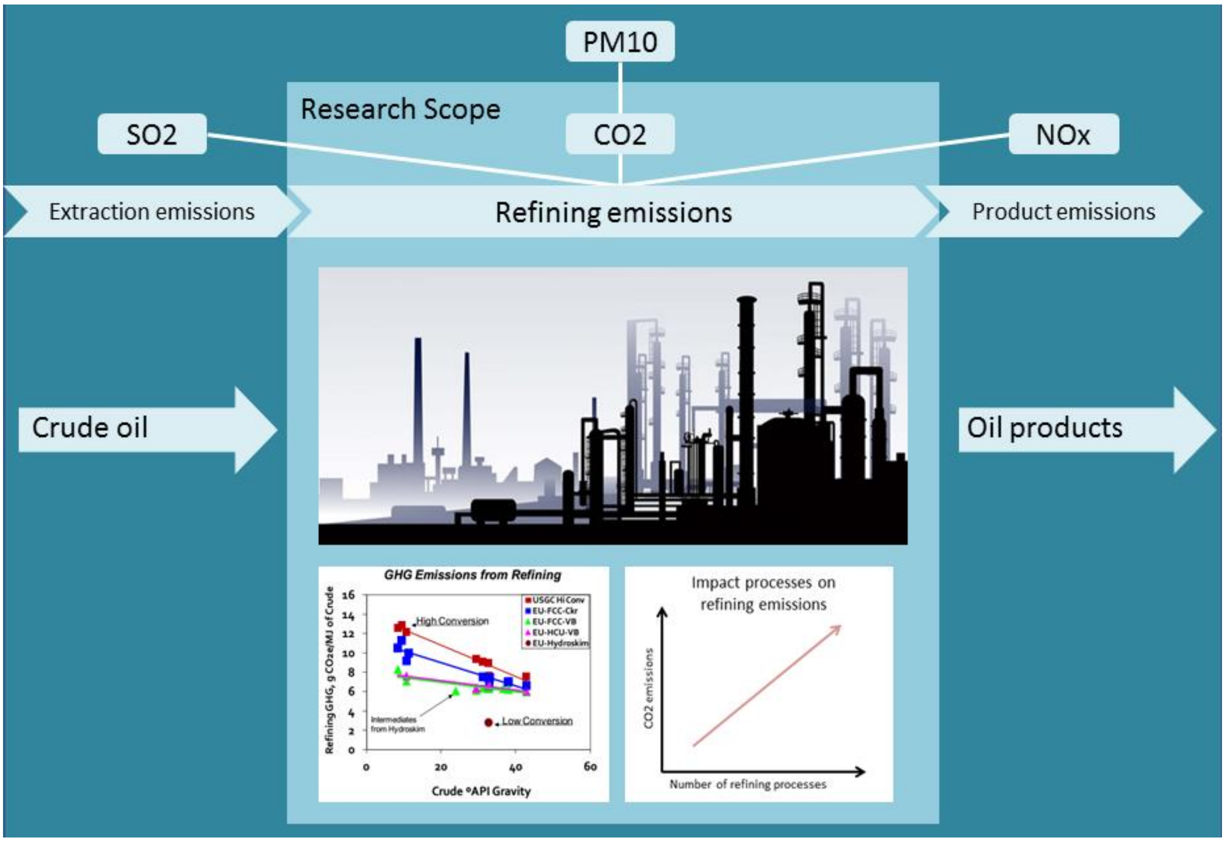

Figure 3 – Research scope

1.3.1 Dutch refining industry

As briefly mentioned before this research focusses on the Dutch refining industry. It is true that the entire North-West European (NWE) refining sector faces similar challenges as the Netherlands. However the focus on the Dutch refining industry is due to the fact that institutional perspectives are incorporated within this research. NWE refineries are subjected to national, European and global legislation. Despite the fact that European and global legislation is equal for every NWE refinery, large differences may occur on a national level (ECN, 2015).

The Dutch refining industry contains 6 refineries of which 5 are located in the port of Rotterdam. These are the Shell Pernis, BP, ExxonMobil, Gunvor and Koch refineries. The last refinery is the Zeeland refinery located near Vlissingen. Each refinery has its own unique configuration and capacity which is presented, along with the locations on a map, in figure 2. Shell Pernis is the largest Dutch refinery and also the biggest in Europe. It has a deep integration with the petrochemical cluster and its world scale steamcracker enables it to have a high feedstock flexibility (van den Bergh et al., 2016). The BP refinery is the second largest, but has a relative simple configuration with limited flexibility. Despite a substantially lower capacity ExxonMobil is a valuable refinery due to its deep integration with the petrochemical cluster and the production of hydrogen makes. The Zeeland, Koch and Gunvor refineries all have relatively small capacities and simple configurations. All refineries except the Koch and Gunvor refinery, are owned by International Oil Companies (IOCs). Figure 4 gives an visualisation of the six refineries located within the Netherlands along with their key features.

Figure 4 - Location and features of Dutch refineries. (Port of Rotterdam, 2016 ; van den Bergh et al., 2016)

1.3.2 Relevance of the research

The main goal of this research is relevant for both the scientific world as it is for social welfare. Exploring the Dutch refining industry and determining the different factors that contribute to their CO_2 emissions is especially of scientific relevance. Overviews exist that provide insight into the processes present in Dutch refineries. However, an allocation of CO_2 emissions to the individual refining processes is not present for the Netherlands. This allocation determines the most polluting refinery processes. The influence of other factors ,such as the crude oil intake and the product slate, on CO_2 emissions of Dutch refineries is also relevant for the scientific world. Few studies have been performed with regard to this topic and these only assess the effects on European scale (Jacobs, 2012). This research applies Technology Assessment, identifies its missing aspects and extends it with economic and institutional perspectives. Such a framework provides a different but more thorough and extensive analysis of the application of CO_2 reducing alternatives within the sector. This framework could prove very useful and might inspire others to implement it as well. Another interesting scientific contribution of this research lies in the analysis of a wide variety of options that refineries can implement in order to reduce their CO_2 emissions. The most promising CO_2 reducing alternatives are identified from the perspective of multiple actors. Such an analysis is not present in current literature.

This research is also of societal relevance since the Dutch refining industry provides a large number of direct and indirect jobs and contributes to the country's GDP (Kernteam versterking industriecluster Rotterdam/Moerdijk, 2016). If investments remain absent the competitiveness of the Dutch refining industry decreases and some refineries may close. Besides providing jobs and contributing to the GDP, refineries also emit large amounts of greenhouse gasses (Purvin & Gertz, 2009). Because this research focusses on the implementation of alternatives that will reduce CO_2 emissions, it also has a positive effect on social welfare. If certain techniques appear to be feasible in a way that they reduce CO_2 emissions of the refineries and at the same time provide them with the investments needed to remain competitive it will have large positive effect on social welfare. Table 2 assigns the sub-goals of this research to both scientific and societal relevance.

Table 2 - Scientific and societal relevance of the research sub-goals

Scientific relevance

- Provide an analysis of the different processes that take place within the Dutch refining industry and allocate CO2 emissions accordingly
- Provide an extended technology assessment which includes both economical and institutional perspectives
- Provide an multi-criteria analysis on CO2 reducing alternatives based on criteria deducted from the designed framework

Societal relevance

- Provide an overview of the wide variety of CO2 reducing options that refineries can implement to meet the increasingly stringent environmental regulation
- Provide an overview of the most promising CO2 reducing alternatives

1.4 Structure of the research

This research starts with an extensive description of the research methodology in chapter 2. Chapter 3 & 4 provide the basis of this research by analysing the CO_2 profile of Dutch refineries. The different processes within Dutch refineries and their contribution to the total CO_2 emissions is described in chapter 3. Chapter 4 assesses the impact of the product slate of Dutch refineries and the type of crude oil they use as feedstock on their CO_2 emissions.

Based on these chapters a thorough analyses can be conducted in chapter 5 exploring the wide variety of options that reduce CO_2 emissions of Dutch refineries and can be implemented in the sector. The design component of this research can be found in chapter 6. An extended Technology Assessment which incorporates economic and institutional perspectives is constructed. This framework allows the deduction of criteria from all four perspectives which can be used in the multi-criteria analysis in chapter 7. Chapter 7 identifies the most promising CO_2 reducing alternatives. Finally chapter 8 presents the conclusion and discussion.

2. Research methodology

To achieve the main research goal; "*To explore the Dutch refining industry, determine the different factors that contribute to their CO_2 emissions and assess which CO_2 reducing alternatives are the most promising for achieving the goals set by increasing stringent environmental regulation.*", multiple methods are used. Section 2.1 describes the research design, shown in figure 6, that places the research questions within the design and methodologies. The methodologies used and the collection of data is discussed in section 2.2.

2.1 Research design

In order to achieve the main research goal, each research question forms an important step within the process. Figure 5 gives a visual representation of the steps taken. The first two research questions are for the most part answered by means of a literature study. Research question three is based on information provided from available literature but also uses expert opinions to construct a complete overview. To answer the fourth research question traditional Technology Assessment is applied to this research' topic and extended if necessary. For answering research question five a multi-criteria analysis is used to determine the most promising CO_2 reducing alternatives

The research starts with an technical analysis of the Dutch refining industry by means of an in-depth literature study. The complexity of the different Dutch refineries is discussed and key processes within the refineries are identified and described. CO_2 emissions are then allocated to the different refining processes. To fully assess the CO_2 profile of Dutch refineries the effects of their crude oil intake and product slate also need to be determined. Research question two describes the influences of these factors on the CO_2 emissions of the Dutch refining industry. Constructing the CO_2 profile of the Dutch refining industry provides the basis for the third research question. To answer research question three, the wide variety of CO2 reducing options that can be implemented within the Dutch refining industry need to be explored. This section will contain options that vary from highly experimental to options that are already being implemented.

The fourth research question is answered by describing in which way Technology Assessment can be applied within this research. First the traditional technical assessment is analysed by consulting relevant literature. Strengths and weaknesses with regard to the Technology Assessment are identified. In order for the Technology Assessment to fully analyse the complexity of the Dutch refining industry, a technology perspective on its own does not suffice. The traditional Technology Assessment needs to be extended with economic and institutional perspectives. By doing so, criteria are deducted from the extended Technology Assessment framework. These criteria are to assess the CO_2 reducing options. Selecting the most promising alternatives, and thereby answering research question 5, will be done by a multi-criteria analysis using the criteria set up in the framework design.

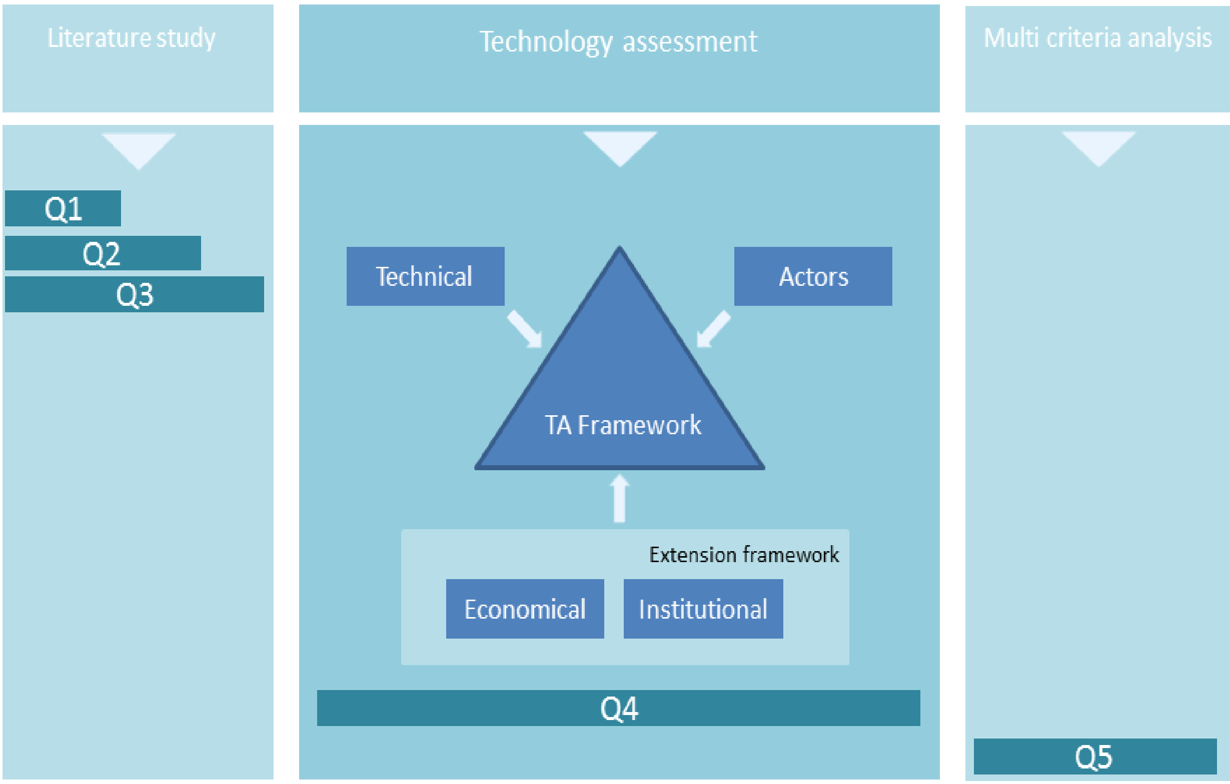

Figure 5 - Research design

The main research goal is to analyse the Dutch refining industry, determine the different factors that contribute to their CO2 emissions and assess which CO2 reducing alternatives are the most promising for achieving the goals set by increasing stringent environmental regulation. Every chapter within this research has its own role in achieving the main research goal. Figure 6 shows all the different steps and chapters along with the relations between them.

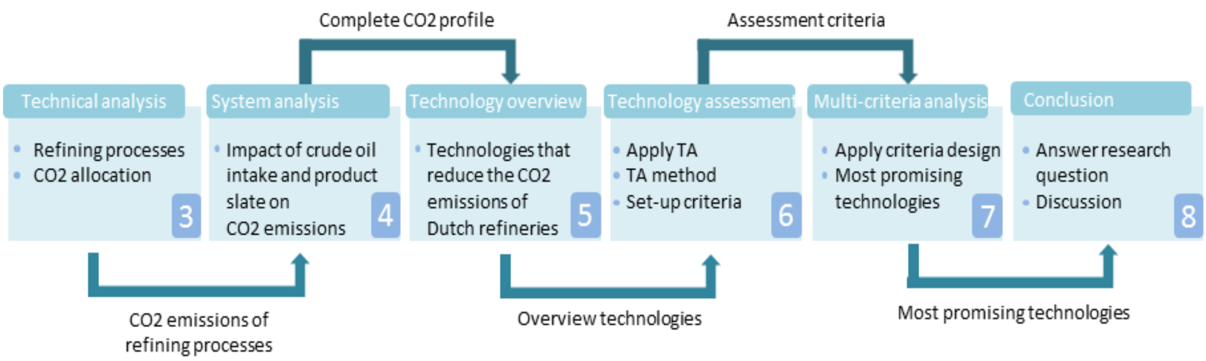

Figure 6 - Coherence between chapters within thesis

2.2 Methodologies and data collection

In order to answer the research questions of this thesis, multiple methods are used. Three methodologies are used, namely a literature study, Technology Assessment and a multi-criteria analyses. Most of the data and information is collected by means of a literature study.

2.2.1 Literature study

The research starts with exploring relevant literature to get a better understanding of the processes that take place within a refinery. Treese et al. (2015), Fahim et al. (2013) and Parkash (2003) are combined to provide an overview of petroleum processing.

In addition processes within Dutch refineries need to be identified. Unfortunately most of the data concerning Dutch refining configurations is not publically available. This research tries to construct the most detailed overview possible using public data. Sources from the Port of Rotterdam (2016) and A Barrel Full (2015) are used. As a result not all processes that are present within Dutch refineries are included in the overview of this research. This overview provides the basis for the allocation of CO_2 emissions of Dutch refineries to their individual processes. Data of refinery throughput is combined with a methodology formulated by the EU (2011).

Not only processes located within Dutch refineries affect their CO_2 emissions. The crude oil intake and product slate might also influences the amount of emitted CO_2. To determine the influence of the crude oil intake on the CO_2 emissions of Dutch refineries the different types of crude oils needed to be determined. Data from the CBS (2015) concerning crude oil imports was combined with data from Jacobs (2012). JODI (2016) provided data with regard to the products output of Dutch refining. Combined with findings from Reinaud (2005) and Bredeson et al. (2010), the effects on the CO_2 emissions of Dutch refineries is determined.

The construction of the CO_2 profile of Dutch refineries formed the basis for the overview of CO_2 reducing options that could be implemented within the Dutch refining industry. Options are assessed that reduce the CO_2 emissions of Dutch refineries by either optimising their energy efficiency of optimising their carbon efficiency. The research of Plomp & Kroon (2010) provided most information. Other CO_2 reducing alternatives were based on the study of Krebbex et al. (2011) and Kampman et al. (2010).

Google scholar and Scopus are the main search engines used for collecting literature in this research. In order to only include relevant selection criteria, such as year of publication and citation index, are applied. Besides these search engines a lot of literature, especially scientific books, is acquired via de TU Delft online library. Besides scientific literature, this research also uses non peer-reviewed articles and other ‘grey’ sources. For example, the publication of van den Bergh et al. (2016) helps to get a better understanding of the Dutch refining industry. Moreover publications from ECN, EC, IEA and CE Delft are consulted. All literature used in this research is listed according to the APA style and presented in the reference list at the end.

2.2.2 Technology Assessment

To assess the wide variety of CO_2 reducing options that can be implemented within the Dutch refining industry this research uses Technology Assessment (TA) as basis. Grunwald (2009) provides an overview of TA and is used as an important source for the comprehension and application of TA within this research. TA is a scientific and analytic approach that contributes to the formation of public and political opinions on societal aspects of science and technology (van Est & Brom, 2012). In earlier studies, TA is defined as a form of policy research that examines the short- and long-term consequences of the application of a technology (Grunwald, 2009). The main goal of traditional TA is to provide policy makers with information on technology alternatives.

TA is suitable for this research because it deals with the relationship between technological change (CO_2 reducing options) an social problems (global warming). There are three main concepts within TA, namely classical TA, participatory TA, and constructive TA. Classical TA is characterized by its positive understanding of science. It aims to produce comprehensive and objective information on state-of-the-art technologies and their impacts (Grunwald, 2009). It is criticised due to its statements that the state represents the public interest and can direct technological developments in the socially desired direction. Participatory TA builds on classical TA but includes societal groups, affected citizens and the public within the process of evaluating technologies and their consequences (Grunwald, 2009). As a result the practical and political legitimacy of TA is improved (Paschen et al., 1978). Constructive TA differs from participatory TA since it constructively accompanies the process of technological developments which allows it to directly react and deal with the consequences of technology.

It is important to select a TA method for assessing the CO_2 reducing options. These methods ensure the transparency and comprehensibility of TA while ensuring its quality standards (Decker & Ladikas, 2004). They can be used for acquiring data, providing knowledge, establishing future scenario's, risk assessment, identifying economic consequences and investigate social acceptance problems (Grunwald, 2009). This research uses decision-analytical methods within TA to assess the wide variety of CO_2 reducing alternatives that can be implemented within the Dutch refining industry. Such methods evaluate alternatives by means of a multidimensional integration of various criteria. In other words, a multi-criteria analysis is used.

Extending TA

The basis for the multi-criteria analysis performed in chapter 7 are the list of CO_2 reducing options and the criteria they are tested on. These criteria are deducted from the perspectives TA focusses on. TA mainly focusses on assessing technologies while accompanying the process of technological developments. Therefore it is logical that a technological perspective is included. Since TA also tries to assess the consequences of technologies with respect to their surroundings and society, a societal perspective is also included. It is important to assess the current developments within TA to determine if criteria from other perspectives need to be included as well.

Due to globalisation impacts of technologies transcend national borders and technology design takes place in global networks (Grunwald, 2009). As a result relevant institutions no longer solely lie within nationally or even regionally orientated decision-making structures. Regulation of technology has shifted from national level to a higher more aggregate level such as the European Union. This is reflected within the Dutch refining industry since it faces European legislation in addition to national regulation. It is therefore important to assess the effects of the CO_2 reducing alternatives on an institutional level. Hence, institutional perspectives are included.

Globalisation also has economic consequences since the Dutch refining industry finds itself operating in a global market. The Dutch refining industry faces a lot of competition from export orientated refineries in the Middle-East and China. It is therefore crucial that the implementation of the CO_2

reducing alternatives does not deteriorate the competitiveness of the Dutch refineries. Therefore TA is also extended with an economic perspective.

2.2.3 Multi-criteria analysis

A multi-criteria analysis is used to identify and choose the most promising CO_2 reducing alternatives. It is a form of decision making equipped to handle the multiplicity of criteria used for judging the alternatives (Mateo, 2012). A multi-criteria analysis can be used for addressing complex problems that feature high uncertainties, conflicting objectives, different forms of data and multiple interests and perspectives (Wang et al., 2010). Multi-criteria decision making usually consist out of five main stages (Mateo, 2012). The first stage defines the problem, generates alternatives and establishes criteria. Objectives, relevant actors, conflicts, constraints and uncertainties all need to be discussed. Most of these aspects are already discussed in the chapters leading up to the multi-criteria analysis. The next step is to allocate weights to the constructed criteria. These weights reflect the relative importance of the criteria with respect to each other. The technique used to determine the weights is the Analytical Hierarchy Process. This method is also used to perform the construction of the evaluation matrix and determining the most promising alternatives. Since the weights assigned to the evaluative criteria can differ per actor involved, they are constructed for multiple actor perspectives. As a result the most promising CO_2 reducing alternatives can differ per actor.

Part II – CO_2 profile of Dutch refineries

3. Technical analysis Dutch refineries

Chapter 3 presents a technical analysis of the Dutch refining industry, providing an overview of the processes within the Dutch refining industry and their contribution to the CO_2 emissions. Section 3.1 describes the different complexity levels of refineries and identifies the processes present within the Dutch refining industry. Refining emissions are assessed in section 3.2. Finally, section 3.3 CO_2 emissions are allocated to each refinery process.

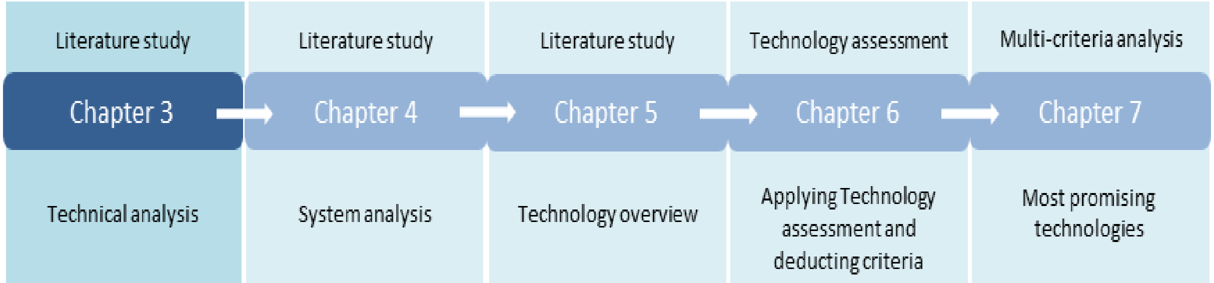

Figure 7 - Overview: chapter 3

To answer the research question "Which processes take place within the Dutch refining industry and how do they contribute to the CO_2 profile of the refineries" it is important to define the scope. Handbooks of petroleum refining are consulted to construct an overview of the wide variety of processes present in refineries (Treese et al., 2015 ; Fahim et al., 2010). The most important step is to determine which of these processes are present within Dutch refineries. Due to the limited amount of publically available data it is impossible to construct a complete overview of all processes present within the Dutch refining industry. As a result, not all processes described in the refining handbooks are included within the overview of processes located in Dutch refineries.

An incomplete overview of refining processes also has consequences for the allocation of CO_2 emissions to the processes of Dutch refineries. In reality additional processes are present which also emit CO_2. This results in differences between the calculated and actual CO_2 emissions of Dutch refineries. The allocated CO_2 emissions to the processes are therefore not exact but do provide a basic understanding of the processes that emit the largest amounts of CO_2 within Dutch refineries.

3.1 Complexity of Dutch refineries

A lot of processes take place within a refinery before useful products are produced from crude oil. These processes can be classified in two categories, namely physical separation and chemical conversion (Fahim et al., 2010). The chemical conversion processes can be further divided into chemical catalytic conversion and thermal chemical conversion. Table 3 shows the different possible processes within a refinery allocated to the different classifications.

Table 3 - Refinery processes allocated to physical and chemical conversion (Fahim et al., 2010)

Physical separation	Chemical conversion	
	Catalytic	Thermal
Distillation	Reforming	Delayed coking
Solvent deasphalting	Hydrotreating	Flexicoking
Solvent extraction	Hydrocracking	Visbreaking
Solvent dewaxing	Cracking (FCC)	
	Alkylation	
	Isomerization	

After entering the refinery, crude oil is in all cases first processed by an atmospheric distillation column. In some cases the residue of this column enters a second distillation unit called the vacuum distillation tower. Products that are formed after the distillation process are: Refinery gases, Liquid petroleum gases (LPG), Light naphtha, Heavy naphtha, Kerosene, middle distillate, Light gas oil, Heavy gas oil, Vacuum gas oil and Vacuum residue (Gary & Handwerk, 2001). Depending on the type of end-product that is demanded further treatment is required.

Therefore, not all processes depictured in table 3 are present in each refinery. Refinery configurations differ a lot and are largely dependent on the type of crude oil that is used as feedstock and product demand. It is therefore useful to make a distinction between refineries based on their processing capability (Treese et al., 2015). They can be classified in four categories of the most common refinery types: 1) topping refinery, 2) hydroskimming refinery, 3) cracking refinery and 4) coking (full conversion) refinery. The types describe refineries that increase in complexity and are more capable to use poor crude qualities to make products.

The **topping refinery** has the simplest configuration of the four. Its primary process is the distillation of crude oil into light ends, naphtha, kerosene and diesel. Since this refinery does not have a vacuum distillation unit, the atmospheric residue that is extracted at the bottom of the crude distillation unit is sold as fuel oil. The distilled fractions do not undergo much further treatment, no chemical conversion methods are used. Due to its simplicity the topping refinery is relatively easy to operate, runs at low costs, is cheap to build and is flexibly in capacity utilisation (Treese et al., 2015). However, it can only process a limited variety of crude oil types and due to the lack of chemical conversion most products do not meet environmental standards and must be sold as intermediates.

A **hydroskimming refinery** is more complex and capable than the topping refinery. After the crude distillation unit separates crude oil into fractions, the diesel and naphtha are further processed. By means of hydrotreatment and catalytic reforming fractions are upgraded to meet final specifications. Hydroskimming refineries produce light ends, gasoline, jet fuel and ultra-low sulphur diesel. These products are formed by blending the different treated fractions. The advantage of this refinery type is that this configuration allows a larger flexibility in the quality of the crude oil. Despite the extra chemical conversion processes it is still relatively inexpensive to build and the hydrogen produced by the reforming can be used for upgrading (Treese et al., 2015). Moreover, the hydroskimming refinery does not contain a vacuum distillation unit and therefore the refinery produces lots of fuel oil and cannot process heavy crudes.

The **cracking refinery** is the first type that processes the atmospheric residue and converts it into more valuable products. A vacuum distillation tower processes the residue and produces vacuum gas oil and vacuum residue (Fahim et al., 2010). Furthermore a cracking refinery uses a fluid catalytic cracking (FCC) unit combined with an alkylation unit or a hydrocracker to convert the vacuum gas oil. After treatment it can be used for gasoline or diesel blending. If the demand for diesel is high a refinery favours a hydrocracking unit while if the demand for gasoline is higher a FCC unit is more favourable (Treese et al., 2015). The main advantage of a cracking refinery is the ability to process a larger variety of crude oil qualities and to produce more high-value products. These advantages are at the expense of higher capital and operating costs of the refinery.

The most complex refinery type is the **coking or full conversion refinery**. This type of refinery is distinguished from the cracking refinery by its ability to convert vacuum residues into higher value products. A Cocking unit enables the refinery to carry out this process (Fahim et al., 2010). The remaining additional processes remain similar to the cracking refinery. Like the cracking refinery the coking refinery also choses between a FCC unit or a hydrocracker based on the market demand for respectively gasoline or diesel. These refinery types have the largest flexibility in processing crude oil quality and make the highest amount of high-value products with a minimum of by-products (Treese et al., 2015). However these coking refineries are significantly more expensive than the other types and have complex operating systems.

Figure 8 shows a simplified schematic visualisation of the processes related to the different refinery types. In this case the refinery configuration in equipped with a FCC unit instead of a hydrocracker.

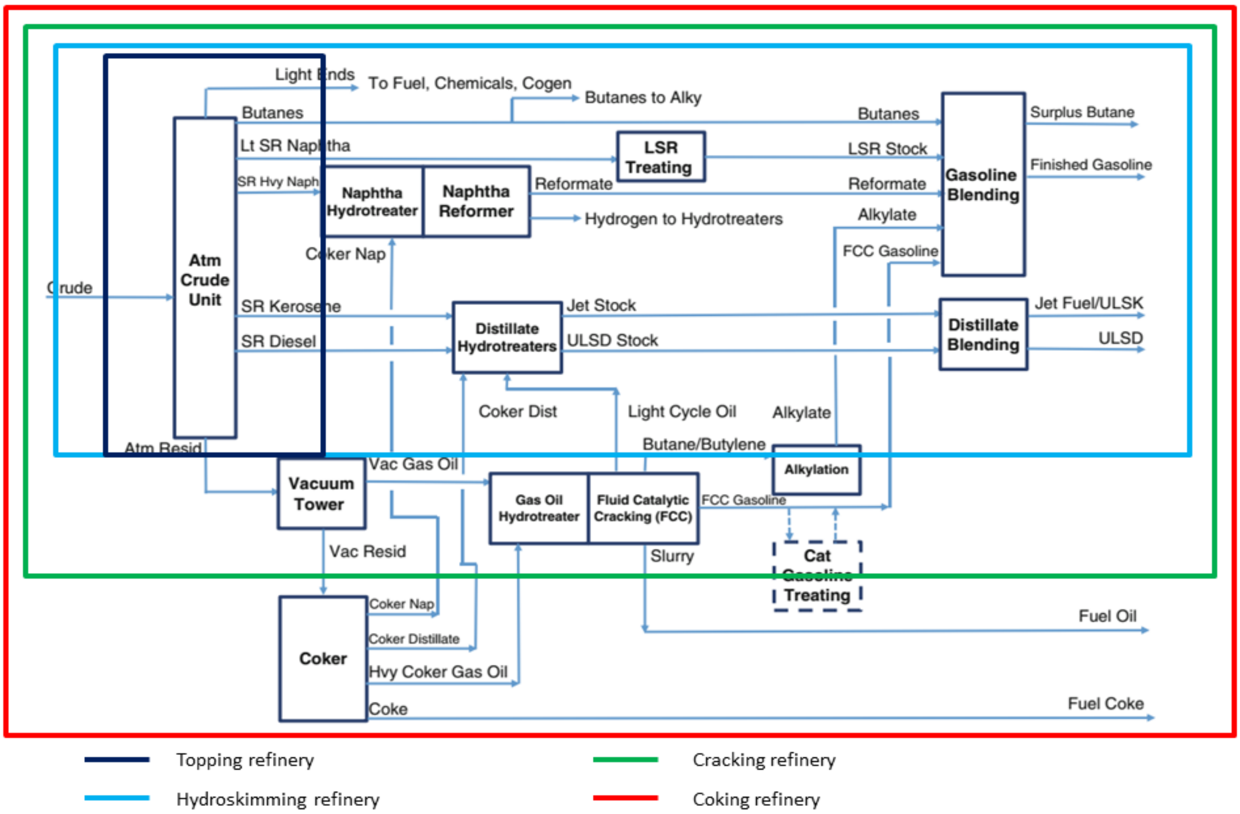

Figure 8 - Schematic overview of processes in the different types of refineries (Treese et al., 2015)

The Dutch refining industry consists of six refineries, five of them are located in the Port of Rotterdam, namely Shell Pernis, ExxonMobil, BP, Gunvor and Koch. The last refinery is the Zeeland refinery located near Vlissingen. Their configurations range from relatively simple to highly complex. Each refinery in the Netherlands has its own configuration and processes installed accordingly. Table 4 shows the processes that are present within each Dutch refinery. Using table 4 it can be concluded that the Koch refinery has the simplest configuration and can be categorized as a topping refinery. The Shell, ExxonMobil and BP refineries are the most complex and can be categorized as a coking or full conversion refinery.

Table 4 - Overview of refining processes allocated to the Dutch refineries (Port of Rotterdam, 2016 and a barrel full, 2015)

	Shell	ExxonMobil	BP	Gunvor	Koch	Zeeland
Atmospheric distillation	X	X	X	X	X	X
Vacuum distillation	X	X	X	X		X
Catalytic reforming	X	X	X	X		X
Alkylation	X		X			
Fluid-bed catalytic cracker	X		X			
Hydrocracker	X	X				X
Hydrotreater	X	X	X	X		X
Thermal cracker	X			X		
Visbreaker			X	X		
Flexicoker		X				

In the beginning of this chapter it was already mentioned that the overview of processes located within Dutch refineries in table 4 is not complete. Despite the fact that some processes are missing this is the most complete overview that can be constructed with publically available data. It forms the basis for determining the contribution of individual processes to the total CO_2 emissions of Dutch refineries. Appendix A explains the refining processes that are present within the Dutch refining industry into more detail.

3.2 Emissions of Dutch refineries

The previous section along with Appendix A elaborated on the different processes that take place within the Dutch refining industry. These processes are highly energy intensive and have a large effect on the environment (Johansson et al., 2013). Since the 1950s the control of contaminants became an important factor for the design and operation of refineries. Refineries face increasingly difficult environmental challenges to protect water, soil and atmosphere from refinery pollution (Fahim et al., 2010). Pollution caused by refineries can be categorized in four sub-areas: air emissions, water effluents, solid wastes and noise (Treese et al., 2015). Each sub-area is important to assess the impact of refineries on the environment. However, since this research aims at analysing options that reduce CO_2 emissions of refineries, the focus lies on air pollution. Hence, the next section describes the emissions of the different processes that take place within the Dutch refining industry.

3.2.1 Air pollution

Refineries emit a large variety of particles that may harm the environment. The most common contaminants are: sulphur, carbon oxides, nitrogen oxides, volatile organic compounds, particulate matter and ozone (Hadidi et al., 2016). Air emissions can arise from point and non-point sources (Fahim et al., 2013). Point sources are most easily monitored and treated because these emissions exit stacks and flares. More difficult to locate are non-point source emissions due to their fugitive character. These fugitive emissions arise from valves, pumps and so on. Almost every process within a refinery produces flue gas and fugitives (Treese et al., 2015). Flue gas is the gas that leaves a furnace or other process conveyed by pipe or channel (Beychok, 2012). Flue gas produced by refineries typically contains nitrogen oxides, carbon dioxide, sulphur and particulate matter.

SO_2 emissions are largely caused by sulphur embedded in the crude oil. The sulphur levels are already reduced by hydrotreating and hydrocracking units. In most cases the remaining sulphur levels are low enough for the gas to be used as a fuel. If the sulphur levels are still too high caustic treatment or a physical solvent can be used to further reduce the sulphur levels (Treese et al., 2015). Combustion sources within the refineries are responsible for the majority of NOx emissions. These can be reduced by keeping the fuel gas clean from nitrogen compounds and operate the burners in a correct manner with the addition of excess air in the furnaces (Hadidi et al., 2016). Particulate matter can come from many different sources within a refinery. These particles are especially a danger to the environment when they are smaller than 10 µm, PM10 (Treese et al., 2015). The biggest potential emitter of PM10 in a refinery is the FCC unit. To avoid the emission of PM10 particles are collected within the unit by a cyclone separator. CO_2 is emitted in large quantities by refineries and accounts for the majority of their total emissions. It is produced from multiple sources such as fired heaters, combustors and FCC units (Bozlakera et al., 2013). Controlling CO_2 emissions can be done by maintaining excess air and not overheating the product within fired heaters and combustors. The FCC unit can reduce CO_2 emissions by ensuring a good distribution of catalysts (Treese et al., 2015).

In the past decade Dutch refineries faced increasingly stringent environmental regulation which required them to reduce their emissions of pollutants. The IMO Marpol legislation addressed the sulphur content in fuels on a global level. On the European level the IED and NEC set standards and maximums for emissions of NOx, SO_2 and PM (EC, 2010 ; 2013). With regard to the reduction of GHG emissions the EU set up directives such as the EU ETS, the fuel quality directive and renewable energy directive. This increased regulation led to a significant reduction of SO_2, NOx and PM10 emissions within the Dutch refining industry which is shown in figure 9.

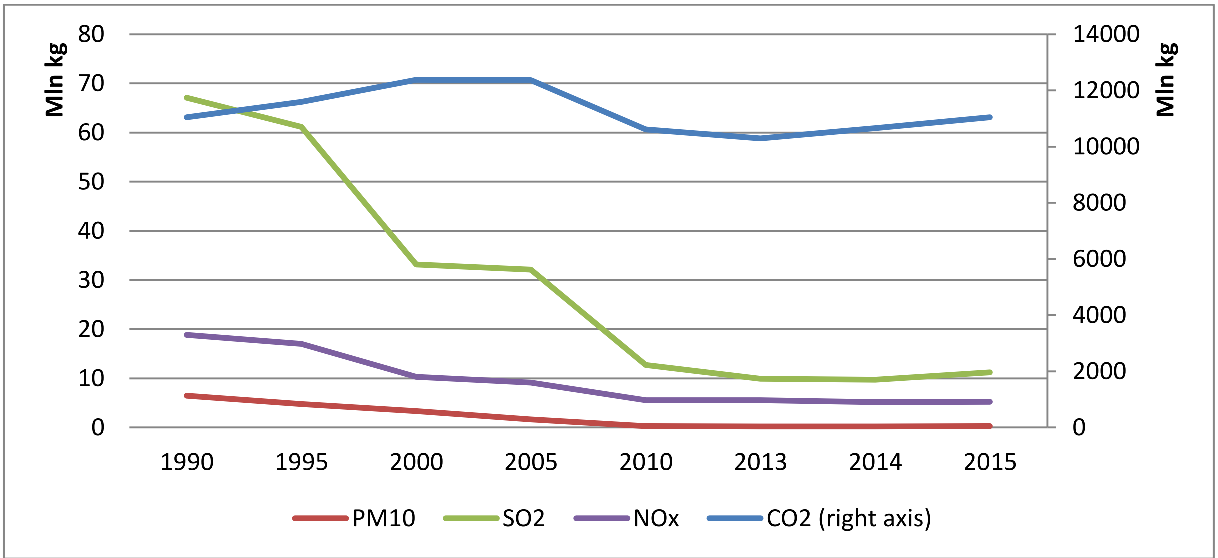

Figure 9 - Emissions of Dutch refineries from 1990 till 2015 (Emissieregistratie, 2016)

From this graph it becomes clear that especially SO_2 emissions dropped significant between 1990 and 2015. The NOx and PM10 emissions also dropped substantial. However, despite the reduction of these emissions the Dutch refining industry still emits large amounts of CO_2. Furthermore no decreasing trend in CO_2 emissions is observed between 1990 and 2015. An important reason for the fact that CO_2 emissions haven't decreased the past decennia is the IMO Marpol regulation. Since refineries are obliged to remove sulphur during the refining process, processes such as hydrotreatment or hydrocracking needed to be installed. These additional processes cause the refineries to emit even more CO_2. Another reason for the absent decline in CO_2 emissions it the fact that it is difficult to reduce CO_2 emissions by just improving refining processes. Ensuring the refinery is operating at maximum efficiency is one of the few options with regard to reducing CO_2 emissions of processes (Treese et al., 2015). Another possibility is the recovery of CO_2 or implementing other CO_2 reducing options. In order to fully understand and assess the impact of these CO_2 reducing options it is important to first allocate the CO_2 emissions to all the refinery processes.

3.3 CO_2 allocation to processes within Dutch refineries

There are many sources of CO_2 emissions within refineries. The quantity of CO_2 emitted by a refinery depends on the kind of crude oil it processes along with its configuration and the produced products. If the refinery processes a heavier crude or produces a high share of lighter products such as gasoline and diesel, the crude oil requires more processing and therefore the refinery emits more CO_2. This chapter allocates CO_2 emissions of Dutch refineries to processes present within the sector. These processes, discussed in section 3.2, contribute differently to the total CO_2 emissions of a refinery. Chapter 4 discusses the impact of the crude oil intake and product slate of Dutch refineries on their CO_2 emissions. Since a significant amount of Data concerning Dutch refineries is not publically available not all processes located within Dutch refineries can be included. Only the processes that report publically available data are included. As a result not all processes located within the Dutch refining industry are included within this analysis.

3.3.1 CO_2 emissions of individual processes within the Dutch refining industry

In general there are two main approaches for the allocation of CO_2 emissions to a refinery (Pierru, 2007). The first approach allocates energy use and emissions at the refinery level and is unable to take the different processes within a refinery into account. It allocates the emissions based on the products that are produced and ignores the fact that these products are treated by different processes. Therefore this approach is relatively insensitive to changes in individual refining processes (Wang et al., 2004). Furoholt (1995) was the first to apply the second allocation approach which is based on the different refining processes. This approach that allocates the CO_2 emissions at the refining process level was also advocated by the International Standard Organisation (ISO, 1998). Since this research aims to allocate refinery emissions to refinery processes the second approach is more suitable.

For each approach a number of methods can be used to allocate CO_2 emissions to a refinery. Individual refinery data on crude import, energy use and product output would be usefull to allocate the CO_2 emissions to the different processes (Wang et al., 2004). However this data is not publicly available and therefore another method is used. Another method is linear programming simulating a typical refinery. The downside of this method is again that it requires detailed information of individual refineries which is not publicly available. Furthermore a simulation differs from the real refinery and calibrating the model to a specific refinery is time consuming and expensive (Wang et al., 2014).

Therefore a methodology is used that tries to overcome the problem of data availability. Despite limited available it allocates the CO_2 emissions at the refinery process level. The foundation for this method is the benchmark study of the European Union (EU, 2011). This study uses a CO_2 weighted ton (CWT) approach to compare the different processes within a refinery with regard to their CO_2 emissions. By doing so, the configurations of Dutch refineries are taken into account.

An extensive description of the used methodology along with the calculations can be found in Appendix B. Before CO_2 emissions are allocated to the individual processes of the Dutch refineries, an overview of the calculated CO_2 emissions per refinery is provided. The results are compared to the actual emitted amount of CO_2 to check the validity of the CWT approach. Table 5 presents the calculated CO_2 emissions of the Dutch refineries according to the methodology described above along with the actually emitted amount of CO_2. As expected, the calculated CO_2 emissions are different form the actual emitted amount due to the lack of available data. Since publicly available data does not contain all processes within Dutch refining, the calculated CO_2 emissions are lower than the actual emissions. This is confirmed by table 5 as the calculated CO_2 emissions of refineries with relative simple configurations are closer to the actual amount of CO_2 emitted than those of more complex refineries. The reason behind this is the degree of additional processes that take place within complex refineries which are not available in publically available data and therefore not included within the calculations. For example the differences between calculated and actually emitted CO_2 for the Koch refinery (simple configuration) is almost none, while the difference between the amounts for the Shell refinery (complex configuration) almost differs by a factor 2.

Table 5 - Calculated CO_2 emissions vs actually emitted CO_2 (ETS, 2015)

Dutch refineries	Calculated CO_2 emissions (Mton)	Actual CO_2 emissions (Mton)
Shell Pernis	2.2	4.3
ExxonMobil	1.9	2.3
BP	1.8	2.3
Gunvor	0.5	0.6
Koch	0.1	0.1
Zeeland	0.9	1.5

Despite inaccuracies, table 5 provides useful insights for this research. It shows that more complex refineries emit more CO_2 than refineries with relatively simple configurations. This is in line with findings from Plomp & Kroon (2010).

