Techno-economic performance of post-combustion CO_2 capture and energy efficiency measures in an oil refinery

Analysis into the interactions between both mitigation options and different deployment opportunities

Final Report
Master Thesis

Name: R.A.M.A. Foppele

Student number: 3479153

E-mail address: r.a.m.a.foppele@students.uu.nl

Postal address: Hermusstraat 15, 4611 BL Bergen op Zoom, The Netherlands

Program: Energy science
Track: System Analysis

Number of ECTs: 37.5
Daily supervisor: N.A. Berghout (UU)
Supervisor: C.A. Ramirez (UU)
Second Reader: M.A. van den Broek (UU)

Universiteit Utrecht

Table of Contents

Summary

To date, the interaction among different mitigation options at one industrial site has not been investigated in literature. There is insufficient knowledge available on the interaction between energy efficiency measures (EEMs) and post-combustion capture. Further research on these interactions is needed as they may strongly influence the techno-economic performance of EEMS and/or post-combustion capture.

The objective of this study is two-fold. First, it examines the CO_2 emission reduction potential and techno-economic performance of post-combustion capture and energy efficiency measures at an oil refinery. Second, this study examines under which conditions EEMs and post-combustion capture can be jointly implemented from a techno-economic and practical perspective.

This is assessed by first calculating the techno-economic performances of post-combustion and energy efficiency measures separately. Then, different scenarios are assessed where these mitigation options are combined at the case refinery. These scenarios differ in implementation order (EEMs first or post-combustion capture first) and regeneration heat supply for post-combustion capture (NGCC or excess heat). For comparison, also scenarios will be assessed where practical issues and interactions between mitigation options are ignored.

The results show that when EEMs and post-combustion capture are combined, a total CO_2 reduction potential of 482 ktCO_2 per year is achievable at the case refinery of this study. This corresponds to a reduction of 87%. This is in a scenario where EEMs are implemented first and the required heat for post-combustion capture is supplied by excess heat. From the perspective of the refinery this proved to be the preferable scenario. From a global perspective, the scenario with NGCC as heat supply proved to be preferable because of the excess electricity production that can be sold to the grid. Indirectly, the total global CO_2 avoidance is then much larger.

Comparing the scenarios with each other shows that implementation order influences the avoidance costs of post-combustion capture by 1-4 €/tCO_2. Practical issues and interactions between mitigation options could lead to avoidance costs for post-combustion capture of up to 28 €/tCO_2 higher (for a NGCC with high heat demand).

1. Introduction

1.1 Background

In order to mitigate the damages climate change can cause, most scientists agree that CO_2 concentrations should be stabilized at twice the pre-industrial level (450 ppmv) or lower (Richels & Edmonds, 1995). Worldwide emissions should therefore be reduced by more than 50% compared to the 1990 level to reach this target (Anderson & Bows, 2008). Oil refineries are responsible for a large share of the CO_2 emissions in the industrial sector. For instance, in 2008, 8% of the total industrial CO_2 emissions in the EU was emitted by EU refineries, which is approximately 150 $MtCO_2/y$ (Johansson et al., 2012). A report made by the IEA (2011) has shown that the CO_2 emission reduction targets in the refinery sector cannot be achieved by implementing energy efficiency measures (EEMs) alone. A combined portfolio of mitigation options including EEMS, feedstock substitution, and CO_2 capture and storage (CCS) is necessary to achieve the reduction targets.

The EU Emission Trading Scheme (EU ETS) came into force on January 1st, 2005. This scheme puts an extra cost on CO_2 emissions from utilities and industrial facilities, including oil refineries (Holmgren & Sternhufvud, 2008). Simultaneously, EU legislation on the production of low-sulphur fuels is becoming more stringent (Holmgren & Sternhufvud, 2008). As a consequence, further refining of crude oils is required to meet the sulphur standards, which requires higher process intensity, and thus, higher energy use and CO_2 emissions (Johansson et al., 2012). As a result, the need for mitigation measures is even larger. Increasing costs is a strong incentive for large energy users to reduce their energy consumption and thus increase their energy efficiency.

To date, several studies have investigated the potential for energy efficiency measures in oil refineries. For example, Worrel et al., (forthcoming) made an extensive inventory of energy efficiency measures available for petroleum refineries in the US. A similar study for Europe was carried out by the IPPC (2003). Saygin et al. (2011) reported that the technical potential for EEMs is around 5.6 EJ/y (16%) and 5.25 ± 1.4 EJ/y (15 ± 4%) from a top-down and bottom up approach, respectively, for the global refinery sector when best practice technologies (BPT) are applied. Most studies on energy efficiency focus on the refinery sector level rather than on the refinery plant level. However, studies on the plant level are important for obtaining in-depth knowledge about the practical feasibility of EEMs, which can be used for drawing broader lessons at the sector level. For example, Holmgren & Sternhufvud (2008) conducted a bottom-up analysis to assess the abatement costs and practical issues (e.g. space limitations, retrofitting) for different EEMs at two Swedish oil refineries. They found CO_2 reduction potential of 8% and 22% for the two refineries and concluded that many of the assessed EEMs show negative avoidance cost. However, they also found that the practical issues related to the implementation are hard to predict.

