Reducing CO_2 emissions of the Dutch refining industry towards 2050

Analysing CO_2 reducing alternatives by applying an extended Technology Assessment

T.W.H. Wanders

Faculty of Technology, Policy & Management, Delft University of Technology

Abstract:

The Dutch refining industry faces increasingly stringent CO_2 reducing policies. In order to comply to these regulations, they have to invest in alternatives that reduce the CO_2 emissions of the Dutch refineries. This paper first of all analyses the Dutch refining industry and determines the factors that contribute to its CO_2 emissions. The most polluting processes within a refinery are the distillation unit, FCC unit, hydrocracker and flexicoker. Besides the effect of the refining processes, the CO_2 emissions of Dutch refineries are also influenced by their crude oil intake. CO_2 emissions increase if crude oil has a lower API gravity (heavy) and a high sulphur content (sour). A wide variety of CO_2 reducing options is identified within this paper which are assessed by an extended Technology Assessment that incorporates economical and institutional perspectives. In the end, a multi-criteria analysis, that includes the perspectives of multiple actors, is used to identify the most promising CO_2 reducing alternatives. It can be concluded that heat exchange, optimisation of the distillation unit, processing lighter and sweeter types of crude oil and CCU are the most promising CO_2 reducing alternatives.

Keywords:

The Dutch refining industry – CO_2 allocation – CO_2 reducing alternatives – Technology Assessment

1. Introduction

The European Union aims to reduce greenhouse gas emissions by 80% to 95% below 1990 levels by 2050 (EFC, 2010). Perhaps even further in view of the recent Paris agreement (UNFCCC, 2015). 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 emitted a total of 11 Mton of carbon dioxide (CO_2) in 2015. 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). Processes that convert crude oil into all kinds of different products are highly energy intensive and cause refineries to emit large amounts of CO_2 and other polluting particles (Johansson et al., 2013). As a result the Dutch refining industry is especially affected by the increasingly stringent environmental legislation (ECN, 2015). Therefore investments are required for the implementation of alternatives that reduce the CO_2 emissions of Dutch refineries.

However, it seems that complying to the increasingly stringent environmental regulations is not the only challenge for the Dutch refining industry. European and global developments also have a large impact on the sector. 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). Competition within the refining industry severely intensified. Refining margins are crucial for the competitiveness of refineries. Despite high refining margins in 2015 due to the 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 caused by high energy and labour costs for European refineries.

So it can be concluded the Dutch refining industry faces increasingly stringent CO_2 reducing policies. In order to comply to these regulations, they have to invest in alternatives that reduce the CO_2 emissions of the Dutch refineries. However, due to increasing competition, decreasing European oil demand an thin refining margins these investments cannot be taken for granted. The main research goal of this paper therefore 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 answer the research question three research questions are formulated

1. How are the CO_2 emissions of Dutch refineries affected by their refining processes and the crude oil they process?
2. What are possible options that can be used to reduce the CO_2 emissions of Dutch refineries?
3. In which way can a Technology Assessment (TA) be used to analyse the CO_2 reducing options and what are the most promising alternatives?

Key within this paper is the reduction of CO_2 emissions from Dutch refineries. Refineries also emit other hazardous pollutants like 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 paper. This is mainly due to the fact that the Dutch refining industry already reduced these emissions quite substantially (Emissieregistratie, 2016). Hence, this paper solely focusses on the CO_2 emissions directly related to refineries. CO_2 emissions related to the extraction of crude oil or the usage of refining products are not taken into account. This paper furthermore focusses on the Dutch refining industry alone.

The next section of this paper describes the applied methodologies. Section 3 provides the foundation of this paper and analyses the CO_2 profile of Dutch refineries. Based on this information a thorough analyses can be conducted in section 4 which explores the wide variety of options that reduce the CO_2 emissions of Dutch refineries and can be implemented in the sector. Section 5 applies TA to assess the variety of CO_2 reducing alternatives and determines the most promising ones. Finally section 6 presents the conclusion and discussion.