Appendix B contains the complete analysis that allocates the CO_2 emissions of Dutch refineries to their individual processes. Table 6 presents the results of this analysis. In most cases the atmospheric distillation unit is the largest emitter of CO_2 within a refinery. When the refinery has a very simple configuration, like Koch, CO_2 emissions of the atmospheric distillation unit amount to 70% of the total emissions. In more complex refineries this unit contributes to around 30% of total CO_2 emissions. This is in line with the findings of Reinaud (2005). Besides the atmospheric distillation unit, the Flexicocker is also a large source of CO_2 emissions. This is not strange since its CWT-factor is 16.6 meaning it produces almost seventeen times more CO_2 per processed unit then the atmospheric distillation unit. Since the ExxonMobil refinery has a large Flexicoking capacity, this unit account for almost 60% of their total emissions. Table 6 furthermore shows that the FCC unit and hydrocracker substantially contribute to the total CO_2 emissions of Dutch refineries. Depending on the configuration the FCC unit and hydrocracker respectively emit 19% to 31% and 9% to 31% of the total CO_2 emissions. Again this is in line with the findings of Reinaud (2005).

Table 6 - CO_2 emissions of processes per Dutch refinery

CO_2 emissions per process as percentage of the refinery's total CO_2 emissions						
	Shell	ExxonMobil	BP	Gunvor	Koch	Zeeland
Atmospheric distillation	28%	14%	33%	29%	72%	24%
Vacuum distillation	9%	6%	7%	13%		8%
Catalytic reforming	12%	9%	10%	32%		21%
Alkylation	3%		4%			
FCC unit	19%		31%			
Hydrocracker	10%	9%				31%
Hydrotreater						8%
Thermal cracker	10%			9%		
Visbreaker			5%	4%		
Flexicoker		57%				

3.4 Sub-conclusion

This chapter tried to answer the research question "Which processes take place within the Dutch refining industry and how do they contribute to the CO_2 profile of the refineries". Processes located within Dutch refineries are: atmospheric distillation, vacuum distillation, catalytic reforming, alkylation, fluid-bed catalytic cracker, hydrocracker, hydrotreater, thermal cracker, visbreaker and flexicoker. The Koch refinery has the relatively simplest configuration and can be categorized as a topping refinery while the Shell Pernis and ExxonMobil refineries are the most complex and can be categorized as a coking or full conversion refinery.

Allocating the CO_2 emissions of Dutch refineries to their individual process revealed that in most cases the atmospheric distillation unit is the largest emitter of CO_2 within a refinery. When the refinery has a very simple configuration, CO_2 emissions of the atmospheric distillation unit amount to 70% of the total emissions. In more complex refineries this unit contributes to around 30% of total CO_2 emissions. Besides the atmospheric distillation unit, the Flexicocker, the FCC unit and hydrocracker substantially contribute to the total CO_2 emissions of Dutch refineries.

4. The effect of crude oil intake and product slate of Dutch refineries on their CO_2 profile

The core function of the Dutch refining industry is the production of useful products from crude oil (Treese et al., 2015). Among these products are transport fuels, such as gasoline, diesel, kerosene, LPG, and gas oil (Speight, 2009). Refineries also produce naphtha which can serve as feedstock for petrochemical industry or gasoline manufacturing (Parkash, 2003). Processes that convert crude oil into these different products are highly energy intensive and cause refineries to emit large amounts of CO_2 (Johansson et al., 2013). This chapter completes the construction of the CO_2 profile of Dutch refineries by performing a system analysis. The system analysis examines the effect of crude oil intake and product slate of Dutch refineries on their CO_2 emissions.

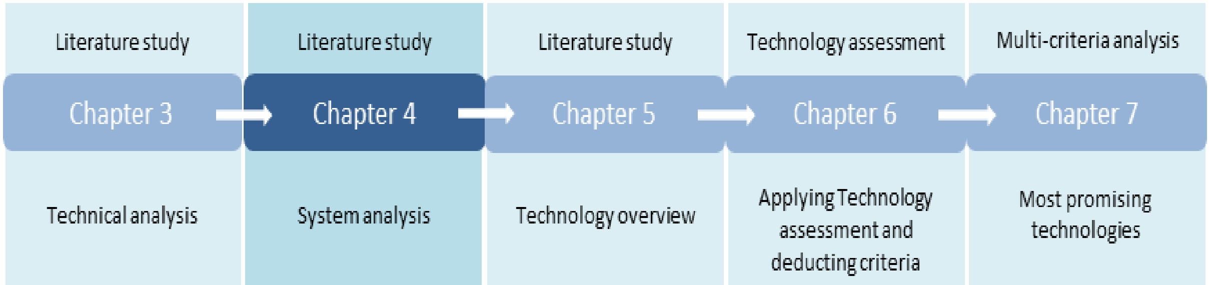

Figure 10 - Overview: Chapter 4

The CO_2 emissions of Dutch refineries is dependent on the crude oil intake and product slate of refineries since they influence the required refinery configuration. Many types of crude oil are produced around the world, each of these crudes has its own characteristics. These characteristics affect the required complexity of refineries and thereby the processes needed to convert crude oil into products. CO_2 emissions of Dutch refineries are therefore influenced by the crude oil intake. Another factor that influences the CO_2 emissions of Dutch refineries is their product slate. Refineries produce a wide variety of products, some of these products require few conversion steps while others require a lot of additional treatment. As a result the number of refining processes and thereby the CO_2 emissions of Dutch refineries is largely determined by the products slate of the refineries. In turn, the product slate of Dutch refineries is mainly determined by the demand for transport fuels. This chapter does not include CO_2 emissions related to the production of crude oil and the burning of transport fuels.

Chapter 4 starts by analysing the effect of crude oil intake on CO_2 emissions in section 4.1. The first step is determining the characteristics and properties that vary within different types of crude oil. Subsequently the different types of crude oils that are used by Dutch refineries are mapped. The second part of this chapter analyses the effect of the product slate on the CO_2 emissions of refineries in section 4.2. It is important to first explore the different products that are currently produced by Dutch refineries. Since the product slate is for a large part dependent on the demand for transport fuels the final step is to analyse future demand expectations.

4.1 Crude oil and CO_2 emissions Dutch refineries

To assess the influence of different types of crude oils on the CO_2 emissions, section 4.1.1 explores the characteristics of crudes. Followed by an overview of crude oils processed within the Dutch refining industry in section 4.1.2. Section 4.1.3 analyses the influence of these types of crude oil on the CO_2 emissions of Dutch refineries.

4.1.1 Crude oil characteristics

Crude oil is produced all around the world, the largest producers are Saudi-Arabia, the United States and Russia (BP, 2016). At first glance, crude oil seems a homogeneous product, however, each oil reservoir contains its own specific type of crude. As a result, oil producing countries can supply one or more different types of crude oil. The most important properties of crude oil are its density and sulphur content (EIA, 2013). With regard to crude oil density a distinction is made between light and heavy crude oils. According to the API gravity, crude oils are classified as light when their API is high and classified as heavy when their API is low. Crude oils are classified as “heavy” when their API gravity is less than 20. For the sulphur content, crude oils are classified in sweet (low sulphur) and sour (high sulphur) crude oils. Sour crude oil contains a high amount of sulphur while sweet crude oil contains little sulphur impurities. If the total level of sulphur in a crude oil exceeds 0.5% it is characterized as sour (Gulen, 1999). An extensive elaboration on the characteristics of crude oil can be found in Appendix C.

Overall it can be concluded that light and sweet crude oils are preferred by refineries and are therefore usually higher priced than heavy and sour crude oils. The underlying reason for this preference and higher price is the fact that these light and sweet crude oils can be more easily and cheaply refined into gasoline and diesel fuels. They require less complex and energy intensive processes within refineries. Gasoline and diesel fuels are typically the most valuable transports fuels and can therefore be sold at a premium with respect to residual fuel oil and other bottom of the barrel products (Fattouh, 2010). Figure 11 shows a wide variety of crude oil produced around the world sorted by API gravity and sulphur content.

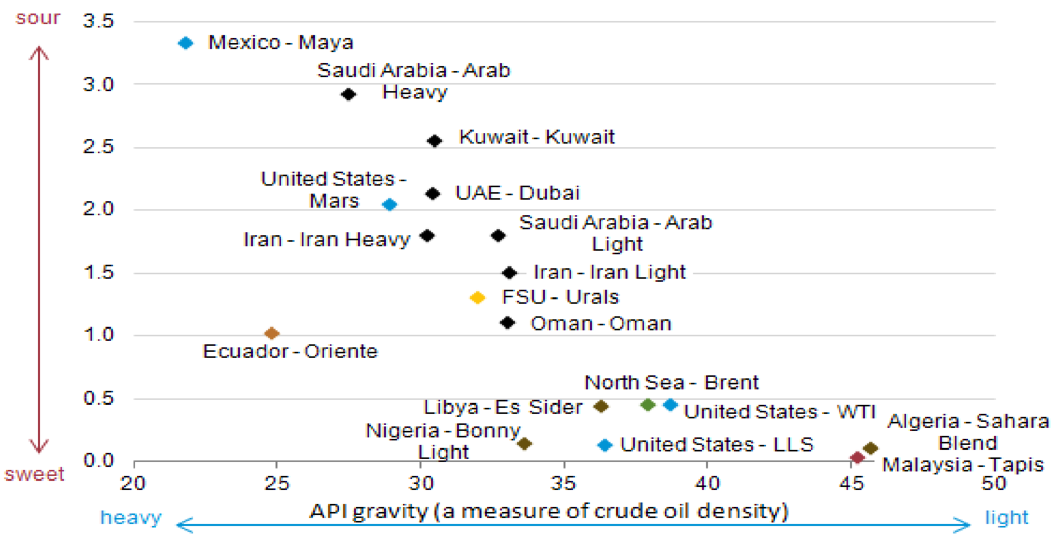

Figure 11 - Crude oils sorted to API and sulphur content (EIA, 2013).

4.1.2 Types of crude oil processed within the Dutch refining industry

In order to explore the different types of crude oils that Dutch refineries use, the countries that supply crude oil to the Netherlands are mapped. In 2015 the Netherlands imported a total of 62 million tons of crude oil (CBS, 2015). Russia and Norway are the largest suppliers of crude oil to the Netherlands, other important suppliers are Nigeria, Kuwait and the United Kingdom. Figure 12 represent the share of crude oil imported from different countries to the Netherlands. Appendix C gives a complete overview of all countries supplying crude oil to the Netherlands.

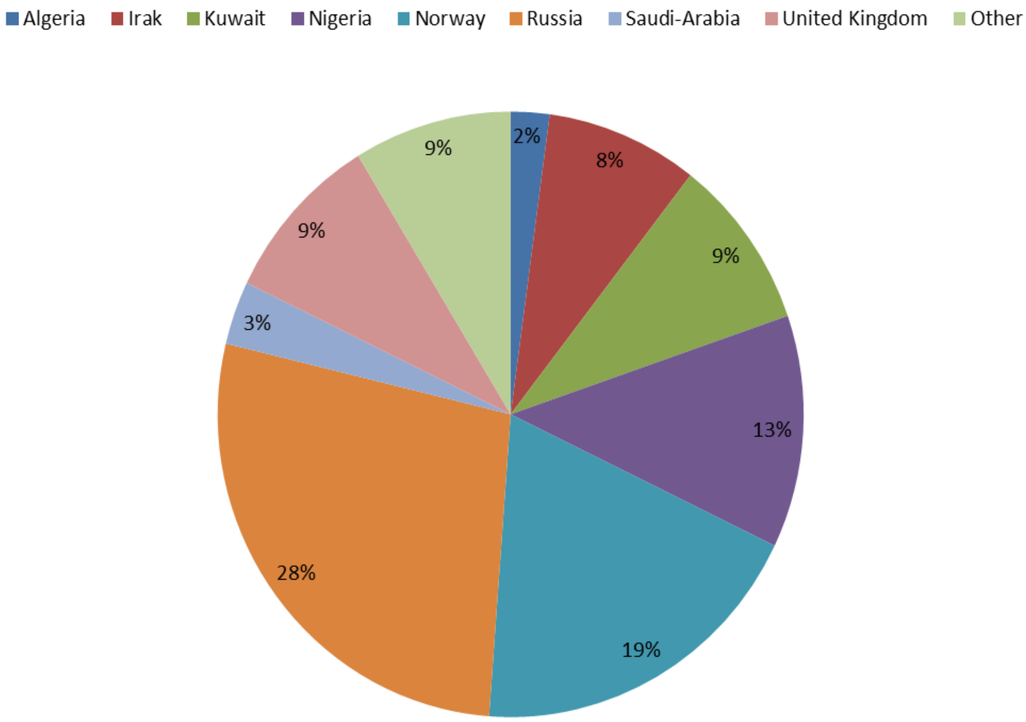

Figure 12 - Share of crude oil imported by the Netherlands (CBS, 2015)

Each oil producing country has its own type of crude oil or sometimes even more than one depending on their oil sources. For each country their most common and most produced crude oil type is selected. Table 7 and Appendix C show these different countries with their crude oil types along with the properties of API gravity and sulphur content. The Netherlands imports light and medium crudes with an API ranging from 32.4 to 43.6. These crude oils have a sulphur content ranging from 0.1 to 2.6.

Table 7 - Properties of the crude oil types from the largest suppliers to the Netherlands (Jacobs, 2012 ; BP, 2015).

	Crude name	API	Sulphur
Russia	Urals	32.7	1.3
Norway	Ekofisk	38.1	0.2
Nigeria	Bonny light	35.4	0.2
United Kingdom	Forties	38.9	0.5
Kuweit	Kuweit	32.4	2.6
Irak	Bashra Light	33.7	1.9
Saudi-Arabia	Arab medium	31.3	2.5
Algeria	Saharan Blend	43.6	0.1

Note that table 7 present the most common and most produced crude oil types of each oil producing country. However, since the Dutch refining industry has some highly complex refineries it could be the case that instead of the most common crude oil type an alternative is chosen that has is heavier and more sour but is sold at a discount. Complex refineries are able to process these heavier and sour crude oils. When they are sold at a discount they could increase their refining margins. In addition the imported crudes do not necessarily go to the Dutch refineries since the Netherlands is a large hub for crude re-exports.

4.1.3 Effect of crude oil on CO_2 emissions Dutch refining industry

CO_2 emissions of Dutch refineries are influenced by the API gravity of the crude oil they process. This is due to the fact that the energy that is required to refine crude oil depends on the type of crude oil and its properties. Crude oils with a high API gravity require less energy to refine. These crudes need less additional treatment and therefore less refining processes. The CO_2 emissions related to refining crude oil decrease as the API gravity increases. Refining heavy crudes increases the CO_2 emissions of Dutch refineries. Figure 13 shows the results of a study performed by Jacobs (2012) which assesses the impact of the API gravity on CO_2 emissions of refineries. They examined CO_2 emissions for different refining configurations with regard to the API gravity of the crude oil. It shows that as the API gravity increases the CO_2 emissions decrease.

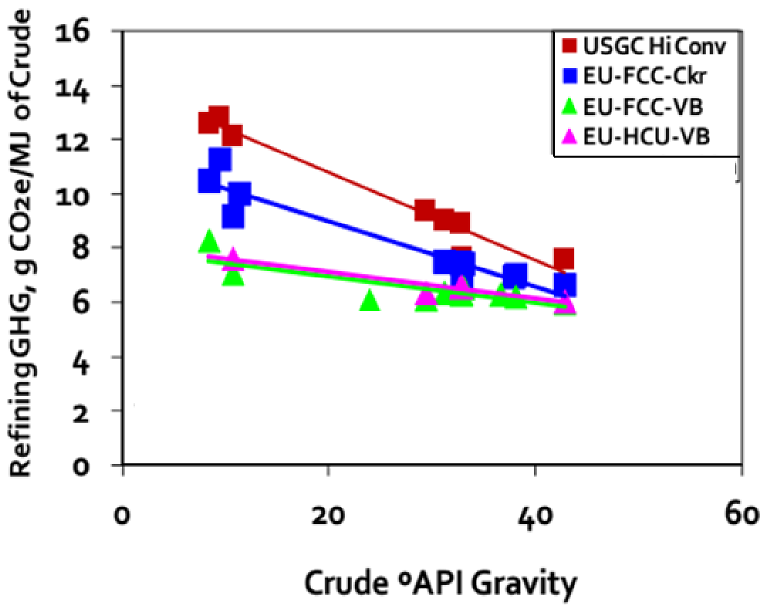

Figure 13 - CO_2 emissions of refineries with regard to the API gravity of crude oil (Jacobs, 2012).

The CO_2 emissions of Dutch refineries are not only influenced by the API gravity of the crude oil they process. Also the sulphur content within the crude oil influences the CO_2 emissions. Strict regulations exist that limit SO_2 emissions. They are therefore forced to remove sulphur when processing crude oil. This can be achieved by hydrotreatment and hydrocracking (Treese et al., 2015). These processes are, however, highly energy intensive and lead to increased CO_2 emissions of Dutch refineries. A high sulphur content of crude oil will result in higher CO_2 emissions. The CO2 emissions of refineries therefore increase if heavier (low API) and sourer (high sulphur) types of crude oil are processed.

4.2 Product slate (demand) and CO_2 emissions Dutch refineries

The types of products produced by a refinery have consequences for the required complexity and the number of energy intensive processes. Lighter fractions such as gasoline and diesel require more additional processing. As a result the product slate of Dutch refineries might also have an effect on their CO_2 emissions (Johansson et al., 2013). To assess the influence of the product slate of Dutch refineries on their CO_2 emissions the section 4.2.1 explores the different products produced by Dutch refineries. The impact of the product slate on the CO_2 emissions of Dutch refineries is assessed in section 4.2.2. Section 4.2.3 explores future demand expectations and analyses its influence on CO_2 emissions of refineries towards 2050. CO_2 emissions related to usage of these products are not taken into account. The following sections solely focus on the effects of produced products on the CO_2 emissions of the Dutch refining industry.

4.2.1 Which products are produced within Dutch refineries and in what quantities.

The JODI database provides the output of refineries per country. They classify refinery products into seven classes, namely LPG, naphtha, gasoline, kerosines, gas/diesel oil, fuel oil and other oil products. Refinery product outputs are monthly and in thousands of barrels. Table 8 present the output of the Dutch refining industry for April 2016. It seems that the Dutch refining industry mainly produces naphtha, gas/diesel oil and fuel oil. Gasoline and LPG are not produced in large quantities. Naphtha is produced in large quantities since it serves as feedstock for petrochemical installations located within the cluster of Rotterdam (Port of Rotterdam, 2016). The large diesel production of Dutch refineries is related to the high demand of diesel within Europe (IEA, 2015). Fuel oil is produced as residue and therefore relatively high in quantity.

Table 8 - Output of the Dutch refining industry per product for April 2016 (JODI, 2016)

Refinery products	Output (Kb)	Percentage of total output
LPG	1462	3.9%
Naphtha	8597	22.8%
Gasoline	1935	5.1%
Kerosines	5477	14.5%
Gas / Diesel oil	10586	28.1%
Fuel oil	7740	20.5%
Other oil products	1898	5.0%

4.2.2 Product slate of Dutch refineries and their CO_2 emissions

Naphtha, a relatively light fraction that is formed after the crude oil, is distilled by the CDU. If a refinery has a coking unit at their disposal extra naphtha can be obtained from the heavy residues produced by the CDU unit (Treese et al., 2015). The ExxonMobil refinery is the only Dutch refinery that has such a unit at their disposal (Port of Rotterdam, 2016). To remove impurities, naphtha can thereafter be hydrotreated or catalytically reformed. The remaining naphtha is then transferred to other petrochemical installations where it serves as feedstock or fed into a gasoline blending unit. Besides the distillation by the CDU, the formation of naphtha requires some additional processes such as hydrotreating, catalytic reforming and in some cases even coking. As a result the production of naphtha within Dutch refineries contributes substantial to CO_2 emissions.

Light fractions such as diesel and gasoline are the more valuable products produced by refineries. A lot of additional processes located within refineries are installed to ensure a maximum production of these light ends. A small fraction of diesel and gasoline is directly produced by the CDU. However, the remaining amount is acquired by upgrading heavy residues. For the production of diesel a hydrocracker is used to upgrade heavier residues (Treese et al., 2015). As a result the wide variety of additional energy intensive processes is required. The large production of diesel within the Dutch refining industry therefore contributes substantially to CO_2 emissions of Dutch refineries.

The produced amount of fuel oil originates from the heavy residues produced by the CDU unit. Refineries aim to upgrade the heavy residues by additional processes to obtain lighter and more valuable fractions. Refineries that are not very complex do not have means for upgrading this fuel oil (Treese et al., 2015). Fuel oil production itself does not require any additional processing and is produced by the CDU itself. Therefore the large quantity of produced fuel oil does not substantially contribute to the CO_2 emissions of the Dutch refineries.

Overall it can be concluded that the CO_2 emissions of Dutch refineries are partially caused by their product slate. Light and valuable products such as gasoline, diesel and naphtha require more additional processes than heavy products such as fuel oil. As a result the production of these lighter fractions cause Dutch refineries to emit more CO_2. A remark to this analysis needs to be made. The performed analysis tries to assess the impact of the product slate on CO_2 emissions by determining the kind and number of processes required. Linking this to the results of chapter 3 (CO_2 emissions of different processes) an estimation of the CO_2 intensity of different products is made. There is however no straightforward methodology to allocate CO_2 emissions to final products (Reinaud, 2005). In other words it is almost impossible to determine the CO_2 emissions of a refinery for the production of one tone of gasoline or diesel. This is due to the fact that oil refineries produce a number of different products simultaneously from a single feedstock. Bredeson et al. (2010) endorses this statement by showing that the most important factors that drive the CO_2 emissions of refineries are its crude intake and configuration.

4.2.3 Future demand developments and CO_2 emissions of Dutch refineries

The previous section concluded that there is no straightforward methodology to allocate CO_2 emissions to final products. It is however possible to analyse the number of processes required for producing certain refinery products. Linking this information to the results of chapter 3 it is possible to make an estimation of the CO_2 emissions related to the produced products. In that respect it is useful to assess the future demand expectations for refinery products and discuss its possible effects on the CO_2 emissions of Dutch refineries towards 2050.

Figure 15 shows that oil product demand in Europe decreases for all product types. This is in line with the views of the IEA (2015) whom foresee a structural decline in European oil product demand. Only the demand for gasoline remains almost equal towards 2040. Residual fuel oil shows the largest decline in demand within Europe and decreases by almost two thirds. According to figure 14, the demand for oil products worldwide, except residual fuel oil, still increases towards 2040. This is again in line with the findings of the IEA (2015). Diesel demand is expected to increase the most worldwide.

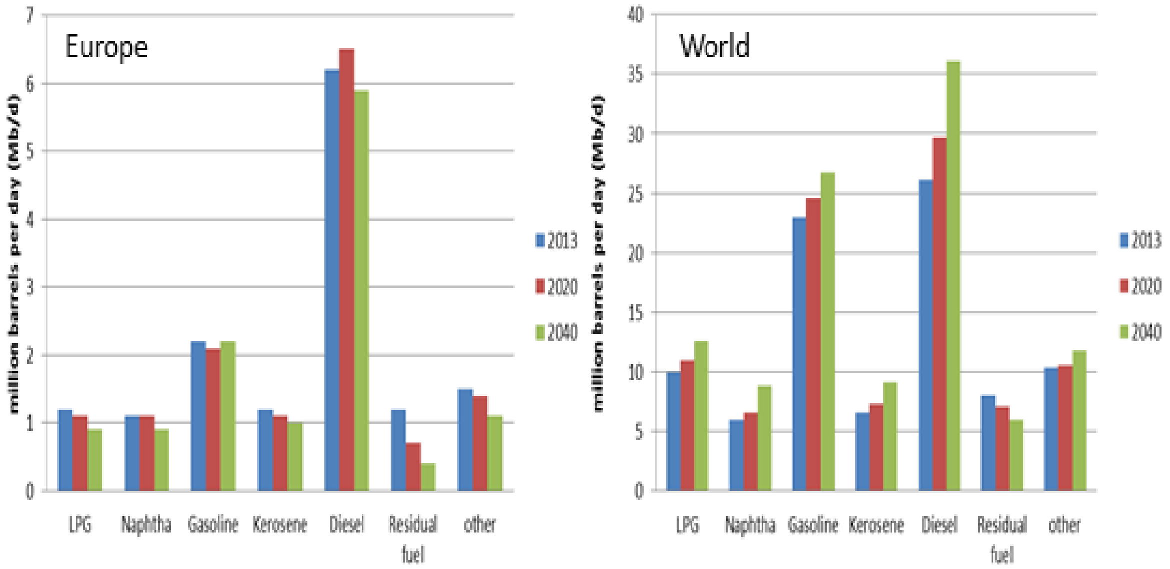

Figure 14 - Oil product demand towards 2040 for Europe and the World (OPEC, 2014)

Worldwide and European future demand developments might influence the CO_2 emissions of Dutch refineries towards 2050. The overall decline in oil products demand within Europe could lead to lower CO_2 emissions if Dutch refineries produces less products. However the demand for diesel will most likely remain high towards 2040. The production of diesel requires more additional processes which leads to high CO_2 emissions. Increased demand might also have consequences for the CO_2 emissions of Dutch refineries and result of the export orientated refining industry (ECN, 2015). Refinery products are also exported beyond Europe and the increase in worldwide demand may therefore counteract the decrease of demand in Europe.

4.3 Sub-conclusion

Chapter 4 tried to answer the research question "In which way is the CO_2 profile of Dutch refineries affected by their crude oil intake and product slate". In order to answer this question the effect of the crude oil intake on the CO_2 emissions of Dutch refineries was first assessed. Crude oil properties such as the API gravity and the sulphur content have a large influence on the CO_2 emissions of refineries. The Netherlands import light and medium crude oils with an API ranging from 31.3 to 43.6. These crude oils have a sulphur content ranging from 0.1 to 2.6. Jacobs (2012) stated that the CO_2 emissions related to refining crude oil decrease as the API gravity increases. Refining heavy crudes increases the CO_2 emissions of Dutch refineries. The CO_2 emissions of Dutch refineries are furthermore influenced by the sulphur content of crude oil. A high sulphur content of crude oil results in higher CO_2 emissions.

To assess the effect of the product slate of Dutch refineries on their CO_2 emissions an overview of refinery products along with their quantities must be provided first. It appeared that the Dutch refining industry mainly produces naphtha, gas/diesel oil and fuel oil. Gasoline and LPG are not produced in large quantities. However, there is no straightforward methodology to allocate CO_2 emissions to final products (Reinaud, 2005). In other words it is almost impossible to determine the CO_2 emissions of a refinery for the production of one tone of gasoline or diesel. This is due to the fact that oil refineries produce a number of different products simultaneously from a single feedstock.

Part III – CO_2 reducing options for the Dutch refining industry

5. Options that reduce CO_2 emissions of Dutch refineries

Chapter 5 presents an extensive overview of options that can reduce the CO_2 emissions of the Dutch refining industry. Since the sector faces increasingly stringent environmental regulations it is important to describe and analyse available options that could help them achieve the reduction of CO_2 emissions.

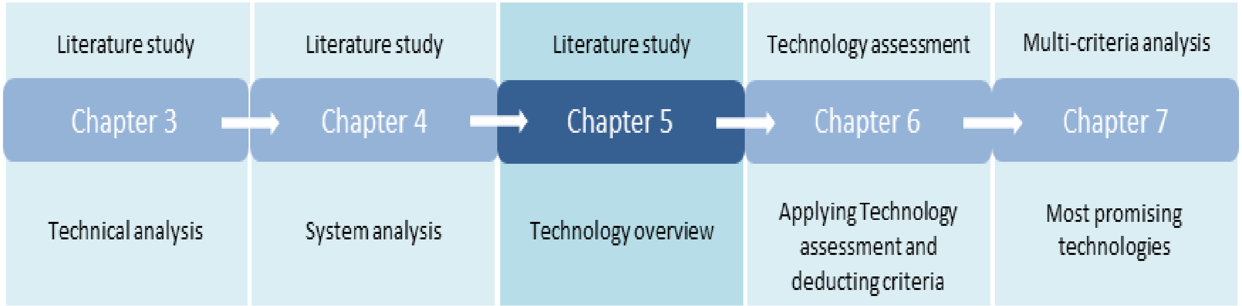

Figure 15 - Overview: chapter 5

The CO_2 profile of Dutch refineries, constructed in chapter 3 and 4, formed the basis for the overview of CO_2 reducing options that can be implemented within the Dutch refining industry. At first, options are analysed that reduce CO_2 emissions of the most polluting processes within Dutch refineries. By improving the efficiency of the distillation column, FCC unit, hydrocracker and flexicoker total emissions of can be reduced (Plomp & Kroon, 2010). Secondly, CO_2 reducing alternatives are discussed that show the the possibilities of processing a different type of crude oil. Other CO_2 reducing options are based on the studies of Krebbex et al. (2011) and Kampman et al. (2010). This researches includes options that improve regional integration (heat exchange), alter the fuel usage (cogeneration and renewables), integrate biofuels or capture CO_2 emitted by Dutch refineries.

In general two overarching categories of CO_2 reducing options can be identified. The ones that optimize energy efficiency and the ones that optimize the carbon efficiency. Options that reduce the CO_2 emissions of individual processes in refineries by improving their energy efficiency are explored in the section 5.1. Section 5.2 discusses alternatives that affect the type of crude oil refineries process and thus the carbon efficiency. Regional energy efficiency is assessed in section 5.3 and explores the possibility of heat exchange and the supply of CO_2 to nearby greenhouses. Section 5.4 discusses the option of alternative fuels that can be used to reduce the CO_2 emissions of the refinery's furnaces and heaters. The possibility of integrating biomass into the Dutch refining industry are explored in section 5.5. Finally, section 5.6 assesses options related to CO_2 capture.

5.1 Process optimisation (on-site)

There are numerous options that can reduce CO_2 emissions of refining processes, however, this research only focuses on alternatives that reduce CO_2 emissions of the most polluting processes. Chapter 3 shows that the atmospheric distillation unit is in most cases the largest emitter of CO_2. Other processes that substantially contribute to CO_2 emissions are hydrocracking, FCC and flexicoking. Technologies that influence the emissions of these four processes are analysed within this section.

5.1.1 Distillation

Since distillation is one of the most energy intensive operations within a refinery, improving the efficiency of this process offers great potential for CO_2 emission reduction. A possible technology that can be used is the integration of the atmospheric distillation unit with a vacuum distillation unit (Plomp & Kroon, 2010). If these units operate on a stand-alone configuration a lot of heat is lost when oil flows are repeatedly heated and cooled again. Normally the heated product flow within a distillation column is cooled down by the incoming feedstock resulting in a maximum heat exchange (Treese et al., 2015). However, by not cooling down the product flows that leave the atmospheric distillation column and directly redirect them to the next unit a lot of fuel can be saved. As a result the vacuum distillation unit requires a substantially lower furnace capacity. Furthermore, by not cooling down the product flow, heat exchangers are no longer required. This process can be further improved by also integrating a coker unit with the atmospheric and vacuum distillation unit. Applying this technology to the Dutch refining industry would mean that less fuel is needed to heat the distillation processes which results in lower CO_2 emissions. Plomp & Kroon (2010) estimate that CO_2 emissions can be reduced by around 2% when this technology is applied to a generic refinery.

A second method for improving the efficiency within a refinery is the optimisation of the atmospheric distillation unit. This can be achieved by preheating the feedstock, heat integration and optimizing the reflux ratio (Plomp & Kroon, 2010). Recently more efficient designs with regard to the crude distillation units have been developed. Gadalla et al. (2006) show that by improving and optimizing the distillation process emission reductions up to 22% can be achieved. It is possible to further optimize the distillation unit by using heat integrated distillation columns. Mascia et al. (2007) report that applying this technique leads to a 30% reduction of energy usage for the light ends section of the distillation column. The downside of this technology is its complexity, especially when applied to heavier fractions. It is a particular useful technology for refineries that are newly constructed which is an unlikely situation for the Dutch refining industry (Vleeming & Hinderink, 2011).

To further improve the efficiency of the atmospheric distillation unit a preflash column or preflash drum can be installed (Errico et al., 2009). A preflash column is an extra distillation column that is placed before the furnace of the atmospheric distillation unit separating the lightest fractions. Installing these units result in a reduction of the required heat for the distillation column and increases the production of middle distillates. Since the lighter parts are already separated, less crude oil enters the atmospheric distillation unit which results in a higher primary refinery capacity up to 30% (Plomp & Kroon, 2010). Both technologies are not overly complex and are starting to be implemented within existing refineries, for example the Leuna refinery in Germany (Plomp & Kroon, 2010)**.** To achieve an even higher energy efficiency the preflash column can be integrated in a multicolumn design. Multiple columns are connected resulting the crude oil to be gradually heated while the pressure decreases. This concept is called progressive distillation and can increase energy efficiency by 30% (Szklo & Schaeffer, 2007). The downside of this technology is that it is only applicable with newly build distillation units and cannot be applied to existing ones.

Finally, “dividing wall distillation” integrates two conventional distillation columns by placing a separation wall between them. This technique is especially interesting for refineries that focus on the production of middle distillates (Vleeming & Hinderink, 2011). Major advantages of this technique are the low capital expenditures and the reduction of operating costs due to a higher energy efficiency. Moreover, it is also suitable for implementation in existing refineries making it an interesting option for the Dutch refining industry. The implementation of this technique reduces energy usage by around 30% (Szklo & Schaeffer, 2007).

5.1.2 Fluidized catalytic cracker

The analysis performed in chapter 3 shows that the FCC unit is a large emitter of CO_2. In a normal configuration the FCC unit operates in the rising mode meaning that the catalyst is sent up with the gasflow against gravity. A new design, the Downer reactor, lets the catalyst and gasflow run downwards with the force of gravity. This new reactor design improves the energy efficiency of the FCC unit but hasn't reached its mature phase (Cheng et al, 2008). New technologies are not only limited to this new reactor design. The rising mode also experiences new developments such as the Millisecond Catalytic Cracking. By shortening the time that the reactant is in contact with the catalyst the formation of by-products is prevented (Harding et al, 2001). Furthermore power recovery turbines can be installed on FCC units which produce power from the gasses that leave the FCC. This technology is commercially proven but not generally applied (Speight, 2010).

5.1.3 Hydrocracker

With regard to hydrocracking processes two areas of technology innovations can be identified that increase the efficiency of the refinery. The first innovation uses new catalysts which allow the unit to process more, heavier and higher sulphur content products. These new catalysts prolong the lifespan of a hydrocracker and increase the energy efficiency. Apart from direct energy savings, more efficient catalysts also reduce the amount of hydrogen required for the cracking process. Since the production of hydrogen is a highly carbon intensive process, reducing the amount of required hydrogen results in an indirect reduction of CO_2 emissions. The second innovation with regard to hydrocracking is residual hydroconversion. The technology applies hydrocracking to refinery residues which is more advantageous than gasification (Plomp & Kroon, 2010). Residual hydrocracking is more costly but it produces more valuable products making it more cost efficient.

5.1.4 Flexicoker

There are currently little to no technologies available for directly reducing the CO_2 emissions of the flexicoking unit (Vleeming & Hinderink, 2011), which is unfortunate since this unit emits a substantial amount of CO_2. However there is a new approach with regard to the refining of crude oil which places the coking unit at the beginning of the process. In this case oil refining does not start with distillation but with cracking. Coking would in this case replace the crude and vacuum distillation unit and as a result crude oil is cracked instead of distilled. These cracking fractions have a lower boiling point which means the separation is simplified and requires less energy (Szklo & Schaeffer, 2007). Despite this promising idea, the "coking first" principle is not yet a commercially proven technique.

5.2 Changing the crude oil intake

This section explores alternatives with regard to the crude oil intake of Dutch refineries to reduce CO_2 emissions. The type of crude oil that Dutch refineries process influences their CO_2 emissions. Especially API gravity and sulphur content impact the total CO_2 emissions of a refinery. Crude oils with a high API gravity require less energy to refine as a less refining processes are needed. As the API of crude oil increases the CO_2 emissions of a refinery decrease. An increase of API gravity by 35 could result in a decrease of CO_2 emissions by 25% to 33%, depending on the refining configuration (Jacobs, 2012). Besides API gravity the sulphur content within the crude oil also influences CO_2 emissions of refineries. Due to strict SO_2 regulations, refineries are forced to remove sulphur when processing crude oil. This can be achieve by hydrotreatment and hydrocracking (Treese et al., 2015). These processes are highly energy intensive and lead to increased CO_2 emissions of Dutch refineries. A high sulphur content of crude oil therefore results in higher CO_2 emissions. An overview of crude oils that the Dutch refining industry processes, provided in section 4.1.2, shows that the Netherlands imports light and medium crude oils with an API ranging from 31.3 to 42.9. These crudes have a sulphur content ranging from 0.1 to 2.6. The Dutch refining industry can lower its CO_2 emissions by changing the type of crude it processes.

A straightforward possibility is to reduce CO_2 emissions by processing lighter and sweeter crudes. Figure 16 shows the lightest and sweetest crude oil types according to the EIA (2013). Especially Malaysia-Tapis and Algeria-Sahara Blend are light crudes with almost no sulphur content. Note that in most cases the configuration of Dutch refineries is adjusted to the type of crude oil they process. Complex Dutch refineries such as Shell and ExxonMobil have complex and expensive units such as hydrocrackers and flexicokers in order to process heavier crudes. If they switch to lighter crudes many processes may not be used which results in a decreased utilisation. Therefore switching to a lighter and sweeter type of crude is especially interesting for Dutch refineries with simple configurations like the Koch refinery. The downside of lighter and sweeter types of crude oil is that they are higher priced and thus expensive as feedstock.

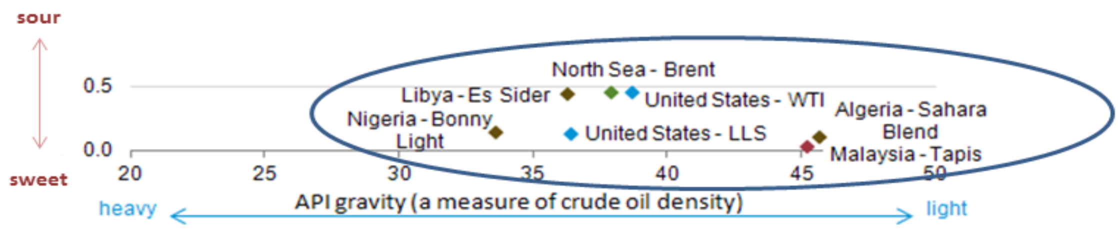

Figure 16 - Light and sweet crude oils (EIA, 2013)

5.3 Regional integration

Decarbonisation of the Dutch refining industry can also be achieved by integrating refineries with the surrounding regions. The first option is to exchange heat with nearby city districts and greenhouses. Since refineries produce a lot of excess heat this is an interesting option which increases efficiency and indirectly reduces CO_2 emissions. A second option is supplying the CO_2 to greenhouses used for cultivation.

5.3.1 Heat exchange

Excess heat produced by refineries cannot only be coupled to the local heat demand of a refinery on-site but can also be exchanged with others. One of the most promising possibilities of heat exchange is the connection of refineries to close-by residential districts (Kampman et al., 2010). Exchanging heat with residential districts is not the only option. Industrial areas that require low temperature heat for their production processes are suitable alternatives. If excess heat of refineries is exchanged with residential districts it is awarded with CO_2 credits per Terajoule (TJ) according to the ETS. If the heat is instead transported to another industrial instillation the emissions rights are awarded to the consumer of heat and not the refineries. Therefore heat exchange with residential districts is more favourable for refineries (Agentschap NL, 2010). Kampman et al. (2010) assesses an energy reduction potential of exchanging excess heat between 2 and 23 Petajoule (PJ) per year. Figure 17 shows the current heat exchange infrastructure and plans for further extension towards 2030. Heat exchange projects regarding refineries are already realized in Goteborg and Karlsruhe.

Figure 17 - Current and planned heat integration network (Energeia, 2015)

5.3.2 CO_2 exchange

A second option to improve regional integration of Dutch refineries is the supply of CO_2 to nearby greenhouses. Supplying CO_2 to nearby greenhouses realizes a reduction on two sides. First of all the CO_2 emissions of refineries are directly reduced. Secondly, greenhouses require less natural gas as CO_2 is now provided by the refineries. Transportation of carbon dioxide can also be coupled with the exchange of heat to residential areas, since the carbon dioxide, as a gas, can function as a heat carrier trough the pipes (krebbekx et al., 2011). When greenhouses have no demand for CO_2 the pipelines can be filled up to a certain pressure, acting as a CO_2 buffer and the greenhouses can retrieve CO_2 at their preferred time (Kampman et al., 2010). Currently E.ON and OCAP have realized two projects that supply CO_2 to greenhouses. So far this CO_2 is not produced by refineries but by hydrogen production facilities. In total 0.4 Mton of CO_2 is supplied to approximately 1.700 hectares of greenhouses. Apart from the direct reduction of CO_2 by refineries, the greenhouses reduce their natural gas consumption by 95 million m3 resulting in a CO_2 reduction of 230 Kton (Kampman et al., 2010). OCAP expects a potential supply of CO_2 to greenhouses of around 1 Mton per annum representing energy saving of 6.2 PJ per year for refineries (Kampman et al., 2011). Figure 18 shows the current and planned CO_2 pipeline infrastructure of OCAP. A downside of CO_2 supply to greenhouses by refineries is the current EU ETS regulation. This regulation does not allow refineries to deduct their delivered CO_2 from their total CO_2 emissions. In order for CO_2 supply to greenhouses to be beneficial for refineries EU ETS regulations have to be altered.

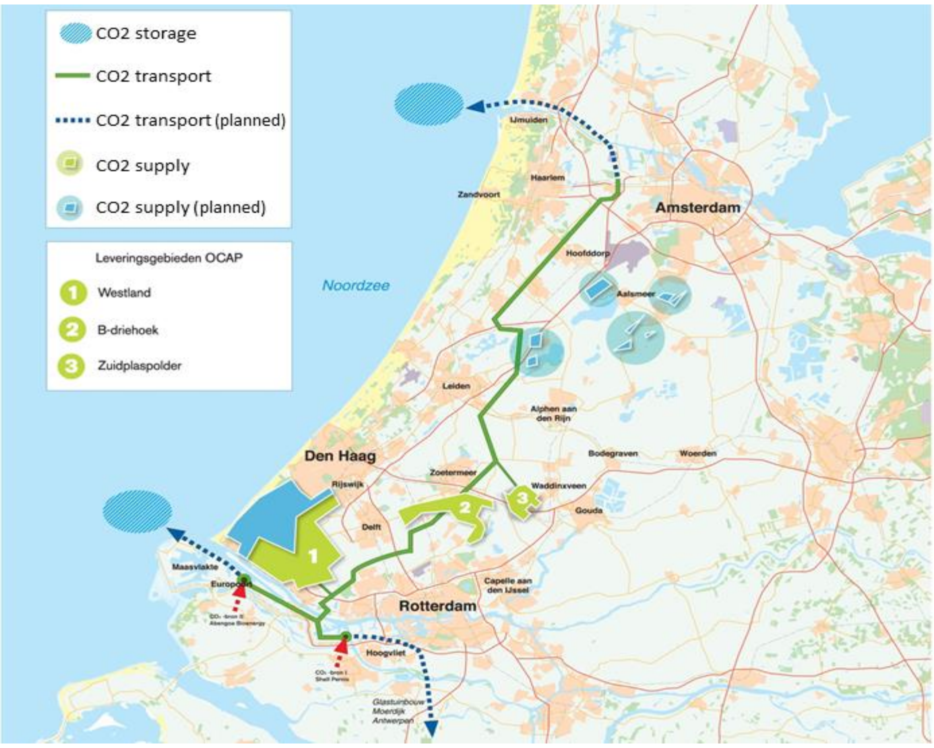

Figure 18 - Current and planned CO_2 supply from OCAP to greenhouses (OCAP, 2010)

5.4 Heat and electricity production

Processes within a refinery are either dependent on heat or electricity. For example, one of the most CO_2 intensive processes, distillation, needs heat provided by furnaces. In order to produce this heat furnaces burn fuel, in most cases refinery gas. Burning fuel and generating electricity are large sources of CO_2 emissions. Therefore this section discusses alternative options for the production of heat and electricity. The first option, cogeneration, still uses gas as fuel source. However, it also produces electricity which is an advantage for integration with refineries. Renewable energy sources (RES) are assessed for the refinery's electricity requirements. Besides directly using electricity within refineries, technologies have been developed that either convert electricity into heat (power-to-heat) or into gas (power-to-gas). These alternatives might prove interesting when the electricity is generated with RES.