Next to the studies on EEMs at refineries, several studies have looked into the potential to reduce CO_2 emissions by means of CO_2 capture technologies (e.g. Kuramochi et al. (2012), Berghout et al. (2013), Johansson et al. (2012) and Saygin et al. (2013)). Kuramochi et al. (2012) made an extensive comparison of the three main carbon capture technologies in different industrial sectors by assessing their CO_2 reduction potential and techno-economic performance. Berghout et al. (2013) examined, among other things, the CO_2 reduction potential and techno-economic performance of CO_2 capture in two refineries in the Netherlands. They found a CO_2 reduction potential via post-combustion capture of 81-83% on the short term (2020-2025). Kuramochi et al. (2012) found a CO_2 reduction potential of post-combustion capture of 59-77% on the short term.

Saygin et al. (2013) analyzed the potential of both energy efficiency measures and CO_2 capture. This was done for several industrial sectors in the Netherlands, including the refinery sector. Johansson et al. (2012) investigated the CO_2 reduction potential of both EEMs and carbon capture for Europe.

So far, the interaction among the mitigation options has not been investigated in literature. An interaction refers to the impact a mitigation measure has on the CO_2 emission reduction potential and/or practical feasibility of another mitigation measure. Further research on these interactions is needed as they may strongly influence the techno-economic performance of EEMS and/or post-combustion capture. For example, an EEM may reduce the potential of other EEMs in case they address the same inefficiency problem or make other EEMs more expensive due to practical issues. The latter EEMs then become economically less attractive. Additional research at the refinery plant level is required to assess the CO_2 reduction potential and mitigation costs of EEMs and CO_2 capture technologies, including the joint implementation of both options. Especially more insights are needed into the required conditions for a joint implementation of the mitigation options and how this affects the overall CO_2 emission reduction potential and techno-economic performance.

1.2 Objectives

This MSc thesis builds on a research carried out during an internship at Chalmers university of Technology in Gothenburg, Sweden (Foppele et al., 2014). The related research focused on the practical implementation of EEMs and their reduction potential. This master thesis extends the research by including post-combustion carbon capture in the analysis.
The objective of this study is two-fold. First, it examines the CO_2 emission reduction potential and techno-economic performance of post-combustion capture and energy efficiency measures at an oil refinery. Second, this study examines under which conditions EEMs and post-combustion capture can be jointly implemented from a techno-economic and practical perspective. The study will be based on a detailed bottom-up analysis for a Swedish oil refinery. The results of this research can serve as valuable input for the development of a

cost effective strategy to achieve far-reaching CO_2 emission reductions by deploying several mitigation options in the refinery sector over time. A merit order for implementing these technologies will be determined. Efforts will be made to draw broader lessons for refineries in general.
Due to confidentiality reasons detailed data for the case refinery is not presented throughout the report. The main research questions are:

What is the techno-economic performance and CO_2 reduction potential of post-combustion capture and energy efficiency measures at the refinery plant level, and how can these mitigation options be implemented jointly?

The main research question is divided into several subquestions:

- What is the CO_2 reduction potential of post-combustion capture for the case refinery?
- How does post-combustion capture perform from a techno-economic perspective?
- What are the marginal abatement costs of post-combustion capture and EEMs?
- Under which conditions can EEMs be jointly implemented with post-combustion capture at the case refinery, and under which conditions are they mutually exclusive from a techno-economic (and practical) perspective?

The following system boundaries will be maintained throughout this research:

- This study focuses on one case refinery.
- For the case study, the boundaries are set at the refinery site's boundaries.
- Only post-combustion capture based on MEA absorption is taken into account, because it is probably the only capture technology available in the short term (Intergovernmental Panel on Climate Change (IPCC), 2005). CO_2 compression is part of the post-combustion capture process.
- CO_2 transport and storage are not investigated in detail in this study. Instead, generic figures are used to account for the costs related to these parts of the CCS chain.
- The techno-economic performance will be based on detailed calculations. However, no process simulation software (e.g. Aspen Plus) will be used in this study.

2. Theory

To date, energy efficiency measures and CO_2 capture technologies at the refinery plant level have mostly been assessed separately from each other. An overview of recent studies regarding EEMs is given in the internship report (see Foppele et al. 2014). The case refinery and practical issues are also discussed in the internship report. This section gives a short summary of the theory section from the internship report and discusses recent studies about CCS at refineries and different configuration options.

2.1 Summary of theory section from the internship report

2.1.1 Energy efficiency measures

The techno-economic performance of energy efficiency measures at refineries have been analyzed by e.g. Holmgren & Sternhufvud (2008), Johansson et al., (2012) and Stockle et al., (2008). These studies assessed the costs (savings) and CO_2 emission reduction potential of potential efficiency measures. Examples of these measures are waste heat recovery, co-generation of heat and power (CHP) and combustion efficiency improvements. The total overview of the measures assessed in this study can be found in the appendix.
Worrell & Galitsky (2005) presented available energy efficiency measures for refineries in the US. First, they described the trends, structure, and production of the refining industry as well as the energy used in the refining and conversion processes. They calculate that the technical potential of energy savings was close to 20-30% and the economic potential of energy savings was 10-20% for most US oil refineries.