2. Research methodology

Research question one and two are answered by collecting information using a desk research. To get a better understanding of the processes that take place within a refinery, literature is consulted that provides an overview of petroleum processing. Treese et al. (2015), Fahim et al. (2013) and Parkash (2003) are combined for a thorough analysis of the refining industry. Thereafter the processes located within Dutch refineries need to be determined. This paper tried to construct the most detailed overview possible using public data. Sources from the Port of Rotterdam (2016) and a barrel full (2015) were used. The constructed overview also provides the basis for the allocation of the CO_2 emissions of Dutch refineries to their individual processes. Besides the refining processes, the amount of CO_2 emitted by Dutch refineries is also influenced by their crude oil intake. Data from the CBS (2016) concerning crude oil imports was combined with data from Jacobs (2012) to determine this influence.

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. First technologies that reduce the CO_2 emissions of the most polluting processes were identified. The research of Plomp & Kroon (2010) provided most information. A second CO_2 reducing alternative is the processing of a different type of crude oil. Other CO_2 reducing alternatives were based on the study of Krebbex et al. (2011) and Kampman et al. (2010).

To assess the wide variety of CO_2 reducing options that can be implemented within the Dutch refining industry this paper uses Technology Assessment (TA) as basis. Grunwald (2009) provided an overview of TA and was used as an important source for the comprehension and application of TA within this paper. The most suitable TA concept and methodology is determined. Where needed, the TA framework is extended and used to deduct the criteria for assessing the CO_2 reducing alternatives. This paper uses decision-analytical methods to evaluate alternatives by means of a multidimensional integration of the various criteria. In other words, 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).

3. CO_2 profile of Dutch refineries

The CO_2 emissions of Dutch refineries are for the most part determined by their refining configuration and crude oil intake (Bredeson et al., 2010). Part two of this paper further explores these two factors and their effects on the CO_2 emissions of Dutch refineries.

Allocating CO_2 emissions to refinery processes

Before the CO_2 profile of Dutch refineries can be constructed it is necessary to get a better understanding of the different Dutch refineries and the processes within them. There are 6 refineries located in the Netherlands 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. Configurations of Dutch refineries range from relatively simple to highly complex.

In general, refineries can be classified into four common types, namely topping refinery, hydroskimming refinery, cracking refinery and coking (full conversion) refinery. These types describe refinery configurations that increase in complexity and are more capable to process heavier types of crude oil. The construction of 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 is impossible to construct a complete overview of all processes present within the Dutch refining industry. Processes present within Dutch refineries that can be identified were: atmospheric distillation, vacuum distillation, catalytic reforming, alkylation, fluid-bed catalytic cracker, hydrocracker, hydrotreater, thermal cracker, visbreaker and flexicoker (Port of Rotterdam, 2016 ; A Barrel Full, 2015). It can concluded that the Koch refinery had the relatively simplest configuration and could be categorized as a topping refinery. The Shell Pernis and ExxonMobil refineries are the most complex and can be categorized as a coking or full conversion refinery.

Refining processes are highly energy intensive and have a large effect on the environment (Johansson et al., 2013). The most common contaminants are: sulphur (SO_2), carbon oxides (COx), nitrogen oxides (NOx), volatile organic compounds, particulate matter (PM10) and ozone (Hadidi et al., 2016). In the past decade Dutch refineries faced increasingly stringent environmental regulation which required them to reduce their emissions of most 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). 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 1. Nevertheless, CO_2 emissions of Dutch refineries remain high.