5.4.1 Cogeneration

Traditional installations that create heat, burn fossil fuels and transfer this heat through a heat exchanger to a transport medium. In a cogeneration unit the burning of fuel is used for both heating and the generation of electricity. The produced electricity can be used on-site or fed into the electricity grid. Cogeneration is a common technology within the Dutch refining industry and is present at most refineries (Krebbekx et al., 2011). There are two main configurations for cogeneration units, namely the conventional steam cogeneration unit and the process integrated cogeneration unit (Vleeming & Hinderink, 2011).

A conventional cogeneration unit is already present at most Dutch refineries and therefore has a limited CO_2 reduction potential (Vleeming & Hinderink, 2011). The technical potential for energy reduction by using process integrated cogeneration units, shown in figure 19, lies around 4.5 PJ per year (Vleeming & Hinderink, 2011). With regard to all cogeneration technologies the maximum energy reduction is 7.4 PJ per year. However, current economic feasible energy reduction is in the range of 1.6 PJ per year for the Dutch refining industry (Krebbekx et al., 2011).

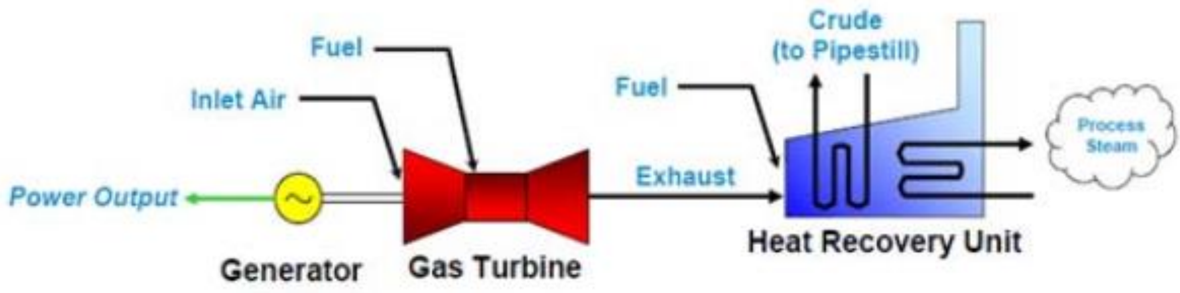

Figure 19 - An example of a process integrated cogeneration unit (Kampman et al., 2011)

In the current situation, Dutch refineries have installed a total of 255 Megawatt (MW) of cogeneration capacity which amounts to a total energy consumption of 16 PJ per year (Krebbekx et al., 2011). In most cases the installed cogeneration capacity concerns conventional cogeneration units. Some refineries already have process integrated cogeneration units at their disposal (Vleeming & Hinderink, 2011).

5.4.2 Renewable energy sources

Another option to reduce the CO_2 emissions of Dutch refineries is to replace the energy that is acquired from fossil fuels by RES. Possible alternatives are wind and solar power. These sources can be used within the Dutch refining industry in two forms. The generated electricity can be directly used by refinery processes that require electricity. An alternative use is the conversion of electricity to heat (power-to-heat) or gas (power-to-gas).

Wind and Solar

The first option for refineries to make use of renewable energy is wind energy. Wind turbines fit well within the industrial landscape of the harbour of Rotterdam and benefit from high wind speeds due to their location near sea. Safety concerns are the largest hurdle with regard to implementation of turbines at refinery sites. Technical potential of wind turbines at refinery sites is around 1.7 PJ per year. This would lead to a CO_2 reduction of 110 Kton per year. Currently the BP refinery already installed a total of 9 wind turbines in 2002 adding up to a total of 22,5 MW (ECN, 2003). This installed wind capacity reduced their CO_2 emissions by 28 Kton.

The second RES option is solar power for refineries. In theory refinery sites offer the possibility for the implementation of solar panels. However, in practice this option cannot be applied on a large scale since only 20% of the roof surface of storage tanks can be utilized (Kampman et al., 2010). A maximum of 15 TJ can be reduced which results in a reduction of 1 Kton CO_2 per year. Krebbekx et al. (2011) state that the usage of solar power for the Dutch refining industry has little potential in combination with high costs.

Power-to-heat and power-to-gas

Power-to-heat, can be utilised to convert electricity from wind and solar power into steam using an electric boiler. By using electricity as a source of heat the conventional gas-fired boilers and cogeneration units are bypassed resulting in a decrease of CO_2 emissions. Until now power-to-heat technology has not been implemented within the Dutch refining industry. The technology is however highly developed and implemented in Denmark and Germany (Hers et al., 2015), mainly due to their high share of renewable energy production.

Besides converting electricity generated by renewables to heat, electricity can also be converted to gas. Power-to-gas uses electricity to split water into hydrogen and oxygen (electrolysis). The produced hydrogen can be directly used in desulphurisation processes or can be used as a heat source for other processes within the refineries. So converting abundant wind and solar energy into "renewable hydrogen" and use this hydrogen in Dutch refineries (ECN, 2014). Converting electricity to hydrogen is costly. Using regular electricity is therefore not an option. It can be possible when a high share of renewables is available and the price of electricity is very low or even negative. Within the Netherlands only small-scale demonstration projects are currently in operation. However Germany, due to their high share of renewable energy, already applies the power-to-gas concept.

5.5 Biofuels

Another possibility for reducing CO_2 emissions of the Dutch refining industry is the implementation of biomass. There are two main types of biomass, namely dry and wet. Examples of dry biomass are wood and dried crops. Wet biomass mainly consists out of manure and algae. Biomass can be burned directly or indirectly by conversion into various forms of biofuels. Direct biomass burning is currently used most within industry (Krebbekx et al., 2010). Creating biofuels from biomass can be achieved by thermal, chemical and biochemical conversion. Thermal conversion, converts biomass into biofuels at high temperatures. Bio-refining is a chemical method that separates valuable parts of organic material to create biofuels. Fermentation is used to create biogas by means of biochemical conversion. This section examines implementation possibilities of biofuels within Dutch refineries and their effects on the CO_2 emissions.

Using biomass products in refining

The first option is adding biomass products into the blending unit at the end of the refining process. In this case biofuels are created due to the mixture of bio-products and fossil fuels. However, since this option does not affect the CO_2 emissions of the refinery itself but only reduces carbon intensity of the transport fuels, it is not taken into account. A second option is the implementation of biomass into the refining processes. This can be either as feedstock or as energy carrier (Kampman et al., 2010). The Dutch refining industry currently only uses feedstock of mineral origin (Crude oil). However, biomass could help reduce the CO_2 emissions of a refinery since it replaces part of the mineral feedstock. There are three main biofuel feedstock possibilities for refineries that respectively use vegetable oil, pyrolysis oil and algae-based biofuels.

Vegetable oil can be converted into diesel using the existing infrastructure of refineries. In order to achieve this vegetable oils need to be hydrotreated. This hydrotreating combines vegetable oils with heavy vacuum oils. Using standard hydrotreating catalysts, vegetable oils can be converted into liquid alkanes (Huber et al., 2007). Furthermore, pyrolysis oil can be co-processed within refineries to create conventional refinery products. It is fed into the FCC unit where gasoline and diesel range bio-hydrocarbons are produced with similar yields as with a crude feedstock (Mercader et al., 2010). Another interesting alternative for the Dutch refining industry is the feed-in of algae based biofuels. Algae is an alternative biomass source and especially interesting due to its high production potential.

They can be cultivated in greenhouses using CO_2 supplied by refineries. This technology is still in its experimental phase (Masceralli, 2009)

In order for biofuels to result in a reduction of CO_2 emissions of Dutch refineries it needs to replace conventional straight run diesel. Krebbekx et al. (2011) estimates that replacing 1% of the conventional diesel by biofuels will result in a reduction of 20 Kton CO_2 per year for the Dutch refining industry. A minimum of 3% of diesel production can be replaced by biofuels but a replacement of 10% is also realistic when the performance of the Goteborg refinery is assessed. It can be concluded that the implementation of biofuels within the Dutch refining industry could lead to an annual reduction of 60-200 Kton of CO_2 emissions for the Dutch sector (Kampman et al., 2010).

5.6 Carbon capture

The nature of refinery processes implies that even highly energy efficient refineries continue to consume large amounts of energy and thereby keep emitting considerable amounts of CO_2 (van Straelen et al., 2010). A way to further reduce CO_2 emissions of Dutch refineries is through the capture of CO_2. Carbon capture makes is possible to extract CO_2 before it is emitted into the air. In theory this can greatly reduce the CO_2 emissions of Dutch refineries (Krebbekx et al., 2011). In general, three possibilities are identified for the capture of CO_2, namely pre-combustion capture, post-combustion capture and oxyfuel firing (van Straelen et al., 2010 ; Concawe, 2015).

Carbon capture technologies

Post-combustion carbon capture removes CO_2 from the flue gas before it is emitted into the atmosphere. It is therefore referred to as an end-of-pipe solution (van Straelen et al., 2010). CO_2 is captured by means of adsorbing it in a suitable solvent. The adsorbed CO_2 is then extracted from the solvent and compressed. CO_2 can also be separated by high pressure membrane filtration, adsorption or desorption processes and cryogenic separation. Simmonds et al. (2004) presents a case study of the capture of CO_2 at the BP Grangemouth site. Carbon capture at refineries is examined by Miracca et al. (2009) as well.

The pre-combustion alternative for carbon capture implies that the fuel is first pre-treated before it is combusted. Solid, liquid or gaseous fuels are converted into a mixture of hydrogen and carbon dioxide processes such as gasification or reforming. This enables the removal of CO_2 from a relatively pure exhaust stream (Weydahl et al., 2013). The remaining hydrogen can be used as a fuel. Since the CO_2 is at a high pressure and has not yet expanded to atmospheric pressure it is easier to remove. Figure 22 shows the process of pre-combustion carbon capture. Within Dutch refineries, gasifiers equipped with pre-combustion capture capabilities can be used to supply the utilities of the refinery (van Straelen et al., 2010). Reforming and gasification are highly developed processes and already widely applied within refineries and chemical plants around the world.

In the process of oxyfuel firing pure oxygen is used for combustion instead of air. The required oxygen is separated from air before combustion takes place. An air separator removes nitrogen, which makes up 78% of air, providing an almost pure stream of oxygen. Pure oxygen diluted with recycled flue-gas is used to combust fuel. As a result a stream is produced that only contains CO_2 and water. The produced CO_2 is much more concentrated which makes it easier to capture. Within refineries oxyfuel firing can be applied to burners. However, its applicability to the FCC unit is also under investigation (van Straelen et al., 2010).

CCS and CCU

After CO_2 is captured and compressed a solution needs to be found for the remaining CO_2 stream. In general two alternatives exist, namely carbon capture and storage (CCS) and carbon capture and utilisation (CCU). CCS captures CO_2 and stores it in a location so that the emissions do not enter the atmosphere. CCU captures CO_2 and utilizes it in different ways.

CCS tries to achieve permanent storage of CO_2 in geological formation, oceans or minerals. For several decades CO_2 has been injected into geological formation to enhance oil recovery. Long term storage of CO_2 remains, despite experience, a relatively new concept. Possibilities are storing CO_2 in deep geological formations or oceans (Cuéllar-Franca & Azapagic, 2015). Empty gas or oil fields are also a promising alternative. Storing CO_2 in oceans is currently not feasible since it acidifies the water. With regard to the Netherlands CCS looks promising due to the large storage capacity in empty gas fields. However, plans for storing CO_2 in these fields encountered great resistance since there are fears that CO_2 might leak to the environment. Plans to store CO_2 in empty gas fields in the North Sea have been realized overtime though.

CCU tries to convert captured CO_2 into valuable products such as chemicals and fuels. Other options are mineral carbonation, enhanced oil recovery etc. (Cuéllar-Franca & Azapagic, 2015). CCU has as advantage over CCS as utilisation of CO_2 can turn out to be a profitable activity. If CO_2 is converted into chemicals or fuels it has the advantage of being a 'renewable' resource, low in cost and non-toxic (Yu et al., 2008). Multiple CCU projects have already been realised in the Netherlands. Until now CO_2 is only used as a fertiliser for growing plants in greenhouses. Since CO_2 can also serve as heat carrier, the heat of the gas is also used for the heating in greenhouses. Figure 20 provides an overview of all possibilities with regard to CCS and CCU.

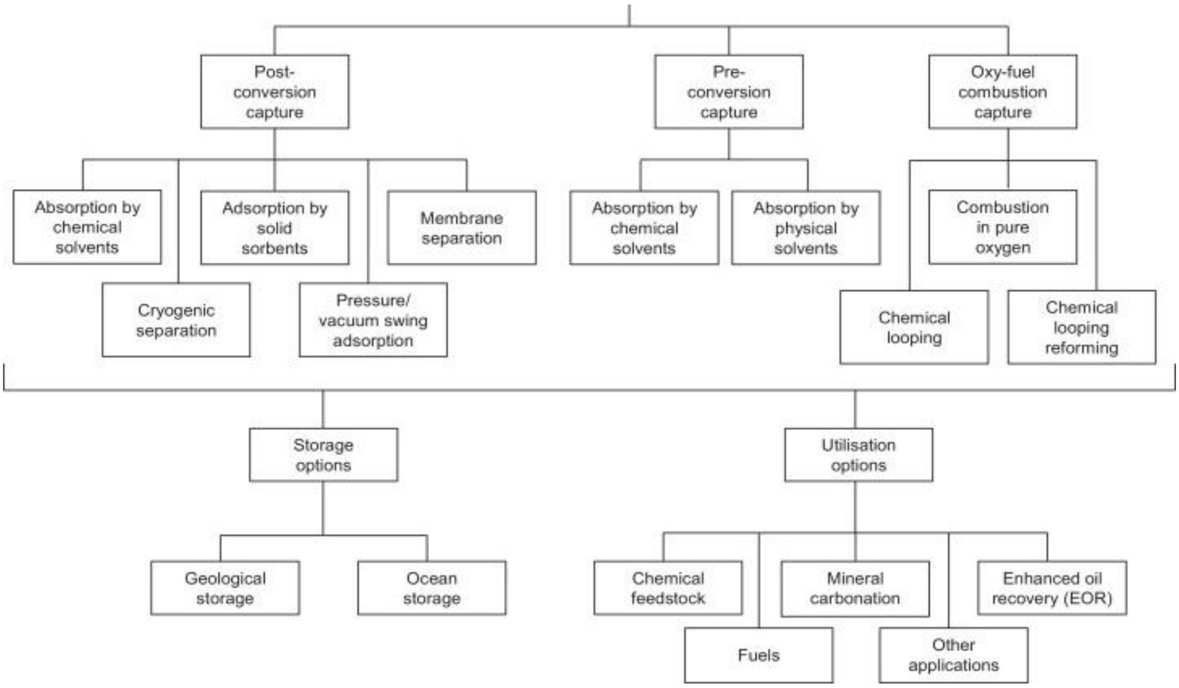

Figure 20 - Carbon capture options and possibilities for storage or utilisation (Cuéllar-Franca & Azapagic, 2015)

The CO_2 reduction potential for CCS and CCU is high but difficult to determine since it is not yet implemented on a large scale. It largely depends on technologies with regard to capturing CO_2 and the developments in storage capabilities and utilization possibilities. Krebbekx et al. (2011) estimates the cost effective CO_2 reduction potential by carbon capture within the Dutch refining industry at 350 Kton per year. However, if projects take off and prices decrease this could increase significantly. Therefore the technical potential is not specified in Krebbekx et al. (2011). CCS or CCU technologies are currently not implemented within the Dutch refining industry. Carbon capture is, however, applied to hydrogen production processes. Production of hydrogen is viable for carbon capture since it produces a relatively pure flow of CO_2.

5.7 Sub-conclusion

Chapter 5 answers the research question "What are possible options that can be used to reduce the CO_2 emissions of Dutch refineries". Figure 21 presents an overview of al CO_2 reducing options that can be implemented within the Dutch refineries. Six categories are classified into two overarching classes, namely options that reduce CO_2 emissions of Dutch refineries by improving energy efficiency and alternatives that reduce CO_2 emissions by carbon efficiency. Optimisation of the processes within Dutch refineries reduce their CO_2 emissions by improving the energy efficiency. The same goes for heat exchange and cogeneration. Reducing CO_2 emissions of Dutch refineries by improving the carbon efficiency is done by the remaining alternatives.

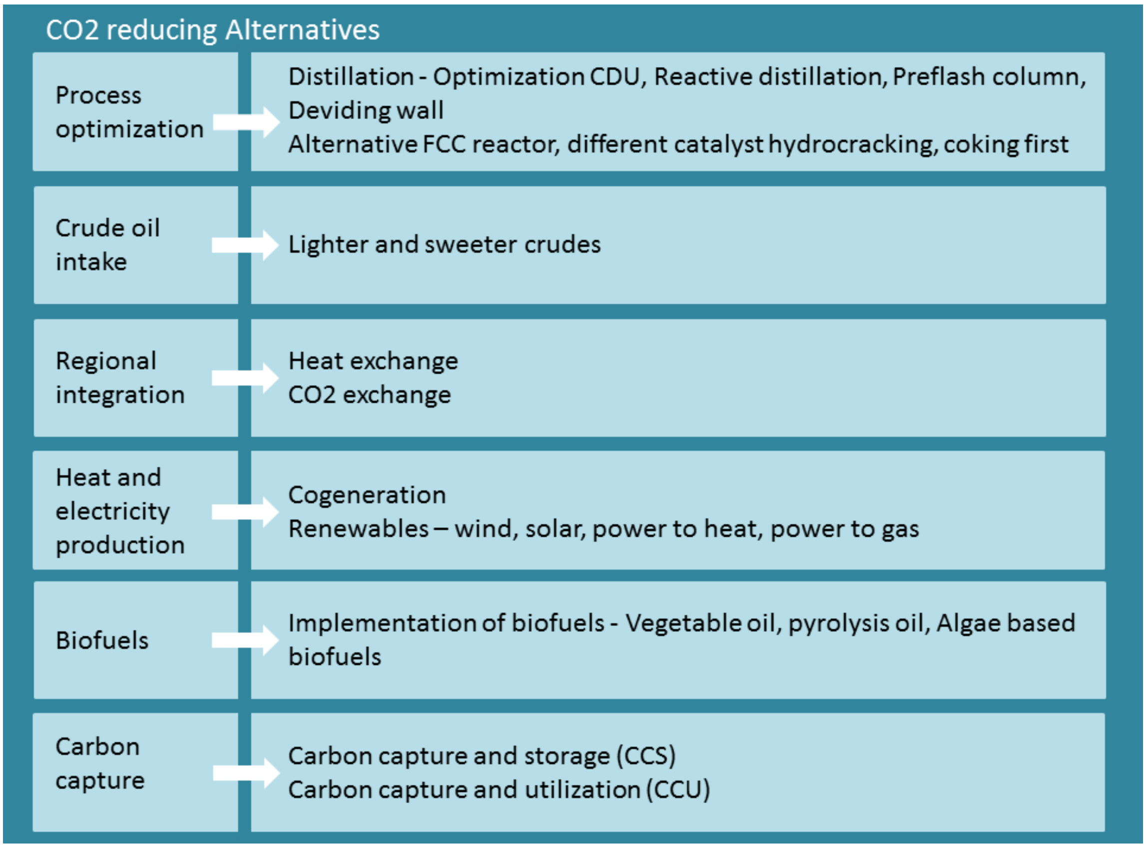

Figure 21 - Overview of CO_2 reducing options

Part IV – Technology Assessment

6. Technology Assessment as a framework

The previous chapter provides an extensive overview of options to reduce CO_2 emissions of the Dutch refining industry. In order to assess these options and determine the most promising ones they need are assessed by means of a framework. The traditional Technology Assessment forms the basis of this framework. However, within this research Technology Assessment is extended with both economic and institutional perspectives. From this newly designed framework criteria are deducted which are used in the multi-criteria analysis of chapter 7.

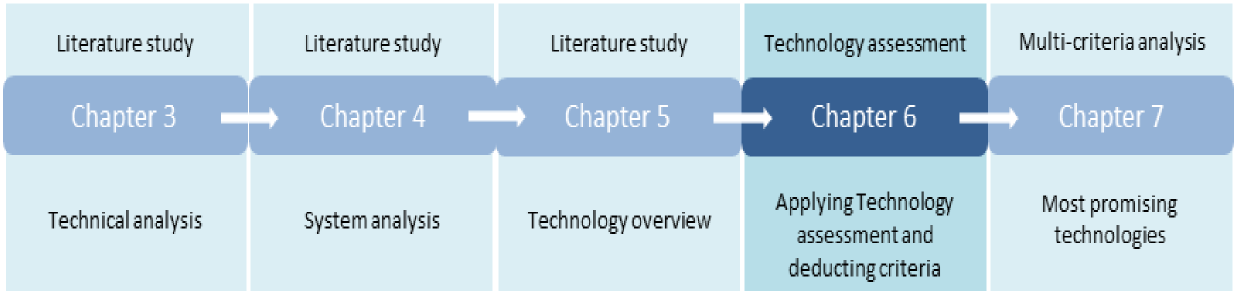

Figure 22 - Overview: chapter 6

This chapter starts with a short literature overview on the practice of traditional Technology Assessment in section 6.1. An elaboration on containing its history, important concepts and criticisms can be found in Appendix D. Section 6.2 applies the concept of TA to this research with the most suitable concept and possible methodologies. This section ends with a discussion on aspects that are missing within TA but are nevertheless relevant for this research. These missing economic and institutional perspectives are analysed and included in section 6.3. The last section of this chapters deducts criteria from the extended TA which forms the basis for the multi-criteria analysis in the next chapter.

6.1 Technology Assessment: an overview

Technology Assessment (TA) is a scientific, analytic and democratic practice that aims to contribute to the formation of public and political opinion on societal aspects of science and technology (van Est & Brom, 2012). In other words, TA is the study and evaluation of new technologies. It is based on the idea that technological developments within the scientific community are not only relevant to the experts themselves but also for a wider public (Grunwald, 2009). Technology Assessment as a term came into use in the 1960s in the United States (Banta, 2009). In earlier studies, TA is defined as a form of policy research that examines short- and long-term consequences of the application of a technology. The main goal of TA is to provide policy makers with information on technology alternatives. In general, TA can be used as a response to five societal issues. These societal problems are visualized in figure 23 and further discussed in Appendix D. Societal challenges arising alongside technological developments form the background for TA as a practice and represents problems it can to solve.

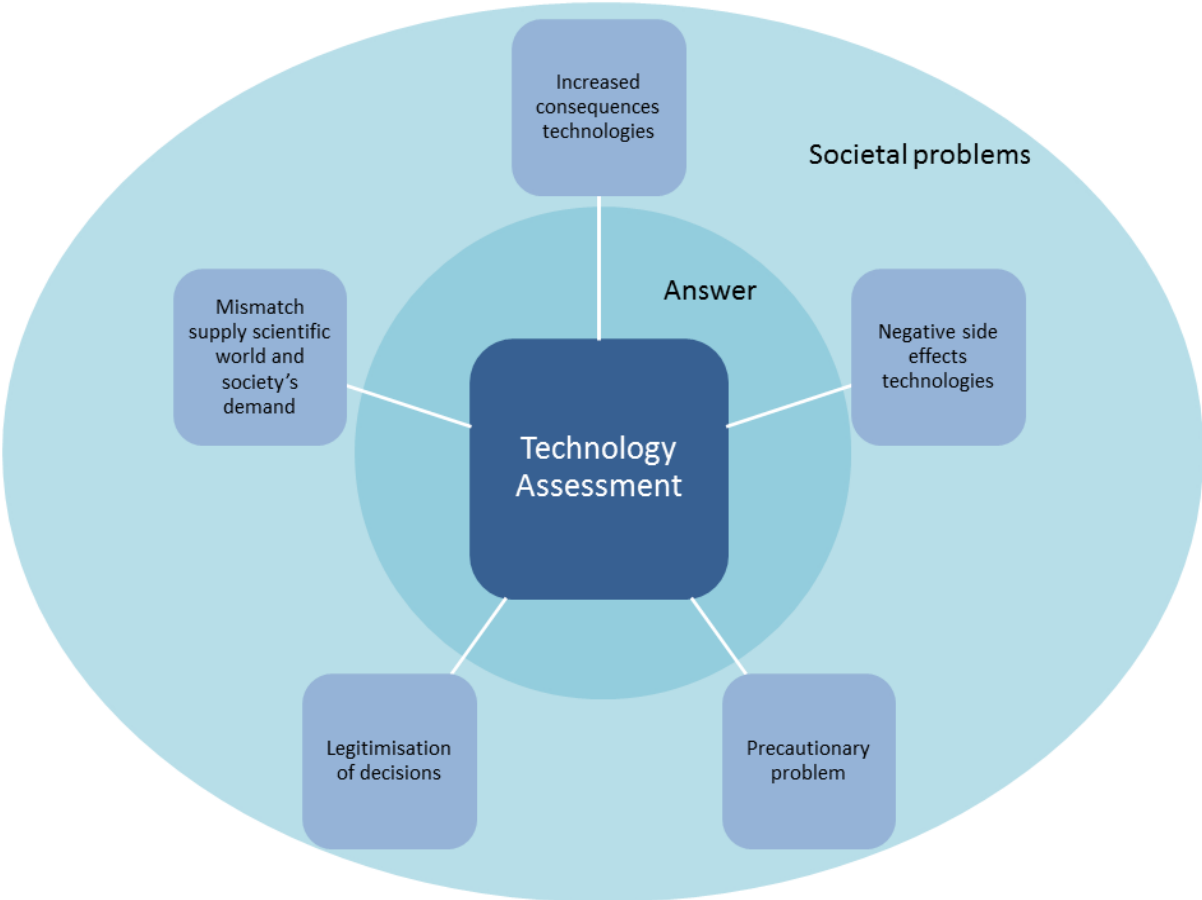

Figure 23 - TA as an answer to societal problems

Figure 24 shows the main focus of TA along with its corresponding characteristics. A more extensive elaboration on the focus and characteristics of TA can be found in Appendix D. TA contributes to problem solving but does not provide actual solutions (Decker & Ladikas, 2004). Instead it provides knowledge on how to cope with certain problems related to the effect of technological developments on society. Its focus is on undesired side-effects. TA does not provide solutions because it can only be legitimized by society through institutions and decision-making processes (Grunwald, 2009). TA fulfils an advisory role by scientific research and is not involved in the decision-making process (Bechmann et al., 2007).

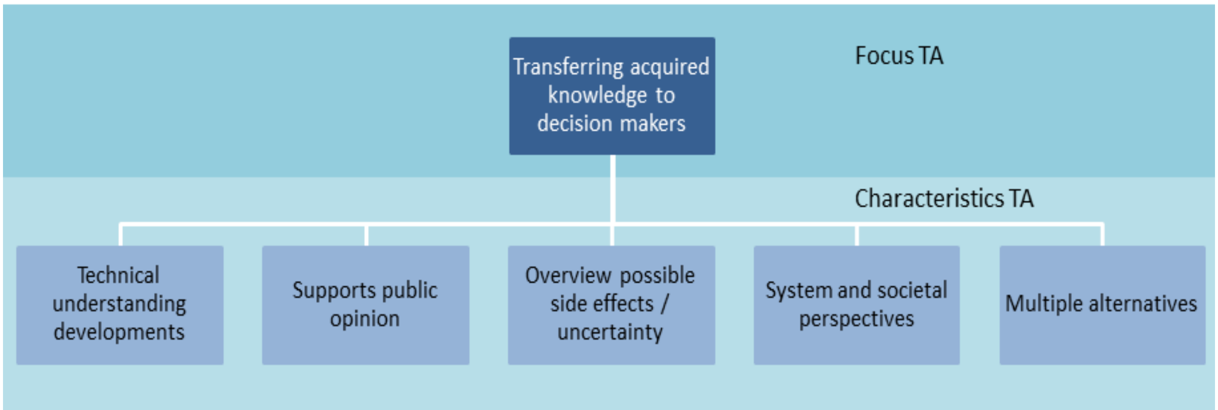

Figure 24 - Focus and characteristics of TA

TA is context dependent and its results are therefore sensitive to changes in fields of technology, political setting and relevant actors. Currently there are multiple developments that affect future TA practice. First of all TA is influenced by increasing globalisation. A second important development is the increase of the so called "knowledge society". The third and final development that affects TA practice is related to new technologies and the importance of societal acceptance.

6.2 Applying Technology Assessment

TA is suitable for this research because it deals with the relationship between technological change an social problems. It is used to scientifically investigate conditions for and consequences of technology along with societal evaluation of technologies (Grunwald, 2009). With regard to this research TA can be used to assess the development of CO_2 reducing alternatives for the Dutch refining industry.

In general TA can be used as a response to five societal issues, that are reflected in the research's problem of reducing CO_2 emissions of Dutch refineries in order for TA to successful in assess CO_2 reducing options. Suitable CO_2 reducing alternatives inevitably have consequences for refineries and society. Therefore negative side-effects of these alternatives must be limited which is one of the societal issues that TA addresses. While trusting technological innovation and progress, society must protect itself from their undesirable side effects. Another societal issue that TA addresses and relevant in this research is the legitimisation of decisions. Actors involved have different interests, opinions and values with regard to CO_2 reducing alternatives. As a result, TA overcomes the challenge that decisions with regard to the implementation of certain technologies is acknowledged as legitimate even it goes against the interest of certain parties. The final relevant societal issue that TA concerns is the mismatch between supply from the scientific world and society's demand. This is especially relevant for this research since there is a wide variety of CO_2 reducing options available. The challenge is to align these options with society's demand.

Besides societal challenges TA tries to overcome there are also general characteristics assigned to TA. TA's main characteristic is the focus on transferring acquired knowledge to those who are going to make decisions with regard to the technological developments in the future. By providing a comprehensive overview of alternatives along with possible side effects and consequences, the acquired knowledge can be used by the Dutch government in the decision-making process to reduce CO_2 emissions of Dutch refineries. Another characteristic of TA is that it uses a systematic approach to assess technical developments. Besides technical understanding of developments, TA also includes perspectives on systems, society and institutions (Grunwald, 2009). Including these additional perspectives is essential as the Dutch refining industry is very complex and a technical analysis alone does not suffice. Since TA does not confine itself on a single technology but assesses a multitude of alternatives it is suitable for assessing the wide variety of CO_2 reducing options.

Methodology

After determining that TA can be used within this research, the appropriate TA method needs to be established. TA needs to fulfil its responsibilities with regard to research, assessment and advice. Methods ensure the transparency and comprehensibility of TA. By making use of standardized methodologies TA ensures its quality standards (Decker & Ladikas, 2004). These methods are used for acquiring data, providing knowledge, establishing future scenario's, risk assessment, identifying economic consequences and investigate social acceptance problems (Grunwald, 2009). Possible methods that can be used within TA are:

- Modelling, system analysis, risk analysis, **decision-analytical methods**
- Trend extrapolation, simulation, scenario building
- The Delphi method
- Expert interviews
- Discourse analysis, values research

This research uses decision-analytical methods within TA to assess the wide variety of CO_2 reducing options. This method evaluates alternatives by means of a multidimensional integration of various criteria. In other words, a multi-criteria analysis is used. These criteria initially evaluate the alternatives separately but by means of weighting and aggregation the multi-criteria analysis results in a comprehensive evaluation.

6.2.1 TA and relevant perspectives

The previous section argues that TA along with a multi-criteria analysis (as method) is most suitable for this research. Before individual criteria, used to assess CO_2 reducing alternatives, are formulated it is useful to first establish overarching perspectives in which the criteria can be placed. TA mainly focusses on assessing technologies while accompanying the process of technological developments. Therefore it is logical that the first perspective includes criteria related to the technical feasibility. Since TA also tries to assess the consequences of technologies with respect to their surroundings and society, the second perspective includes criteria related to the interests of involved actors.

Technical perspectives

TA tries to produce comprehensive and objective information on state-of-the-art technologies and their impacts. An important aspect of CO_2 reducing options is the potential to actually reduce CO_2 emissions of Dutch refineries. Furthermore, the innovation status (technology readiness level) of the alternatives is important to discuss. Are certain CO_2 reducing alternatives already currently available and ready for implementation or are they still in an experimental phase? Besides the technology readiness level implementation possibilities of CO_2 reducing alternatives is also relevant. Are options easy to implement within existing Dutch refineries or do certain alternatives require a newly build refinery. The complete list of technical criteria is presented in section 6.4

Societal perspectives

To include society within the process of technological development, TA includes involved actors and stakeholders. Criteria are formulated that represent the interests of the actors involved. This societal perspective only represents interests of those directly involved with the implementation or consequences of the CO_2 reducing alternatives. It is inevitable that actors have conflicting interests with regard to the implementation of CO_2 reducing alternatives. however, by mapping these interest and converting them into criteria the most favourable option can be selected in the end. This is achieved by incorporating a multi-actor perspective in the multi-criteria analysis. As a result the most promising CO2 reducing alternatives differ per actor perspective. Criteria representing the societal perspective are found in section 6.4

6.2.2 Missing aspects within TA

Due to globalisation, impacts of technologies transcend national borders and technology design takes place in global networks (Grunwald, 2009). As a result relevant institutions no longer solely lie within nationally or even regionally orientated decision-making structures. Regulation of technology has shifted from national level to a more aggregate level such as the European Union. This is reflected within the Dutch refining industry as it faces European legislation besides national regulation. It is therefore important to assess the effects of CO_2 reducing alternatives on an institutional level. How well do certain CO_2 reducing alternatives fit within existing regulations and to what extend is institutional change required for the implementation of these alternatives? In order to answer these questions, institutional criteria need to be added to the multi-criteria analysis.

The Dutch refining industry finds itself operating in a global market. As a result Dutch refineries are export-oriented and their output exceeds national demand. Due to the global market the Dutch refining industry faces a lot of competition from export orientated refineries in the Middle-East and Asia. Refining costs, such as energy costs and regulation costs, for the Dutch industry are higher than those for non-European refineries (FuelsEurope, 2015). Implementation of CO_2 reducing alternatives will even further increase the refining costs. It is crucial that implementation of CO_2 reducing alternatives does not deteriorate the competitiveness of the Dutch refineries. Economic aspects need to be included within the multi-criteria analysis to ensure this.

From the observed trends it can be concluded that for a thorough assessment of CO_2 reducing alternatives traditional TA does not suffice. A multi-criteria analysis can be useful to provide a comprehensive analysis but economic and institutional perspectives need to be added. This is achieved by adding two more groups in which the criteria are classified. As a result four categories, each with a set of criteria, is used within the multi-criteria analysis. These groups are labelled: technical criteria, criteria representing interests of actors, economic criteria and institutional criteria. Figure 26 gives a schematic overview of the TA process in this research.

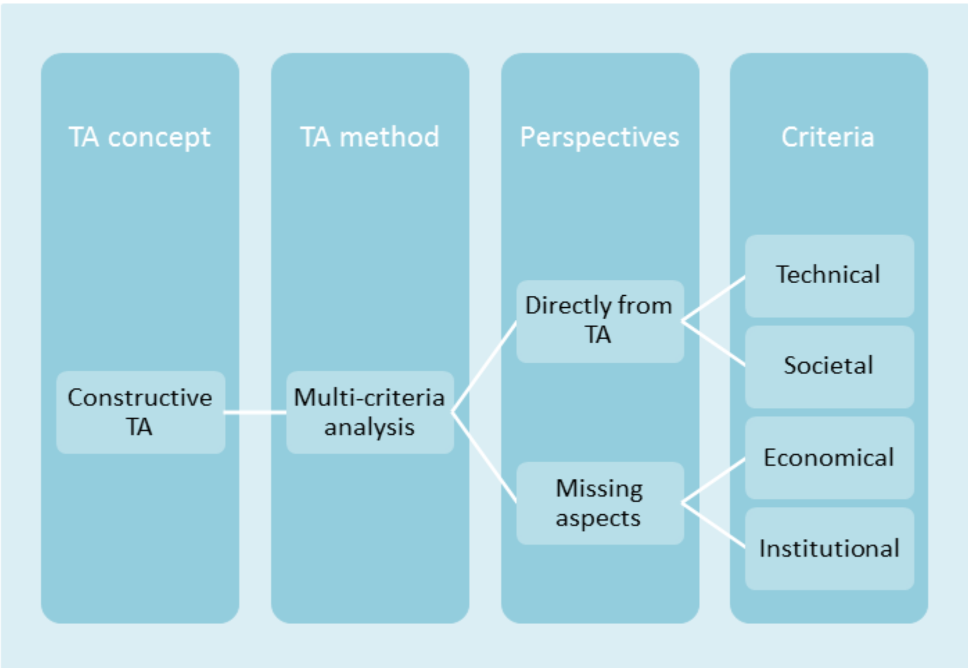

Figure 26 - Process of applying TA within this research

6.3 Extending TA with economic and institutional perspectives

Economic and institutional perspectives need to be included within the TA framework. By doing so, criteria from four perspectives can be deducted and used within the multi-criteria analysis. This chapter elaborates on these two perspectives.

6.3.1 Economic perspectives

Economic perspectives are important to include when assessing CO_2 reducing alternatives. The Dutch refining industry is important economic sector for the Netherlands. Five out of the six Dutch refineries are located within the industrial cluster of the Port of Rotterdam. According to Porter (2003) an industrial cluster is a geographically adjacent group of interconnected companies, suppliers, service providers and associated institutions in a particular field. Due to the connections between companies, exchange of technologies, skills and knowledge can take place (Porter, 2003). Since the Dutch refining industry is highly integrated within the industrial cluster of the Port of Rotterdam it is important to assess the possibilities for system integration of CO2 reducing alternatives.

The Dutch refining industry is of great economic importance but at the same time faces increasing competition. One of the main reasons for this increased competition is the shift towards source refining, with lower energy costs compared to European refining. Dutch refineries also face strict environmental regulation which increases their costs even further. The competitiveness of Dutch refineries could decrease even further when obliged to implement CO_2 reducing alternatives. It is therefore crucial that the implementation of CO_2 reducing alternatives does not significantly worsens the competitiveness of Dutch refineries.

Costs of alternatives play an important role in the decision process. Demand and supply developments within oil markets are an important economic factor to assess. The first developments are related to the changing EU oil demand which is perceived to only shows marginal future growth. A second cause for disruption of current market structures is the United States light tight oil (LTO) abundance and the loss of export markets (Meijknecht et al., 2012). The new IMO regulations also affects the Dutch refineries as it further reduces the allowed sulphur content in fuel oil, of which Dutch refineries produce a large quantity (JODI, 2016). Demand for fuel oil is therefore likely to reduce in the future. CO_2 reducing alternatives therefore have to be able to cope with changing demand and supply of crude oil and oil product markets.

6.3.2 Institutional perspectives

This section analyses and highlights important institutional perspectives that the Dutch refining industry encounters when they implement alternatives to reduce their CO2 emissions. The New Institutional Economics approach forms the foundation of this analysis. Important existing institutions are thereafter identified by using Williamson's model. Finally Goodin's theory on changing institutions is used to discuss the required institutional change for the implementation of CO_2 reducing alternatives in the Dutch refining industry.

The New Institutional Economics approach consists of three theories, namely Property Rights, Agency Theory and Transaction cost economics. Property rights are constructs that determine in which way an economic good or resource is used and owned. CO_2 reducing alternatives and the accompanied infrastructures can be owned by individuals, associations or governments. Property rights assesses the right to use the good, earn income from the good, transfer the good to others and the right to enforce property rights. The agency problem arises when interests or objectives of two parties, the principal and agent are in conflict. Furthermore information asymmetry makes it difficult or expensive for the principal to verify what the agent is actually doing (Eisenhardt, 1989). With respect to this research the Dutch refining industry has different interests than the parties whom impose the increasingly stringent CO_2 policies. Dutch refineries are aimed at maximizing their profit while the European Union and Dutch government wants them to reduce their CO_2 emissions. Since such a reduction requires the implementation of CO_2 reducing alternatives, their profitability is affected and conflicting interests arise. Furthermore Dutch refineries have much more knowledge about their refineries than the Dutch government which results in information asymmetry. Transaction Costs Theory states that involved parties try to minimize transaction costs, while they are bounded in rationality. It also states that actors do not have all information, may act opportunistically and operate in a complex and uncertain environment. For Dutch refineries there is the risk that they don't know what the future will bring in terms of decreasing oil demand, increased competition and low refining margins. Investing in costly CO_2 reducing alternatives therefore increases the risk for Dutch refineries. This makes it even harder for them to minimize their transaction costs.

Williamson (1998) classified institutions into four layers. The first layer in Williamsons model concerns the embeddedness of informal institutions which includes customs and traditions but also norms and values. Layer two includes the formal institutions that are divided into four categories, namely policy interventions, regulation, power market structure effects and property rights. The third layer, also called "the play of the game", focuses on governance and the interactions of actors. Contracts and arrangements are often used as an example of institutions in the third layer. Finally, the fourth layer concerns resource allocation and employment. With regard to this research the first and second layer containing informal and formal institutions are the most important. A change in norms and values need to result in an increased awareness that CO_2 emissions need to be reduced. This should result in a change in customs and traditions that prioritises CO_2 reductions within the Dutch refining industry. Formal institutions are required to ensure the CO_2 reductions of Dutch refineries. Currently the only formal institution in place is the ETS, but this system is criticized.

In order for CO_2 reducing alternatives to be successfully implemented within the Dutch refining industry existing institutions might need to be changed. Changing institutions is not a very straightforward but there are three main options for to achieve this, namely intentional intervention, evolution and by accident. With regard to the reduction of CO_2 emissions of Dutch refineries, institutions will most probably change by evolution or intentional intervention (Goodin, 1996). Intentional intervention is the result of rational choices made by institutional designers. Their focus is on changing existing institutions so that they better serve the current situation. A second way for institutions to change is via evolution. This means institutions evolve over time caused by the acknowledgement of limitations of existing institutions.

Important is the change in institutional support of the Dutch refining industry. Future institutions are dependent on to what extend Dutch refineries are viewed as important by the Port of Rotterdam, Dutch government and citizens. To assess the CO_2 reducing options that can be implemented within the Dutch refining industry, institutional perspectives are crucial. Especially the timeframe in which CO_2 emissions need to be reduced is important. Key to this reduction is the share of the available CO_2 budget for Dutch refining industry, as determined by ETS or the government in case of misallocation among sectors in the economy. Towards 2030, less costly short term alternatives can provide a sufficient reduction of CO_2 emissions. A significant reduction of the CO_2 budget towards 2050 requires the implementation of other, more costly alternatives. Such a decrease in CO_2 budget can result in competition among Dutch refineries for the remaining CO_2 allocation of the budget. In this case the ETS does not work. If these alternatives appear to be too costly for certain refineries they might close. A closure of one of the Dutch refineries implies that the CO_2 budget can be divided by less refineries.

Institutional perspectives are therefore necessary for a complete assessment of the CO_2 reducing alternatives. The extent to which these options fit within current regulations influences their implementation possibilities. Certain options require a change in current institutions in order to function properly. These two institutional perspectives are therefore included in the multi-criteria analysis to determine the most promising CO_2 reducing alternatives. Williamson's third institutional layer is especially important when the actual implementation of CO_2 reducing alternatives is discussed since transaction cost economics operates at this level. "The play of the game" focuses on governance and concerns contracts and arrangements between the actors involved. Property rights are crucial with respect to this institutional level since the implementation of CO_2 reducing alternatives can result in shared ownership which creates dependencies between the different actors. Institutions are required for a successful implementation of the CO_2 reducing alternatives. Since this research does not focus on the actual implementation of the alternatives and the issues of coordination that may arise, the third layer is not included within the multi-criteria analysis. However, the discussion presented in section 8.2 does elaborate on the challenges for implementation and corresponding institutional challenges.

6.4 Criteria from the extended TA design

A multi-criteria analysis is used to select the most promising alternatives based on a wide variety of criteria. Criteria categories containing technical and societal criteria are deducted from applying TA. However, missing aspects within TA are economic and institutional perspectives, which should be included. This section states individual criteria per category; technical criteria, societal criteria, economic criteria and institutional criteria. It is inevitable that some criteria some overlap between the perspectives and could therefore be placed in multiple criteria groups.

6.4.1 Technical criteria

The first criterion that is applied to assess CO_2 reducing alternatives is the CO_2 reduction potential. In order for the Dutch refining industry to meet CO_2 reduction policies it is important that the alternatives significantly reduce CO_2 emissions of Dutch refineries. Avoided kilotons CO_2 emitted is used as unit for measuring the performance. Possibilities for implementation of CO_2 reducing alternatives within the Dutch refining industry forms the second technical criterion. Processes and systems within Dutch refineries are highly integrated and alternating these could have disastrous consequences. Implementing CO_2 reducing alternatives unavoidably affect existing processes and must be kept to a minimum. Furthermore, it is important that CO_2 reducing alternatives can be implemented within existing refineries. Another important factor is the development stage of the alternatives. The wide variety of alternatives presented in Chapter 5 range from proven technologies to highly experimental ones. Alternatives that have a higher degree of development score higher with regard to this criterion.