Saygin et al. (2011) applied both bottom-up and top-down approaches and developed an improved dataset for Best Practice Technologies (BPT) energy use in Europe. As a result, Saygin et al. (2011) calculated a global energy efficiency potential of 16% for the chemical and petrochemical sector.

According to Johansson et al. (2012), energy efficiency improvements and the transition to less carbon intensive fuels are the most promising strategies to reduce CO_2 emissions in the short term. Fuel substitution would imply the transition from fuel oil to natural gas and could result in a CO_2 emission reduction of 30%. However, a viable supply of natural gas is required and there are other drawbacks, economical and technological (e.g. the disposal of the additional fuel oil product while the fuel oil market is heavily over-supplied) (Stockle et al., 2008). Stockle et al. (2008) mentions a short inventory of potential energy efficiency improvements, including maintaining insulation, minimizing steam leaks and improving heater efficiencies. Other CO_2 abatement measures that are mentioned are crude oil substitution (switch to lighter crudes to reduce the need for hydrotreating) and hydrogen production optimization.
Heat integration and waste heat recovery are options that have the possibility to reduce CO_2 emissions on-site as well as off-site. Using waste heat for refining processes (e.g. preheating

of mass flows using low-temperature waste heat) decreases the total energy demand and concomitant CO_2 emissions. Using low-temperature heat from the refinery for district heating is another way of reducing overall energy use and CO_2 emissions (Johansson et al., 2012).

2.1.2 Practical issues

Next to a technical and economic assessment, it is necessary to assess whether potential problems would arise during the implementation and/or operation of new EEMs. In this study, we refer to these potential problems as practical issues. Practical issues could interfere with the core refinery processes and/or with another CO_2 mitigation options, and make the application of the mitigation option technically more difficult or even impossible. Examples of practical issues are limited plot space availability, lower core process reliability and technical difficulties with retrofitting refinery units. Practical issues may also result in higher costs for implementing mitigation technologies, and, if no solutions for the practical issues are available, reduce the CO_2 reduction potential.

Berghout et al. (2013) assessed the possible issues related to implementation and operation of post-, pre- and oxyfuel combustion capture. Technical feasibility, space limitations and operational issues (i.e. chance for operational failure and its effect) were assessed for these three capture technologies. The main findings regarding practical issues were that, on the short term, space limitations could increase the indicated avoidance costs, especially for post-combustion capture.

Chew et al. (2013) established a complete overview of issues that can influence the practical implementation of total site heat integration. This was done to provide guidance for future total site heat integration implementation or extension methods from an industrial perspective.

In this study, the potential mitigation options are assessed on several practical issues. These potential issues are mainly derived from Chew et al. (2013). A brief description of each issue is given below.

- *Retrofitting* looks at whether a mitigation option is deployable in the current state of the refinery. If this is not the case, it must be assessed how much adjustments the refinery should make before the measure can be implemented. This requires extra investments.
- *Layout of the refinery's* site can have a large influence on the costs of implementing mitigation options because it influences the distance of piping that must be overcome. Also, when there are critical parts of the refinery which may not be affected (e.g. because of safety and risk), these areas should remain unimpaired. This can result in more piping, fittings and valves requirements, which leads to larger pressure drops (Chew et al., 2013). Pressure drops may negatively influence the

features of the flux, so extra pumping is required. Extra costs to overcome this practical issue include additional piping, insulation, pumping and compressing.

- *Space availability* covers whether the required space for a mitigation measure is available at the refinery's site or not, or whether this space has already been considered for another application in the (near) future. This accounts for the refinery site overall (e.g. large storage units) and around existing process units (e.g. ducting).
- *Reliability* measures the chance of operational failure of the processes. If a mitigation option increases the risk of downtime, this is an issue and must therefore be assessed. This can account for the whole core process of the refinery or for a single process unit. An important aspect related to reliability is *controllability.* Processes at a refinery can have strict requirements in order to optimize the quality of the production output. Therefore, it is important to have a high controllability on e.g. temperature and pressure. If a mitigation option decreases the controllability, this may lead to production loss (Chew et al., 2013).
- *Flexibility* measures the potential to operate in a variable and flexible manner. A mitigation measure should not reduce the flexibility of the refinery processes by a too large extent, since this might result in sub-optimal process conditions. A refinery should be able to operate in different modes, for example, with different feedstock compositions, varying demand (and thus varying flow rates), or seasonal differences (i.e. different ambient temperatures), and must therefore be flexible.
- A mitigation measure may influence the *start-up or shut-down time*, which could decrease the total operation time. Also, when additional equipment is required for start-up or shut-down because of the mitigation measure, this should be included in the investment costs.
- During the operation of the refinery, changes on the long term may occur, for example, fouling or catalyst exhaustion (Chew et al., 2013). Therefore, routine *maintenance* is required. Implemented mitigation measures may influence the need for maintenance and this increases operational costs, which should be considered before implementation.