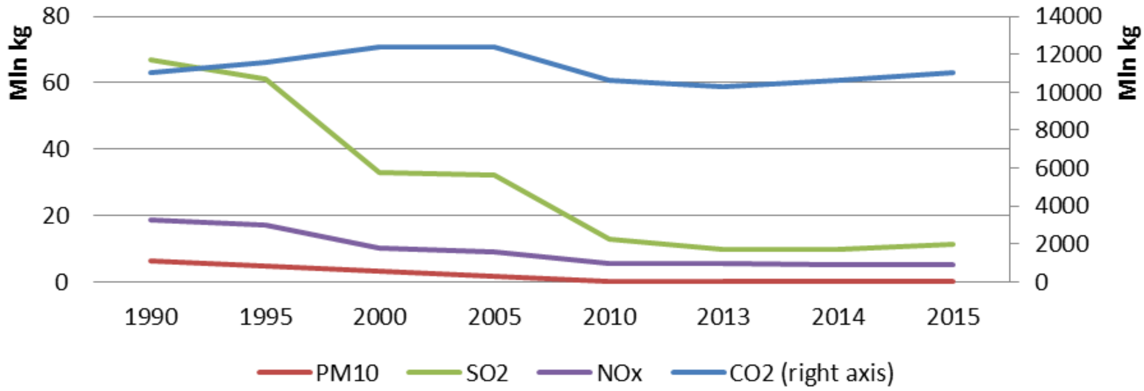

Figure 1 emissions of Dutch refineries from 1990 till 2015 (Emissieregistratie, 2016)

In order to determine which processes emit the most CO_2 within Dutch refineries, the CO_2 emissions need to be allocated. The allocation of CO_2 emissions to the different processes requires data on the throughput of each process. Since a significant amount of Data concerning Dutch refineries is not publically available, not all processes located within Dutch refineries could be included. Data is used from the Port of Rotterdam (2016). and a barrel full (2015). Due to the limited amount of available data a methodology is used that tries to overcome this problem. 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).

Wanders (2017). conducted this analysis and found the following results. As expected, the calculated total CO_2 emissions of Dutch refineries differed from the actual emitted amount due to the lack of available data. Despite the inaccuracies, this analysis provides some useful insights that can be used within this Paper. From the CO_2 allocation to the different refinery processes it becomes clear 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, like the Koch refinery, 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. The analysis furthermore showed 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).

Crude oil intake

To complete the CO_2 profile of Dutch refineries the crude oil intake must also be assessed. Wanders (2017) concluded that the CO_2 emissions of Dutch refineries are also dependent on the crude oil intake. 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.

To assess the impact of the crude oil intake on the CO_2 emissions of Dutch refineries it is necessary to first explore the different types of crude oils that are used by Dutch refineries. In 2015 the Netherlands imported a total of 62 million tons of crude oil (CBS, 2016). Russia and Norway are the largest suppliers of crude oil for the Netherlands. Other important suppliers are Nigeria, Kuwait and the United Kingdom. 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. Table 1 shows the different countries with their crude oil types along with the properties API gravity and sulphur content. It can be concluded that 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.

Table 1- 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	Kirkuk blend	33.7	1.9
Saudi-Arabia	Arab medium	31.3	2.5
Algeria	Saharan Blend	43.6	0.1

The overview provided in Table 1 makes is possible to assess the effect of the crude oil intake of Dutch refineries on their CO_2 emissions. CO_2 emissions of Dutch refineries are first of all 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. Jacobs (2012) concluded that as the API gravity of crude oil increases, the CO_2 emissions of refineries decrease. 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 which limit the amount of SO_2 that refineries are allowed to emit. They are therefore forced to remove the sulphur when processing the crude oil. This can be achieve 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. As a result, a high sulphur content of crude oil results in higher CO_2 emissions of refineries.

4. CO_2 reducing options for the Dutch refining industry

The CO_2 profile of Dutch refineries, constructed in the previous part of this paper, formed the basis for the overview of CO_2 reducing options that can be implemented within the Dutch refining industry. 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 alternatives for reducing the CO_2 emissions of Dutch refineries.

Process optimisation

There are numerous technologies that can reduce the CO_2 emissions of refining processes by improving the efficiency. However, this paper only focusses on the technologies that reduce the CO_2 emissions of the most polluting processes idenftified in the part two of this paper. It became clear that the atmospheric distillation unit was in most cases the largest emitter of CO_2 within Dutch refineries. FCC, hydrocracking and flexicoking. also substantially contributed to the total CO_2 emissions of the Dutch refineries.

Since distillation is one of the most energy intensive operations within a refinery, improving the efficiency of this process has the greatest potential for CO_2 emissions reductions. The first possible technology that can be used to increase the efficiency of a refinery is the integration of the atmospheric distillation unit with the vacuum distillation unit (Plomp & Kroon, 2010). A second method for improving the efficiency within a refinery is the optimization of the atmospheric distillation unit. To further improve the efficiency of the atmospheric distillation unit a preflash column or preflash drum can be installed (Errico et al., 2009). An even higher energy efficiency can be achieved by integrating the preflash column into a multicolumn design. Finally, dividing wall distillation is assessed which integrates two conventional distillation columns by placing a separation wall between them.