The following criteria also contain economic aspects and could therefore show some overlap with economic criteria. CO_2 reducing alternatives implemented within the Dutch refining industry can be classified as long-term investments. Profitability of a refinery is, however, highly dependent on its ability to produce products that are in demand. It is therefore necessary that the implemented CO_2 reducing alternative can cope with a certain flexibility in production. CO_2 reducing alternatives are rated higher if they can cope with flexibility in demand for refining products. Besides the capability of dealing with demand flexibility, the possibility of scaling up the capacity of the CO_2 reducing alternative is an important criterion. Most alternatives are first implemented on a small scale to ensure their effectiveness. The final technical criterion is used to assess the different CO_2 reducing alternatives and their suitability for system integration. Five out of the six Dutch refineries are located close to each other in the industrial cluster of the Port of Rotterdam. If an alternative can reduce the emissions of multiple refineries at once it would be very beneficial. In some cases refineries could even cooperate with other industries to reduce their joint emissions.

6.4.2 Societal criteria

The first societal criterion focuses on the consequences of CO_2 reducing alternatives for surrounding areas. Some alternatives are applied within refineries and therefore only affect the refineries themselves, these result in minimum consequences for the surrounding areas. However, other CO_2 reducing alternatives could have a greater impact on the surrounding area. Alternatives are rated less promising as the risks of CO_2 reducing alternatives on surrounding areas increases. Besides the impact on surroundings, alternatives might also lead to conflicting interests of stakeholders. This includes the societal resistance that could occur when certain alternatives are implemented. Storage of CO_2 in empty gas fields, for example, already led to quite some disturbances in neighbouring villages. This criterion also includes conflicts that may arise between refineries and the government pressing the Dutch refining industry to reduce their CO_2 emissions. Certain CO_2 reducing alternatives might not be in favour of the Dutch refining industry and therefore result in conflicting interests. In most cases this is due to developments within the refining industry, changing regulations or present configuration of refineries.

6.4.3 Economic criteria

A very important economic criterion is the cost of implementation of the CO_2 reducing alternatives. Dutch refineries are facing increasingly fierce competition from export orientated refineries. It is important that the implementation of CO_2 reducing alternatives does not significantly decreases the competitiveness of the Dutch refining industry. Less costly CO_2 reducing alternatives are more likely to be implemented towards 2030. A significant reduction of the CO_2 budget towards 2050 enables the implementation of more costly alternatives. Therefore alternatives are rated higher if operational costs are lower. Section 6.4.4 discusses some technical criteria that could also be placed within an economic perspective. Especially the demand flexibility, scaling up of capacity and system integration of CO_2 reducing alternatives are also very important for the economic performance of Dutch refineries.

6.4.4 Institutional criteria

The first institutional criterion that is used to assess the CO_2 reducing alternatives explores how well alternatives fit within current regulations. Especially the suitability within the ETS is important. Furthermore, the number of obstructive regulations are identified and used to assess the CO_2 reducing alternatives. The better an alternative fits within current regulations, the higher it is rated.

Besides the fit within current regulations, the required institutional change necessary for the implementation of certain CO_2 reducing alternatives is discussed. Some alternatives require little to no adjustments in current legislation while others require substantial change. An alternative is rated higher if it requires less institutional change.

6.5 Sub-conclusion

Chapter 6 answers the research question "In which way can Technology Assessment be applied within this research and what criteria can be deducted from this framework". TA is used to assess the CO_2 reducing options since it aims to produce comprehensive and objective information on state-of-the-art technologies and their impact. TA along with a multi-criteria analysis is most suitable for this research. TA is suited to deduct criteria for the multi-criteria analysis from both technical and societal perspectives. However, two perspectives alone do not suffice to fully assess CO_2 reducing alternatives. Therefore economic and institutional perspectives are added. Criteria for assessing CO_2 reducing alternatives are deducted from the extended TA framework and shown in figure 27.

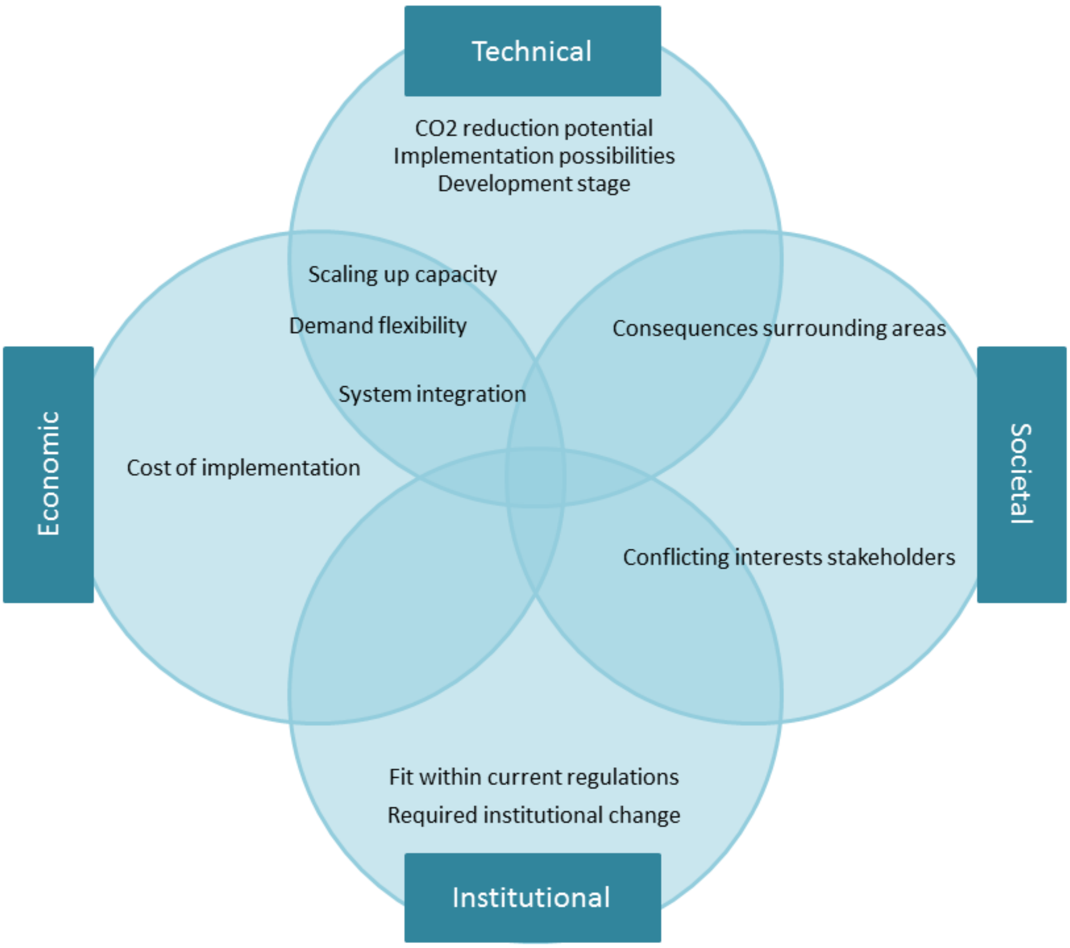

Figure 27 - Criteria from all four perspectives

7. Most promising CO_2 reducing alternatives

Criteria from four perspectives are used within the multi-criteria analysis to assess CO_2 reducing alternatives. This chapter applies the deducted criteria on the alternatives and determines the most promising ones. This chapter starts with a literature overview on multi-criteria analyses in section 7.1. Its practice in general, important concepts and different applications are all discussed within this section. Section 7.2 selects the most suitable type of multi-criteria analysis for assessing the variety of CO_2 reducing alternatives. The actual multi-criteria analysis takes place in section 7.3.

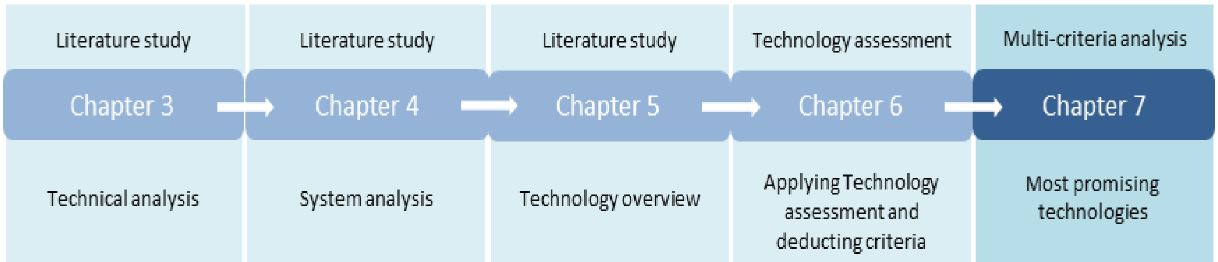

Figure 28 - Overview: chapter 7

7.1 Multi-criteria analysis

A multi-criteria analysis is a form of decision making equipped to handle the multiplicity of criteria used for judging the alternatives (Mateo, 2012). A multi-criteria analysis can be used for addressing complex problems often featuring high uncertainties, conflicting objectives and multiple interests and perspectives (Wang et al., 2010). Within the field of multi-criteria analysis a distinction can be made between Multi-objective decision-making and Multi-attribute decision-making. The distinction between the two is the number of available alternatives. Multi-attribute decision-making selects a limited amount of alternatives while Multi-objective decision-making determines the alternatives based on a function to optimize a set of constraints (Belton & Stewart, 2002).

Multi-criteria decision making is considered a complex and dynamic process which includes both managerial and engineering components. The first-mentioned component defines goals and chooses the most promising alternatives. Engineering components relate to defining alternatives and discussing possible consequences of these alternatives. Accepting or rejecting the proposed alternative is assigned to the managerial component (Opricovic & Tzeng, 2004). Multi-criteria decision making usually consist out of five main stages (Mateo, 2012). The first stage defines the problem, generates alternatives and establishes criteria. In order for multi-criteria decision making to function properly it is crucial that the problem is clearly defined. Objectives, relevant actors, points of conflicts, constraints and uncertainties all need to be discussed. Step two concerns the allocation of weight to the constructed criteria. These weights reflect the relative importance of the criteria with respect to each other. The third steps is the construction of the evaluation matrix. Alternatives are scored with regard to their expected performance against the criteria. Step four selects the appropriate method used to determine the most promising alternatives. Available data and the degree of uncertainty are important factors for selecting the multi-criteria method. Ranking of the alternatives takes place in the fifth and final step of the multi-criteria decisions making.

7.2 Multi-criteria analysis and CO_2 reducing options

In order for a multi-criteria analysis to determine the most promising CO_2 reducing options, the options are first converted in alternatives. These alternatives are constructed in the first part of this section. The second part of this section discusses the most suitable multi-criteria decision making tool that is applied for assessing the CO_2 reducing alternatives. This tool is used to perform the remaining four steps.

7.2.1 Generating alternatives

Chapter 5 presented an overview of CO_2 reducing options. In order for the multi-criteria analysis to determine the most promising options, alternatives are generated. In general the wide variety of CO_2 reducing options can be divided into two categories. Options that reduce the CO_2 emissions by optimizing the energy efficiency and options that optimize the carbon efficiency. In total eleven alternatives are identified based on the CO2 reducing options of Chapter 5.

1. Technologies that reduce the CO_2 emissions of the distillation unit
2. Technologies that reduce the CO_2 emissions of other refining processes
3. Processing lighter and sweeter types of crude oil
4. Heat exchange to residential districts or nearby industries.
5. CO_2 exchange to greenhouses
6. Implementation of process integrated cogeneration units
7. Using renewable energy for electricity requiring processes within refinery
8. Using renewable energy in combination with power-to-heat or power-to-gas
9. Feed-in of biofuels within refinery processes
10. Carbon capture and storage
11. Carbon capture and utilization

Alternatives 1,2,4 and 6 optimize the energy efficiency of refineries while the remaining alternatives optimize the carbon efficiency.

7.2.2 Methodology for performing a Multi-criteria analysis

It can be difficult to choose between alternatives if the performance of a number of alternatives needs to be evaluated and multiple objectives are important. Alternatives can be evaluated by assessing them on a wide variety of evaluative criteria. The analytical hierarchy process (AHP) is a method that deals with multiple, sometimes conflicting criteria. AHP is one of the most widely used multiple criteria decision making tools (Vaidya & Kumar, 2006). There are several reasons for applying AHP within this research. First of all, the list of criteria identified in the end of Chapter 6 does not only quantitative criteria but also qualitative criteria, such as institutional and social factors. Furthermore a large quantity of criteria was identified which makes it even more difficult to determine the most promising one. Finally this research deals with future CO_2 reducing technologies and some of their characteristics may not be well known. According to Mateo (2012). these three properties make AHP a suitable multi-criteria decision making tool within this research.

AHP is a decision making procedure developed by Saaty in the 1970s (Mateo, 2012). It is considered an effective tool in analysing situations with multiple and sometimes even conflicting objectives. The main goal of AHP is to determine the most promising alternative based on the established criteria. It ranks the alternatives by considering all criteria simultaneously. AHP breaks a problem down in hierarchical structure with the main goal at the top. The evaluative criteria are placed in the middle and the alternatives at the bottom (Mateo, 2012). The fundamental input for AHP is the relative importance of criteria on each other and the performance of alternatives on these criteria. Pair-wise comparisons are made to express the relative strength of the alternatives towards the criteria and the criteria towards the goal. According to Saaty (1990) AHP can be divided into four steps, namely structuring the problem into an hierarchical model, obtaining the weights for each criteria, determining the score of each alternative for each criteria and establishing the overall score for each alternative.

7.2.3 Incorporating a multi-actor perspective within AHP

To determine the most promising CO_2 reducing alternatives the weights of the evaluative criteria are crucial. They eventually determine which alternative has the best overall performance. Depending on the interests of the different actors, weights of the evaluative criteria differ. It is therefore important to incorporate a multi-actor perspective within the analytical hierarchy process. The first actor perspective taken into account is the Dutch government. To meet the increasingly stringent CO_2 reduction targets refineries must substantially reduce their CO_2 emissions. Dutch refineries are another important actor whose interests must be assessed. However, due to the fact that the Dutch refineries differ in configurations and therefore have different interests, they are split up into two categories. Complex refineries with a high integration, such as Shell Pernis and ExxonMobil, and the other less complex non-integrated Dutch refineries (van den Bergh et al., 2016). The final actor perspective that is taken into account are Dutch citizens. Negative externalities must be kept to a minimum. Each of the four actors have different interest which result in a different weighting of the evaluative criteria. The next section identifies the main interests of these four actors.

The main interest of the Dutch government is the reduction of CO_2 emissions by 80% to 95% below 1990 levels by 2050 (EFC, 2010). Since the Dutch refining industry has a high economic value, it is also important that the sector remains competitive. Costs related to the realisation and implementation of CO_2 reducing alternatives are therefore very important. The government would prefer an alternative that reduces the CO_2 emissions of multiple refineries or other industries at once. Such an alternative would have a far greater impact. The government furthermore protects the interest of its citizens. They therefore find it important that the risks and consequences that accompany the CO_2 reducing alternatives are kept to a minimum.

According to van den Bergh et al. (2016), Dutch refineries can be classified into two general categories. Highly complex and integrated refineries, indicated as must-run, and other either less complex or non-integrated refineries. The Shell Pernis refinery and the ExxonMobil refinery are classified as must-run. Since these refineries are more complex and have a high integration with the petrochemical industry their interest might differ from the other Dutch refineries. Implementing certain CO_2 reducing alternatives might not be in their favour due to their high complexity and result in a less optimal utilisation. Also the possibilities for system integration are more important to them. The less complex refineries assign a higher value to the development stage of alternatives since these are easier to implement.

Finally the interests of the Dutch citizens need to be taken into account. Reducing the CO_2 emissions in general is also in the best interest of the citizens. The costs involved with the implementation of the CO_2 reducing alternatives are less important to them. However, the risks and consequences that accompany the CO_2 reducing alternatives are a crucial factor for them. Citizens would like to benefit from certain alternatives if possible. Since the citizens like to see results sooner than later, CO_2 reducing alternatives that find themselves in a far developed face are preferred.

7.3 Analytical Hierarchy Process

This section discusses and applies the four steps of AHP. It starts by structuring the situation into an hierarchical model. Then the weights for each criteria are obtained which is followed by determining the score of each alternative for each criteria. Finally the overall score of each alternative is constructed.

7.3.1 Hierarchical model

The hierarchical model used for structuring a problem in AHP consists out of three layers. The main objective, in this case reducing the CO_2 emissions of the Dutch refineries, is placed at the top. Evaluative criteria are placed in the middle layer. Within Chapter 6, eleven criteria were identified for assessing the CO_2 reducing alternatives. The bottom layer of the model contains the alternatives for reducing the CO_2 emissions of Dutch refineries. Within the model eleven alternatives, identified in the previous section, are included. Figure 29 represents the hierarchical structure applied to this research. The criteria and alternatives are numbered (C1…C11 and A1…A11) and these numbers will be used within the rest of this section.

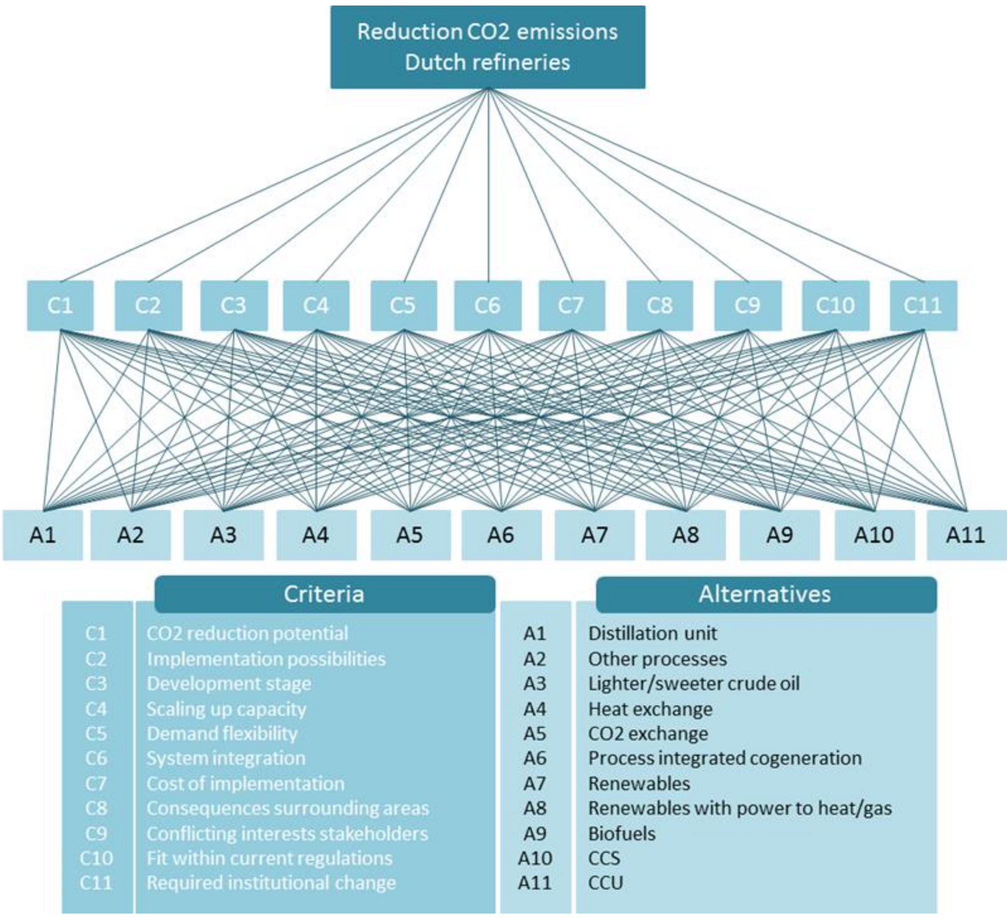

Figure 29 - Hierarchical model according to AHP

7.3.2 Weights of the evaluative criteria

The second step is to determine the weights of the evaluative criteria. A pairwise comparison, reflecting the relative importance of the criteria to each other, is executed. The importance of one criteria on another is coded in a nine-point scale (Saaty, 1990). Criteria receive a 1 if they equally contribute to the main objective. If a criteria has a weak importance or is slightly favoured over another criteria it receives a 3. A 5 is assigned to a criteria if it is strongly more important and a 7 if it is favoured very strongly. Finally a 9 can be assigned to a criteria that is absolutely more important than another. If necessary, criteria can receive the values 2, 4, 6 and 8 if they score intermediate between values. The assigned values can be visualised in a 11 by 11 matrix, a so-called pairwise comparison matrix. In this case the relative importance of each criteria towards the other criteria is assessed.

The performed multi-criteria analysis incorporates the perspectives of multiple actor perspectives. Since the different actors all have a different perspective with regard to the importance of criteria the assigned weights will differ per actor. The four most important actors are: the Dutch government, highly complex/integrated refineries, less complex/non-integrated refineries and the Dutch citizens. Therefore, four different pairwise comparison matrixes are constructed, one for each of the actor perspectives. Assigning different weights depending on the interests of the actors also has consequences for the overall performance of the alternatives. As a result the most promising CO_2 reducing alternatives differ depending on the actor perspective.

In total four pairwise comparison matrixes are constructed, each for one of the actor perspectives. The first step in constructing the pairwise comparison matrix for the evaluative criteria is determining which criteria are most important for each actor. This is based on the main preferences of the actors identified in section 7.2.3. Ranking the criteria makes it easier to fill in the matrix. Chapter 6 identified eleven evaluative criteria for assessing the CO_2 reducing alternatives. These eleven criteria are classified into four categories per actor, shown in figure 30, that reflect their importance.

The main interest of the Dutch government is the reduction of CO_2 emissions by 80% to 95% below 1990 levels by 2050 (EFC, 2010). Since the Dutch refining industry has to reduce their CO_2 emissions to achieve this targets the CO_2 reduction potential of alternatives is also one of the most important criteria from their perspective. Reducing the CO_2 emissions of Dutch refineries is also in the best interest of the Dutch citizens which makes it an important criteria from their perspective. Since the Dutch refining industry has an high economic value for the Netherlands it is also important that it remains competitive. As a result the costs of the CO_2 reducing alternatives must be kept to a minimum. The criteria with regard to the costs of implementation is therefore important for both the Dutch government and the Dutch refineries. The Dutch citizens attach a lower importance with respect to this criteria. The criteria that contains possible conflicting interests between stakeholders first of all includes the societal resistance that could occur when certain alternatives are implemented. Secondly it includes conflicts that may arise due to the fact that certain CO_2 reducing alternatives might not be in favour of some Dutch refineries and therefore result in conflicting interests. As a result this criteria is very important for the highly complex/integrated refineries since some alternatives might negatively influence their utilisation. The Dutch citizens also attach a higher weight to this criteria since some alternatives might negatively influence their interests.

Consequences for surrounding areas is especially important for the Dutch citizens. They benefit from a reduction of CO_2 emissions of refineries but do not want to experience the possible negative side effects of alternatives. Since the Dutch government protects the interest of its citizens it is also in their interest that the consequences of CO_2 reducing alternatives for surrounding areas are kept to a minimum. Both categories of Dutch refineries have a lower interest with respect to this criteria. Possibilities for system integration are especially important for the Dutch government and the highly complex/integrated refineries. They benefit the most from these possibilities for integration. Dutch citizens also find this criteria important since they might benefit from these integration possibilities like heat exchange. The less complex/non-integrated refineries attach a lower value to this criteria. The CO_2 reducing alternatives need to be able to be implemented within the existing Dutch refineries. Therefore this criteria is especially important for the Dutch refineries. With respect to the Dutch government and the Dutch citizens this criteria is of less importance.

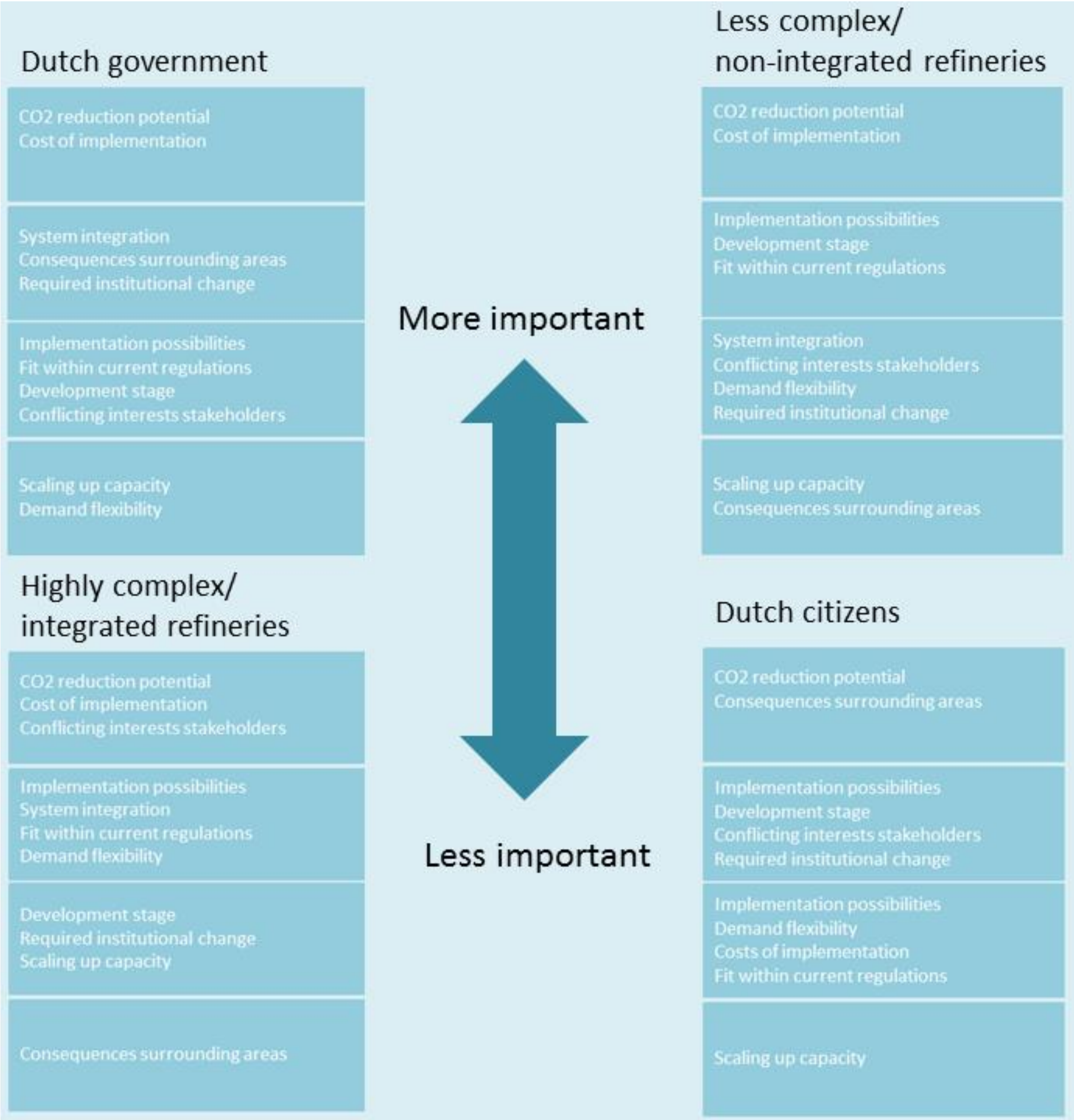

Figure 30 - Ranking of evaluative criteria according to their importance from each of the four actor perspectives

To assess the timespan in which the CO_2 reducing alternatives can be implemented within the Dutch refining industry their current development stage is of importance. Especially the less complex/non-integrated refineries add a higher value to this criteria. This is due to the fact that they cannot rely on system integration alternatives and therefore need to implement alternatives at an early stage. The Dutch citizens also find the development stage of alternatives important since they would rather see the CO_2 emissions reduced sooner than later. Abilities for alternatives to scale up in capacity and thereby reduce the CO_2 emissions even further is not seen as a crucial criteria from all perspectives. In most cases, the implementation of CO_2 reducing alternatives is very costly and they are therefore designed in a way that they will reduce the CO_2 emissions by a substantial amount. For highly complex/integrated this criteria is slightly more important since they relatively emit the most CO_2. Demand flexibility is also seen as a less important criteria from all actors perspectives. This is in most cases due to the fact that most available alternatives do not affect the demand flexibility. Highly complex/integrated refineries attach a slightly higher value to this criteria since they have a more flexible product slate and are therefore more affected by possible changes in demand flexibility.

Alternatives become more promising when they fit within the current regulations. If they do not fit in refineries are not awarded, either with CO_2 credits or with subsidies, and have no incentive to implement these alternatives. As a result this criteria is especially important to the entire Dutch refining industry. Dutch citizens and the Dutch government attach less value to this criteria. The Dutch government does however attach a higher value to the institutional change that required for alternatives to fit within regulations. Ideally no change is required because it prevents changes in current regulations. Furthermore institutional change is a slow process and certain regulations are made on a European level which limits the influence of the Dutch government. Since institutional change is a long term process it is less important to the refineries than the fit within current regulations. Table 9 shows the weights assigned to the criteria from all four actor perspectives. The individual pairwise comparison matrixes along with the calculations can be found in Appendix E

Table 9 - Weights assigned to the evaluative criteria from all four actor perspectives

	Weight assigned to the criteria from all four actor perspectives			
	Dutch government	Highly complex and integrated refineries	Less complex and non-integrated refineries	Dutch citizens
C1	0.23	0.19	0.23	0.22
C2	0.05	0.08	0.11	0.04
C3	0.05	0.03	0.11	0.10
C4	0.02	0.03	0.02	0.02
C5	0.02	0.08	0.05	0.04
C6	0.11	0.08	0.05	0.10
C7	0.23	0.19	0.23	0.04
C8	0.11	0.02	0.02	0.22
C9	0.05	0.19	0.05	0.10
C10	0.05	0.08	0.11	0.04
C11	0.11	0.03	0.05	0.10

7.3.3 Scores of alternatives on evaluative criteria

Step three within the AHP determines the performance of the alternatives on each criteria. Unlike the weights of the evaluative criteria, the scores of the alternatives are not subjective to the interests of different actors. Similar to the weights of the evaluative criteria, pairwise comparison matrixes are constructed to determine the performances of the alternatives on the evaluative criteria. Since a total of eleven criteria are included within this research, eleven pairwise comparison matrixes are constructed to assess the performance of the alternatives on each criteria. The same nine-point scale is used to determine the relative performance of alternatives on each criteria.

All eleven pairwise comparison matrixes for this analysis can be found in Appendix E . Appendix E also contains the explanations of the scores of the alternatives on the criteria along with the performed calculations. Table 10 provides an overview of the scores of the alternatives on all the evaluative criteria. Colours are added to the table in order to provide a better overview of the scores. A score is assigned a green colour if an alternative performs well on a criteria and a red colour is it performs not so well.

Table 10 only shows the scores of the alternatives on the evaluative criteria. In order to determine the most promising CO_2 reducing alternatives, the assigned weights need to be taken into account. As explained before, these weights differ per actor perspective. The next section includes the weights of the evaluative criteria from the different actor perspectives to determine the most promising alternatives.

Table 10 - Scores of the CO_2 reducing alternatives on the evaluative criteria

	Scores of alternatives on the evaluative criteria										
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
C1	0.13	0.02	0.06	0.27	0.13	0.06	0.02	0.03	0.03	0.13	0.13
C2	0.04	0.02	0.12	0.12	0.04	0.04	0.12	0.12	0.12	0.12	0.12
C3	0.10	0.02	0.20	0.20	0.20	0.10	0.05	0.05	0.05	0.02	0.02
C4	0.02	0.02	0.05	0.23	0.05	0.02	0.05	0.11	0.11	0.11	0.23
C5	0.11	0.02	0.04	0.11	0.11	0.11	0.11	0.11	0.04	0.11	0.11
C6	0.02	0.02	0.08	0.19	0.19	0.02	0.04	0.08	0.08	0.08	0.19
C7	0.19	0.19	0.19	0.08	0.08	0.08	0.04	0.02	0.08	0.02	0.04
C8	0.14	0.14	0.14	0.05	0.05	0.14	0.02	0.02	0.14	0.02	0.14
C9	0.17	0.17	0.02	0.07	0.07	0.07	0.03	0.03	0.17	0.02	0.17
C10	0.15	0.15	0.15	0.03	0.02	0.07	0.15	0.03	0.15	0.03	0.07
C11	0.17	0.17	0.17	0.07	0.07	0.03	0.17	0.03	0.07	0.02	0.03

7.4 Most promising CO_2 reducing alternatives

Perspectives of the Dutch government, highly complex/integrated refineries, less complex/non-integrated refineries and the Dutch citizens are all taken into account. As a result, four different sets of weights of the evaluative criteria are constructed. Each set represents the interests of the corresponding actor. Section 7.3.3 constructed the scores of the alternatives on the evaluative criteria. Combining these two sets of data results in the overall scores of the CO_2 reducing alternatives, shown in table 11. It can be concluded that exchanging heat (A4) is the most promising CO_2 reducing alternative for all four actor perspectives. Other alternatives that perform well are the optimisation of the distillation column (A1), the processing of lighter and sweeter crudes (A3) and CCU (A11). However, differences between the different actors occur with respect to these alternatives. As expected, highly complex/integrated refineries less favour the option of processing lighter and sweeter crudes. This alternative indeed reduces their CO_2 emissions but also decreases their utilisation. It is interesting to see that the renewables receive a relatively low score overall. An explanation could be that their reduction potential is not that large and the construction of wind turbines encounters a lot of resistance by citizens. Renewables in combination with power to heat/gas has a higher CO_2 reduction potential but is very costly and not yet suitable within current regulations. Other less promising alternatives are process integrated cogeneration and CCS. CO_2 reducing alternatives that score average are the optimisation of other refining processes, biofuels and CO_2 exchange.

Table 11 - Overall scores of alternatives for each actor perspective

	Weighted scores of alternatives for the four actor perspectives			
	Dutch government	highly complex and integrated refineries	less complex and non-integrated refineries	Dutch citizens
A1	0.13	0.13	0.13	0.12
A2	0.10	0.10	0.09	0.09
A3	0.12	0.10	0.13	0.11
A4	0.14	0.13	0.14	0.14
A5	0.10	0.09	0.10	0.10
A6	0.07	0.07	0.07	0.08
A7	0.06	0.06	0.06	0.05
A8	0.04	0.05	0.05	0.04
A9	0.08	0.09	0.08	0.09
A10	0.06	0.06	0.07	0.06
A11	0.10	0.11	0.09	0.12

7.5 Sub-conclusion

This chapter answers the research question "what are the most promising CO_2 reducing alternatives that can be implemented within the Dutch refining industry". A multi-criteria analysis is used within this research since it addresses complex problems that feature high uncertainties, conflicting objectives and multiple interests and perspectives. Weights of the evaluative criteria are a crucial factor, depending on the interests of the different actors involved, weights of the evaluative criteria can differ. As a result, a multi-actor perspective was incorporated. The four most important actors are the Dutch government, highly complex/integrated refineries, less complex/non-integrated refineries and Dutch citizens. Since different actors allocate different weights to the evaluative criteria, overall performance of the CO_2 reducing alternatives also differs per actor. Table 11 provides an overview of the scores of alternatives for each of the four actor perspectives. It can be concluded that heat exchange, optimizing the distillation unit, processing lighter and sweeter types of crude oil and CCU are the most promising CO_2 reducing alternatives for the Dutch refining industry.

Part V – Conclusion and Discussion

8. Conclusion and discussion

The final chapter of this research gathers the outcomes obtained from the performed analyses. Section 8.1 discusses the answers to the research questions and checks if the main research goal is achieved. A discussion of the outcomes, identifying the institutional challenges that arise when alternatives are implemented and recommendations for future research are elaborated on in section 8.2. finally, the last section, section 8.3, gives a reflection on the process of constructing this thesis and quality of results.

8.1 Answers to the research questions

The main research goal of this work is: "*To analyse the Dutch refining industry, determine the different factors that contribute to their CO_2 emissions and assess which CO_2 reducing alternatives are the most promising for achieving the goals set by increasing stringent environmental regulation".* To achieve this goal five research question needed to be answered.

1 - Which processes take place within the Dutch refining industry and how do they contribute to the CO_2 profile of the refineries

The research started by exploring the configurations of the Dutch refineries. Constructing the overview of refining processes present within the Dutch refining industry proved to be difficult. Due to the limited amount of publically available data it was impossible to construct a complete overview of all processes present within the Dutch refining industry. Processes present within Dutch refineries that could be identified were: atmospheric distillation, vacuum distillation, catalytic reforming, alkylation, fluid-bed catalytic cracker, hydrocracker, hydrotreater, thermal cracker, visbreaker and flexicoker. It could be concluded that the Koch refinery had the relatively simplest configuration while the Shell Pernis and ExxonMobil refineries are the most complex.

The CWT approach is used to determine the total emissions of Dutch refineries along with the contribution of individual processes. If the complexity of Dutch refineries increases, the CO_2 emissions also increase. The atmospheric distillation unit is the largest emitter of CO_2 within most refineries. It contributes up to 70% of the total CO_2 emissions in Dutch refineries with a relatively simple configuration and up to 30% in Dutch refineries with a more complex configuration. Besides the atmospheric distillation unit, the Flexicocker, the FCC unit and hydrocracker substantially contribute to the total CO_2 emissions of Dutch refineries.

2 - In what way is the CO_2 profile of Dutch refineries affected by their crude oil intake and product slate

After determining the influence of the individual refining processes on the CO_2 emissions of Dutch refineries, the second research question could be answered. Each type of crude oil is characterized by different properties, such as the API gravity and the sulphur content, that influence the CO2 emissions of Dutch refineries. The Netherlands imports light and medium crude oils with an API ranging from 31.3 to 43.6. These crude oils are relatively sour with an sulphur content ranging from 0.1 to 2.6. CO_2 emissions related to refining crude oil decrease as the API gravity increases. Refining heavy crudes increases CO_2 emissions of Dutch refineries. CO_2 emissions of Dutch refineries are furthermore influenced by the sulphur content of crude oil. A high sulphur content of crude oil will result in higher CO_2 emissions.

To assess the effect of the product slate of Dutch refineries on their CO_2 emissions an overview of refinery products along with their quantities was constructed. It appeared that the Dutch refining industry mainly produces naphtha, gas/diesel oil and fuel oil. Gasoline and LPG are not produced in large quantities. However, no straightforward methodology exists which allocates the CO_2 emissions of refineries to their final products. In other words it is almost impossible to determine the CO_2 emissions of a refinery for the production of one tone of gasoline or diesel. This is due to the fact that oil refineries produce a number of different products simultaneously from a single feedstock. Even if the data related to the total amount of energy and other resources used within refineries is available, there is no simple way to allocate emissions to a specific product.

3 - What are possible options that can be used to reduce the CO_2 emissions of Dutch refineries

Research question one and two formed the basis required for answering the third research question. In general, Dutch refineries can reduce their CO_2 emissions by implementing options that either optimise their energy efficiency or optimise their carbon efficiency. Six different categories were constructed each containing options for reducing the CO_2 emissions of Dutch refineries. The first category contained technologies that reduce the CO_2 emissions of the most polluting processes (CDU, FCC unit, hydrocracker and flexicoker) within Dutch refineries by optimizing their energy efficiency. CO_2 reducing alternatives within category two focussed on processing a different type of crude oil. Lighter and sweeter types of crude oil can result in a reduction of CO_2 emissions. Increased regional integration is the third category of CO_2 reducing options and includes exchanging excess heat and CO_2 exchange. Heat exchange reduces the CO_2 emissions of refineries by optimising their energy efficiency while CO_2 exchange optimises the carbon efficiency.

The fourth category included options that alternate the processes with regard to the production of heat and electricity within Dutch refineries and thereby reduce their CO_2 emissions. Cogeneration, renewables and renewables with power-to-heat or power-to-gas are all incorporated within this category. CO_2 emissions of Dutch refineries can also be reduced by implementing biomass within the sector. There are three main biofuel feedstock possibilities for refineries that respectively use vegetable oil, pyrolysis oil and algae based biofuels. The final category reduces the CO_2 emissions of Dutch refineries through the capture of CO_2. Three possibilities were identified for the capturing of CO_2, namely pre-combustion capture, post-combustion capture and oxyfuel firing. After the CO_2 is captured and compressed a solution needs to be found for the remaining CO_2. Carbon capture and storage (CCS) and carbon capture and utilisation (CCU) are the two existing options.

4 - In which way can a Technology Assessment be applied within this research and what criteria can be deducted from this framework

Research question one and two constructed the CO_2 profile of Dutch refineries and the third research question identified the wide variety of CO_2 reducing options. To assess the wide variety of CO_2 reducing options a Technology Assessment was used. For this research, TA along with a multi-criteria analysis as method is most suitable. TA allows the deduction of criteria from both technical and societal perspectives that could be used in the multi-criteria analysis. However, from analysing the missing aspects within TA it became clear that these two perspectives do not suffice to fully assess the CO_2 reducing alternatives. It could be concluded that in order for TA to be successfully applied within this research it needed to be extended with both economic and institutional perspectives. Figure 31 shows the evaluative criteria from the four perspectives that are used to determine the most promising CO_2 reducing alternatives.

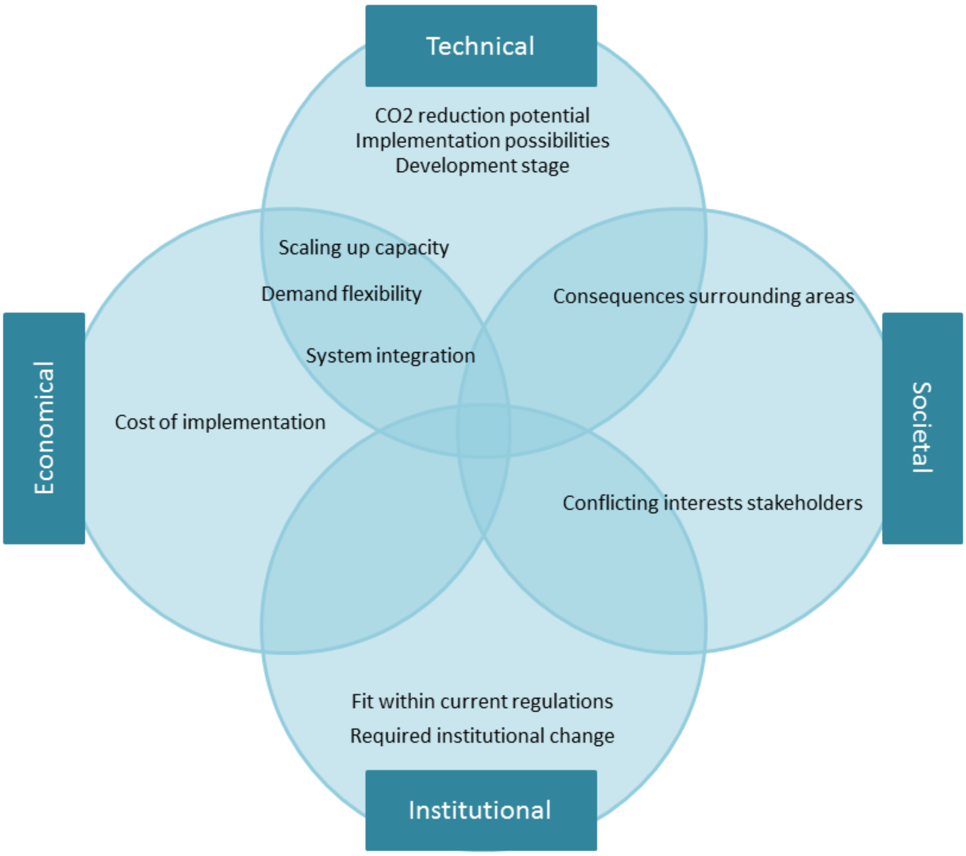

Figure 31 – The evaluative criteria from all four perspectives used to determine the most promising CO_2 reducing alternatives

5 - What are the most promising alternatives that reduce the CO_2 emissions of Dutch refineries based on the criteria deducted from the designed framework

The final research question used the information acquired from the performed analyses to determine the most promising CO_2 reducing alternatives via a multi-criteria analysis. A multi-criteria analysis was used due to the fact that it addresses complex problems that feature high uncertainties and multiple interests and perspectives. The wide variety of CO_2 reducing options were transformed into eleven alternatives. Determining the most promising CO_2 reducing alternatives, was done by applying the analytical hierarchy process (AHP). To determine the most promising CO_2 reducing alternatives the weights of the evaluative criteria are a crucial factor. They eventually determine which alternative has the best overall performance. Depending on the interests of the different actors involved, weights of the evaluative criteria can differ. As a result a multi-actor perspective was incorporated within the analytical hierarchy process. The four most important actors with regard to the implementation of CO_2 reducing alternatives within the Dutch refining industry were identified. These actors are: the Dutch government, highly complex/integrated refineries, less complex/non-integrated refineries and the Dutch citizens. Each of the four actors allocated different values to the evaluative criteria. Consequentially, the most promising CO_2 reducing alternatives are dependent on the various actor perspectives. The results of the performed multi-criteria analysis is presented in table 12. From this table it could be concluded that heat exchange (A4), optimizing the distillation unit (A1), processing lighter and sweeter types of crude oil (A3) and CCU (A11) are the most promising CO_2 reducing alternatives for the Dutch refining industry.