2.1.3 Case refinery

The refinery that is used for this study, which will be referred to as the case refinery, is a hydro skimming refinery. Figure 1 shows a flow scheme of the case refinery.

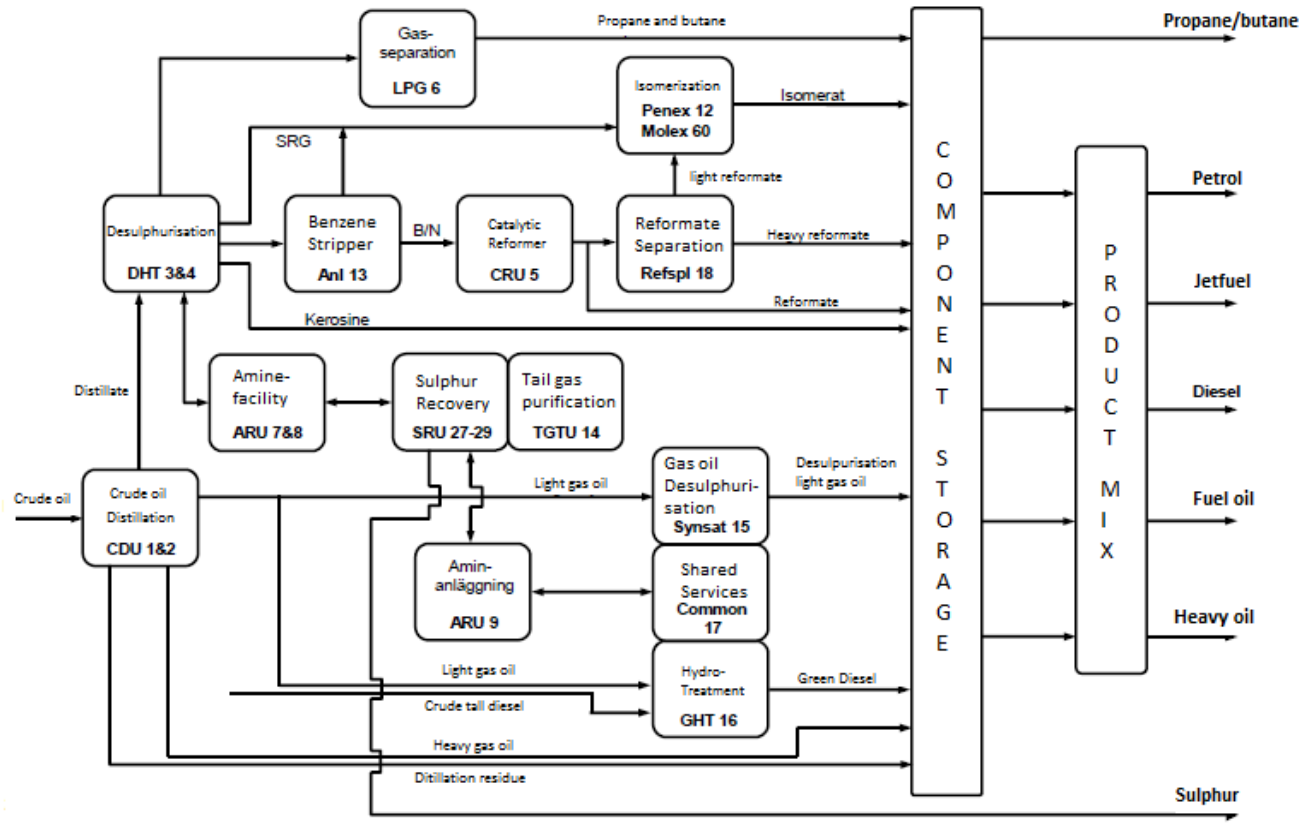

Figure 1. Flow scheme overview of the case refinery (gained from case refinery. Each unit has its own number which is also shown)

Crude oil arrives at the case refinery. The crude oil is fractionated at the CDUs (Crude Distillation Unit) into several fractions. The lighter fractions are sent to desulphurization units, i.e. the DHT (Distillate Hydrotreatment). The resulting naphtha goes to the CRU (Catalytic Reformer Unit) to increase the octane number. Light naphtha goes to the isomerization unit and increases the octane number together with the Molex unit. Gas oils are first desulphurized and then dearomatized in the synergetic saturation unit (SYNSAT). Heavy gas oils are sold for further processing. Sulphur is separated in the SRU (sulphur recovery unit) from the H_2S which comes from the desulphurization units. Since 2012, the case refinery also produces 'green diesel' which is produced from vegetable oils in the GHT unit (Green Hydrotreatment).

Table 1 shows an energetic overview of the case refinery in 2012.