The FCC unit can be optimised by a new design, the Downer reactor, which lets the catalyst and gasflow run downwards with the force of gravity and thereby improves its efficiency. With regard to the hydrocracking process two areas of technology innovations can be identified that increase the efficiency of the refinery. The first innovations uses new catalysts which allows the unit to process more, heavier and higher sulphur content products. A 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). There are currently little to no technologies available for directly reducing the CO_2 emissions of the flexicoking unit (Vleeming & Hinderink, 2011). There is however a new approach with regard to the refining of crude oil which places the coking unit at the beginning of the process. In this the separation is simplified and requires less energy (Szklo & Schaeffer, 2007).

Crude oil intake

Wanders (2017) concluded that the type of crude oil that Dutch refineries process influences their CO_2 emissions. Especially the 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. They furthermore require less additional treatment and as a result less refining processes are needed. An increase of API gravity of 35 could result in a decrease of CO_2 emissions by 25% to 33% (Jacobs, 2012). Furthermore a high sulphur content of crude oil also results in higher CO_2 emissions. A straightforward possibility for Dutch refineries is to reduce their CO_2 emissions by processing lighter and sweeter crudes.

Regional integration

Reducing the CO_2 emissions of the Dutch refining industry can also be achieved by integrating refineries with the regions surrounding them. With regard to this integration, there are two interesting options for the Dutch refining industry (Kampman et al., 2010). The first option is to exchange heat with nearby city districts and greenhouses. Since refineries produces a lot of excess heat this is an interesting option which increases the efficiency and indirectly reduces CO_2 emissions. 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 its surroundings. 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 areas is not the only option. Industrial areas that require low temperature heat for their production processes are suitable alternatives. A second option is supplying the CO_2 to greenhouses which use this for their cultivation. Greenhouses have a high demand for CO_2 and it is expected that this demand will rise even further the upcoming years. The CO_2 is used by horticulturists to increase the production of their crops. At the moment the CO_2 is supplied by cogeneration units. However, due to high gas prices and low electricity prices the market conditions for cogeneration units seem to deteriorate. This offers a great opportunity for refineries to supply CO_2 to the greenhouses (Kampman et al., 2010).

Heat and electricity production

All processes within a refinery are either dependent on produced heat or electricity. The burning of fuel and the generation of electricity can be large sources of CO_2 emissions. Therefore alternative options for the production of heat and electricity are assessed. 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). Another option to reduce the CO_2 emissions of Dutch refineries is to replace the energy that is acquired from fossil fuels by energy from renewable energy sources. Possible alternatives are wind and solar power. Renewable energy from these sources can be used within the Dutch refining industry in two forms. The generated electricity can be directly used by processes that require electricity within the refinery. An alternative use for the heat requiring processes is the conversion of electricity to heat (power-to-heat) or gas (power-to-gas) (Hers et al., 2015 ; ECN, 2014).

Biofuels

Another possibility for reducing CO_2 emissions of the Dutch refining industry is the implementation of biomass within the sector. There are two main possibilities to implement biomass within the Dutch refining industry. The first option is adding biomass products into the blending unit at the end of the refining process. However, since this option does not affect the CO_2 emissions of the refinery itself but only reduces the carbon intensity of the transport fuels, it is not taken into account. The second option is the implementation of biomass into the refining processes (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 replace a part of this mineral feedstock by an oil or liquid from biological origin. There are three main biofuel feedstock possibilities for refineries that respectively use vegetable oil, pyrolysis oil and algae-based biofuels.

Carbon capture

Finally, a way to further reduce the CO_2 emissions of Dutch refineries is through the capture of CO_2. Carbon capture makes is possible to extract the CO_2 from the effluent before it is emitted into the air. In theory such technology can greatly reduce the CO_2 emissions from 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). After the CO_2 is captured and compressed a solution needs to be found for the remaining CO_2. In general two alternatives exist, namely carbon capture and storage (CCS) and carbon capture and utilisation (CCU). Both alternatives aim at preventing the release of large quantities of CO_2 into the atmosphere. CCS captures the CO_2 and stores it in a location so that the emissions do not enter the atmosphere. CCU captures the CO_2 and utilizes it in different ways.