Table 12 - Scores of the CO_2 reducing alternatives on the evaluative criteria from four actor perspectives

	Dutch government	highly complex and integrated refineries	less complex and non-integrated refineries	Dutch citizens
A1	0.13	0.13	0.13	0.12
A2	0.10	0.10	0.09	0.09
A3	0.12	0.10	0.13	0.11
A4	0.14	0.13	0.14	0.14
A5	0.10	0.09	0.10	0.10
A6	0.07	0.07	0.07	0.08
A7	0.06	0.06	0.06	0.05
A8	0.04	0.05	0.05	0.04
A9	0.08	0.09	0.08	0.09
A10	0.06	0.06	0.07	0.06
A11	0.10	0.11	0.09	0.12

8.1.1 Overall conclusion

Overall it can be concluded that the main research goal of this thesis is achieved. The Dutch refining industry is analysed and the factors that contribute to its CO_2 emissions identified. A wide variety of CO_2 reducing options was provided. TA was applied and extended with economic and institutional perspectives. In the end, a multi-criteria analysis was used to identify the most promising CO_2 reducing alternatives. Due to the fact that the weighting of the evaluative criteria is subjective, a multi-actor perspective was included. The Dutch government, highly complex/integrated refineries, less complex/non-integrated refineries and the Dutch citizens all allocated different weights to the evaluative criteria. As a result, the most promising CO_2 reducing alternatives also differed per perspective which is shown in table 13.

Table 13 – Three most promising CO_2 reducing alternatives for each of the four actor perspectives

	1st	2nd	3rd
Dutch government	Heat exchange	Distillation unit	Lighter and sweeter crude oil
Highly complex and integrated refineries	Heat exchange	Distillation unit	CCU
Less complex and non-integrated refineries	Heat exchange	Lighter and sweeter crude oil	Distillation unit
Dutch citizens	Heat exchange	Distillation unit	CCU

It can be concluded that exchanging heat to nearby residential areas of industries is the most promising alternative for all actor perspectives. Another promising alternative from all actor perspectives is the optimisation of the Distillation unit. This is not unexpected due to the fact that it only effects the refineries, can lead to significant CO_2 reductions and is a relatively cheap alternative. Processing lighter and sweeter types of crude oil is especially interesting for the less complex/non-integrated refineries since they can substantially reduce their CO_2 emissions via this alternative, although these crudes usually trade at a premium. This alternative is less interesting for the highly complex/integrated refineries since the processing of lighter and sweeter crudes will lower the utilisation of their complex configuration. These three alternatives are especially promising for Dutch refineries towards 2030. However, A significant reduction of the CO2 budget towards 2050 requires the implementation of other alternatives. CCU is an interesting alternative but has not yet reached a mature phase within the Netherlands and is a large cost for the highly competitive industry. Nevertheless, this alternative shows great potential towards 2050.

8.2 Discussion

The previous section concludes that the main research goals is achieved and the most promising CO2 reducing alternatives for the Dutch refining industry are identified. However, this research does not includes challenges that arise when these alternatives are actually implemented. Section 8.2.1 analyses these challenges from an institutional perspective. Recommendations for further research are done in section 8.2.2

8.2.1 Coordination challenges of implementing CO_2 reducing alternatives

Implementation of CO_2 reducing alternatives might prove difficult since multiple actors, with their own interests are involved. Depending on the alternatives, actors differ and particular conflicting interest can arise, often as a consequence of the types of interdependencies that are created and the uncertainties that these involve. Therefore, some degree of cooperation and adequate operational and economic coordination between the actors is crucial. Layer 3 of Williamsons institutional model, introduced in section 6.3.2 where institutional perspectives are added to TA, is useful to assess the challenges that originate when CO_2 reducing alternatives are implemented. Transaction costs economics operates at this level. "The play of the game" focuses on governance and describes alternative ways of organisation. It concerns contracts and arrangements between the actors involved. These institutions are required for a successful implementation of the CO_2 reducing alternatives. Property rights are important to take into account since implementation of the alternatives can result in shared ownership which creates dependencies between the actors. Transaction costs economics goes beyond assessing the direct costs related to implementing CO_2 reducing alternatives. It also includes those costs that arise from the fact that actors don't have all information, may act opportunistically and operate in a complex and uncertain environment. All of which requires specific means and arrangements. The next section identifies and discusses institutional challenges that occur when CO_2 reducing alternatives are implemented. Options are assessed that improve the cooperation and coordination between the actors involved.

Optimisation of distillation unit and other processes

One of the most promising alternatives for reducing the CO_2 emissions of Dutch refineries is the optimisation of refinery processes. This alternative has a mixed/high asset specificity since it concerns the purchasing of site specific, customised equipment. Each refinery has its own specifications to which the equipment has to be adjusted. Such investments are classified as occasional with a low frequency of recurrence. As a result, optimisation of refinery processes requires little coordination between the actors involved. Refineries themselves are responsible for the implementation of these technologies and therefore own all property rights. The total costs are largely determined by the direct costs of the technologies involved. However, coordination between refineries is required to reduce the overall costs. Uncertainty and opportunistic behaviour of individual refineries can increase the total costs. Dutch refineries can cooperate during the process of optimising refinery processes. If certain technologies can be implemented within multiple refineries, contracts with the supplier can be concluded to decrease the total costs. However, it has to be taken into account that the implementation of technologies that optimise refinery processes, lead to a decrease in the output of a refinery or even downtime of entire processes. Uncertainty exists with respect to the total downtime of a refinery. The first refinery implementing process optimisation technologies probably experiences the most negative side effects and highest costs. This is due to the learning curve related to the implementation of new technologies. In most cases the first project encounters delays in the time schedule and costs exceeding the predetermined budget. Dutch refineries might act opportunistically, making sure they are not the first at implementing these technologies. Arrangements can be made between the refineries to share the additional costs of the refinery that implements the technologies first.

Processing lighter and sweeter crudes

Lighter and sweeter types of crudes can be processed by Dutch refineries to reduce their CO_2 emissions. Despite the reduction in CO_2 emissions, processing lighter and sweeter crudes increases refining costs. Refineries cannot increase the prices of their products since these products can be substituted by imports. As a result, refining margins decrease. In order for the Dutch refining industry to remain competitive and keep its economic importance, a solution is needed. Lighter and sweeter types of crude oil have a low asset specificity. These types of crude oil are widely available despite the fact that they are location specific. Purchasing lighter and sweeter crudes is a highly recurrent investment for Dutch refineries with a high frequency. Transactions are relatively simple but have a high degree of uncertainty due to fluctuating crude oil prices. If processing of lighter and sweeter types of crude oil becomes a accepted alternative of reducing CO_2 emissions of refineries, prices may increase even further. Dutch refineries can cooperate amongst each other by the joint purchase and storage of lighter and sweeter crudes. This might result in a minimisation of the transactions costs. However, such a joint purchase can lead to opportunistic behaviour of individual refineries. Since the capacity of Dutch refineries differs substantially, certain refineries might use a larger share of the jointly purchases/stored lighter and sweeter crudes. Classical contracts between Dutch refineries in which the market itself is the main governance structure can reduce this opportunistic behaviour of individual refineries.

Heat exchange and CO_2 exchange

Reducing CO_2 emissions of refineries by heat exchange and CO_2 exchange includes the cooperation of a lot of different actors. The Dutch refineries, the government, other industries and citizens all need to coordinate with each other to successfully implement these alternatives. Property rights are in this case are divided between the actors involved. Direct costs are related to the technologies that the Dutch refineries need to install for the capturing and distribution of CO_2 and excess heat. They have a mixed asset specificity since it concerns the purchasing of refinery specific, customised equipment. Heat exchange and CO_2 exchange technologies are furthermore physical specific as they are designed for a single task. Due to the fact that the heat and CO_2 is delivered to specific customers it is considered a dedicated asset. The investments regarding the implementation of the technologies for capturing heat and CO_2 are occasional with a low frequency of recurrence. Property rights of the technology itself are owned by the refineries. Indirect costs concern the construction of the infrastructure that actually supplies the CO_2 and excess heat to industries and residential districts. This asset has a low asset specificity and low frequency of recurrence. Costs and ownership of this infrastructure cannot be solely assigned to the Dutch refineries for multiple reasons. First of all, these costs decrease the competitiveness of the industry making the exchange of heat and CO_2 an unviable alternative. Secondly if Dutch refineries own the infrastructure their power becomes too large. They can control the heat and CO_2 flows and act opportunistically by only supplying to the industries and residential districts when it is in their advantage. A lock-in effect is created implying that citizens and industries are fully dependent on Dutch refineries for their required heat. Vice versa, Dutch refineries are dependent on the citizens and industries for acquiring the necessary permits. Contracts need to be concluded in which is arranged that the government provides the necessary infrastructure and becomes the owner with the corresponding property rights. This prevents opportunistic behaviour of Dutch refineries and ensures that all parties have access to the infrastructure. Citizens and industries that receive supplied heat and CO_2 might face uncertainty with regard to the supplied amount and its consistency. Therefore refineries need to be obliged, by contracts, to supply a baseload quantity of heat and CO_2 to industries and residential districts.

Process integrated cogeneration

Implementation of process integrated cogeneration units to reduce CO_2 emissions especially affects the Dutch refineries. Since the installations are implemented by Dutch refineries they own the own the corresponding property rights. Similar to the refinery process optimisation alternatives, this alternative has a mixed asset specificity since it concerns the purchasing of site specific, customised equipment. It does serve more than one function since it generates both heat and electricity. Investing in process integrated cogeneration units is has a low frequency of recurrence. This alternative requires some coordination between the actors involved since the produced electricity is most likely fed into the electricity grid. Implementation of process integrated cogeneration units is accompanied with high uncertainty. It can result in a decrease in refining output or even downtime of certain refinery processes. Budgets might me exceeded and schedules can be delayed with regard to the actual implementation. Like any other cogeneration unit, its economic viability is largely determined by the feed-in tariff of electricity. This tariff has decreased significantly the past couple of years making it an costly and unprofitable option. If the government wants to stimulate the reduction of CO_2 emissions by process integrated cogeneration units they have to cater to the needs of the Dutch refineries. Contracts can be concluded or regulations installed that include a fixed feed-in tariff for electricity produced by refineries. However, such a fixed tariff can lead to opportunistic behaviour by the owners of cogeneration units. If the tariff is too high, refineries will increase their cogeneration capacity unproportionally due to the fact that these units are now highly profitable. Another way to increase the attractiveness of process integrated cogeneration units is by subsidies. In this case, Dutch refineries can also use the generated electricity on-site and are not obliged to feed the electricity back into the grid. This option reduces opportunistic behaviour.

Renewable energy sources

Implementation of RES, especially wind power, in most cases leads to some form of resistance of actors involved. This is mainly due to its high “Not In My BackYard” (NIMBY) character. However, this CO_2 reducing alternative mainly focusses on installing wind or solar power near refinery sites. Wind turbines fit well within the industrial landscape of the harbour of Rotterdam and benefit from high wind speeds due to their location near sea. As a result, citizens are not likely to object this alternative. Safety concerns are the largest hurdle with regard to implementation RES at refinery sites. Especially for installing wind turbines since the risk exists that one of the wicks breaks of and damages the refinery. Such an incident would have disastrous consequences for the refinery and the environment. Furthermore, fire risks, air traffic and distance to power lines are all aspects that need to be taken into account. Formal regulations are already in place that provide the necessary safety requirements. RES on-site have a low/mixed asset specificity since it concerns the purchase of relatively standard equipment. A wind turbine or solar panel for a refinery does not differ from any other. It is slightly physical specific as its produces a single product but this product can serve many customers. Investing in RES is an investment with a low frequency. Since the refineries can implement RES on-site, little to no cooperation is required between the actors involved. In this case the large majority of costs are direct costs for by the Dutch refineries. As a result they own all property rights of these installations. Infrastructure required to transport the electricity to the refineries can be also be operated by the refineries. As long as no citizens are connected contracts are not required and refineries can also own these property rights. Arrangements between citizens can be made that object to the instalment of wind turbines, but in most cases they are not affected.

Renewable energy sources with power-to-heat/gas

Power-to-heat/gas implementation is only beneficial for Dutch refineries in combination with large scale renewable energy projects. When demand for electricity is low and the production is high, electricity prices drop substantially or even become negative. In this situation, the abundant electricity can be transformed into hydrogen. Dutch refineries can use this "green hydrogen" within refinery processes and thereby reduce their CO_2 emissions. However, this alternative is only viable in combination with large scale renewable energy projects with which refineries need to cooperate. An option is the joint investment in off-shore wind parks. These off-shore wind parks can be constructed using subsidies from the Dutch government. As a result the share of renewables within the Netherlands increases. This is also beneficial for the Dutch government since they aim at a share of 16% renewable energy in 2023. A large part of the costs related to the implementation of renewables and power-to-heat/gas originates from direct costs. Even if the constructing the off-shore wind parks is done by another party the costs of the power-to-heat/gas technologies remain. These technologies have a mixed asset specificity as it concerns the purchase of customized equipment able to transform electricity into heat or hydrogen. Power-to-heat is a site specific technology since refineries need to use it directly and heat is lost at transport. The production of hydrogen is less site specific due to the fact that hydrogen can be more easily transported. Both investments have a high physical specificity because they serve a single function. The produced heat or hydrogen is consumed by the refineries which also makes it an dedicated asset. Investments have a low frequency of transaction. Another important factor is the uncertainty of available electricity. Power-to-gas is only viable when the electricity prices are very low. This is most likely to occur at times of abundant generation from wind turbines relative to electricity demand. It is unclear when these periods occur and Dutch refineries might invest in a costly technology with limited possibilities for usage. Indirect costs of power-to-gas lie in the construction of a infrastructure that transports the hydrogen to the Dutch refineries. This infrastructure must be owned by the government because otherwise the owner might behave opportunistically. Certain refineries can be excluded or very high prices can be asked for using the infrastructure.

Biofuels

Implementing biofuels within Dutch refineries requires a substantial form of coordination. Especially between the suppliers of the biofuels and the Dutch refineries. Biofuels have a low asset specificity since they are widely produced can be blended into existing refining processes. Besides usage in the Dutch refining industry biofuels have a large variety of other applications. For refineries it is a recurrent investment with a high frequency of transaction. Biofuels can be classified into three categories based on the source of biomass. First generation biofuels are directly produced from food crops and have the advantage that they can be blended with petroleum-based fuels, combusted in existing internal combustion engines and distributed through existing infrastructure. As a result, the direct costs related to first generation biofuels are relatively low. Despite these advantages, first generation biofuels also have substantial negative aspects. Its main disadvantage is the food-versus-fuel debate. Since first generation biofuels are produced from food sources, their production is one of the reasons for rising food prices. Furthermore, uncertainty exists with regard to the actual reduction of CO_2 emissions by using first generation biofuels. Second generation biofuels use non-food materials such as wood, organic waste and food crop waste. These biofuels face less uncertainty since they significantly reduce CO_2 emissions and do not compete with food crops. As a result their direct costs are higher. Coordination is necessary to ensure the supply of first and second generation biofuels by the producers to the refineries. Producers of biofuels can behave opportunistically since the refineries are dependent on their biofuels for the reduction of CO_2 emissions. Classical contracts can be concluded to prevent this and ensure the supply of biofuels to refineries. Third generation biofuels are based on improving the production of the underlying biomass source. It uses specially engineered crops, such as algae, as an energy source. Algae have the potential to produce more energy per acre than conventional crops. To avoid the food-versus-fuel dilemma of first generation biofuels, algae can be cultured on land and water that is unsuitable for food production or in greenhouses. If Dutch refineries use biofuels based on algae, they can cooperate with nearby greenhouses. These greenhouses require CO_2 for the growth of algae so the cooperation can even be extended if Dutch refineries deliver the greenhouses with CO_2. Since such a cooperation creates mutual dependencies and might lead to opportunistic behaviour of one of the parties. Therefore this transactions needs to be coordinated. Contracts between Dutch refineries and nearby greenhouses can be concluded with respect to the exchange of algae based biofuels and CO_2.

CCS and CCU

CCS and CCU implementation within Dutch refineries requires significant coordination. The assets required to capture the CO_2 are highly specific since it concerns refinery specific and customised equipment. Refinery configurations and CO_2 emissions differ per refinery and the technologies perform a specific task, capturing CO_2. Investing in carbon capture technologies is an investment with a low frequency of transaction. Direct costs, related to the capturing of CO_2, make up the majority of the total costs. However, costs related to uncertainty and opportunistic behaviour of actors involved can increase the total costs even further. CCS tries to store the captured CO_2 permanently in geological formations, oceans or minerals. For several decades CO_2 has been ejected into geological formation to enhance the oil recovery. The long term storage of CO_2 remains, despite the experience, a relatively new concept with high uncertainties. With regard to the Netherlands CCS looks promising due to the large storage capacity in empty gas fields. Nevertheless, plans for storing CO_2 in these fields encountered great resistance since the risk exists that CO_2 leaks from the gas field. CO_2 is already stored in empty gas fields in the North Sea. If CCS is applied on a large scale, arrangements need to take place which explore the possibilities of storing the CO_2 in empty gas fields on land. CCU tries to convert the stored CO_2 into valuable products such as chemicals and fuels. Other options are mineral carbonation, enhanced oil recovery and other applications. CCU has as advantage over CCS that the utilisation of CO_2 can turn out to be a profitable activity. Uncertainty remains high with respect to converting CO_2 into a valuable product. Until now the CO_2 is only used as a fertiliser for the growth of plants in greenhouses. Since CO_2 can also serve as a heat carrier, the heat of the gas is also used for the heating in greenhouses. Contracts between the Dutch refineries and greenhouses can be concluded that ensure the delivery of CO_2. Such contracts are beneficial for both parties. Despite the advantageous an interdependency is created between both parties which might lead to opportunistic behaviour.

8.2.2 Recommendations

Based on the results of this research and the discussion presented in the previous section, certain topics for future research can be identified.

The performed research determined the most promising CO_2 reducing alternatives via the analytical hierarchy process. A semi-quantitative multi-criteria analysis was used because of time constraints and due to the fact that a majority of the data is not publically available. Future research could use this research as the basis for a new analysis based on quantitative data. It is important that the Dutch refining industry cooperates with such a study to provide the necessary information. Secondly, it could be interesting to further examine the interest of the identified actor perspective within this research. Via surveys the actual interests of the actors can be determined and included within the research. As a result, the conducted analysis would increase in relevance.

The main goal of this research was to "*To analyse the Dutch refining industry, determine the different factors that contribute to their CO_2 emissions and assess which CO_2 reducing alternatives are the most promising for achieving the goals set by increasing stringent environmental regulation".* Problems that may arise with regard to the actual implementation of the most promising CO_2 reducing alternatives were not taken into account. Future research might examine how these most promising alternatives can be implemented. All alternatives require some form of coordination between the actors involved. The discussions presented above, shortly elaborates on the challenges that arise from implementing the CO_2 reducing alternatives. The most important actors need to cooperate and it is important to identify what is required for the implementation. Costs of implementation need to be fairly distributed between the actors and institutions, such as the ETS, might need to be altered. Contracts and arrangements are required to minimize transactions costs and ensure that the actors do not act opportunistically.

8.3 Reflection

This research provides new insights with regard to the Dutch refining industry and the CO_2 reducing alternatives they can implemented. However, some results of the performed analyses might be open for discussion. Therefore this reflection elaborates on the quality of results in this thesis.

Chapter 3 provides an overview of the refining processes present within Dutch refineries. Though, due to the limited amount of publically available data it is impossible to construct a complete overview of all processes present within the Dutch refining industry. Such detailed information is unfortunately not available. As a result, the constructed overview of processes located in Dutch refineries does not contain every process that is actually present within the Dutch refining industry. Only the processes on which data is available are included. Nevertheless the most important refining processes are included in the overview.

The overview of Dutch refining processes is constructed using publically available data retrieved from Port of Rotterdam (2016) and A Barrel Full (2015). A incomplete overview of refining processes also has consequences for the allocation of CO_2 emissions to the processes of Dutch refineries. In reality additional processes are present which also emit CO_2. However, since no data with regard to these processes is publically available they are not included. This results in differences between the calculated and actual CO_2 emissions of Dutch refineries. The allocated CO_2 emissions to the processes are therefore not exact but do provide a basic understanding of the processes that emit the most amount of CO_2 within Dutch refineries.

Allocating the CO_2 emissions of refineries to their individual processes based on incomplete data has consequences for the results. Calculated total CO_2 emissions of Dutch refineries differ from the actual amount of CO_2 emitted. The difference between the calculated and actual CO_2 emissions of Dutch refineries increases as the complexity of refineries increases. This is due to the fact that complex refineries have more processes present that are not included in the constructed overview. Nevertheless, the CO_2 allocation to the individual processes is useful and determines the most polluting processes within Dutch refineries. The actual percentages are not correct but the conclusions that are made, match with results from other studies (Reinoud, 2005).

One of the most important refining processes that is not included within the overview is the production of hydrogen by refineries. Hydrogen is required for removing the sulphur via hydrotreatment or hydrocracking (Treese et al., 2015). The production of hydrogen is very CO_2 intensive and receives a CWT score of 300 (EU, 2011). Per processes unit, the process of producing hydrogen emits 300 times more CO_2 than the distillation unit. However, no data is publically available with respect to hydrogen production processes within the Dutch refining industry.

Based on the CO_2 profile of Dutch refineries, this research provides an overview on the wide variety of CO_2 reducing options that can be implemented within Dutch refineries. In general, two categories are identified. Options that reduce the CO_2 emissions of refineries by maximising their energy efficiency and options that maximize their carbon efficiency. This research only included options that are identified in other studies with regard to reducing the CO_2 emissions of refineries. Off course more experimental options exist but these are not taken into account. As a result, some promising experimental options for the reduction of CO_2 emissions of Dutch refineries may not be included in the overview.

In order to assess the wide variety of CO_2 reducing options that can be implemented within the Dutch refining industry a Technology Assessment is applied. A multi-criteria analysis is used to determine the most promising CO_2 reducing alternatives. From the missing aspects within TA it is concluded that economic and institutional perspective need to be included. The evaluative criteria, used in the multi-criteria analysis, are deducted from the extended TA framework. As a result criteria form four perspectives (technical, societal, economic, institutional) are used to determine the most promising CO_2 reducing alternatives. In total, eleven criteria are identified. However, it can be argued that more criteria are required for a complete assessment. Due to limited amounts of time and data this research was not able to include more criteria and only included the most important ones.

To determine the most promising CO_2 reducing alternatives a multi-criteria analysis is used. Unfortunately such an analysis is always sensitive to subjectivity. First of all, the weights assigned to the evaluative criteria can differ per actor perspective. Therefore, this research includes the four most important actors and allocates the weights according to their expected preferences. Nevertheless, these weights can differ in reality which results in a different outcome. Furthermore the lack of publically available data makes it impossible to construct a quantitative multi-criteria analysis. As a result, this research uses the a semi-quantitative multi-criteria analysis, namely the analytical hierarchy process. Criteria and alternatives are respectively scored based on their relative importance and performance. Despite its scientific foundation, the analytical hierarchy process remains sensitive to subjectivity.

The results of the multi-criteria analysis show that the CO_2 reducing alternative of implementing renewables with power to heat/gas receives a low score. Despite a low score, this alternative is viewed as very promising since it can produce “green” hydrogen. The electricity produced by renewables is converted into hydrogen by power-to-gas. This renewable hydrogen can then be used within Dutch refineries. However, due to the fact that no data is available on hydrogen producing processes it is not included within the overview. Renewables with power-to-gas therefore partially fall outside the scope of this research and receive a lower score.

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Appendices

Appendix A - Refining processes within the Dutch sector

Section 3.1 described the complexity of Dutch refineries and made a distinction between four general types. It furthermore identified the different processes that are present within the six Dutch refineries. This appendix will explain the refining processes that are present within the Dutch refining industry into more detail. The processes will be split up into 4 sections starting with a more extensive explanation of the atmospheric an vacuum distillation units. Then the processes related to the light distillates are described, followed by the middle and heavy distillates.

Atmospheric and vacuum distillation

The first processing step in the refinery is distillation. Every Dutch refinery has a crude distillation unit. By distilling the crude oil it is separated into a number of fractions. The incoming crude oil is first preheated by heat exchangers that obtain their heat from other streams and desalted before heated even further by more heat exchangers. After the preheating it is led into a fuel-fired furnace. This furnace reaches a temperature of around 450 degrees Celsius at the bottom of the unit to prevent cracking (Parkash, 2003). If temperatures are too high and cracking does occur, petroleum coke is formed. The formation of coke could result in an obstruction of the pipes (Treese et al., 2015). Refining products are created by using the different boiling points of the fractions that arise from heating the crude oil. The liquids leaving the distillation unit still contain some distillate components which are recovered by stream stripping. Gasses that originate from the crude oil are captured at the top of the column. Light and heavy naphtha, kerosene, middle distillates, and gas oil are further processed in other units of the refinery (Fahim et al., 2010). At the bottom of the distillation column reduced crude is discharged from the column and directed to the vacuum distillation tower.

All Dutch refineries except for the Koch refinery are equipped with such a unit. In this vacuum distillation tower the reduced crude is distilled under very low pressure which causes the evaporation of even the most volatile liquids (Treese et al., 2015). It operates at a minimum practical vacuum but the precise conditions depend on the cracking and the required product quality (Parkash, 2003). Generally the objectives of this column is to extract vacuum gas oil from the reduced crude. This vacuum gas oil becomes feedstock for other processes within the refinery. The vacuum distillation unit also leaves a residue which can be used for the production of asphalt or is mixed with other products to produce fuel oil (Fahim et al., 2010).

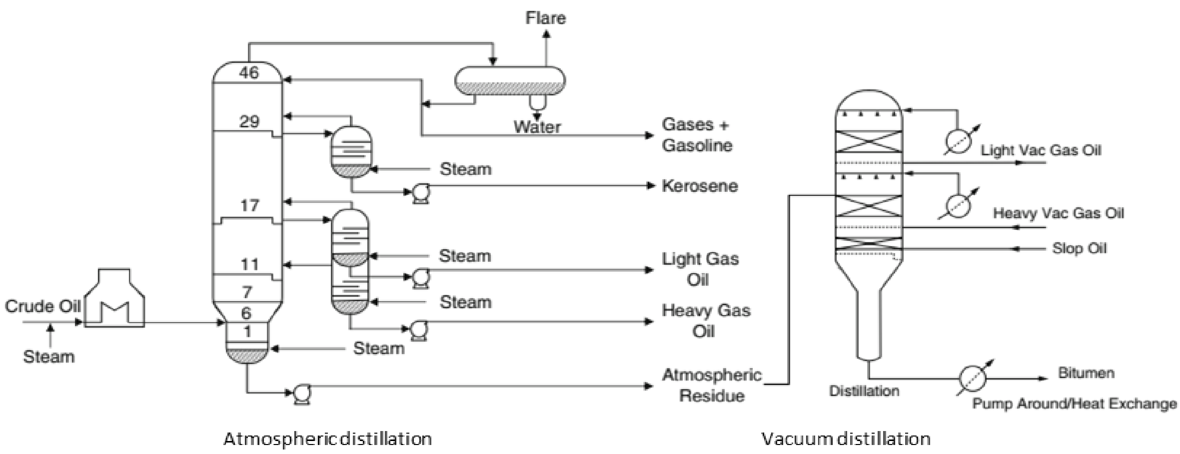

Figure 1 - Atmospheric and vacuum distillation column (Treese et al., 2015 ; Fahim et al., 2010)

Processes light distillates

After the crude distillation unit has separated the crude oil into different fractions the lightest fractions are captured at the top of the unit. To enhance these light fractions they can be alkalized by the alkylation unit. This is quite a complex process and the only two refineries that have such a unit are the Shell Pernis and BP refinery. Figure 2 shows the treatment processes that the light distillates can undergo when they leave the top of the distillation column.

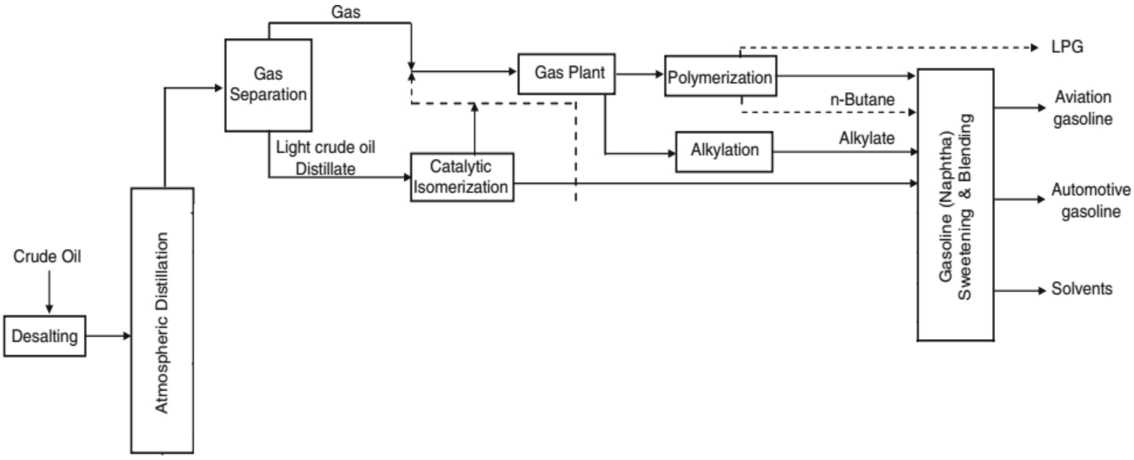

Figure 2 - Processes related to the light distillates (Fahim et al., 2010)

Alkylation

In order to upgrade the lightest fractions produced by the distillation of crude oil two processes can be used. The first process is called catalytic isomerization and processes low octane number hydrocarbons into higher octane number products. An advantage of this process is that is separates hexane before it enters the reformer and thus prevents it from turning into benzene. The catalyst in the isomerization process is a Pt-zeolite base (Fahim et al., 2010). After the catalytic isomerization products are led to an alkylation unit. These products are then combined with lights gasses from the distillation unit and products (isobutanes) from the FCC. In this unit reactions take place between the feedstocks to form gasoline range alkylates (Treese et al., 2015). The catalysts are sulphuric or hydrofluoric acid which react with the hydrocarbons.

Product blending

The products that leave the alkylation unit are still not entirely finished. After the alkylation process the fractions are directed to a blending unit. However, blending is not exclusively related to the alkylation process but is also applied after many other processes. It is a necessary final step in the refining process because blending produces the commercially usable products that meet demand specifications (Fahim et al., 2010). This process is therefore not only applied to the light distillates but also to the middle and heavy distillates. Commercial grade products such as gasoline, kerosene, diesel and fuel oils are formed by the blending process. Their quality is always checked by a laboratory before products are sent to the market. So are for example gasolines tested for their octane number and gas oils for their diesel index. The products that leave the alkylation unit are quite light and are therefore added to the gasoline blending mix

Processes middle distillates

Most of processes that take place within refineries are related to the treatment of middle distillates. Figure 3 gives a visualisation of these processes. Within the Dutch refining industry catalytic reforming and hydrotreating are the most common, present in all refineries except the Koch refinery. These processes will therefore be described first. Hydrocracking and fluid catalytic cracking units are also present within the sector. However, only the Shell Pernis and BP refineries have an FCC unit to their disposal. A Hydrocracker can be found at both the ExxonMobil and Shell Pernis refinery.

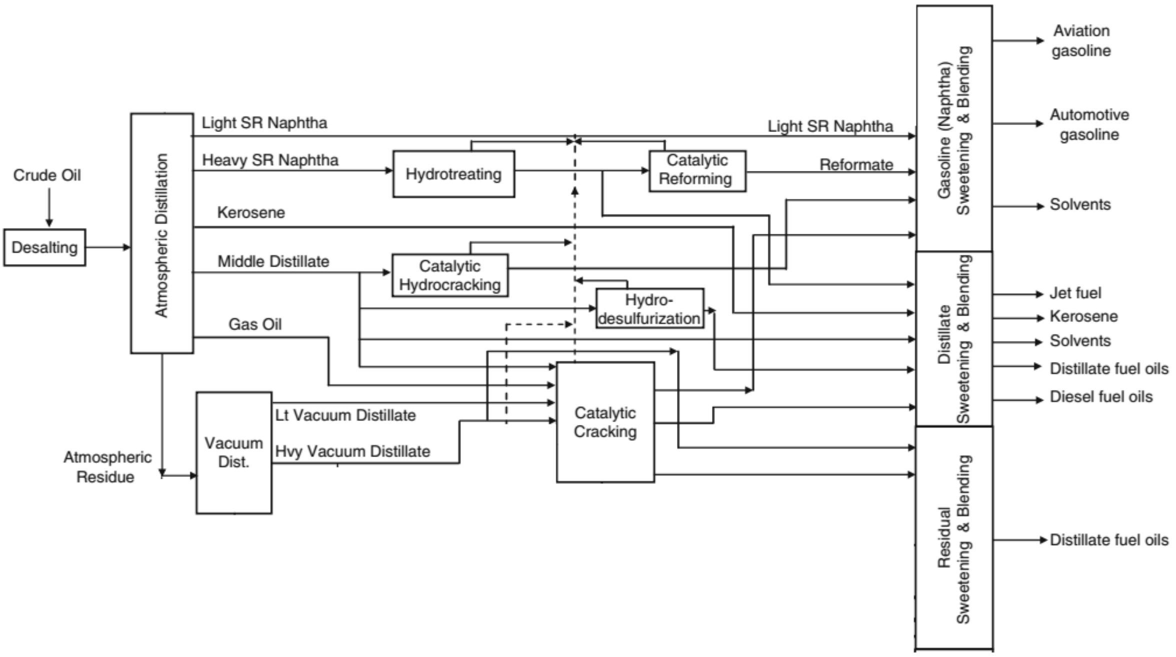

Figure 3 - Processes related to the middle distillates (Fahim et al., 2010)

Hydrotreating

The streams that leave the distillation units often contain impurities, such as sulphur, nitrogen, oxygen or some forms of metals. Of these impurities sulphur is by far the most common. Unfortunately this is also the least tolerable impurity because its presence lowers the quality of the finished products and negatively effects the performance of refining processes (Treese et al., 2015). Sulphur can be removed from the distillate by hydrotreating. This process lets hydrogen react with the sulphur molecules to forms hydrogen sulphide which can be removed as a gas. Hydrotreating is also used for removing other impurities by using different catalysts. So is Cobalt used for desulfurizing and Nickel for denitrification (Parkash, 2003). The most common hydrotreaters within a refinery use naphtha and gas oil as feedstock (Fahim et al., 2010). Processes take place at relatively high temperatures but moderate pressures.

Catalytic reforming

After the impurities are removed from the naphtha by hydrotreatment it is sent to a catalytic reforming unit. Within this unit a chemical process takes place that transforms hydrocarbons (paraffins) with low octane numbers to aromatics and iso-paraffins with high octane numbers (Fahim et al., 2010). These products are called reformates. Within the process naphtha comes in contact with a catalyst at increased temperatures and pressures (Treese et al., 2015). By-products such as Hydrogen and other light hydrocarbons are produced in the process and can be used in other processes within the refinery. Catalytic reforming is a highly endothermic process and therefore requires large amounts of energy.

Catalytic reforming can serve two purposes. First of all, produced high-octane reformates are key components for the production on gasoline. As a result it is one of the most important units for the production of gasoline in refineries and it can produce up to 37% of the total gasoline pool (Fahim et al., 2010). In addition to being a key component for gasoline productions, reformates are also the main source of aromatics such as benzene, toluene and xylene. These aromatics have different uses but for the most part they serve as the materials which are converted into plastics.

Catalytic hydrocracking

Hydrocracking is in most cases applied to upgrade the heavier fractions that are produced after the distillation of crude oil. Cracking is a process in which complex high weight molecules, such as long chain hydrocarbons, are broken down into smaller and lighter parts. Hydrocracking achieves this by adding hydrogen gas. In the hydrocracker hydrogen is added to break the bonds between the carbon atoms (Treese et al., 2015). It is therefore different from a hydrotreater which uses hydrogen so separate the bond between carbon and sulphur atoms. The main feedstock for this process are gas oils which are typically heavy molecules.

Since hydrocracking is one of the main conversion processes in a refinery it plays an important role. It produces highly saturated fractions with lower boiling point. LPG, jet fuels, diesel fuels, lubrication oil and reformer feedstock are all possibilities (Treese et al., 2015). Catalytic hydrocracking uses a catalyst that is composed out of two parts, namely a metallic part and an acid part. The metallic part positively affects hydrogenation which removes the impurities such as sulphur, nitrogen and metals. Cracking is promoted by the acid part of the Catalyst. (Fahim et al., 2010). They can be operated in three possible modes, namely single-stage operation, single-stage operation with partial or total recycling, and two-stage operation (Parkash, 2003).

Fluid catalytic cracking

The process which represents the heart of the refinery is the fluidised catalytic cracking unit. This unit upgrades the heavy low-value fractions like gas oil and vacuum distillates into higher value products. These are in most cases gasoline, distillate fuel oil, LPG, and olefins. The cracking is achieved at high temperatures and while a powdered zeolite catalyst is added to the process (Parkash, 2003). Unlike the hydrocracking unit no hydrogen is used within this process. Before FCC was used the cracking of petroleum hydrocarbons was achieved by thermal cracking. The replacement took place because FCC produces more gasoline and this gasoline also has an higher octane level. Furthermore its by-products are more olefinic and therefore more valuable.

Impurities in the feedstock affect the yield and quality of the product. It also influence the amount of catalyst that is needed within the unit. If the feedstock contains high values of sulphur this is also reflected in the product. The sulphur distributions vary widely and cannot be controlled by altering the design of the process (Parkash, 2003). However , the yield of the product is mostly affected by nitrogen compounds because they temporarily deactivate the catalyst. This can be counteracted by increasing the process' temperature. In order to remove the containments and improve the cracking yields the catalyst must be protected. This can be achieved by different forms of feedstock pre-treatment Since the FCC is the heart of the refinery new processes (reactor design and catalysts) have been developed recently. The yield is improved, emissions are better controlled and it is adaptable for different qualities of crudes (Fahim et al., 2010)

Hydrogen production

The hydrotreatment and hydrocracking units within the refineries require substantial amounts of hydrogen. Using hydrogen is especially useful to meet environmental requirement because it removes impurities from the product (Parkash, 2003). If a refinery contains a catalytic reforming unit, in most cases, this unit is able to produce enough hydrogen to suffice the demand of the refinery. However, more complex refineries such as cracking refineries require incremental hydrogen (Treese et al., 2015). Most refineries do not produce this hydrogen themselves but acquire it from a second party who is specialized in making hydrogen. This implies that the refinery is not directly responsible for the hydrogen plant operations. Such companies are typically common in areas where the hydrogen can be used by multiple facilities like the port of Rotterdam. Air Products is a company in the port of Rotterdam that supplies the refineries of their hydrogen (Port of Rotterdam, 2016). Some processes that can be used for the making of hydrogen are: steam-methane reforming, electrolytic hydrogen and refinery gas recovery (Fahim et al., 2010).

Processes heavy distillates

From the bottom of the crude distillation unit the atmospheric residue is captured and further processed. A large part is led to the vacuum distillation unit were it is broken up into light and heavy gas oils. The distilled fractions are again led to the FCC but the heavy distillates are also used as lube feedstock. After solvent extraction and dewaxing the lube feedstock is converted into lubricants and waxes. Vacuum residues can undergo several treatments to upgrade it into higher value fractions. Coking, visbreaking or thermal cracking are possible processes that can upgrade these residues (Treese et al., 2015). Within the Dutch refining industry four refineries have such units at their disposal. A thermal cracker is present at the Shell and Gunvor refinery while the latter also has a visbreaking unit at its disposal. The BP refinery also features a visbreaker and the ExxonMobil refinery is the only one that has an flexicoker included in its configuration (Port of Rotterdam, 2016).

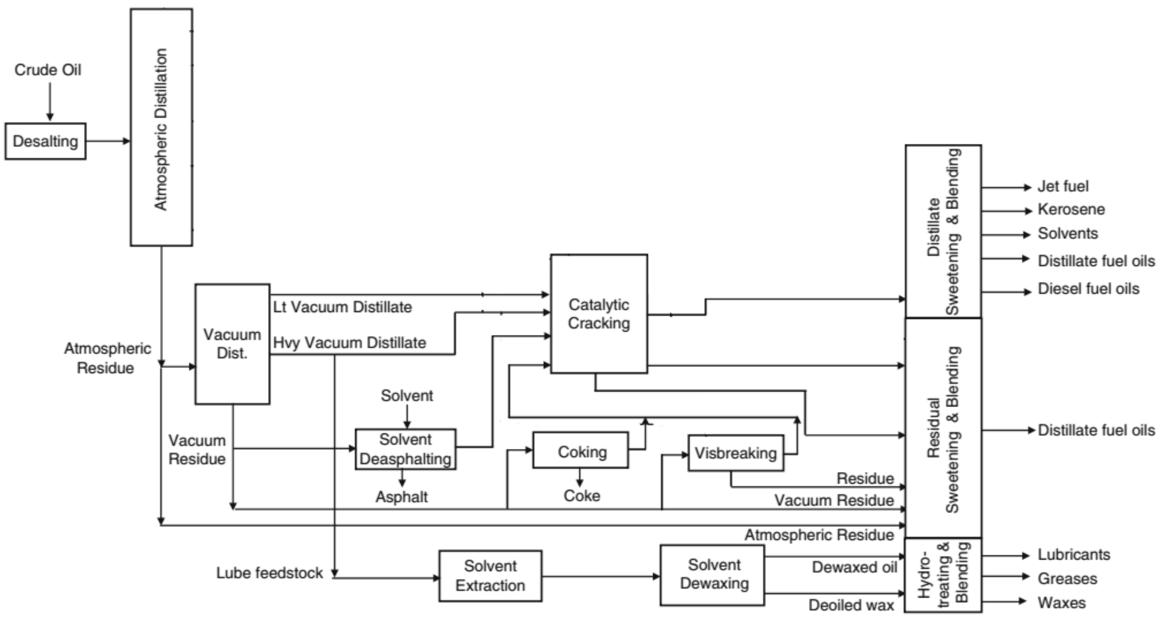

Figure 4 - processes related to the heavy distillates (Fahim et al., 2010)

Thermal chemical conversion

Thermal chemical conversion can be divided into three categories: thermal cracking, visbreaking and cokers. These processes convert heavy and invaluable fractions such as residues and fuel oil, into lighter and higher value products. Thermal crackers are in most cases used to convert atmospheric residues in lighter products. It is a different process than visbreaking due to differentiation on the type of feedstock and the severity of cracking (Treese et al., 2015). Visbreaking is a relatively mild thermal cracking process which is used to break down the vacuum residue so that is can be used in further refining processes. The objective of visbreaking is to reduce the quantity of produced residual oil and increase the production of middle distillates. Its name implies that the viscosity of the residue is lowered (Treese et al., 2015). It produces light products and 75–85% cracked materials with a low viscosity that can be used as fuel oil (Fahim et al., 2010).