Table 1 Key characteristics of the case refinery in 2012 (internal database of refinery)

	Unit	Value
Crude oil input	Mt/yr	5.3
Total heat demand	PJ/yr	8.6
Number of stacks		6
Flares		1
Fuel gas use	PJ/yr	8.0
Natural gas imports	PJ/yr	0.6
Boilers	PJ/yr	1.3
Furnaces	PJ/yr	7.3
Electricity imports	PJ/yr	1.7
Fans	PJ/yr	approx. 0.5
Pumps	PJ/yr	approx. 0.5
Other	PJ/yr	0.2
Total energy sources	**PJ/yr**	**10.6**
Energy sold (district heating)	PJ/yr	1.5
Total energy use	**PJ/yr**	**9.1**
Total CO_2 emissions	**ktCO2/yr**	**546**

2.2 Carbon capture

There are three main categories of technologies for carbon capture: post-combustion, pre-combustion and oxyfuel combustion (Rootzén et al., 2011). Post-combustion separates the CO_2 from the flue gas, most commonly via chemical absorption. In this concept, the solvent needs to be regenerated to obtain a high-purity CO_2 stream. This process consumes much energy and therefore gives an energy penalty to the refinery (IPCC, 2005). In the pre-combustion route, the carbon in the fuel is separated from the fuel before it is combusted. With oxyfuel combustion, the fuel is combusted with nearly pure oxygen, resulting in an almost pure CO_2 stream after the combustion (Rootzén et al., 2011).

Examples of studies that focus on carbon capture at the refinery plant level are van Straelen et al. (2009), Johansson et al. (2013), Andersson et al. (2013), Berghout et al. (2013), and DNV (2010). Whereas the first three studies only assessed post-combustion capture technology, the latter two analyzed also pre-combustion and oxyfuel combustion. Andersson et al., (2013) investigated post-combustion at the refinery plant level and focused on the heat requirement for chemical solvent (monoethanolamine, MEA) regeneration and its dependence on the temperature in the stripper reboiler.

Kuramochi et al. (2012) assessed the techno-economic performance of these three capture technologies for different industrial sectors, including the refinery sector. It was found that

for the petroleum refinery sector oxyfuel capture is the most economic option with avoidance costs of 50-60 €$_{2007}$/tCO_2 in the short-midterm and 30 €$_{2007}$/tCO_2 in the long term. However, retrofitting oxyfuel capture with an existing refinery is complicated. Avoidance costs for post-combustion capture in the short and midterm were calculated to be more than 100 €$_{2007}$/tCO_2 with a CO_2 avoidance rate of 59-77%. This might decrease considerably in the future because solvents may be improved. Also, the excess electricity production can have a large influence on the avoidance costs, depending on the power market.

Berghout et al. (2013) found similar costs for oxyfuel combustion in the short term (66 €$_{2010}$/tCO_2) but a lower value for post-combustion in the short term (76 €$_{2010}$/tCO_2). Berghout et al. (2013) found that avoidance costs increase for smaller CO_2 emitters due to economies of scale. This applies to all capture configurations. Also the CO_2 concentration in the flue gas influences the avoidance costs. Flue gases with lower concentrations require more expensive capture plants. Regarding practical implementation issues, Berghout et al. (2013) found that retrofitting might become the most important issue. Also space limitation is a potential issue, however this is differs for each refinery site.

The study of van Straelen et al. (2009) evaluates the opportunities and costs for post-combustion capture at a large complex refinery and found that post-combustion capture is technically feasible. However, with costs in the range of 90-120 €$_{2007}$/tonne CO_2, for post-combustion capture to be implemented a technological breakthrough would be required or mandatory regulations would have to come into force (van Straelen et al., 2009). It was also concluded that for large refineries, with a large amount of small CO_2 sources, it is probably not attractive to combine and route these point sources to one absorber due to the extra costs for ducting.

Pre-combustion and oxyfuel combustion are promising technologies. However, these technologies are still in the development phase and have not been demonstrated yet on a large scale, which is required for commercial deployment (Det Norske Veritas, 2010). Post-combustion capture is currently better known because it is applied in the chemical industry and natural gas sector to remove sulfur from natural gas. For carbon capture it is only applied on a pilot scale. It is also a technology with relatively less risk because it is an add-on technology and thus can be switched off. This reduces the risk of a lower plant capacity factor. However, as refineries have multiple, distributed CO_2 point sources, post-combustion capture is difficult and costly to implement, due to large diameter ducting required for onsite flue gas transport from the point sources to the CO_2 absorber(s) (Det Norske Veritas, 2010). On a cramped refinery site, this is a challenge (van Straelen et al., 2009). This is an example of a practical issue that could make the implementation of post-combustion carbon capture more difficult.

2.3 Configurations of post-combustion capture

2.3.1 Regeneration heat sources

As said, when applying post-combustion capture, the regeneration of the solvent consumes energy in the form of steam, thus resulting in an energy penalty for the refinery (IPCC, 2005). This additional energy can be produced by several sources. Johansson et al. (2012) evaluated four heat supply alternatives, namely Natural Gas Combined Cycle (NGCC), Natural Gas Boiler (NB), Biomass Boiler (BB) and Excess Heat (EH).