5. 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. Within this paper TA is used to analyse the wide variety of CO_2 reducing options that the Dutch refining industry can implement to meet the increasingly stringent CO_2 policies. TA is suitable for this paper because it deals with the relationship between technological change an social problems (Grunwald, 2009). Wanders (2017). determined that the usage of TA along with a multi-criteria analysis at method is most suitable for determining the most promising CO_2 reducing alternatives. TA mainly focusses on assessing technologies while accompanying the process of technological developments. Therefore it is logical that first of all criteria related to the technical feasibility of the alternatives are included. Since TA also tries to include economic players and societal actors criteria related to the interests of involved actors are also taken into account.

Missing aspects within TA

However it is important to assess the current developments within TA to determine if criteria from other perspectives need to be included as well. Since TA is highly context dependent its results are therefore very sensitive to changes in fields of technology, relevant actors, and political settings. Due to the fact that the role of technology in society is less determined by the product's or system's feasibility, economic aspects and societal acceptation become increasingly important (Grunwald, 2009).

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. It is therefore important to also include institutional criteria within the multi-criteria analysis. Besides the shifting of institutions from national structure to a higher and more aggregate level, globalisation also has economic consequences. The Dutch refining industry finds itself operating in a global market and faces a lot of competition from export orientated refineries in the Middle-East and China. It is crucial that the implementation of the CO_2 reducing technologies does not deteriorate the competitiveness of the Dutch refineries. Therefore, economic aspects also need to be included within the multi-criteria analysis. Figure 2 presents the evaluative criteria that are used in the multi-criteria analysis.