Coking is the most extreme form of thermal cracking. It uses residue feeds from the vacuum distillation tower. All feedstock is converted into light ends and coke, no fuel oil remains behind. Coking processes can be classified in two commonly used types, namely delayed coking and flexicoking (Treese et al., 2015). Delayed coking is the thermal cracking of the vacuum residue from crude distillation. In a furnace the residue is heated and flashed into large drums. This creates coke deposits on the walls of the drums (Fahim et al., 2010). Besides coke also lighter products are produced such as gas, gasoline and gas oils. Separation takes place by distillation. The process is an endothermic reaction and the furnace provide the heat for the coking reactions (Parkash, 2003). Flexicoking is a thermal process that uses steam and air to gasify coke into fuel gas. This process converts the coke into gases, gasoline and gas oils while producing very little coke (only 2%). Such a small amount of coke is produced because the coke is used to heat the feedstock.

Solvent deasphalting, extraction and dewaxing

The port of Rotterdam does not report the presence of any solvent deasphalting, extraction or dewaxing units within the Dutch refinery sector. Due to their importance in the processing of the heaviest residues they will be shortly discussed. Solvent Deasphalting uses heavy petroleum fractions like vacuum residue to produce asphalt. This is the only process within the refinery were carbon is rejected (Parkash, 2003). Solvent deasphalting is also used to prepared feedstock for the catalytic crackers because deasphalted oil is easily processed by catalytic units. This is in contrast to the vacuum residue which is very difficult to process in catalytic units. Solvent extraction uses lube oil feedstock from the vacuum distillation tower and treats this with a solvent. In the first phase of the process the solvent dissolves the aromatic components in the feedstock. The second phase removes the remaining oil from the raffinate (Fahim et al., 2010). After the solvent is removed the raffinate is dewaxed. Solvent dewaxing dissolves the raffinate again by using another solvent. Then the solution is gradually decreased in temperature which make the high weight paraffin molecules crystallize, creating wax. The remaining solution is filtered and this dewaxed oil is used as lube oil.

Appendix B - Allocating the CO_2 emissions of Dutch refineries to their processes

Before the CO_2 emissions of Dutch refineries can be allocated to their individual processes it is important to first identify the different processes present within the Dutch refining industry. However, due to the limited amount of publically available data it is impossible to construct a complete overview of all processes present within the Dutch refining industry. Such detailed information is unfortunately not available. As a result, not all processes described in the refining handbooks are included within the overview of processes located in Dutch refineries. Only the processes on which data is available are included. The overview of Dutch refining processes was constructed using publically available data retrieved from Port of Rotterdam (2016) and A Barrel Full (2015). A incomplete overview of refining processes will also have consequences for the allocation of CO_2 emissions to the processes of Dutch refineries. In reality additional processes are present which also emit CO_2. However, since no data with regard to these processes is publically available they are not included. This results in differences between the calculated and actual CO_2 emissions of Dutch refineries. The allocated CO_2 emissions to the processes are therefore not exact but do provide a basic understanding of the processes that emit the most amount of CO_2 within Dutch refineries.

Table 1 - Overview of refining processes allocated to the Dutch refineries (Port of Rotterdam, 2016 and a barrel full, 2015)

	Shell	ExxonMobil	BP	Gunvor	Koch	Zeeland
Atmospheric distillation	X	X	X	X	X	X
Vacuum distillation	X	X	X	X		X
Catalytic reforming	X	X	X	X		X
Alkylation	X		X			
Fluid-bed catalytic cracker	X		X			
Hydrocracker	X	X				X
Hydrotreater	X	X	X	X		X
Thermal cracker	X			X		
Visbreaker			X	X		
Flexicoker		X				

Despite the limited available data with regard to the processes present within the Dutch refining industry it aims to allocate the CO_2 emissions at the refinery process level. The foundation for this method is the benchmark study of the European Union (EU, 2011). This study uses an CO_2 weighted ton (CWT) approach to compare the different processes within a refinery with regard to their CO_2 emissions. By doing so, the different configurations of Dutch refineries can be taken into account. The CWT approach compares all refining processes with the atmospheric distillation column and assigns them with a CWT-factor that represents their CO_2 emissions relative to the atmospheric distillation column. The column is assigned CWT-factor 1 and if a process emits more CO_2 per unit of crude oil it receives a higher value and vice versa. Table .. presents all CWT-factor for the processes that are present within the Dutch refining industry. From table .. it becomes clear that all processes except the vacuum distillation unit emit more CO_2 per unit of processed product than the atmospheric distillation column.

Table 2 - CWT-factors of processes within Refineries (EU, 2011)

Refinery process	CWT-factor
Atmospheric distillation unit	1
Vacuum distillation unit	0,85
Catalytic reforming	4,95
Alkylation	7,25
FCC	5,5
Hydrocracking	2,85
Hydrotreatment	1,1
Visbreaking	1,4
Thermal cracking	2,7
Flexicoking	16,6

Besides the CWT-factor, the allocation of CO_2 emissions is also dependent of the amount of product that is processed by the unit. This information is hard to obtain since almost no data is publically available. Nevertheless the Port of Rotterdam (2016) provides some key statistics about the refineries located in the Rotterdam harbour. For data on the Zeeland refinery van den Berg et al. (2016) and a barrel full (2015) were consulted. These sources made it able to map the amount of product that is processed by each unit within the Dutch refining industry. Table .. presents this data in Megaton per year. As a result of the limited availability of publically available data a remark has to be placed with regard to this data. This data only contains the most important processes implying that not all processes located within the Dutch refining sector are present in table .. consequently the accuracy of the CO_2 allocation somewhat decreases but it is still useful in order to indicate the processes that emit the most CO_2.

Table 3 - Throughput of different refining processes (Port of Rotterdam, 2016 ; a barrel full, 2015)

	Throughput in Mt/y					
	Shell	ExxonMobil	BP	Gunvor	Koch	Zeeland
Atmospheric distillation	21.0	9.1	20.0	4.5	3.5	7.5
Vacuum distillation	8.0	4.5	4.9	2.4		3.0
Catalytic reforming	1.8	1.2	1.2	1.0		1.3
Alkylation	0.3		0.33			
FCC unit	2.6		3.5			
Hydrocracker	2.6	2.1				3.4
Hydrotreater						2.4
Thermal cracker	2.7			0.53		
Visbreaker			2.1	0.48		
Flexicoker		2.2				

The amount of product that is processed by each unit forms the basis of the CWT approach. In order to determine the CO_2 emissions of refineries using the CWT-factors, the following formula can be used to calculate the (EU, 2011):

$$HAL_{CWT} = \left(1.0183 * \sum_{i=1}^{n}(TP_i * CWT_i) + 298 + (0.315 * TP_{ad})\right)$$

In which:

HAL_{CWT} = activity level of a refinery expressed in CWT,
TP_i = throughput of process i in Kton/y
CWT_i = CWT-factor of process i
TP_{ad} = throughput of atmospheric distillation column in Kton/y

So to calculate the activity level of a refinery the first step is to multiply the throughput of every process by its CWT-factor and add them all together. The HAL_{CWT} can be calculated by multiplying this number by 1.0183 and then the constants depending on the throughput of the atmospheric distillation column can be added. When the HAL_{CWT} is calculated it does not yet represent the CO_2 emissions of a refinery. To determine the actual CO_2 emissions of the refinery a second formula needs to be applied:

$$CO2emissions\ refinery = HAL_{CWT} * sectorbenchmarkvalue$$

Where the $sectorbenchmarkvalue$ equals 0,0295 for the refining sector.

This leads to the following CO_2 emissions of Dutch refineries.

Table 4 - Calculated CO2 emissions vs actually emitted CO_2 (ETS, 2015)

Dutch refineries	Calculated CO_2 emissions (Mton)	Actual CO_2 emissions (Mton)
Shell Pernis	2.2	4.3
ExxonMobil	1.9	2.3
BP	1.8	2.3
Gunvor	0.5	0.6
Koch	0.1	0.1
Zeeland	0.9	1.5

To allocate CO_2 emissions to individual processes the formula needs to be analysed into more detail. The formula can be divided into two parts, emissions dependent on the different processes and a constant that depends on the throughput of the atmospheric distillation column.

$$\sum_{i=1}^{n}(TP_i * \ CWT_i) \ and \ 298 + (0.315 * TP_{ad})$$

The first part is crucial for the allocation of CO_2 emissions to the individual processes. By applying the first part of the formula on only one process and multiplying it by the refining sector benchmark the CO_2 emissions of induvial processes can be calculated. Table .. presents the CO_2 emissions of the individual processes within Dutch refineries while table .. presents the contribution of all the different processes to the total CO_2 emissions of the refineries in percentages.

Table 5 - CO_2 emissions per refining process in Kton

CO_2 emissions per process (Kton)						
	Shell	**ExxonMobil**	**BP**	**Gunvor**	**Koch**	**Zeeland**
Atmospheric distillation	631	273	601	135	105	224
Vacuum distillation	204	115	125	61		76
Catalytic reforming	268	178	178	149		195
Alkylation	65		72			
FCC unit	430		578			
Hydrocracker	223	180				290
Hydrotreater						79
Thermal cracker	219			43		
Visbreaker			88	20		
Flexicoker		1097				

Table 6 - CO_2 emissions in percentage of total per Dutch refinery

CO_2 emissions per process (percentage of total)						
	Shell	**ExxonMobil**	**BP**	**Gunvor**	**Koch**	**Zeeland**
Atmospheric distillation	28%	14%	33%	29%	72%	24%
Vacuum distillation	9%	6%	7%	13%		8%
Catalytic reforming	12%	9%	10%	32%		21%
Alkylation	3%		4%			
FCC unit	19%		31%			
Hydrocracker	10%	9%				31%
Hydrotreater						8%
Thermal cracker	10%			9%		
Visbreaker			5%	4%		
Flexicoker		57%				

Appendix C - Crude oil intake and product slate of the Dutch refineries

The CO_2 emissions of Dutch refineries are dependent on the crude oil intake and the product slate of refineries. Many different types of crude oil are produced all around the world. Each one of these crude oils has its own characteristics and properties. These characteristics affect the required complexity of refineries and thereby the number of processes needed to convert the crude oil into useful products. As a result the CO_2 emissions of Dutch refineries are also dependent on the crude oil intake. Another factor that influences the CO_2 emissions of Dutch refineries is their product slate. Refineries produce a wide variety of useful products from crude oil. Some of these products require few conversion steps while others require a lot of additional treatment. In turn, the product slate of Dutch refineries is mainly determined by the demand for transport fuels. Appendix C contains the necessary analysis that are performed to determine the influence of the crude oil intake and product slate of Dutch refineries on their CO_2 emissions.

Crude oil characteristics

The density of crude oil ranges from light to heavy and is reflected by the American Petroleum Institute gravity (API gravity). This API gravity measures the weight of petroleum liquids compared to water. If the API gravity exceeds 10 it is lighter than water and floats. An API gravity less than 10 means that the petroleum liquid is heavier than water and sinks. The API gravity is in most cases used to compare the densities of different petroleum liquids. If a certain crude oil has a greater API gravity it means that it is less dense than another petroleum product.

The formula to calculate API gravity from Specific Gravity (SG) is:

$$API\ gravity = \frac{141.5}{SG} - 131.5$$

According to this API gravity crude oils can be classified as light (high API) or heavy (low API).

Light crude oils are petroleum products that are characterized by high API gravities an thus a low density. Due to the presence of high proportions of light hydrocarbon fractions other properties of light crude oils are a low viscosity and a low specific gravity. Light crude oil produce a higher percentage of gasoline and diesel fuel when they are converted by refineries (Jacobs, 2012). They furthermore require less additional processes and have a low wax content. This results in a high price for light crude oils on the commodity market (Fattouh, 2010).

Heavy crude oils are petroleum products that are, unlike light crude oils, characterized by a low API gravity and have a high density. Crude oils are classified as “heavy” when their API gravity is less than 20. Compared to light crude oils, heavy crude oils have different physical properties such as a heavier molecular composition as well as a higher viscosity and specific gravity. Due to their high viscosity, heavy crude oils do flow easily under normal conditions. These properties of heavy crude oil result in extra challenges with regard to its production, transportation and refining when compared to light crude oil (Davids, 2012). As a result the refining costs for processing heavy crude oil are higher compared with light crude oil. Despite the extra challenges and costs related to refining heavy crude oils they can be an interesting option for refineries. This is in the first place due to the fact that heavy crudes are often priced at a discount compared to lighter crude oils (Fattouh, 2010). It is furthermore estimated that the resources of heavy oil in the world are more than twice those of conventional light crude oil (Faergestad, 2016).

Crude oil containing sulphur content is characterized as sweet or sour. Sour crude oil contains a high amount of sulphur while sweet crude oil contains little sulphur impurities. If the total level of sulphur in a crude oil exceeds 0.5% it is characterized as sour (Gulen, 1999). Sulphur impurities have to be removed within the refineries in order for the crude oil to be converted into transport fuels. Hydrotreatment and hydrocracking are processes within refineries that remove the sulphur impurities (Treese et al., 2015). Sour crude oil therefore require additional processing which increases refining costs. They are therefore often priced at a discount compared to sweet crude oils since the latter requires less additional processing (Fattouh, 2010).

Crude oil intake

The core function of the Dutch refining industry is the production of useful products from crude oil (Treese et al., 2015). However, crude oil is not an homogenous products and the different types of crude oil all have their own characteristics and properties. These properties of crude oils have consequences for the required complexity of refineries and the number of different energy intensive processes they need to apply. As a result the properties of crude oils might also have an effects on the CO_2 emissions of the Dutch refining industry. Section 4.1 concluded that the API gravity and the sulphur content appeared to have the most influence on the CO_2 emissions of refineries. Since these properties differ per type of crude oil it is necessary to first explore the different types of crude oils that are used by Dutch refineries. Each oil producing country has its own type of crude oil or in some cases even multiple different types. So in order to explore the different types of crude oils that Dutch refineries use, the countries that supply crude oil to the Netherlands have to be mapped. In 2015 the Netherlands imported a total of 62 million tons of crude oil (CBS, 2015). Table .. lists the countries that supply the Netherlands with crude oil along with the corresponding quantities.

Table 7 - Overview of all the countries that supplies crude oil to the Netherlands (CBS, 2015)

Countries	Crude oil import (tons)	Countries	Crude oil import (tons)
Wereld	6,196E+10	Letland	26102
Afghanistan		Libanon	100
Albanië	3	Libië (Arabische Republiek)	90407073
Algerije	1,32E+09	Litouwen	6418
Andorra	1	Luxemburg	42825
Antigua en Barbuda	3	Macedonië	223
Argentinië	1194	Madagaskar	26
Aruba	24	Malawi	2
Australië	1097	Maleisië	4893
Azerbeidzjan	7	Mali	30
Bahrein	26	Malta	665
Bangladesh	899	Marokko	412
België	86243452	Mauritius	181
Benin	3	Mexico	652778274
Bhutan	13	Moldavië	19
Birma	11	Montenegro	2
Bolivia	83	Mozambique	8
Bosnië-Herzegovina	25	Namibië	262

Britse Maagdeneilanden	64	Nepal	41
Brunei Darussalam	18	Nicaragua	56
Bulgarije	5752	Niet nader aangegeven landen binnen EU	94
Burkina Faso	22	Niet nader bepaald derde land	463
Cambodja	130	Niet nader bepaalde lidstaat	2246
Canada	36472508	Nieuw-Zeeland	1235
Caribisch Nederland	2	Nigeria	7,708E+09
Chili	1396	Noorwegen	1,184E+10
China (Volksrepubliek)	39634	Oeganda	131
Colombia	163905420	Oekraïne	907
Congo	36	Oman	87
Costa Rica	1041	Oostenrijk	33217
Cuba	124	Pakistan	730
Curaçao	4	Panama	306
Cyprus	546	Papoea-Nieuw-Guinea	5
Denemarken	914777160	Paraguay	63
Dominicaanse Republiek	812	Peru	1111
Duitsland	135948151	Polen	73931
Ecuador	616	Portugal	15894
Egypte	134841323	Qatar	101219648
Estland	3695	Roemenië	10223
Ethiopië	158	Russische Federatie	1,707E+10
Faeröereilanden	67	Saoedi-Arabië	2,087E+09
Filipijnen	948	Senegal	1252
Finland	40238	Servië	301
Frankrijk	3840997	Sierra Leone	7
Gabon	583209007	Singapore	1731
Gambia	5	Slovenië	21086
Gebied onder Palestijnse autoriteit	1	Slowakije	5245
Georgië	6	Soedan	4
Ghana	56	Spanje	63729
Griekenland	5714	Sri Lanka	250
Guatemala	39679214	Suriname	48
Guinee-Bissau		Swaziland	10
Guyana	43	Syrië (Arabische Republiek)	1
Honduras	18	Taiwan	5807
Hongarije	10696	Tanzania (Verenigde Republiek)	70
Hongkong	3369	Thailand	3173
Ierland	24676	Togo	66
IJsland	1103	Trinidad en Tobago	23598011
India	6168	Tsjechië (Republiek)	18296
Indonesië	2893	Tunesië	332
Irak	5,19E+09	Turkije	6981

Iran (Islamitische Republiek)	54	Turkmenistan	10
Israël	1713	Uruguay	346
Italië	58931613	Venezuela	22063017
Ivoorkust	105753146	Verenigd Koninkrijk	5,671E+09
Japan	8647	Verenigde Arabische Emiraten	271169795
Jemen	9	Verenigde Staten van Amerika	40382
Jordanië	167	Vietnam	1532
Kameroen	70	Wit-Rusland	601
Kazachstan	31	Zambia	212
Kenia	1588	Zeegebied buiten de territoriale wateren	100
Koeweit	5,715E+09	Zimbabwe	143
Korea (Republiek)	3091	Zuid-Afrika	2161
Kroatië	2983	Zweden	49402
Laos (Democratische Volksrepubliek)	7	Zwitserland	5424

The most important countries that supplied crude oil to the Netherlands in 2015 are visualized in figure 5.

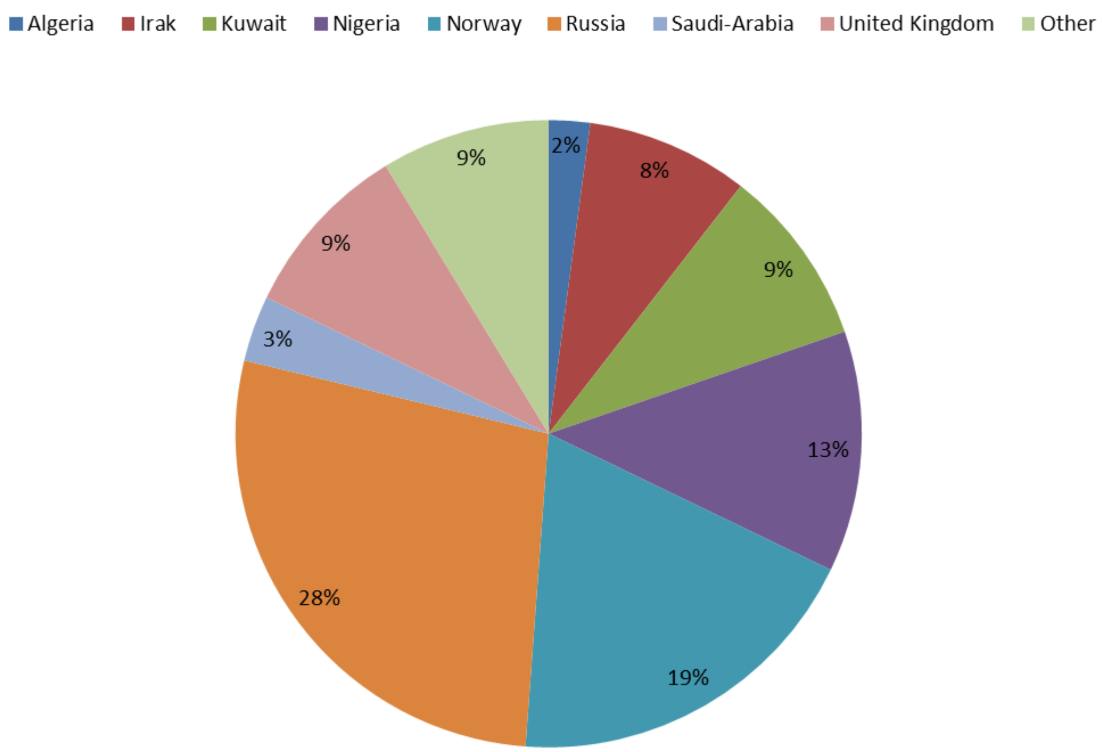

Figure 5 - Share of crude oil imported by the Netherlands

From figure 5 it can be concluded that Russia and Norway are by far the largest suppliers of crude oil to the Netherlands. Nigeria, Kuwait and the United Kingdom also supply substantial amounts of crude oil.

Now that the suppliers of crude oil to the Dutch refining industry are known the types of crude oil can be determined. Each oil producing country has its own type of crude oil or sometimes even more than one depending on the amount of oil sources. These types of crude oil all have their own specific properties. For each country their most common and most produced crude oil type is selected. Figure 6 gives an overview of the most common crude oil types used within Europe (Jacobs, 2012). The most common crude oil types of all large suppliers to the Netherlands except Algeria are included within this overview.

	API Gravity	Sulfur	ConCarbon	C_4-	Naphtha C_5-177°C	Distillate 177-243°C	Heavy Gas Oil 343-550°C	Resid 550 °C+
		wt%	wt%	wt%	wt%	wt%	wt%	wt%
Athabasca	8.1	4.8	12.9	0.0	2.6	11.6	32.0	53.8
Athabasca-PFT	9.4	5.3	9.3	0.0	2.8	12.5	34.3	50.5
Bachaquero	10.7	2.8	12.9	0.0	1.2	15.7	28.7	54.4
Mariner	11.9	1.3	6.6	0.0	0.1	21.8	41.9	36.2
Tupi	29.5	0.4	4.6	1.1	13.5	24.0	26.5	34.9
Arab Medium	31.3	2.5	6.1	1.8	18.3	25.9	23.2	30.9
Bonny Light	31.4	0.2	1.3	0.4	17.2	40.8	29.1	12.4
Urals	32.7	1.3	3.5	2.6	16.4	28.2	26.3	26.5
Sirri	33.1	1.8	3.7	1.5	19.9	29.2	26.2	23.2
Kirkuk Blend	36.7	1.9	4.4	1.7	23.4	30.1	24.1	20.6
Es Sider	37.9	0.4	2.8	2.3	19.9	30.5	26.1	21.2
Ekofisk	38.1	0.2	1.4	1.3	24.0	30.5	26.3	18.0
Forties	42.9	0.5	1.3	2.7	31.5	30.4	21.2	14.2
SCO-Coker	29.5	0.4	0.1	1.5	14.6	32.5	51.1	0.0

Figure 6 - Most common crude oil types within Europe (jacobs, 2012)

Table .. shows the overview of largest crude oil suppliers to the Netherlands. This table also contains Algeria's most common crude oil type, the Saharan Blend. It furthermore contains the API gravity and sulphur content of each type of crude oil.

Table 8 - Crude oil types and characteristics of the largest suppliers to the Netherlands

	Crude name	API	Sulphur
Russia	Urals	32.7	1.3
Norway	Ekofisk	38.1	0.2
Nigeria	Bonny light	31.4	0.2
United Kingdom	Forties	42,9	0.5
Kuweit	Kuweit	32.4	2.6
Irak	Kirkuk blend	36.7	1.9
Saudi-Arabia	Arab medium	31.3	2.5
Algeria	Saharan Blend	43.6	0.1

Product slate of Dutch refineries

Dutch refineries produces useful products from crude oil (Treese et al., 2015). Among these products are naphtha, gasoline, diesel, kerosene, LPG, and gas oil (Speight, 2009). The types of products that are produced by a refinery have consequences for the required complexity of refineries and the number of different energy intensive processes they need to apply. Lighter fraction such as gasoline and diesel for example require more additional processing. As a result the product slate of Dutch refineries also effects their CO_2 emissions (Johansson et al., 2013). To assess the influence of the product slate of Dutch refineries on their CO_2 emissions it is important to first explore the different products produced by Dutch refineries.

Table .. present the outputs of the Dutch refining industry per product for April 2016. It furthermore contains the output per product expressed in a percentage of the total products produced. It seems that the Dutch refining industry mainly produces naphtha, gas/diesel oil and fuel oil. Gasoline and LPG are not produced in large quantities.

Table 9 - Overview of the monthly produced oil products by Dutch refineries (JODI, 2016)

Refinery products	Output (Kb)	Percentage of total output
LPG	1462	3.9%
Naphtha	8597	22.8%
Gasoline	1935	5.1%
Kerosines	5477	14.5%
Gas / Diesel oil	10586	28.1%
Fuel oil	7740	20.5%
Other oil products	1898	5.0%

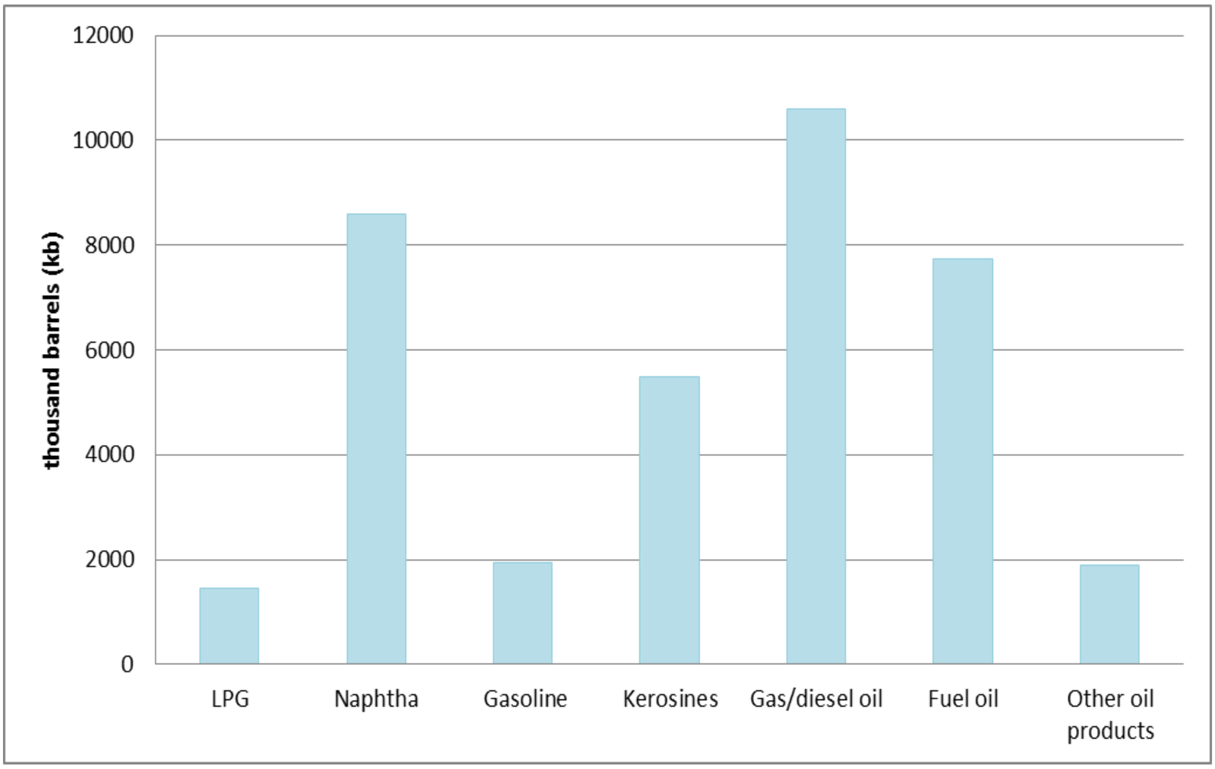

Figure 7 - Output of Dutch refineries in April 2016 (JODI, 2016)

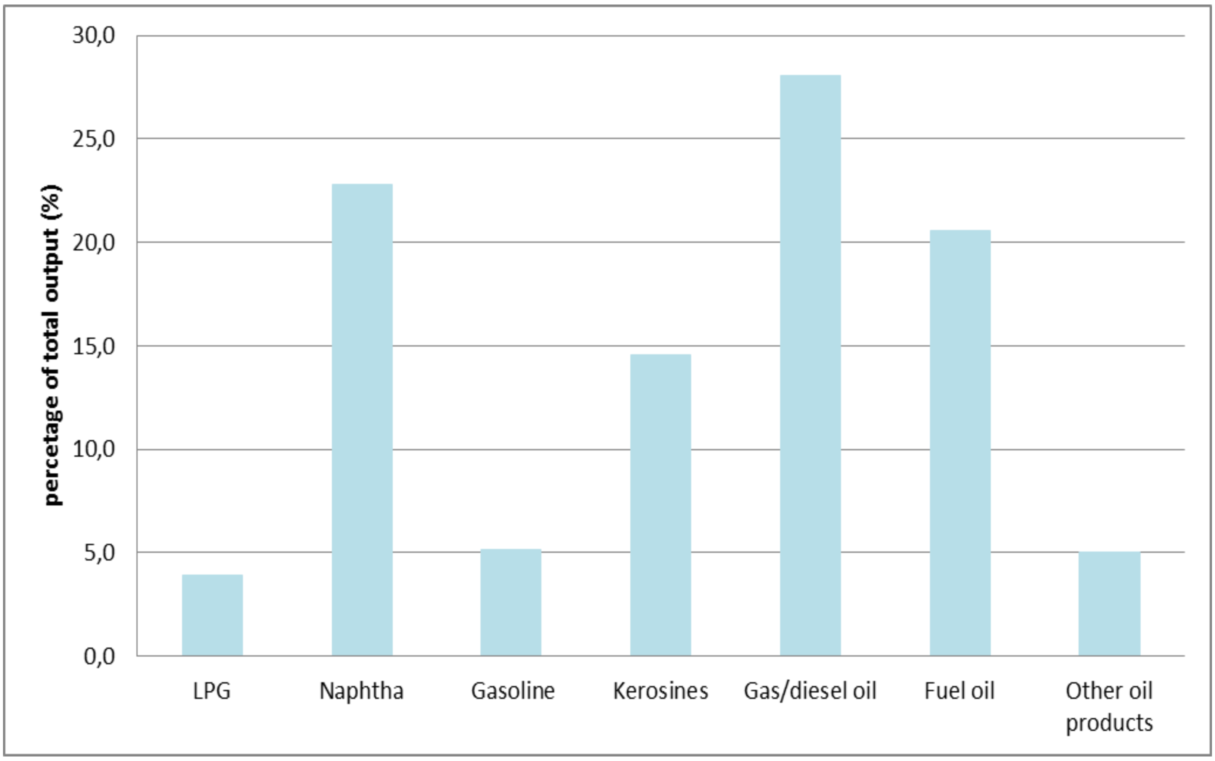

Figure 8 - Output of Dutch refineries in April 2016 expressed as a percentage of the total (JODI, 2016)

If the product slate of Dutch refineries indeed influences their CO_2 emissions it is useful to assess the future demand expectations for refinery products. That way, possible effects on the CO_2 emissions of Dutch refineries towards 2050 can be discussed. Table .. shows the demand expectations for oil products towards 2040 for Europe and the World. Figure .. gives a visual representation of the date presented in table ..

Table 10 - Oil product demand expectations towards 2040 for Europe and the World(OPEC, 2014)

Demand for oil products (Mb/d)							
Europe				world			
	2013	2020	2040		2013	2020	2040
LPG	1,2	1,1	0,9	LPG	10	11	12,6
Naphtha	1,1	1,1	0,9	Naphtha	6	6,6	8,8
Gasoline	2,2	2,1	2,2	Gasoline	23	24,6	26,7
Kerosene	1,2	1,1	1	Kerosene	6,6	7,3	9,2
Diesel	6,2	6,5	5,9	Diesel	26,1	29,7	36,1
Residual fuel	1,2	0,7	0,4	Residual fuel	8	7,1	6
other	1,5	1,4	1,1	other	10,4	10,6	11,8
total	14,5	14,1	12,4	total	90	96,9	111,1

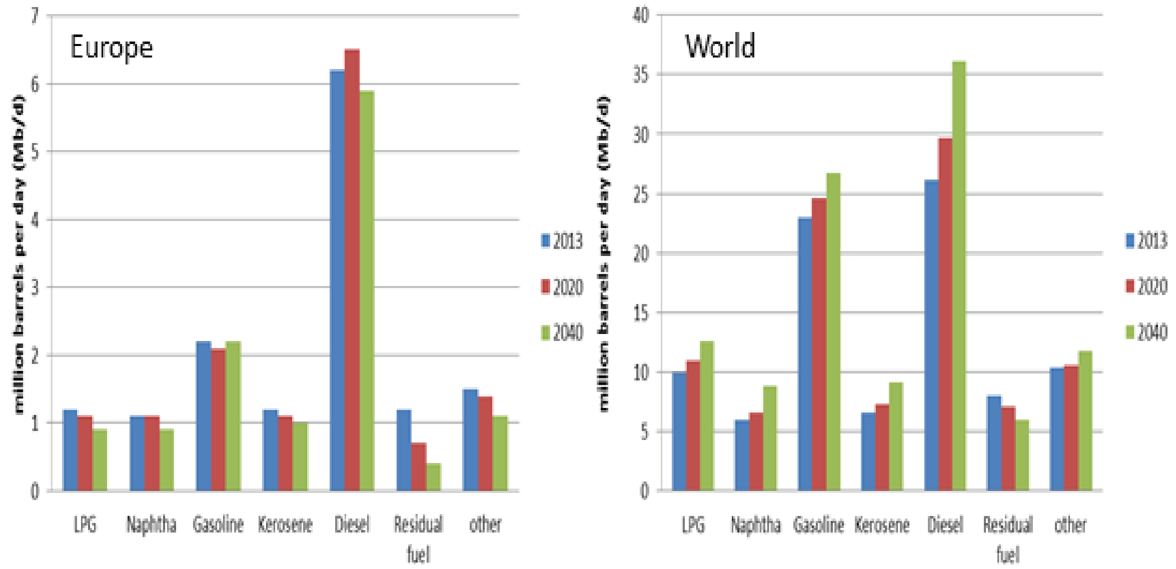

Figure 9 - Oil product demand towards 2040 for Europe and the World (OPEC, 2014)

Figure 9 shows that the oil product demand in Europe decreases for all product types. This is in line with the views of the IEA (2015) whom foresee a structural decline in European oil product demand. Only the demand for gasoline remains almost equal towards 2040. Residual fuel oil shows the largest decline in demand within Europe and decreases by almost two thirds. According to figure 9, the demand for all oil products worldwide, except residual fuel oil, still increases towards 2040. This is again in line with the findings of the IEA (2015). Diesel demand is expected to increase the most worldwide.

Appendix D - An overview of technology assessment

Technology assessment (TA) is a scientific, analytic and democratic practice that aims to contribute to the formation of public and political opinion on societal aspects of science and technology (van Est & Brom, 2012). In other words, TA is the study and evaluation of new technologies. It is based on the idea that technological developments within the scientific community are not only relevant to the experts themselves but also for the world at large. Technology assessment as a term first came into use in the 1960s in the United States (Banta, 2009). In early studies, TA was defined as a form of policy research that examines the short- and long-term consequences of the application of a technology. The main goal of TA is to provide policy makers with information on technology alternatives. According to Grunwald (2009) multiple challenges arise from TA. The first challenge addresses the integration of knowledge on the side effects of technology in early stage decision making. Furthermore, each technology has an value and an impact on its surroundings. Supporting the evaluation of these aspects is the second challenge. The third challenge relates to creating strategies that deal with uncertainties related to the technologies. Finally a challenge arises when societal conflicts, that originate from implementation of new technologies, need constructive solving. TA is characterized by a combination of knowledge production, evaluation of this knowledge and recommendations (Grunwald, 2009). The field of TA is constantly evolving and the next sections provide an overview of the history of TA, the different TA concepts and relevant developments.

History of TA

TA deals with the relationship between technological change an social problems. In the case of this research the developments of CO_2 reducing technologies for the Dutch refining industry and the effects of climate change. The overall philosophy of TA aims at reducing the human costs of trial and error learning when society handles new technologies (Schot & Rip, 1997). It tries to achieve this by anticipating potential impacts of technologies and feeding these insights back into decision making. In summary TA identifies positive and negative effects of technologies so that one can anticipate on these effects. In 1972 TA was institutionalized by the office of technology assessment in the US. The reason behind this institutionalisation was the asymmetrical access to relevant information regarding developments of new technologies between the US's legislative and executive bodies (Grunwald, 2009). This asymmetry endangered the balance of power between the two bodies when technology related issues were discussed. TA was in this case used to restore parity (Bimber, 1996).

Along with the origination of TA came changes in society's view on technology. Its optimistic view on technical developments came under pressure. Side effects of technological progress became more obvious when environmental problems were brought to the attention. Without this questioning of technological progress, TA would have probably never developed beyond the confines of the US congressional office (Grunwald, 2009). Another key development within the field of TA were the legitimization problems that occur when decisions related to technologies have to be made. Legitimacy of technology became an important topic within decision making due to the social conflicts that arose from the negative side effects of technologies. Critical aspects of technological and scientific progress needed to be evaluated within a public arena. This encouraged the development of TA since it focusses on criteria technologies have to comply to instead of the development of technologies itself. In other words, TA does not focus on technology alone but also on its products, processes, systems and societal impacts (Grunwald, 2009).

TA as an answer to societal problems

The changing views of society in the 1960s and 1970s formed the basis for TA and led to a specific profile which is still relevant nowadays. Of course TA is subject to new developments which lead to new requirements. Nevertheless TA can still be used to structurally analyse the new technologies and societal challenges that arise from them. In general, TA can be used as a response to five societal issues. First of all, science and technology have embedded themselves deeper into society. As a result the consequences of current technologies have also increased dramatically (Roco & Bainbridge, 2002). The second societal issue TA addresses are the negative side effects of technologies such as large-scale accidents (Chernobyl) and environmental damage. TA tries to solve a so called precautionary problem by answering the following question: in which way can a society that trusts technical innovation and progress protect itself from their undesirable side effects. By including ethical perspectives within the assessment TA tries to respond to the third societal issue. In the past technologies were seen as value free but recently the normative background of technologies is also recognized (van de Poel, 2001). As a result TA must also concern itself with normative questions which results in a close connection to ethics (Grunwald, 1999). Legitimisation of decisions with regard to the implementation of technologies is the fourth issue TA tries to address. The challenge lies in the fact that decisions have to be acknowledged as legitimate even if they run against the interest of certain parties. TA and particularly participative TA tries to find a solution for this problem. The fifth and final issue is the mismatch between the supply from the scientific world and society's demand. More attention needs to be paid to include economic perspectives within TA (Smits & den Hartog, 2007).

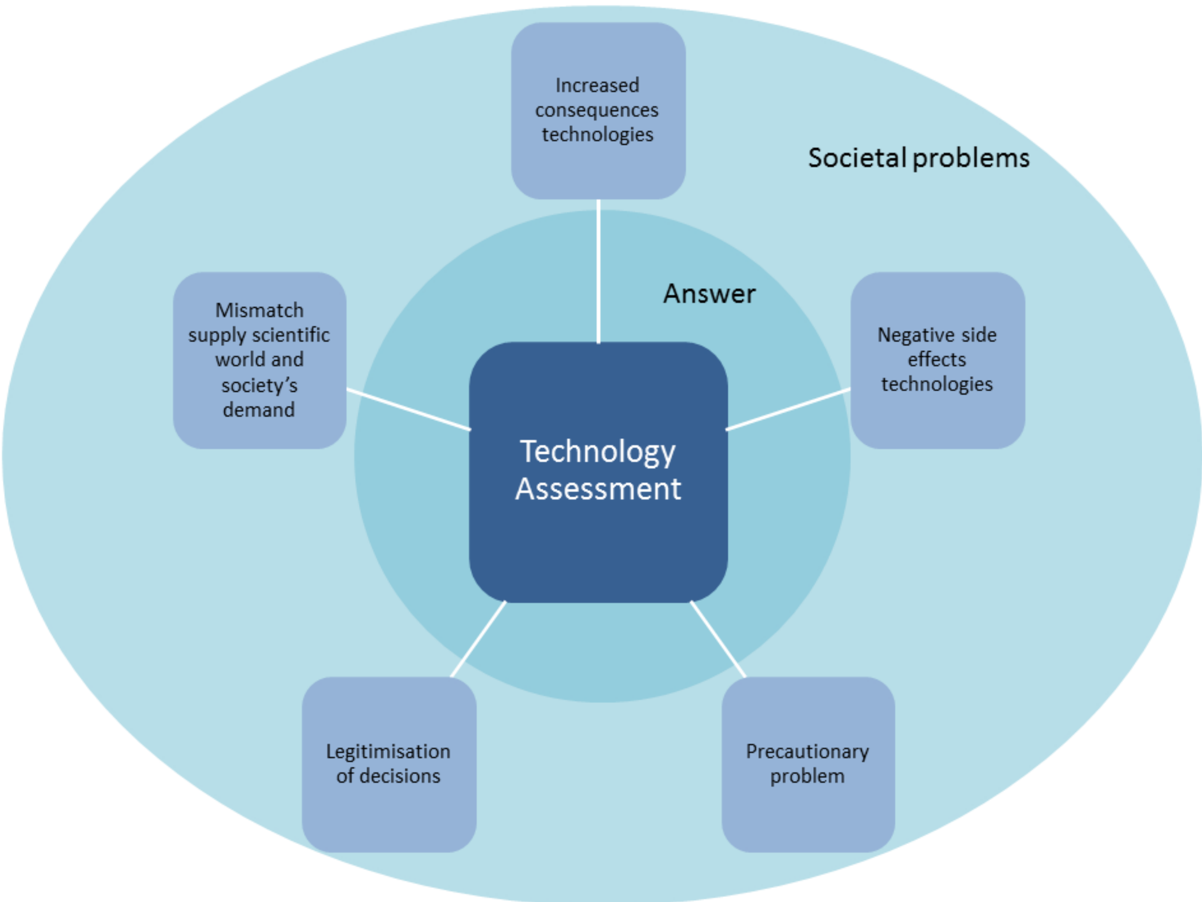

figure 10 - TA as an answer to societal problems

Definitions and characteristics of TA

The societal challenges, mentioned above, that arise alongside technological developments form the background for the formulation of TA and represent the problems it tries to solve. Despite the heterogeneity of these societal challenges, general characteristics can be assigned to TA.

TA's main focus is on transferring acquired knowledge to those who are going to make decisions with regard to the technological developments in the future. It supports public opinion and public participation in the decision making process. This advice to decision making is accompanied with a wide variety of possible side effects. Looking towards the future and assessing these side effects leads to considerable uncertainty and risk. This implies that TA, in all cases, advices on decision making while dealing with uncertainty. However, the rationality of decisions does not only depend on knowledge and limiting negative side effects and uncertainty. It also depends on basic normative principles (Grunwald, 1999).

TA tries to achieve this comprehensive view on the development of technologies by using a systematic approach. Perspectives from different scientific disciplines need to be incorporated in order to provide a coherent overview. This is among other things achieved by obtaining a broad understanding of innovation. Besides the technical understanding of developments, TA also includes perspectives on systems, society and institutions (Grunwald, 2009). While TA tries to construct a complete overview of technological developments it does not confine itself on a single technology but assesses a multitude of alternatives. TA, in all cases, tries to answer the question if the desired result could be achieved in a different manner. Scientific research forms the basis of TA. This assures that the complex societal challenges are interdisciplinary or transdisciplinary analysed. Like any other study, TA is limited by imposed deadlines with regard to finalizing the analysis.

Now that the characteristics of TA have been identified the contribution of TA becomes clearer. TA contributes to problem solving but does not provide actual solutions (Decker & Ladikas, 2004). Instead it provides knowledge on how to cope with certain problems related to the effect of technology developments on society. Its focus lies on undesirable side effects. TA does not provide solutions because they can only be legitimized by society through institutions and decision-making processes (Grunwald, 2009). It can be concluded that TA fulfils a advisory role with scientific research at its foundation and does not involves itself in the decision-making processes (Bechmann et al., 2007).