The NGCC option uses a heat recovery steam generator (HRSG) that produces high-pressure steam (80 bar). This pressure is expanded to low-pressure steam (2.3 bar). This way, enough low-pressure steam is produced for the capture plant and excess electricity is produced. This electricity can be sold to the grid.

The Natural Gas Boiler and Biomass Boiler are quite similar. Only the fuel differs and their efficiencies. The Natural Gas Boiler has an efficiency of 91% and the Biomass boiler of 87%. These boilers also produce excess electricity.

In the Excess Heat alternative, water is evaporated to steam of 2.3 bar by exchanging heat with gaseous and liquid streams and flue gases of 129 °C and higher. The steam is used at the capture plant. When the available excess heat is not sufficient, an additional heat pump is required. The heat pump uses streams between 90 and 129 °C.

The choice of heat supply influences the costs and the overall amount of CO_2 emission reductions. Johansson et al. (2012) found that the NGCC option has the largest global CO_2 reduction potential because of the large electricity production (assuming this electricity is sold and reduces CO_2 elsewhere). However, most CO_2 is avoided when excess heat or a Biomass Boiler are used as heat supply.

The choice of heat supply will also influence the interaction with EEMs and have several practical implications on its own. The total reduction potential of the refinery is therefore also influenced. This will be assessed in this study.

2.3.2 Centralized or Decentralized

Post-combustion capture can be configured in different ways at refineries. Refineries have several stacks and thus multiple CO_2 point sources. When the flue gases from the stacks go through scrubbers and then to one centralized stripper, it is a centralized configuration. A decentralized configuration implies a stripper per scrubber.

These different configurations have different investment costs and also different technological and practical implications. A centralized configuration requires less plot space for the single centralized stripper, but more ducting for the larger distance. For a decentralized configuration it is the other way around. This also leads to different interactions with EEMs and can therefore lead to a different total CO_2 reduction potential for the case refinery.

3. Method

In this section, the method of this study is described. To give a complete overview, the method of the internship is included as well.

3.1 Data collection

Firstly, quantitative data are acquired from available databases with information on the case refinery. Secondly, qualitative data, gained from expert interviews, are used for assessing the applicability of the energy efficiency measures and post-combustion capture at the refinery. The experts are consulted for the analysis of the practical feasibility of the mitigation options. This means they provide information on how the measures and carbon capture could be implemented at the refinery and what aspects would make it hard (or easy). An example is the possibility of retrofitting of energy efficiency measures.

3.2 Interviews

The interviewees (see table 2) are employees at the case refinery, experts on refinery processes, and/or experts on CO_2 emissions at the case refinery and carbon capture in general. These expert interviews are conducted half open and face to face. This means that questions are prepared in advance, but there is still the opportunity for the interviewee to give his/her own input.

Table 2. Overview of interviewees

Interviewee	Field of expertise
Interviewee 1	Process Engineer, Hydrotreating and Distillation
Interviewee 2	Process Engineer, Catalytic Reforming and Distillation
Interviewee 3	Environmental Engineer, Emissions to Air
Interviewee 4	Controlling Manager, Emission Credit Accounting
Interviewee 5	Control Engineer, Advanced Process Control
Interviewee 6	Control Engineer, Advanced Process Control
Interviewee 7	Mechanical Engineer, Fired equipment
Interviewee 8	Mechanical Engineer, Rotating equipment
Interviewee 9	Process Engineer, Hydrotreating and Isomerization
Interviewee 10	Development Engineer, Refinery and Renewables

3.3 Categorization of energy efficiency measures

In the internship report, the EEMs are subdivided into different categories depending on how their economic viability is estimated in original sources. Interviewees mentioned that a measure with a payback period of 5 years or less is an economically viable measure. This is done as follows:

1. An extensive inventory of energy efficiency measures is done. The complete inventory can be found in the appendix. These EEMs are derived from three sources.

The first source is economic viable suggestions by process engineers from the case refinery. The second source is a recent research done by a Shell consultancy team. They suggest EEMs that are, according to the performed research, economically viable with a payback period of 5 years or less. These measures are therefore called 'quick wins'. The third source of measures is literature studies. The Energy Star Guide (Worrel et al., forthcoming) is the most important example. First a pre-selection was made, dropping EEMs which are not available for the case refinery because of different reasons. This pre-selection was made with the help of experts. The criteria can be found in the appendix.

2. The resulting inventory of EEMs is discussed in interviews with experts on this area: process engineers and other employees of the case refinery (see table 2). The measures are assessed regarding their energy reduction potential, potential cost savings, payback period and possible practical issues that may come along when implemented. Also, when specific values were found in literature, these are discussed.
3. Next, the measures are divided in 3 categories. Each measure with a payback period which is estimated by the interviewees to be 5 years or less are placed in category A. It is estimated by the interviewees that these measures are technically feasible and very likely to be economically viable for the case refinery, taken possible practical issues into account.
4. Measures are placed in category B when the measures come from the consultancy team's quick-wins list, but interviewees assessed that these measures are less likely to have a payback period (PBP) shorter than 5 years. This can be due to uncertainty in saving potential or possible practical issues which are not yet looked into. The interviewees are asked to give a clear argumentation for the higher uncertainty of implementation of these measures.
5. When an energy efficiency measure is obtained from literature and interviewees assessed that these measures are less likely to have a PBP shorter than 5 years, the measure is placed in category C. These measures have a higher uncertainty than the measures in categories A and B because the results in literature are based on different cases and may therefore be very different for the case refinery of this study. It is also possible that EEMs identified in the literature can have a higher uncertainty because they are not technically or commercially available yet and require further investigation.