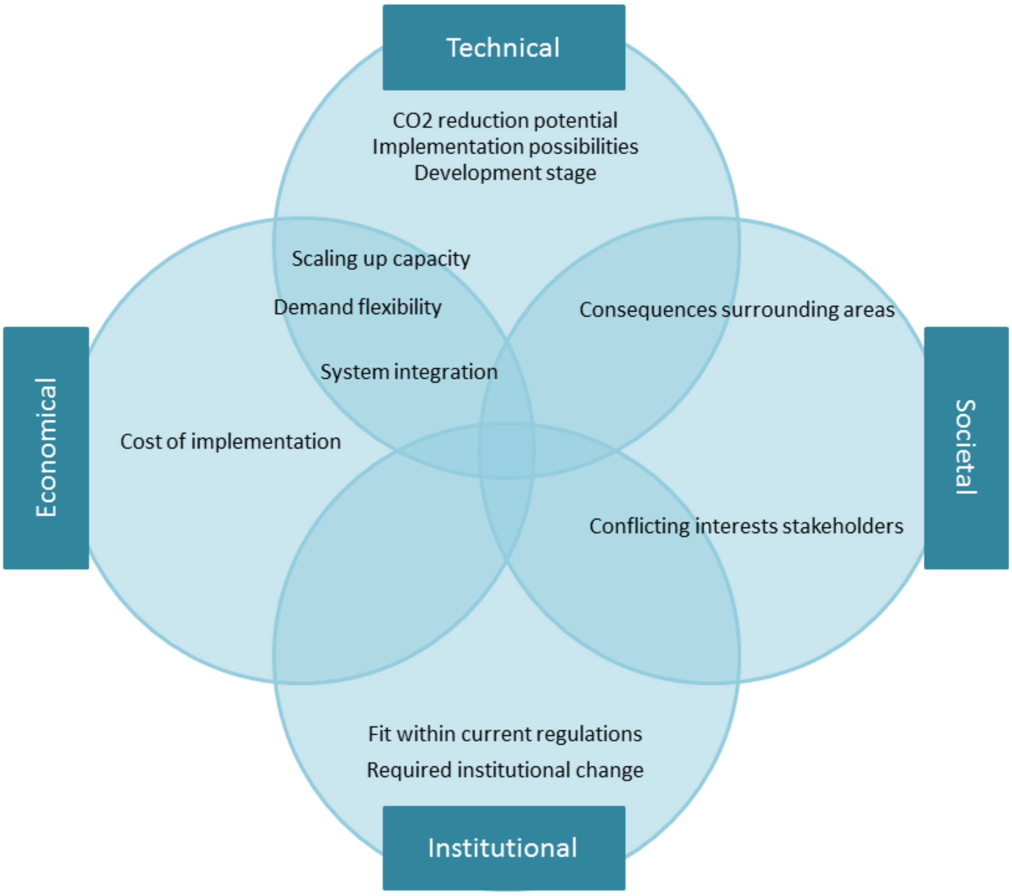

Figure 2 - The evaluative criteria from all four perspectives

Multi-criteria analysis

To determine the most promising CO_2 reducing alternatives that can be implemented within the Dutch refining industry a multi-criteria analysis is performed. The evaluative criteria deducted from the extended Technology Assessment, shown in figure 2, formed the basis of this analysis. A multi-criteria analysis can be used within this paper since it addresses complex problems which feature high uncertainties, conflicting objectives, different forms of data and multiple interests and perspectives (Wang et al., 2010). The wide variety of CO_2 reducing options identified in part two of this paper are transformed into the following eleven alternatives:

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

The next step is the selection of a multi-criteria decision making tool. Within this paper, determining the most promising CO_2 reducing alternatives, was done by applying the analytical hierarchy process (AHP) (Saaty, 1990 ; Mateo, 2012). 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. Wanders (2017) identified the four most important actors with regard to the implementation of CO_2 reducing alternatives within the Dutch refining industry. 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 2. From this table 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.

Table 2 - 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

6. Conclusion

Overall it can be concluded that the main research goal of this paper is achieved. The Dutch refining industry is analysed and the factors that contribute to its CO_2 emissions identified. first of all, the most polluting processes within a refinery appeared to be the distillation unit, FCC unit, hydrocracker and flexicoker. Besides the effect of the refining processes, the CO_2 emissions of Dutch refineries are also influenced by their crude oil intake. CO_2 emissions increase if crude oil has a lower API gravity (heavy) and a high sulphur content (sour). Furthermore this paper provided a wide variety of CO_2 reducing options. TA was applied and extended with economical 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 3.

Table 3 – 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
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 optimization 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 option. 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. It is less interesting for the highly complex/integrated refineries since the processing of lighter and sweeter crudes lowers their utilisation. CCU is an interesting alternative but has not yet reached a mature phase and is still very expensive. However, it shows great potential towards 2050.

7. Discussion

The construction of 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 is impossible to construct a complete overview of all processes present within the Dutch refining industry. An incomplete overview of refining processes had consequences for the allocation of CO_2 emissions to the individual processes of Dutch refineries. It appeared that the calculated total CO_2 emissions of Dutch refineries differed from the actual amount of CO_2 emitted. The difference between the calculated and actual CO_2 emissions of Dutch refineries increased as the complexity of refineries increased. 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 appeared to be useful and determined the most polluting processes within Dutch refineries. The actual percentages are not correct but the conclusions that were made, matched with results from other studies (Reinoud, 2005).

Based on the CO_2 profile of Dutch refineries this paper provided an overview on the wide variety of CO_2 reducing options that could be implemented within Dutch refineries. In general, two categories were identified. Options that reduce the CO_2 emissions of refineries by maximising their energy efficiency and options that maximize their carbon efficiency. This paper only included options that were identified in other studies with regard to reducing the CO_2 emissions of Dutch refineries. Off course more experimental options exist but these were not taken into account.

To determine the most promising CO_2 reducing alternatives a multi-criteria analysis was 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 paper included the four most important actors and allocated the weights according to their expected preferences. Nevertheless, these weights could 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 paper 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.

Based on the results of this paper and the discussion presented above, certain topics for future research can be identified. Future research could use this paper as the basis for a new multi-criteria analysis based on quantitative data. Furthermore 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. This paper determined the most promising CO_2 reducing alternatives. Problems that may arise with regard to the actual implementation of these alternatives were not taken into account. Future research might examine the actual implementation of the most promising CO_2 reducing alternatives.

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