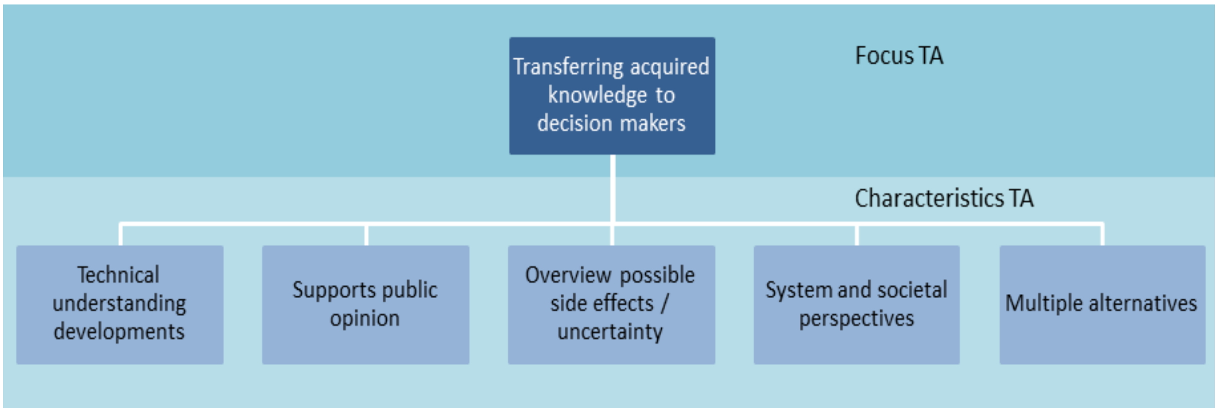

Figure 11 - focus and characteristics of TA

Concepts of TA

To fulfil the goals of TA and show its contribution to complex societal problems by assessing technological developments, a operable framework is required. Since TA practice is constantly evolving it can be divided into multiple categories, each with a different framework. The current TA landscape can however be analysed sufficiently by only discussing the three main concepts: classical TA, participatory TA, and constructive TA.

Classical TA

The classical concept of TA refers to the aspects which were incorporated within TA's classical phase in the 1970s (Bimber, 1996). Thereafter is was stylised and six elements form the foundation for this concept. Classical TA is dominated by a positive understanding of science and aims to produce exact, comprehensive and objective information on technology (Grunwald, 2009). State-of-the-art technologies are assessed long with their presumed consequences. It provides value-free knowledge on technology developments and their impacts while leaving the evaluation of this knowledge and the decision making to the political system. Classical TA justifies this approach by stating that the state has the represents the public interest and can therefore direct technology in the societally desired direction. This has led to harsh criticism on classical TA (van Gunsteren, 1976). To fully understand the discussed technologies and comprehend their consequences, classical TA must acquire complete knowledge on all available data. In the early stages, system analysis was used to achieve this (Paschen et al., 1978). This approach resulted in great expectations with regard to the quantitative modelling of technologies and their effects. Above all, classical TA was perceived as a method for determining the impact of technologies and as a warning mechanism for risks caused by these technologies. Quantitative prognoses, assumptions and trend extrapolations were all used to provide the political system with proficient knowledge to enable them to reacts appropriately (Grunwald, 2009). The focus of classical TA therefore lies on the experts that are required to provide the necessary knowledge.

Participatory TA

The expert orientation of classical TA led to criticism ever since it was introduced. Critics opted that the evaluation of technological development should not be left to scientific experts alone. A demand for participative orientation led to the creation of participatory TA. The task of participative TA is to include societal groups, affected citizens and the public within the process of evaluating technologies and their consequences (Grunwald, 2009). By doing so, the practical and political legitimacy of TA is improved (Paschen et al., 1978). Participatory TA is, in addition to science and experts, informed by people and groups outside the world of science and politics (Josh & Bellucci, 2002). Since the 1980s, people affected by the decisions made on technology were included more often within the process. Participation became especially relevant due to the NIMBY problems related to technological developments. Participatory TA states that the participation of citizens and people affected increases the overall understanding of the problem. This is because these groups have local knowledge which experts often lack. Furthermore it is important to include the interests of all the people participating or affected by technological developments in the decision-making process (Grunwald, 2009). Including these interests again increases the legitimacy of the decisions and prevents conflicts. In practice it is however hard to realize the objectives of participatory TA. Due to the fact that only a few people can attend such participatory TA meeting not all groups are represented. Besides the lack of representation of certain groups the willingness to participate is also correlated to population groups and education level. This correlation also causes a skewed distribution in representation.

Constructive TA

Constructive TA, first developed within the Netherlands, is the third concept within the field of TA (Schot, 1992). It argues that regular TA encounters problems regarding the implementation and effectiveness of technologies after the technology is already developed or in use (Rip et al., 1995). According to the Collingridge dilemma this causes problems because the chances of influencing technologies significantly decreases when technologies reach the development phase that impacts are well-known (Collingridge, 1980). Therefore constructive TA argues that it is more efficient to constructively accompany the process of technological developments. By doing so, it can react and deal directly with the consequences of technology. This already starts in the design phase since this is where technology impacts find their origin. Van Est & Brom (2012) state that constructive TA sees TA as an active contribution to the technological development process instead of an independent impact analysis. The Social Construction of Technology program forms the background of constructive TA. This approach perceives technological development as a result of societal processes and negotiation. Constructive TA tries to include, at an early stage, a broad variety of social actors and economic players. Schot & Rip (1997) describe three strategies that improve the functioning of Constructive TA.

First of all, the state has limited possibilities to influence the process of technological developments and can only intervene by promoting research or by imposing regulation. Other actors that are involved can directly intervene in technological innovations by means of their business and organizational policy (Grunwald, 2009). This is why constructive TA also addresses these actors. Strategic niche management is the second strategy which can be used by Constructive TA. Within these niches technologies can benefit from a protected environment in which they can develop, make use of learning processes and gain acceptance. In the end technologies can hopefully enter the market and compete without public support. A large role within this strategy is reserved for the state whom direct the technologies close to the market. Strategic niche management is especially relevant for sectors that reluctant to invest on innovation. Finally societal dialogue on technology is the third strategy that can be used to improve constructive TA. It is important to create a critical and open dialogue on technological developments that extends science and expert opinions. The people and economically important actors also need to be included. Constructive TA functions at its best when these three processes are harmonized (Schot & Rip, 1997)

Current developments in TA

TA is highly context dependent and its results are therefore very sensitive to changes in fields of technology, political setting and relevant actors. As a result TA has to be very alert to changes to its environment and react to the accordingly.

There are currently multiple developments taking place which affect future TA practice. First of all TA is influenced by increasing globalisation. Until recently TA targeted institutions that lay within nationally or even regionally orientated decision-making structures. Technical and economic globalization resulted in a different situation. Impacts of technologies transcend national borders and technology design takes place in global networks (Grunwald, 2009). Furthermore the regulation of technology has shifted from national level to a higher more aggregate level such as the European Union. Therefore TA has to find a way of dealing with globalisation to keep its importance within the field of technological developments.

A second important development that influences the implementation of TA is the increase of the so called “knowledge society”. The production of, access to and distribution of knowledge is becoming increasingly easy due to increasing amounts of information and communication technology. Scientific knowledge is used more and more to legitimize actions and decisions. However, an increased “knowledge society” also means that society has easy access to information on technological developments and forms its opinion on this subject accordingly. Overall, the importance of knowledge is growing and knowledge management and policy are even becoming social domains (Stehr, 2004).

The third and final development that affects TA practice is related to new technologies and the importance of societal acceptance. With regard to new technological developments the emphasis shifts from constructing large-scale facilities to the development of technologies themselves. New technologies lead to increased integration which makes decision-making processes more complicated. Besides the influence of new technologies TA is also affected by the fact that the role of technology in society is less determined by the products or systems feasibility. Instead societal embedding, economic aspects and societal acceptation become increasingly important (Grunwald, 2009).

Appendix E - Analytical Hierarchy Process

This appendix applies the analytical hierarchy process (AHP) to this research. AHP is a decision-making tool developed by Saaty in the 1970s (Mateo, 2012). It tries to identify the most promising alternatives by determining a raking of alternatives while considering all evaluative criteria simultaneously. A hierarchical structure is formed with the main goal, in this case the reduction of the CO_2 emissions of Dutch refineries, at the top. Evaluative criteria form the second level and the alternative are placed at the bottom of the hierarchy. Pair-wise comparisons are made to express the relative importance and performance of alternatives on criteria and criteria on each other. Numerical values are assigned to the criteria and alternatives on a nine-point scale. According to Saaty (1990) AHP can be divided into four steps, namely structuring the problem into an hierarchical model, obtaining the weights for each criteria, determining the score of each alternative for each criteria and establishing the overall score for each alternative.

Hierarchical model

The hierarchical model consists out of three layers. The main objective is placed at the top, the criteria in the middle layer and the alternatives at the bottom. Figure .. represents the hierarchical structure applied to this research. The criteria and alternatives are numbered (C1…C11 and A1…A11) and these numbers will be used within the rest of this Appendix.

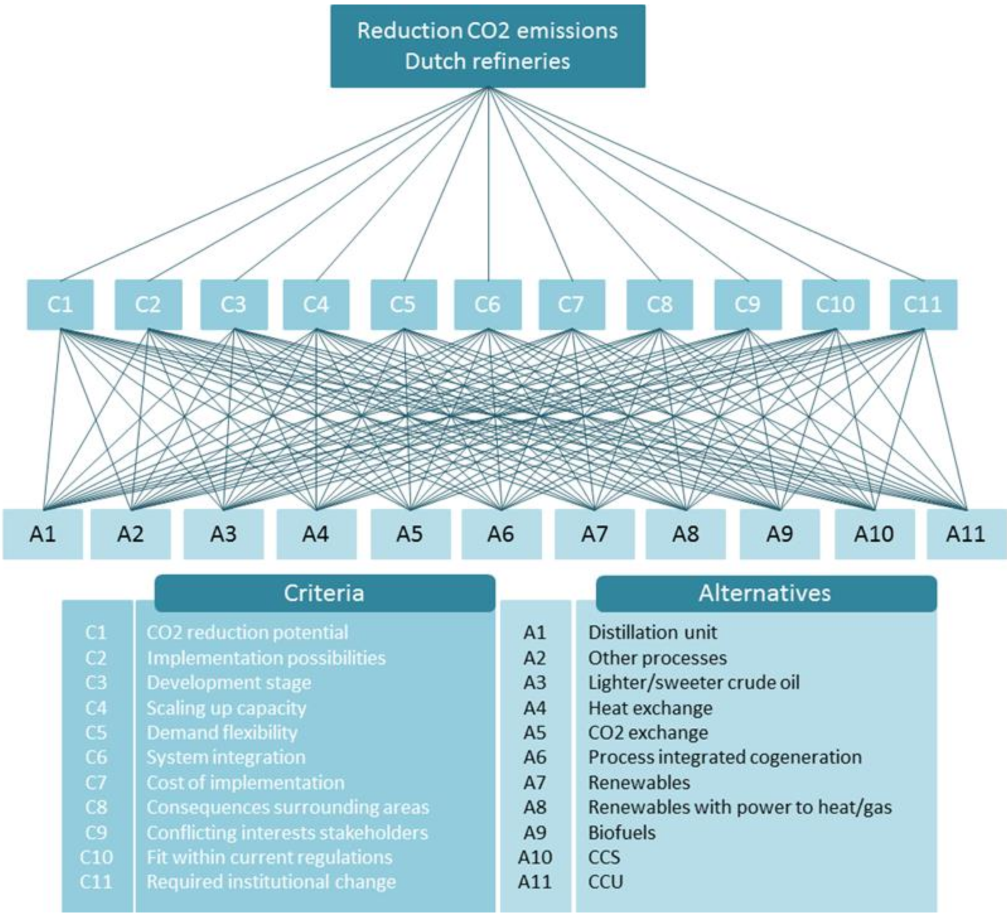

Figure 12 - hierarchical model according to AHP

Determining weights for each criteria

The second step within AHP determines the weights that are assigned to each criteria. Pair-wise comparisons are made to show the relative importance of one criteria with respect to another. A pair-wise comparison matrix (A) is formed. The number in row i and column j of A (a_{ij}) represents how much more important criteria i is with respect to criteria j. A nine point scale is used to indicate the relative importance of one criteria towards another.

Table 11 - Values that are assigned to the criteria based on their importance (Mateo, 2012)

a_{ij} Value	Interpretation
1	Criteria i and j are of equal importance
3	Criteria i is weakly more important than criteria j
5	Criteria i is strongly more important than criteria j
7	Criteria i is very strongly more important than criteria j
9	Criteria i is absolutely more important than criteria j
2,4,6,8	Intermediate values

When constructing the pairwise comparison matrix, a number of mathematical rules need to be verified.

1. If $a_{ij} = x$, then $a_{ji} = \frac{1}{x}$
2. If criteria i is of the same importance then criteria j, $a_{ij} = 1$ and $a_{ji} = 1$
3. The score of criteria i on criteria i is 1 for all i, $a_{ii} = 1$
4. To recover the weight vector of the pairwise comparison matrix needs to be normalized and the average per row needs to be determined
5. These average need to be multiplied by the normalization scores to obtain the matrix' eigenvalue
6. Then the consistency index (CI) can be determined as followed:
$$CI = \frac{(\lambda_{max} - n)}{n - 1}$$
7. The calculated CI can be compared to the Random Index (RI) to determine if the pairwise comparison matrix is consistent. If $\frac{CI}{RI} < 0.10$ the degree consistency is satisfactory.

Table 12 - RI for different values of n (Mateo, 2012)

n	2	3	4	5	6	7	8	9	10	11	12
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

In order to compute the pairwise comparison matrix for the evaluative criteria it is important to first provide an initial ranking of the criteria. Since the weights of the evaluative criteria are subjective they differ for different actor perspectives. Therefore the weights are determined for the four most important actors with regard to the implementation of CO_2 reducing alternatives. The four identified actors are: the Dutch government, highly complex/integrated refineries, less complex/non-integrated refineries and Dutch citizens. Figure .. provides an initial ranking of the criteria per actor perspective. From figure .. it can be concluded that the different actors perspectives have different preferences with regard to the weights of the evaluative criteria.

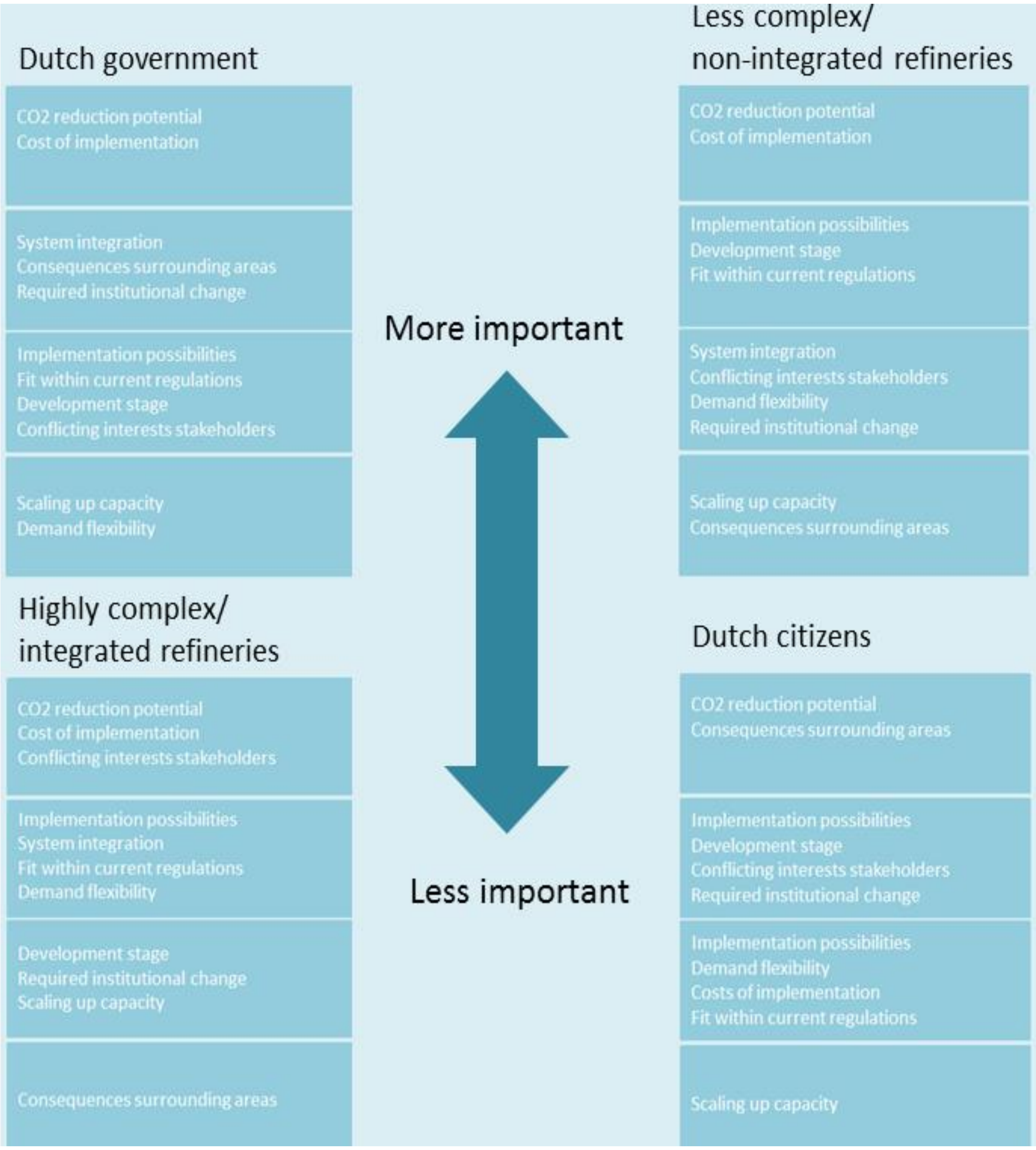

Figure 13 - raking of evaluative criteria according to their importance from the perspective of different actors

The main interest of the Dutch government is the reduction of CO_2 emissions by 80% to 95% below 1990 levels by 2050 (EFC, 2010). Since the Dutch refining industry has to reduce their CO_2 emissions to achieve this targets the CO_2 reduction potential of alternatives is also one of the most important criteria from their perspective. Reducing the CO_2 emissions of Dutch refineries is also in the best interest of the Dutch citizens which makes it an important criteria from their perspective. Since the Dutch refining industry has an high economic value for the Netherlands it is also important that it remains competitive. As a result the costs of the CO_2 reducing technologies must be kept to a minimum. As a result the criteria with regard to the costs of implementation is important for both the Dutch government and the Dutch refineries. The Dutch citizens attach a lower importance with respect to this criteria. The criteria that contains possible conflicting interests between stakeholders first of all includes the societal resistance that could occur when certain alternatives are implemented. Secondly it includes conflicts that may arise due to the fact that certain CO_2 reducing technologies might not be in favour of the Dutch refining industry and therefore result in conflicting interests. As a result this criteria is very important for the highly complex/integrated refineries since some alternatives might negatively influence their utilisation. The Dutch citizens also attach a higher weight to this criteria.

Consequences for surrounding areas is especially important for the Dutch citizens. They benefit from a reduction of CO_2 emissions of refineries but do not want to experience the possible negative side effects of the alternative. Since the Dutch government also protects the interest of its citizens it is also in their interest that the consequences of CO_2 reducing alternatives for surrounding areas are kept to a minimum. Both categories of Dutch refineries have a lower interest with respect to this criteria. Possibilities for system integration are the most important for the Dutch government and the highly complex/integrated refineries. They benefit the most from these possibilities for integration. Dutch citizens also find this criteria important since they might benefit from these integration possibilities like heat exchange. The less complex/non-integrated refineries attach a lower value to this criteria. The CO_2 reducing alternatives need to be implemented within the existing Dutch refineries. Therefore this criteria is especially important for the Dutch refineries. With respect to the Dutch government and the Dutch citizens this criteria is of less importance.

To assess the timespan in which the CO_2 reducing technologies can be implemented within the Dutch refining industry their current development stage is of importance. Especially the less complex/non-integrated refineries add a higher value to this criteria. This is due to the fact that they cannot rely on system integration alternatives and therefore need to implement alternatives at an early stage. The Dutch citizens also find the development stage of alternatives important since they would rather see the CO_2 emissions reduced sooner than later. Abilities for alternatives to scale up in capacity and thereby reduce the CO_2 emissions even further is not seen as a crucial criteria from all perspectives. In most cases, the implementation of CO_2 reducing alternatives is very costly and they are therefore designed in a way that they will reduce the CO_2 emissions by a substantial amount. For highly complex/integrated this criteria is slightly more important since they relatively emit the most CO_2. Demand flexibility is also seen as a less important criteria from all actors perspectives. This is in most cases due to the fact that most available alternatives do not affect the demand flexibility. Highly complex/integrated refineries attach a slightly higher value to this criteria since they have a more flexible product slate and are therefore more affected by possible changes in demand flexibility.

Alternatives become more promising when they fit within the current regulations. If they do not fit in refineries are not awarded, either with CO_2 credits or with subsidies, and have no incentive to implement these alternatives. As a result this criteria is especially important to the entire Dutch refining industry. Dutch citizens and the Dutch government attach less value to this criteria. The Dutch government does however attach a higher value to the institutional change that required for alternatives to fit within regulations. Ideally no change is required because it prevents changes in current regulations. Furthermore institutional change is a slow process and certain regulations are made on a European level which limits the influence of the Dutch government. Since institutional change is a long term process it is less important to the refineries than the fit within current regulations.

Based on this initial ranking it is possible to construct the pairwise comparison matrixes of the evaluative criteria. In total four matrixes can be constructed, one for each perspective. However only the first actor perspective, the Dutch government, is extensively explained. The first row of table .. represents the importance of the CO_2 reduction potential (C1) towards the other criteria. Cost of implementation (C7) and CO_2 reduction potential are the most important criteria and considered to be of equal importance. As a result they are both assigned with a 1. The CO_2 reduction potential is perceived as weakly more important than the possibilities for system integration (C6), consequences for surrounding areas (C8) and the required institutional change (C11) and they are therefore assigned with a 3. A 5 is assigned to the possibilities for implementation (C2), development stage of alternatives (C3), conflicting interest stakeholders (C9) and the fit within current regulations (C10). This is due to the fact that the potential for alternatives to reduce the CO_2 emissions of Dutch refineries is considered strongly more important than these four criteria. Finally the CO_2 reduction potential is perceived very strongly more important than the possibilities for scaling up capacity (C4) and demand flexibility (C5). As a result they are assigned a 7. From this initial ranking of criteria the following pairwise comparison matrix can be constructed.

Table 13 - Pairwise comparison matrix of the evaluative criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	1	5	5	7	7	3	1	3	5	5	3
C2	1/5	1	1	3	3	1/3	1/5	1/3	1	1	1/3
C3	1/5	1	1	3	3	1/3	1/5	1/3	1	1	1/3
C4	1/7	1/3	1/3	1	1	1/5	1/7	1/5	1/3	1/3	1/5
C5	1/7	1/3	1/3	1	1	1/5	1/7	1/5	1/3	1/3	1/5
C6	1/3	3	3	5	5	1	1/3	1	3	3	1
C7	1	5	5	7	7	3	1	3	5	5	3
C8	1/3	3	3	5	5	1	1/3	1	3	3	1
C9	1/5	1	1	3	3	1/3	1/5	1/3	1	1	1/3
C10	1/5	1	1	3	3	1/3	1/5	1/3	1	1	1/3
C11	1/3	3	3	5	5	1	1/3	1	3	3	1

To calculate the eigenvalue of the matrix, the values need to be normalized. Table .. adds the numbers of each column and presents their total

Table 14 - Pairwise comparison matrix of the evaluative criteria with column totals

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	1	5	5	7	7	3	1	3	5	5	3
C2	1/5	1	1	3	3	1/3	1/5	1/3	1	1	1/3
C3	1/5	1	1	3	3	1/3	1/5	1/3	1	1	1/3
C4	1/7	1/3	1/3	1	1	1/5	1/7	1/5	1/3	1/3	1/5
C5	1/7	1/3	1/3	1	1	1/5	1/7	1/5	1/3	1/3	1/5
C6	1/3	3	3	5	5	1	1/3	1	3	3	1
C7	1	5	5	7	7	3	1	3	5	5	3
C8	1/3	3	3	5	5	1	1/3	1	3	3	1
C9	1/5	1	1	3	3	1/3	1/5	1/3	1	1	1/3
C10	1/5	1	1	3	3	1/3	1/5	1/3	1	1	1/3
C11	1/3	3	3	5	5	1	1/3	1	3	3	1
A_{norm}	4.09	23.67	23.67	43.00	43.00	10.73	4.09	10.73	23.67	23.67	10.73

Table 15 - Normalized pairwise comparison matrix of the evaluative criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0,24	0,21	0,21	0,16	0,16	0,28	0,24	0,28	0,21	0,21	0,28
C2	0,05	0,04	0,04	0,07	0,07	0,03	0,05	0,03	0,04	0,04	0,03
C3	0,05	0,04	0,04	0,07	0,07	0,03	0,05	0,03	0,04	0,04	0,03
C4	0,03	0,01	0,01	0,02	0,02	0,02	0,03	0,02	0,01	0,01	0,02
C5	0,03	0,01	0,01	0,02	0,02	0,02	0,03	0,02	0,01	0,01	0,02
C6	0,08	0,13	0,13	0,12	0,12	0,09	0,08	0,09	0,13	0,13	0,09
C7	0,24	0,21	0,21	0,16	0,16	0,28	0,24	0,28	0,21	0,21	0,28
C8	0,08	0,13	0,13	0,12	0,12	0,09	0,08	0,09	0,13	0,13	0,09
C9	0,05	0,04	0,04	0,07	0,07	0,03	0,05	0,03	0,04	0,04	0,03
C10	0,05	0,04	0,04	0,07	0,07	0,03	0,05	0,03	0,04	0,04	0,03
C11	0,08	0,13	0,13	0,12	0,12	0,09	0,08	0,09	0,13	0,13	0,09

The corresponding weight vector of this matrix is calculated by taking the average per row of the table above.

	W
C1	0.23
C2	0.05
C3	0.05
C4	0.02
C5	0.02
C6	0.11
C7	0.23
C8	0.11
C9	0.05
C10	0.05
C11	0.11

The eigenvalue of the pairwise comparison matrix can then be calculated as followed.

$$\lambda_{max} = \sum W_i * A_{norm_i}$$

First the calculated weight of C1 needs to be multiplied with the column total of C1 in table .. . In this case 0.24*3.90. This needs to be repeated for al eleven criteria. Finally the obtained values are all added together to obtain the matrix' eigenvalue. Calculating the CI and CR is already explained.

Eigenvalue: $\lambda_{max} = 11.40$

Consistency Index: CI = 0.040

Consistency Ratio : CR = 0.027

Since the CR < 0.10, It can be concluded that the pairwise comparison matrix is consistent

The pairwise comparison matrixes of the eveluative criteria from the other perspectives can be constructed in a similar matter.

Table 16 - Pairwise comparison matrix of the criteria from the other three perspectives

Pairwise comparison matrix criteria form perspective of highly complex/integrated refineries

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Weights
C1	1	3	5	5	3	3	1	7	1	3	5	0.19
C2	1/3	1	3	3	1	1	1/3	5	1/3	1	3	0.08
C3	1/5	1/3	1	1	1/3	1/3	1/5	3	1/5	1/3	1	0.03
C4	1/5	1/3	1	1	1/3	1/3	1/5	3	1/5	1/3	1	0.03
C5	1/3	1	3	3	1	1	1/3	5	1/3	1	3	0.08
C6	1/3	1	3	3	1	1	1/3	5	1/3	1	3	0.08
C7	1	3	5	5	3	3	1	7	1	3	5	0.19
C8	1/7	1/5	1/3	1/3	1/5	1/5	1/7	1	1/7	1/5	1/3	0.02
C9	1	3	5	5	3	3	1	7	1	3	5	0.19
C10	1/3	1	3	3	1	1	1/3	5	1/3	1	3	0.08
C11	1/5	1/3	1	1	1/3	1/3	1/5	3	1/5	1/3	1	0.03

$\lambda_{max} = 11.33$ CI = 0.033 CR = 0.022

Pairwise comparison matrix criteria from perspective of less complex refineries

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Weights
C1	1	3	3	7	5	5	1	7	5	3	5	0.23
C2	1/3	1	1	5	3	3	1/3	5	3	1	3	0.11
C3	1/3	1	1	5	3	3	1/3	5	3	1	3	0.11
C4	1/7	1/5	1/5	1	1/3	1/3	1/7	1	1/3	1/5	1/3	0.02
C5	1/5	1/3	1/3	3	1	1	1/5	3	1	1/3	1	0.05
C6	1/5	1/3	1/3	3	1	1	1/5	3	1	1/3	1	0.05
C7	1	3	3	7	5	5	1	7	5	3	5	0.23
C8	1/7	1/5	1/5	1	1/3	1/3	1/7	1	1/3	1/5	1/3	0.02
C9	1/5	1/3	1/3	3	1	1	1/5	3	1	1/3	1	0.05
C10	1/3	1	1	5	3	3	1/3	5	3	1	3	0.11
C11	1/5	1/3	1/3	3	1	1	1/5	3	1	1/3	1	0.05

$\lambda_{max} = 11.40$ CI = 0.040 CR = 0.027

Pairwise comparison matrix criteria from perspective Dutch citizens

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Weights
C1	1	5	3	7	5	3	5	1	3	5	3	0.22
C2	1/5	1	1/3	3	1	1/3	1	1/5	1/3	1	1/3	0.04
C3	1/3	3	1	5	3	1	3	1/3	1	3	1	0.10
C4	1/7	1/3	1/5	1	1/3	1/5	1/3	1/7	1/5	1/3	1/5	0.02
C5	1/5	1	1/3	3	1	1/3	1	1/5	1/3	1	1/3	0.04
C6	1/3	3	1	5	3	1	3	1/3	1	3	1	0.10
C7	1/5	1	1/3	3	1	1/3	1	1/5	1/3	1	1/3	0.04
C8	1	5	3	7	5	3	5	1	3	5	3	0.22
C9	1/3	3	1	5	3	1	3	1/3	1	3	1	0.10
C10	1/5	1	1/3	3	1	1/3	1	1/5	1/3	1	1/3	0.04
C11	1/3	3	1	5	3	1	3	1/3	1	3	1	0.10

$\lambda_{max} = 11.30$ CI = 0.030 CR = 0.020

All three pairwise comparison matrixes have CR's<0.10 and are therefore consistent

Performance of alternatives on criteria

Step three within the AHP determines the performance of the alternatives on each criteria. Again, pairwise comparison matrixes need to be constructed to determine the performances of the alternatives on the evaluative criteria. Since a total of eleven criteria are included within this research, eleven pairwise comparison matrixes are constructed to assess the performance of the alternatives on each criteria. The same nine-point scale is used to determine the relative performance of alternatives on each criteria.

CO_2 reduction potential

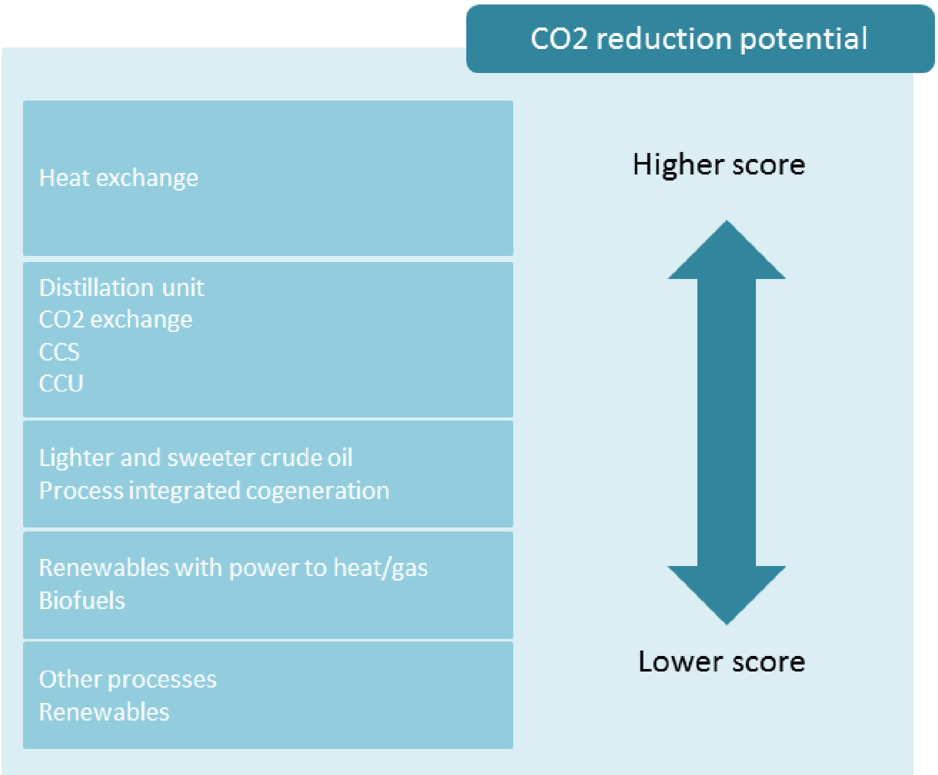

Figure 14 - ranking of alternatives on CO_2 reduction potential

According to krebbekx et al (2011) exchanging heat to nearby residential district or industries has the largest CO_2 reducing potential for the Dutch refineries. Its technical potential lies around a reduction of 1 Mton of CO_2 emissions per year. Optimizing the distillation unit, exchanging CO_2, CCS and CCU have the second highest potential for reducing the CO_2 emissions of Dutch refineries. Optimizing the distillation unit can reduce the CO_2 emission of the distillation column by up to 22% (Gadalla et al., 2006). Supplying CO_2 to nearby greenhouses can also substantially reduce the CO_2 emissions of Dutch refineries (Kampman et al., 2011). CCS and CCU also have a large CO_2 reduction potential. Since this technology is not yet applied at large scale the technical potential is not yet know. However the cost effective CO_2 reducing potential is already estimated at around 350 kton per year. Processing a lighter and sweeter type of crude oil can reduce the CO_2 emissions of refineries by a maximum of 33%. This reduction is however dependent on the configurations of refineries and is therefore assigned with a lower score. Implementing a process integrated cogeneration unit can reduced the CO_2 emissions of Dutch refineries to a maximum of 400 kton per year (Krebbekx et al., 2011). As a result, the process integrated cogeneration unit and processing a lighter and sweeter crude oil are considered to have the third highest potential for reducing the CO_2 emissions of Dutch refineries.

Implementing biofuels within refining processes can result in a CO_2 reduction of around 120 – 170 kton per year. Therefore this option is has a lower CO_2 reduction potential. Using renewables to reduce the CO_2 emissions of Dutch refineries has a low CO_2 reducing potential (Krebbekx et al., 2011). If it is combined with power to heat or power to gas its CO_2 reducing potential increases a bit due to the fact that the electricity that is generated can also be used for refining processes that require heat. Finally, the optimisation of other refining processes such as the FCC unit, hydrocracker and coking unit will not result in a significant CO_2 reduction. So this alternative, along with implementing renewables, is considered to have the lowest CO_2 reduction potential for Dutch refineries.

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 17 - Pairwise comparison matrix of the alternatives on the CO_2 reduction potential

Pairwise comparison matrix alternatives on CO_2 reduction potential												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	7	3	1/3	1	3	7	5	5	1	1	0.13
A2	1/7	1	1/5	1/9	1/7	1/5	1	1/3	1/3	1/7	1/7	0.02
A3	1/3	5	1	1/5	1/3	1	5	3	3	1/3	1/3	0.06
A4	3	9	5	1	3	5	9	7	7	3	3	0.27
A5	1	7	3	1/3	1	3	7	5	5	1	1	0.13
A6	1/3	5	1	1/5	1/3	1	5	3	3	1/3	1/3	0.06
A7	1/7	1	1/5	1/9	1/7	1/5	1	1/3	1/3	1/7	1/7	0.02
A8	1/5	3	1/3	1/7	1/5	1/3	3	1	1	1/5	1/5	0.03
A9	1/5	3	1/3	1/7	1/5	1/3	3	1	1	1/5	1/5	0.03
A10	1	7	3	1/3	1	3	7	5	5	1	1	0.13
A11	1	7	3	1/3	1	3	7	5	5	1	1	0.13
								$\lambda_{max} = 11.59$		CI = 0.059		CR = 0.039

Implementation possibilities

Processes and systems within Dutch refineries are highly integrated and alternating these could have disastrous consequences. Implementing CO_2 reducing technologies unavoidably effect existing processes but these must be kept to a minimum. Some alternatives might even require a completely new build refinery to function properly. A new refinery seems however highly unlikely within the Netherlands. it is therefore important that the CO_2 reducing technologies can be implemented within the existing refineries. The easier an alternative is implemented the higher it is rated. Optimisation of other refining processes such as the FCC unit, hydrocracker and coking unit are the hardest to implement within the Dutch refining industry. In most cases these optimisation alternatives require a newly build refinery (Vleeming & Hinderink, 2011). As a result this alternative score the lowest with regard to the implementation possibilities. Exchanging heat, processing lighter and sweeter types of crude oil, renewables, renewables with power to heat/gas, Biofuels, CCS and CCU can in theory be implemented within existing Dutch refineries and therefore score the highest. Exchanging CO_2 receives a lower score since it is currently only an option for refineries that hydrogen (due to its relatively pure flow of CO_2). Only when carbon capture is applied can CO_2 exchange be implemented by more refineries. Optimisation of the distillation unit is receives the same score since not all optimisation technologies can be implemented within existing refineries (Plomp & Kroon, 2010). Installing a process integrated cogeneration unit also requires some modifications to the existing refineries (Vleeming & Hinderink, 2011). This alternative is therefore assigned with the same score as optimising the distillation unit and exchanging CO_2.

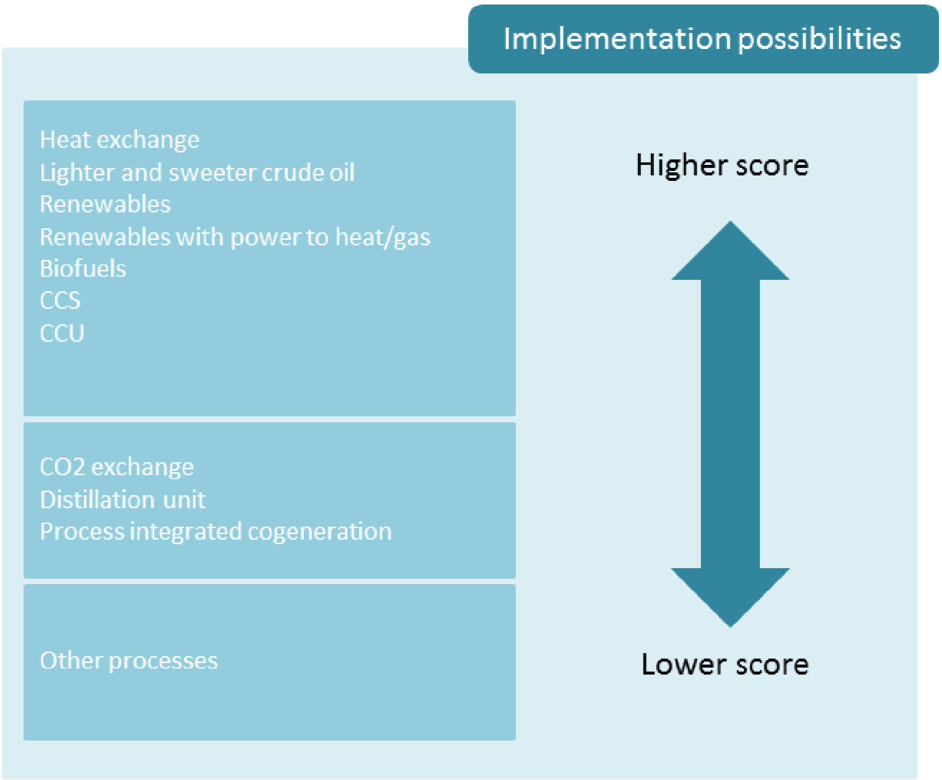

Figure 15 - ranking of alternatives on implementation possibilities

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 18 - Pairwise comparison matrix of the alternatives on their implementation possibilities

Pairwise comparison matrix alternatives on implementation possibilities												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	3	1/3	1/3	1	1	1/3	1/3	1/3	1/3	1/3	0.04
A2	1/3	1	1/5	1/5	1/3	1/3	1/5	1/5	1/5	1/5	1/5	0.02
A3	3	5	1	1	3	3	1	1	1	1	1	0.12
A4	3	5	1	1	3	3	1	1	1	1	1	0.12
A5	1	3	1/3	1/3	1	1	1/3	1/3	1/3	1/3	1/3	0.04
A6	1	3	1/3	1/3	1	1	1/3	1/3	1/3	1/3	1/3	0.04
A7	3	5	1	1	3	3	1	1	1	1	1	0.12
A8	3	5	1	1	3	3	1	1	1	1	1	0.12
A9	3	5	1	1	3	3	1	1	1	1	1	0.12
A10	3	5	1	1	3	3	1	1	1	1	1	0.12
A11	3	5	1	1	3	3	1	1	1	1	1	0.12
							$\lambda_{max} = 11.07$			CI = 0,007		CR = 0,005

Development stage

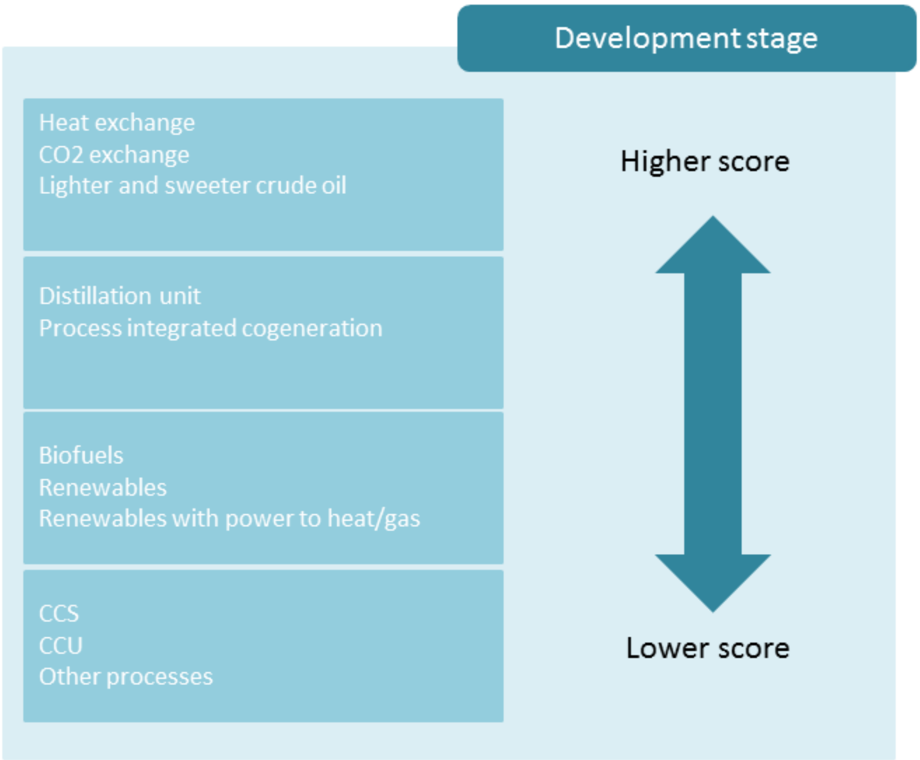

Figure 16 - ranking of alternatives on development stage

The alternatives for reducing the CO_2 emissions of Dutch refineries can be classified into different development stages. From highly developed and already implemented to experimental. Exchanging heat and CO_2 are already implemented and therefore score the highest (Kampman et al., 2010). Processing lighter and sweeter types of crude oil is not yet applied but still highly developed. Optimizing the distillation unit and implementing a process integrated cogeneration unit are highly developed alternatives. However, since they are not implemented at many refineries they receive a lower score (Plomp & Kroon, 2010). Implementing biofuels, renewables and renewables in combination with power to heat/gas are quite developed alternatives and in some cases already implemented within the Dutch refining industry. Despite their recent development these alternatives are not as developed as the ones already mentioned and score lower. CCS, CCU and optimisation technologies for the other processes are in most cases still experimental or in a developing stage. As a result, these three alternatives receive the lowest score.