See table 3 for a complete overview on how the measures are subdivided. In the appendix a complete overview is given of the assessed EEMs as well.

The results of the subdivision and potential of EEMs are presented in a chart with the CO_2 reduction potential on the vertical axis and the categories (A-C) of EEMs on the horizontal axis.

3.4 Assessment of practical issues of energy efficiency measures

Next, the practical issues, which may come along when implementing the EEMs, are discussed. Information on practical issues is mainly qualitative in nature and will mostly be acquired by expert elicitation. The gathered information will be transformed into a scale. There are three possible scores:

- *The first score* is when the measure or combination of measures is not expected to result in practical issues; the practical issue is then indicated with a zero (0). This means that the mitigation measures can be implemented at the case refinery without causing any problems and very low additional costs related to the assessed practical issue.

- *The second score* is when a measure or a combination entails practical issues, which can be technically overcome. For example, extra ducting, pumps, furnaces, coolers or maintenance may become necessary. The related practical issue is then indicated with a minus (-).

- When implementation becomes impossible due to practical issues, either because it is practically impossible or the required investments to overcome the issues are considered to be too high, the practical issues are indicated with a double minus (- -).

The interviewees are asked to assign a score to the potential practical issues of the mitigation options. Also, they are asked to justify their assessment. Furthermore, the experts are asked to elaborate on the assigned score as well as on what is needed to overcome the difficulty (if possible) and what the effects on production, energy efficiency and emissions.

Assuming that category A measures are the most interesting from a profitability and practical perspective, these are likely to be implemented before the category B and C measures. Based on the interview results, it is therefore possible to discuss how the implementation of category A measures will influence the potentials indicated for category B and C measures, and whether there seems to be any risk of lock-in effects. For example, it is possible that some EEMs cannot be implemented jointly due to practical issues or because these measures reduce each other saving potentials significantly. The refinery will then most likely implement the measure with the highest profitability and shortest PBP. However, this EEM is possibly not the measure with the highest emission reduction potential. If this is the case, implementing the most profitable EEM could decrease the total refineries reduction potential. It is assessed whether this could happen and what the potential consequences are.

Table 3. Summary of categories of EEMs

	A	B	C
Short description	These measures are confirmed by the interviewees to be very interesting for the case refinery.	These measures were identified by a consultancy group who performed a short research on how to increase the refinery's efficiency with 'quick wins'.	These measures are identified in the literature. These measures are regarding different refineries or even different industry types.
Source of identification	Process engineers and other experts of the case refinery (interviewees)	Quick-wins list by Shell Consultancy	Mainly the Energy Star guide (Worrel et al., 2013) and other literature, e.g. Holmgren & Sternhufvud (2007), Bergh & Cohen (2012),
Expected profitability	These measures are very likely to have a PBP of less than 5 years.	According to the research team which identified these measures, the PBP is shorter than 5 years. However, due to uncertainty and potential practical issues the actual costs may be higher or potentials may be lower.	According to existing literature, these measures are profitable, with payback periods varying between a few months and several years. However, this is based on different cases. Also EEMS with a PBP longer than 5 years are mentioned. These are mostly measures with perspective on the long run, because technological developments are required.
Uncertainty	The exact investment and operational costs are uncertain. Also, the implementation is expected to entail few practical issues.	This research was not very profound so there is no information on investment and operational costs or potential practical issues.	High level of uncertainty, because data is not related to the case refinery but other cases. Also practical issues are often not assessed.

3.5 Post-combustion capture assessment

For the full master thesis, a detailed bottom-up analysis is performed to assess the techno-economic performance of post-combustion capture at the case refinery. This is done by calculating the avoidance costs of post-combustion capture in terms of €/tCO_2 for different implementation options. These implementation options differ in implementation order and heat supply. The differences in avoidance costs between these options will be analyzed. This is further explained in the below.

To collect the required data and identify practical issues regarding post-combustion capture at the case refinery, existing literature and one of the expert interviews from Chalmers University of Technology (interviewee 4) about the possibilities for post-combustion capture at the case refinery are used. Especially Johansson et al. (2012) has proven to be useful because this study already analyzed the possibilities for post-combustion capture at two refineries, including the case refinery investigated in this study. The required quantitative data is obtained from this study and from the case refinery's database. The goal of the interview was to confirm the found quantitative data and to identify practical issues for post-combustion capture at the case refinery.