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 19 - Pairwise comparison matrix of the alternatives on their development stage

Pairwise comparison matrix alternatives on development stage												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	5	1/3	1/3	1/3	1	3	3	3	5	5	0.10
A2	1/5	1	1/7	1/7	1/7	1/5	1/3	1/3	1/3	1	1	0.02
A3	3	7	1	1	1	3	5	5	5	7	7	0.20
A4	3	7	1	1	1	3	5	5	5	7	7	0.20
A5	3	7	1	1	1	3	5	5	5	7	7	0.20
A6	1	5	1/3	1/3	1/3	1	3	3	3	5	5	0.10
A7	1/3	3	1/5	1/5	1/5	1/3	1	1	1	3	3	0.05
A8	1/3	3	1/5	1/5	1/5	1/3	1	1	1	3	3	0.05
A9	1/3	3	1/5	1/5	1/5	1/3	1	1	1	3	3	0.05
A10	1/5	1	1/7	1/7	1/7	1/5	1/3	1/3	1/3	1	1	0.02
A11	1/5	1	1/7	1/7	1/7	1/5	1/3	1/3	1/3	1	1	0.02
								$\lambda_{max} = 11.50$		CI = 0.050		CR = 0.03

Scaling up capacity

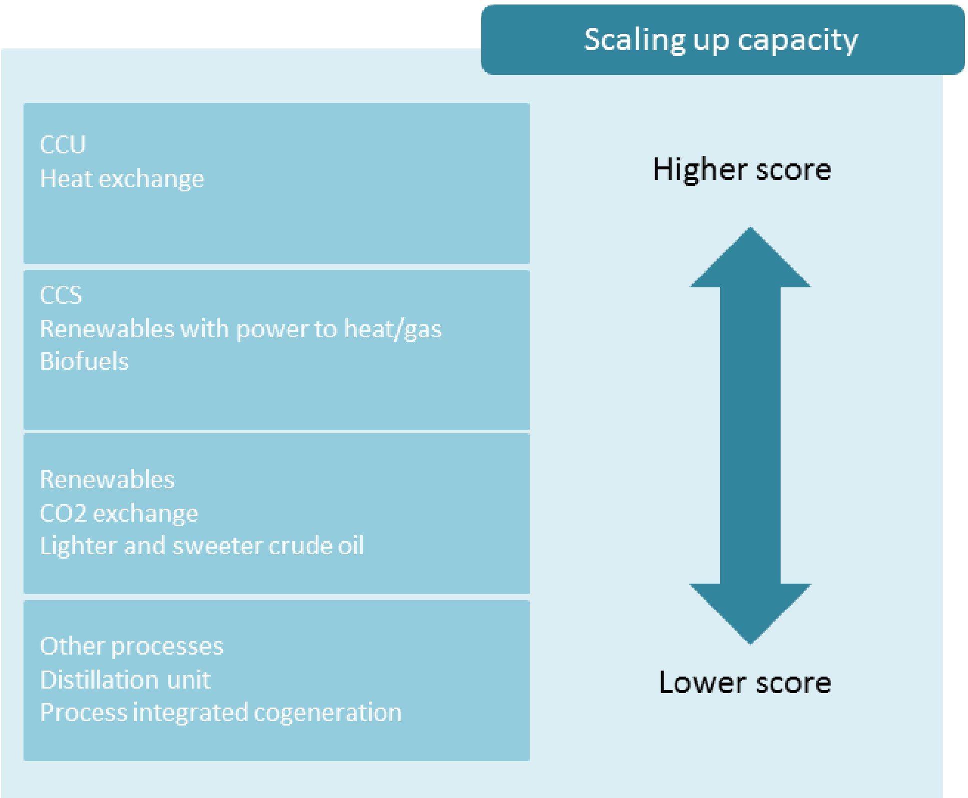

Figure 17 - ranking of alternatives on scaling up capacity

In order for the Dutch refining industry to meet the CO_2 reduction targets of 2050, they need to reduce their CO_2 emissions by 80% to 95%. Most technologies are first implemented on a small scale to ensure their effectiveness. To achieve significant CO_2 reductions it is of great importance that the implemented technologies can be increased in capacity. Alternatives that increase the efficiency of the refineries and thereby reduce their CO_2 emissions are the least capable to scale up in capacity.

These alternatives increase the efficiency of a refinery but are not able to increase this any further without implementing a new technology. Optimisation of the distillation unit or other processes and process integrated cogeneration are therefore assigned with the lowest scores. Implementation of renewables is bounded by the available space which results in a lower score (Krebbekx et al., 2011). Exchanging CO_2 to nearby greenhouses is restricted by the demand of the greenhouses and the development of carbon capture (since it is now only captured at the hydrogen production site). Processing lighter and sweeter crude types of crude oil is also an option that has limited possibilities for upscaling in capacity. At a certain point it becomes impossible to find and process even lighter types of crude oil. These three alternatives therefore receive the second lowest scores. If the renewables are combined with power to heat/gas the possibilities for scaling up the capacity slightly increase. In this case the wind turbines or solar panels can be places further away from the refining site. CCS potentially has a great capacity but is limited by the available storage location. Furthermore biofuels are limited by the produced amounts of biomass. These have a substantial scaling up capacity but are assigned with the second highest score. This is due to the fact that exchanging heat and CCU have even higher scaling up capacities. Unlike CCS, CCU is not limited by storage capacity since it utilizes the captured CO_2 (Cuéllar-Franca & Azapagic, 2015). Exchanging heat has a high potential for increasing the capacity since the heat can be provided to both nearby residential districts and industries.

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 20 - Pairwise comparison matrix of the alternatives on their abilities to scale up capacity

Pairwise comparison matrix alternatives on scaling up capacity												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	1	1/3	1/7	1/3	1	1/3	1/5	1/5	1/5	1/7	0.02
A2	1	1	1/3	1/7	1/3	1	1/3	1/5	1/5	1/5	1/7	0.02
A3	3	3	1	1/5	1	3	1	1/3	1/3	1/3	1/5	0.05
A4	7	7	5	1	5	7	5	3	3	3	1	0.23
A5	3	3	1	1/5	1	3	1	1/3	1/3	1/3	1/5	0.05
A6	1	1	1/3	1/7	1/3	1	1/3	1/5	1/5	1/5	1/7	0.02
A7	3	3	1	1/5	1	3	1	1/3	1/3	1/3	1/5	0.05
A8	5	5	3	1/3	3	5	3	1	1	1	1/3	0.11
A9	5	5	3	1/3	3	5	3	1	1	1	1/3	0.11
A10	5	5	3	1/3	3	5	3	1	1	1	1/3	0.11
A11	7	7	5	1	5	7	5	3	3	3	1	0.23
								$\lambda_{max} = 11.46$		CI = 0.046		CR = 0.031

Demand flexibility

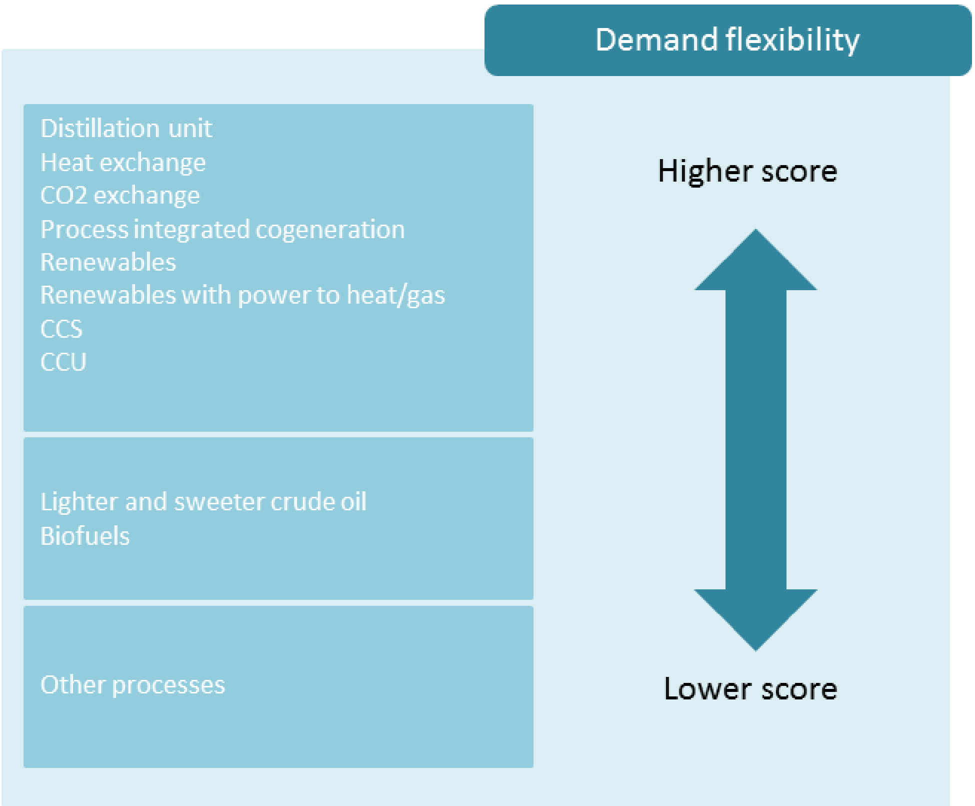

Figure 18 - ranking of alternatives on demand flexibility

CO_2 reducing technologies that are implemented within the Dutch refining industry can be classified as long-term investments. The profitability of a refinery is however highly dependent on its ability to produce refining products that are demanded. It is therefore necessary that the implemented CO_2 reducing alternatives can cope with a certain flexibility in demand. In general, the alternatives can be classified into three categories, namely alternatives that cannot deal with changes in demand, alternatives that are sensitive to changes in demand and alternatives that are flexible to changes in oil product demand. Optimising refining processes such as the FCC unit, hydrocracker and coking unit are the least flexible with regard to oil product demand changes. This is due to the fact that the FFC unit is particularly used for the production of gasoline while the hydrocracker is used for the production of diesel (Treese et al., 2015). Optimising these processes to reduce the CO_2 emissions of Dutch refineries therefore receives the lowest score with respect to demand flexibility. Implementation of biofuels within Dutch refineries is also somewhat sensitive to demand changes. This is because biofuels can only be implemented within the hydrotreater and FCC unit (Mercader et al., 2010). Furthermore the processing of a lighter and sweeter type of crude oil is also slightly sensitive to changes in oil product demand. By processing lighter and sweeter crude oils the product slate of refineries is altered. Light ends, such as gasoline and diesel, are produced in higher quantities. However, if for some reason a refinery wants to produce heavy oil products like fuel oil this is hard to achieve. The remaining CO_2 reducing alternatives are all equally flexible to changes in oil product demand and therefore assigned the same score.

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 21 - Pairwise comparison matrix of the alternatives on demand flexibility

Pairwise comparison matrix alternatives on demand flexibility												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	5	3	1	1	1	1	1	3	1	1	0.11
A2	1/5	1	1/3	1/5	1/5	1/5	1/5	1/5	1/3	1/5	1/5	0.02
A3	1/3	3	1	1/3	1/3	1/3	1/3	1/3	1	1/3	1/3	0.04
A4	1	5	3	1	1	1	1	1	3	1	1	0.11
A5	1	5	3	1	1	1	1	1	3	1	1	0.11
A6	1	5	3	1	1	1	1	1	3	1	1	0.11
A7	1	5	3	1	1	1	1	1	3	1	1	0.11
A8	1	5	3	1	1	1	1	1	3	1	1	0.11
A9	1/3	3	1	1/3	1/3	1/3	1/3	1/3	1	1/3	1/3	0.04
A10	1	5	3	1	1	1	1	1	3	1	1	0.11
A11	1	5	3	1	1	1	1	1	3	1	1	0.11
							$\lambda_{max} = 11.05$			CI = 0.005		CR = 0.003

System integration

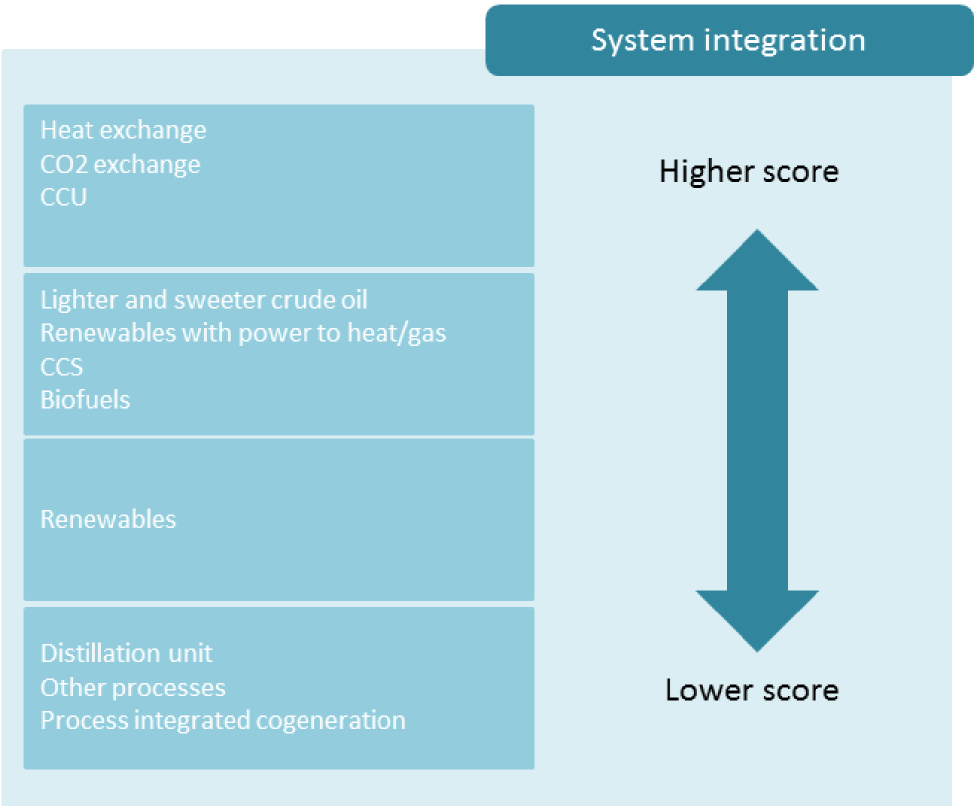

Figure 19 - ranking of alternatives on system integration

Refineries can individually implement certain CO_2 reducing alternatives to reduce individual CO_2 emissions. However, five out of the six Dutch refineries are located close to each other in the Port of Rotterdam industrial cluster. If alternative can reduce the emissions of multiple refineries at once this would be very beneficial. In some cases refineries could even cooperate with other industries to reduce their combined emissions. Heat exchange, CO_2 exchange and CCU are examples of alternatives that offer the opportunity of system integration. Heat exchange and CO_2 exchange integrate the refineries to nearby residential areas or greenhouses (Krebbekx et al., 2011). CCU ensures that the refineries are integrated with other industries that utilize the captured CO_2. Alternatives that are to a lesser extend suitable for system integration are processing lighter and sweeter types of crude oil, renewables with power to heat/gas, biofuels and CCS. Processing lighter and sweeter types of crude oils is an alternative that can be used within every Dutch refinery. Implementation of biofuels can integrate the Dutch refineries with bio-refineries. CCS can integrate the Dutch refineries with oil exploration companies for enhanced oil recovery (Cuéllar-Franca & Azapagic, 2015). Renewables with power to heat/gas can integrate refineries to industries that have the capabilities to convert electricity into hydrogen. Since renewables on their own can only produce electricity, their potential for system integration is considered lower. Process optimisation options offer almost no possibilities for system integration because they only affect the refineries themselves. As a result they are scored the lowest.

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 22 - Pairwise comparison matrix of the alternatives on system integration

Pairwise comparison matrix alternatives on system integration												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	1	1/5	1/7	1/7	1	1/3	1/5	1/5	1/5	1/7	0.02
A2	1	1	1/5	1/7	1/7	1	1/3	1/5	1/5	1/5	1/7	0.02
A3	5	5	1	1/3	1/3	5	3	1	1	1	1/3	0.08
A4	7	7	3	1	1	7	5	3	3	3	1	0.19
A5	7	7	3	1	1	7	5	3	3	3	1	0.19
A6	1	1	1/5	1/7	1/7	1	1/3	1/5	1/5	1/5	1/7	0.02
A7	3	3	1/3	1/5	1/5	3	1	1/3	1/3	1/3	1/5	0.04
A8	5	5	1	1/3	1/3	5	3	1	1	1	1/3	0.08
A9	5	5	1	1/3	1/3	5	3	1	1	1	1/3	0.08
A10	5	5	1	1/3	1/3	5	3	1	1	1	1/3	0.08
A11	7	7	3	1	1	7	5	3	3	3	1	0.19
								$\lambda_{max} = 11.41$		CI = 0.041		CR = 0.027

Costs of implementation

The Dutch refining industry finds itself operating in a global market. Due to the globalized market the Dutch refining industry faces a lot of competition from export orientated refineries in the Middle-East and China. Despite the increase in competition the Dutch refining industry remains an important economic factor for the Netherlands. Due to its great importance, it is crucial that the Dutch refining industry remains competitive. An important economic criteria is the cost of implementation of the CO_2 reducing technologies. Dutch refineries are facing increasingly fierce competition from export orientated refineries. It is important that the implementation of CO_2 reducing technologies does not significantly decreases the competitiveness of the Dutch refining industry. In most cases alternatives that optimise the efficiency of refineries are considered to be the most cost effective (krebbekx et al., 2011). The processing of a lighter and sweeter type of crude oil increases the costs of refineries since it is more expensive but remains a relatively cheap alternative. Exchanging heat, exchanging CO_2, a process integrated cogeneration unit and implementing biofuels are all alternatives that are not extremely expensive. The costs of infrastructure with regard to heat and CO_2 exchange is the largest barrier. Implementation of renewables and CCU are considerably more expensive. Especially since these technologies are less developed. Renewables with power to heat/gas are even more expensive since the technologies that convert the electricity are very expensive (ECN, 2014). CCS is considered more expensive than CCU due to the fact that CCU utilises the CO_2 making it a valuable product.

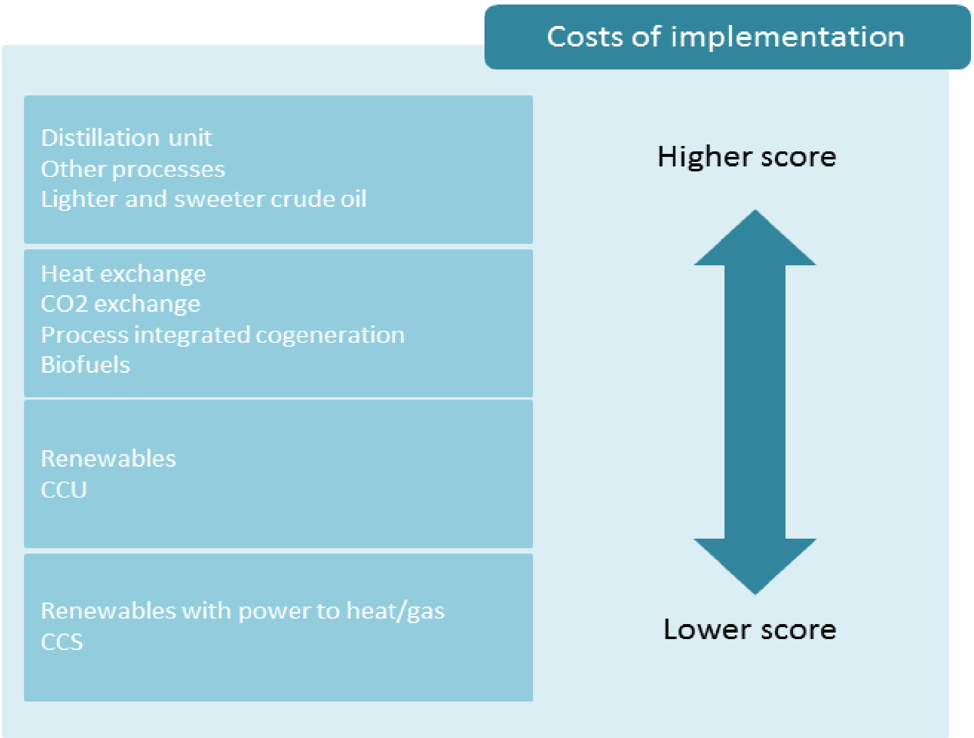

Figure 20 - ranking of alternatives on costs of implementation

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 23 - Pairwise comparison matrix of the alternatives on costs of implementation

Pairwise comparison matrix alternatives on costs of implementation												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	1	1	3	3	3	5	7	3	7	5	0.19
A2	1	1	1	3	3	3	5	7	3	7	5	0.19
A3	1	1	1	3	3	3	5	7	3	7	5	0.19
A4	1/3	1/3	1/3	1	1	1	3	5	1	5	3	0.08
A5	1/3	1/3	1/3	1	1	1	3	5	1	5	3	0.08
A6	1/3	1/3	1/3	1	1	1	3	5	1	5	3	0.08
A7	1/5	1/5	1/5	1/3	1/3	1/3	1	3	1/3	3	1	0.04
A8	1/7	1/7	1/7	1/5	1/5	1/5	1/3	1	1/5	1	1/3	0.02
A9	1/3	1/3	1/3	1	1	1	3	5	1	5	3	0.08
A10	1/7	1/7	1/7	1/5	1/5	1/5	1/3	1	1/5	1	1/3	0.02
A11	1/5	1/5	1/5	1/3	1/3	1/3	1	3	1/3	3	1	0.04
							$\lambda_{max} = 11.40$			CI = 0.040		CR = 0,027

Consequences surrounding areas

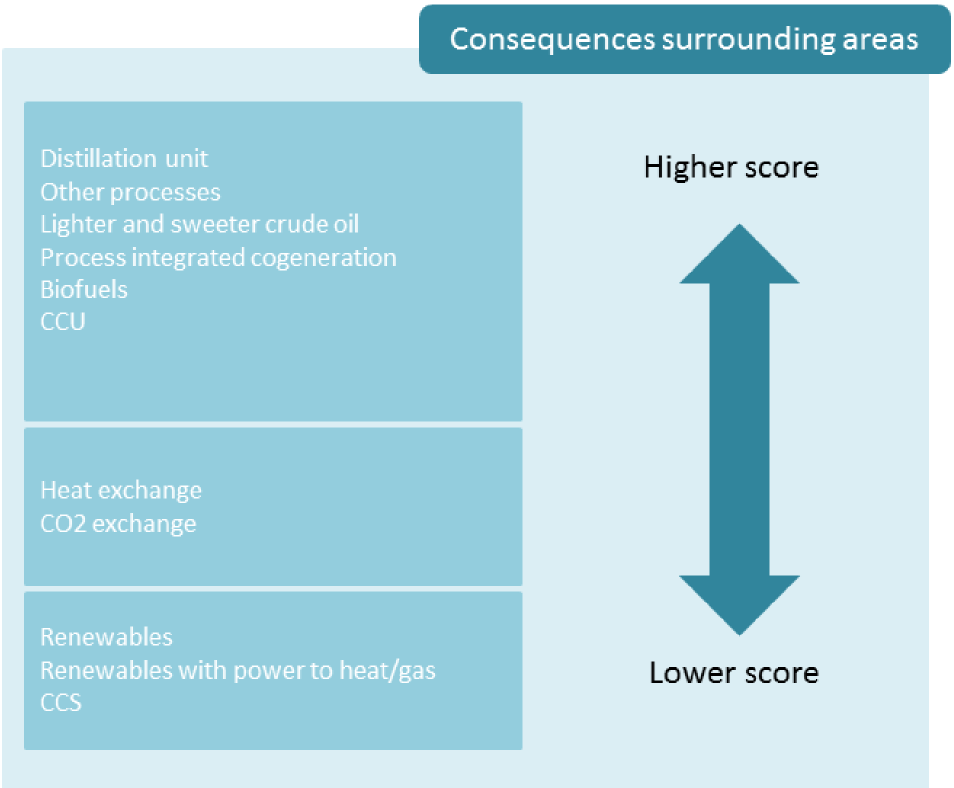

Figure 21 - ranking of alternatives on consequences surrounding areas

To minimize the resistance of citizens against the CO_2 reducing options it is important that the alternatives do not affect the surrounding areas. Some alternatives are applied within the Dutch refineries and therefore only affect the refineries themselves. These alternatives will result in a minimum of consequences for the surrounding areas. However, other CO_2 reducing technologies will have a greater impact on the surrounding area. Both alternatives with respect to renewables and CCS will have the largest impact on surrounding areas. For renewable energy, wind turbines need to be constructed. Due to their high NIMBY character they have a high impact on the surrounding areas. CCS forms a problem when the captured CO_2 needs to be stored in empty gas fields below residential areas. Plans for storing CO_2 in these fields encountered great resistance since the risk exits that CO_2 might leak from the gas field (Krebbekx et al., 2011). Heat exchange and CO_2 exchange do affect the surrounding areas since it connects the refineries to them. Some people might find this connection beneficial while others oppose such a connection. Alternatives with regard to the optimisation of processes within the refineries or the processing of a lighter and sweeter type of crude oil do not affect the surrounding areas. Also installing an process integrated cogeneration unit or CCU does not involve risks for society. Implementing biofuels within the Dutch refineries does not affect the surrounding areas as long as they do not use first generation biofuels (Graham-Rowe, 2011).

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 24 - Pairwise comparison matrix of the alternatives on consequences for surrounding areas

Pairwise comparison matrix alternatives on consequences surrounding areas												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	1	1	3	3	1	5	5	1	5	1	0.14
A2	1	1	1	3	3	1	5	5	1	5	1	0.14
A3	1	1	1	3	3	1	5	5	1	5	1	0.14
A4	1/3	1/3	1/3	1	1	1/3	3	3	1/3	3	1/3	0.05
A5	1/3	1/3	1/3	1	1	1/3	3	3	1/3	3	1/3	0.05
A6	1	1	1	3	3	1	5	5	1	5	1	0.14
A7	1/5	1/5	1/5	1/3	1/3	1/5	1	1	1/5	1	1/5	0.02
A8	1/5	1/5	1/5	1/3	1/3	1/5	1	1	1/5	1	1/5	0.02
A9	1	1	1	3	3	1	5	5	1	5	1	0.14
A10	1/5	1/5	1/5	1/3	1/3	1/5	1	1	1/5	1	1/5	0.02
A11	1	1	1	3	3	1	5	5	1	5	1	0.14
							$\lambda_{max} = 11.14$			CI = 0.014		CR = 0.009

Conflicting interests stakeholders

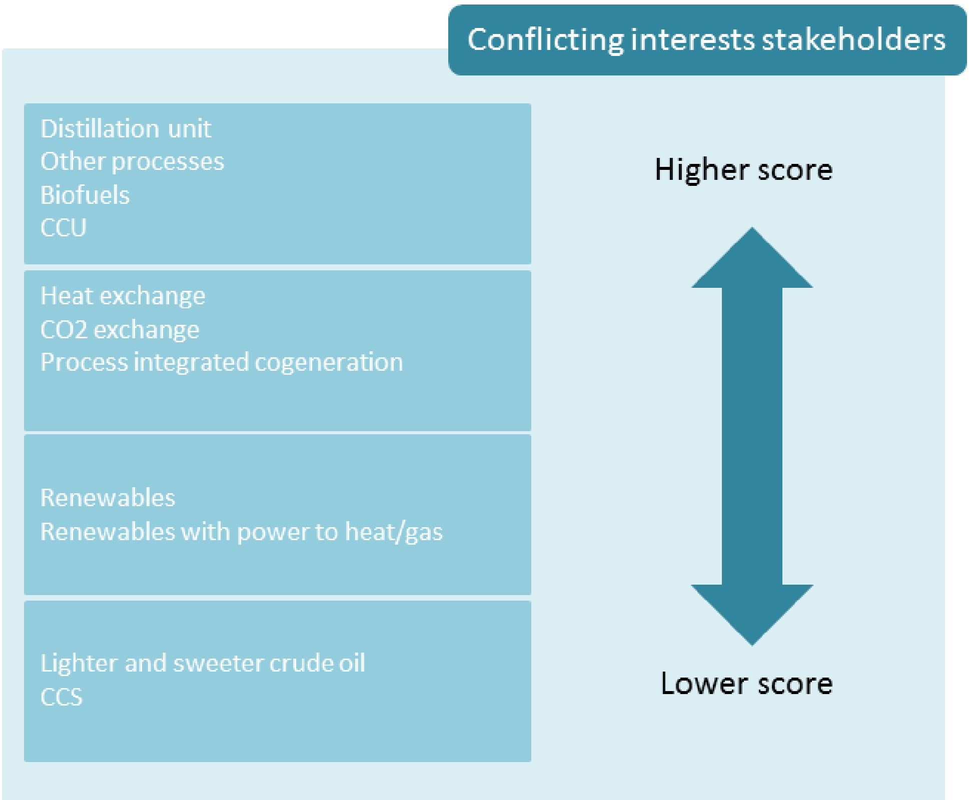

Figure 22 - ranking of alternatives on conflicting interests stakeholders

For the implementation of CO_2 reducing options within the Dutch refining industry it is furthermore important that the technologies do not result in conflicting interests between stakeholders. The alternatives that are most likely to cause conflicting interests are CCS and producing lighter and sweeter types of crude oil. CCS especially encounters resistance from the Dutch citizens when plans are made to store CO_2 in empty gas fields beneath residential areas. Processing lighter and sweeter types of crude oil will lead to opposition from the more complex Dutch refineries (Shell and ExxonMobil). This is due to the fact that these refineries have invested a lot the past couple of years in installing processes that allow these refineries to process very heavy types of crude oil. By doing so they increased their margins. Despite the fact that processing a lighter and sweeter type of crude oil would result in CO_2 reductions, it also results in a lower utilization of those expensive processes equipped to handle heavy crudes. Renewables and renewables with power to heat/gas can to a lesser extent also cause conflicting interests. Especially due to NIMBY behaviour and safety concerns. Heat exchange and CO_2 exchange might light to conflicting interests since their CO_2 allocation is not yet included within the ETS (Kampman et al., 2010). With respect to the process integrated cogeneration unit conflicting interest may arise when the feed-in tariffs for electricity further decrease. Alternatives that optimise the processes within the refineries (distillation unit and others), biofuels and CCU will not cause substantial conflicting interests.

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 25 - Pairwise comparison matrix of the alternatives on conflicting interest stakeholders

Pairwise comparison matrix alternatives on conflicting interests stakeholders												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	1	7	3	3	3	5	5	1	7	1	0.17
A2	1	1	7	3	3	3	5	5	1	7	1	0.17
A3	1/7	1/7	1	1/5	1/5	1/5	1/3	1/3	1/7	1	1/7	0.02
A4	1/3	1/3	5	1	1	1	3	3	1/3	5	1/3	0.07
A5	1/3	1/3	5	1	1	1	3	3	1/3	5	1/3	0.07
A6	1/3	1/3	5	1	1	1	3	3	1/3	5	1/3	0.07
A7	1/5	1/5	3	1/3	1/3	1/3	1	1	1/5	3	1/5	0.03
A8	1/5	1/5	3	1/3	1/3	1/3	1	1	1/5	3	1/5	0.03
A9	1	1	7	3	3	3	5	5	1	7	1	0.17
A10	1/7	1/7	1	1/5	1/5	1/5	1/3	1/3	1/7	1	1/7	0.02
A11	1	1	7	3	3	3	5	5	1	7	1	0.17
								$\lambda_{max} = 11.41$		CI = 0.041		CR = 0.027

Fit within current regulations

Optimisation alternatives for the distillation unit and other process fit perfectly within the current regulations. Implementation of biofuels and the processing of lighter and sweeter types of crude oil also do not encounter any obstructive regulations. Using renewables fits perfectly within the ETS and is even subsidized by the SDE+. Process integrated cogeneration fits a bit less within the current regulations since it is not subsidized and the beneficial feed-in tariffs for electricity do not longer exist. CCU is also not subsidized but at the same time does not faces any obstructive regulations. CCS fits a bit less within current regulations since the storage of CO_2 is subjected to strict safety regulations. Heat exchange is in the same category since it only fits within the current ETS when the heat is exchanged with residential areas instead of industries (Kampman et al., 2010). Renewables in combination with power to heat/gas encounter more difficulties since the ETS does not clearly state how the CO_2 credits are allocated in this case. CO_2 exchange is the technology that currently fits the worst within current regulations since the refineries are not awarded with the corresponding CO_2 credits (Krebbekx et al., 2011).

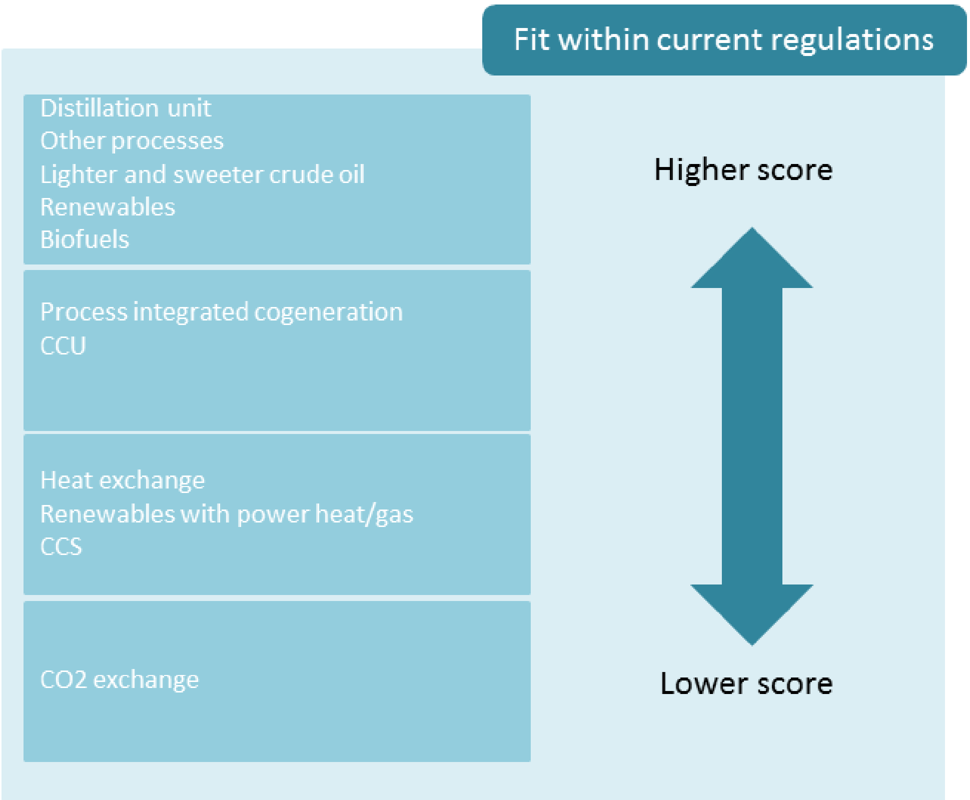

Figure 23 - ranking of alternatives on fit within current regulations

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 26 - Pairwise comparison matrix of the alternatives on fit within current regulations

Pairwise comparison matrix alternatives on fit within current regulations

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	1	1	5	7	3	1	5	1	5	3	0.15
A2	1	1	1	5	7	3	1	5	1	5	3	0.15
A3	1	1	1	5	7	3	1	5	1	5	3	0.15
A4	1/5	1/5	1/5	1	3	1/3	1/5	1	1/5	1	1/3	0.03
A5	1/7	1/7	1/7	1/3	1	1/5	1/7	1/3	1/7	1/3	1/7	0.02
A6	1/3	1/3	1/3	3	5	1	1/3	3	1/3	3	1	0.07
A7	1	1	1	5	7	3	1	5	1	5	3	0.15
A8	1/5	1/5	1/5	1	3	1/3	1/5	1	1/5	1	1/3	0.03
A9	1	1	1	5	7	3	1	5	1	5	3	0.15
A10	1/5	1/5	1/5	1	3	1/3	1/5	1	1/5	1	1/3	0.03
A11	1/3	1/3	1/3	3	5	1	1/3	3	1/3	3	1	0.07

$\lambda_{max} = 11.29$ CI = 0.029 CR = 0.019

Required institutional change

Besides the fit within current regulations, the required institutional change that is necessary for the implementation of certain CO_2 reducing options is discussed. Some alternatives require little to no adjustments in current legislation while others require a large change. Again the alternatives that optimise the processes within refineries, distillation unit and others, require the least institutional change. The same goes for processing lighter and sweeter types of crude oil and renewables. Heat exchange and CO_2 exchange do not completely fall within the ETS regulations but this requires a small institutional change. Process integrated cogeneration and renewables with power to heat/gas require a bit more institutional change. Feed-in tariffs and ETS CO_2 credits need to be installed. CCS and CCU require the largest institutional change to be viable options. The reason that CCU is scored higher is due to the fact that CCU transforms CO_2 in a valuable product which is more beneficial. Furthermore, the storage of CO_2 is subjected to strict safety regulations which makes it even harder to implement for refineries.

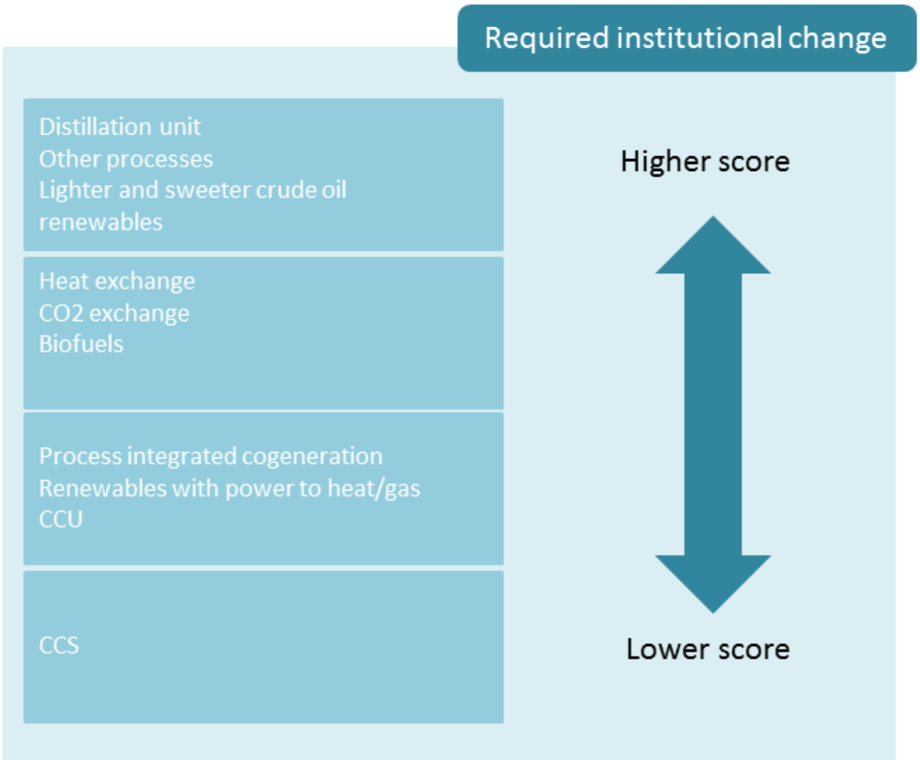

Figure 24 - ranking of alternatives on required institutional change

According to this ranking of alternatives the following pairwise comparison matrix can be constructed. Since the CR <0.10 the matrix can be considered as consistent.

Table 27 - Pairwise comparison matrix of the alternatives on required institutional change

Pairwise comparison matrix alternatives on required institutional change												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Weights
A1	1	1	1	3	3	5	1	5	3	7	5	0.17
A2	1	1	1	3	3	5	1	5	3	7	5	0.17
A3	1	1	1	3	3	5	1	5	3	7	5	0.17
A4	1/3	1/3	1/3	1	1	3	1/3	3	1	5	3	0.07
A5	1/3	1/3	1/3	1	1	3	1/3	3	1	5	3	0.07
A6	1/5	1/5	1/5	1/3	1/3	1	1/5	1	1/3	3	1	0.03
A7	1	1	1	3	3	5	1	5	3	7	5	0.17
A8	1/5	1/5	1/5	1/3	1/3	1	1/5	1	1/3	3	1	0.03
A9	1/3	1/3	1/3	1	1	3	1/3	3	1	5	3	0.07
A10	1/7	1/7	1/7	1/5	1/5	1/3	1/7	1/3	1/5	1	1/3	0.02
A11	1/5	1/5	1/5	1/3	1/3	1	1/5	1	1/3	3	1	0.03
								$\lambda_{max} = 11.34$		CI = 0.034		CR = 0.022

Summary of alternative scores

Table.. provides an overview of the scores of all alternatives on the evaluative criteria. It is a summary of the eleven pairwise comparison matrixes described previously.

Table 28 - Scores of the CO_2 reducing alternatives on the evaluative criteria

Scores of alternatives on the evaluative criteria											
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
C1	0.13	0.02	0.06	0.27	0.13	0.06	0.02	0.03	0.03	0.13	0.13
C2	0.04	0.02	0.12	0.12	0.04	0.04	0.12	0.12	0.12	0.12	0.12
C3	0.10	0.02	0.20	0.20	0.20	0.10	0.05	0.05	0.05	0.02	0.02
C4	0.02	0.02	0.05	0.23	0.05	0.02	0.05	0.11	0.11	0.11	0.23
C5	0.11	0.02	0.04	0.11	0.11	0.11	0.11	0.11	0.04	0.11	0.11
C6	0.02	0.02	0.08	0.19	0.19	0.02	0.04	0.08	0.08	0.08	0.19
C7	0.19	0.19	0.19	0.08	0.08	0.08	0.04	0.02	0.08	0.02	0.04
C8	0.14	0.14	0.14	0.05	0.05	0.14	0.02	0.02	0.14	0.02	0.14
C9	0.17	0.17	0.02	0.07	0.07	0.07	0.03	0.03	0.17	0.02	0.17
C10	0.15	0.15	0.15	0.03	0.02	0.07	0.15	0.03	0.15	0.03	0.07
C11	0.17	0.17	0.17	0.07	0.07	0.03	0.17	0.03	0.07	0.02	0.03

Most promising alternatives

To determine the most promising CO_2 reducing alternatives, the scores of the alternatives have to be multiplied by corresponding weights of the evaluative criteria.

The overall score is calculated by the following formula

$$\sum_{i=1}^{n} A_i * C_i$$

Since four actor perspectives were identified, four different overall scores of the CO_2 reducing alternatives can be constructed.

Table 29 - Weights assigned to the evaluative criteria from all four actor perspectives

	Weight assigned to the criteria from all four actor perspectives			
	Dutch government	Highly complex and integrated refineries	Less complex and non-integrated refineries	Dutch citizens
C1	0.23	0.19	0.23	0.22
C2	0.05	0.08	0.11	0.04
C3	0.05	0.03	0.11	0.10
C4	0.02	0.03	0.02	0.02
C5	0.02	0.08	0.05	0.04
C6	0.11	0.08	0.05	0.10
C7	0.23	0.19	0.23	0.04
C8	0.11	0.02	0.02	0.22
C9	0.05	0.19	0.05	0.10
C10	0.05	0.08	0.11	0.04
C11	0.11	0.03	0.05	0.10

Table 30 - Scores of the CO2 reducing alternatives on the evaluative criteria

	Scores of alternatives on the evaluative criteria										
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11
C1	0.13	0.02	0.06	0.27	0.13	0.06	0.02	0.03	0.03	0.13	0.13
C2	0.04	0.02	0.12	0.12	0.04	0.04	0.12	0.12	0.12	0.12	0.12
C3	0.10	0.02	0.20	0.20	0.20	0.10	0.05	0.05	0.05	0.02	0.02
C4	0.02	0.02	0.05	0.23	0.05	0.02	0.05	0.11	0.11	0.11	0.23
C5	0.11	0.02	0.04	0.11	0.11	0.11	0.11	0.11	0.04	0.11	0.11
C6	0.02	0.02	0.08	0.19	0.19	0.02	0.04	0.08	0.08	0.08	0.19
C7	0.19	0.19	0.19	0.08	0.08	0.08	0.04	0.02	0.08	0.02	0.04
C8	0.14	0.14	0.14	0.05	0.05	0.14	0.02	0.02	0.14	0.02	0.14
C9	0.17	0.17	0.02	0.07	0.07	0.07	0.03	0.03	0.17	0.02	0.17
C10	0.15	0.15	0.15	0.03	0.02	0.07	0.15	0.03	0.15	0.03	0.07
C11	0.17	0.17	0.17	0.07	0.07	0.03	0.17	0.03	0.07	0.02	0.03

Table 31 - Overall score of the alternatives from the four different actor perspectives.

	Weighted scores of alternatives for the four actor perspectives			
	Dutch government	highly complex and integrated refineries	less complex and non-integrated refineries	Dutch citizens
A1	0.13	0.13	0.13	0.12
A2	0.10	0.10	0.09	0.09
A3	0.12	0.10	0.13	0.11
A4	0.14	0.13	0.14	0.14
A5	0.10	0.09	0.10	0.10
A6	0.07	0.07	0.07	0.08
A7	0.06	0.06	0.06	0.05
A8	0.04	0.05	0.05	0.04
A9	0.08	0.09	0.08	0.09
A10	0.06	0.06	0.07	0.06
A11	0.10	0.11	0.09	0.12