3.6 Calculations

To calculate the annual costs of mitigation options, the CAPEX and OPEX are required. CAPEX is calculated by:

$$CAPEX = I * \alpha \qquad [1]$$

where I (M€) is the investment and

$$\alpha = \frac{r}{1-(1+r)^{-L}} \qquad [2]$$

where *r* is the discount rate and *L* the lifetime in years.

OPEX is calculated by adding up all the operational costs that are required for the energy efficiency measure. Examples are materials, labor, maintenance, electricity or other fuels. Because of the lack of data, OPEX is based on assumptions and is calculated as a share of the total investment costs. In table 4 an overview is given for all EEMs. For most EEMs, an OPEX is assumed of 10%. These EEMs are measures with high capital investment costs and not necessarily high costs for labor, maintenance or materials. For EEMs with lower capital investment costs but high operational costs (e.g. due to high required amount of maintenance, manpower or materials), the OPEX are assumed to be higher. The operational costs are assumed to be higher than 10% for EEMs 1, 2, 6, 12, 13, 14 and 18. It must be noted that, because of the lack of data, these operational costs are rough estimations. Still, these values from table 4 are all within the range of the operational costs that are indicated

by the BREF report (IPPC, forthcoming). This report found EEMs with operational costs ranging from 0.1% to over 100% of total investment costs.

Table 4. Assumed operational costs for all EEMs as a percentage of total investment costs

EEM#	OPEX (percentage of investment)	EEM#	OPEX (percentage of investment)
1	50%	14	20%
2	30%	15	10%
3	10%	16	10%
4	10%	17	10%
5	10%	18	20%
6	20%	19	10%
7	10%	20	10%
8	10%	21	10%
9	10%	22	10%
10	10%	23	10%
11	10%	24	10%
12	15%	25	10%
13	20%	26	10%

The total annualized cost of an energy efficiency measure is the sum of CAPEX and OPEX.

Investment costs for post-combustion capture are calculated with the usage of economies of scale. This means that a post-combustion capture plant for a small emission is relatively more expensive than for a large emission. This is calculated by:

$$C_2 = C_1 * (S_2/S_1)^{0.7} \qquad [3]$$

Where C_1 is the costs for the capture plant (in M€) with a CO_2 capture of S_1 (in $ktCO_2/y$) and C_2 is the costs for the capture plant (in M€) with a CO_2 capture of S_2 (in $ktCO_2/y$). The scaling factor has no unit and is 0.7.

To calculate the CO_2 reduction, the energy use reduction must be estimated for each fuel. For some EEMs it is in the form of natural gas, for others in electricity. Then this must be multiplied with the corresponding CO_2 emission factor:

$$CO_{2\,reduction} = ER_{ng} * EF_{ng} + ER_e * EF_e \qquad [4]$$

ER_{ng} and ER_e are the energy reductions of natural gas and electricity in TJ/y. EF_{ng} and EF_e are the emission factors of natural gas and electricity in tCO_2/TJ. To calculate emission reduction

from fuel savings, the emission factor of natural gas is used. In section 3.7.1 this is explained further.

The CO_2 abatement cost is calculated by:

$$CAC = {TC_j - (ER_{ng} * P_{ng} + ER_e * P_e)} \Big/ {CO_{2\ abatement\ j}} \qquad [5]$$

where CAC is the CO_2 abatement cost (€/tCO_2), TC_j is the total annualized costs of measure j (€/y), ER is the energy savings of measure j (GJ/y), P is the fuel price (€/GJ), and $CO_{2\ abatement}$ is the annual amount of CO_2 emissions (tCO2/y) reduced.

With the help of the estimations of the payback periods of Berghout et al. (forthcoming), the investments can be indicated. This is done with the help of the formula:

$$PBP = \frac{I}{B-C} \qquad [6]$$

where I is the total capital investment costs (M€), B is the annual benefits (M€/y) or cost reduction, and C is the annual costs (M€/y).

The calculation of the costs in terms of €/tCO_2 of post-combustion capture is similar to the calculation of energy efficiency measures, except that post-combustion capture only reduces the CO_2 emission and not energy use (post-combustion capture increases energy use). The calculation for CO_2 abatement is different as well, because there is a difference between CO_2 captured and CO_2 avoided. First, an assumption must be made for the capture ratio (cr). This number shows the part that is actually captured of the total post-combustion carbon emission flux.

$$CO_{2\ captured} = CO_{2\ emission} * cr \qquad [7]$$

where $CO_{2captured}$ (ktCO_2/y) is the annual amount of CO_2 that is captured, $CO_{2emission}$ (ktCO_2/y) is the annual CO_2 emission by the refinery. The capture ratio is a percentage. The value that is used in Johansson et al. (2012) is maintained: 85%.

Then the energy penalty and the associated emission of post-combustion capture must be determined. This is subtracted from the amount of carbon that is captured in order to calculate the avoided per year. The actual CO_2 abatement is therefore calculated by:

$$CO_{2\ abatement} = CO_{2\ captured} - CO_{2\ due\ to\ energy\ penalty} \qquad [8]$$

where $CO_{2abatement}$ ($ktCO_2/y$) is the annual amount of CO_2 that is avoided, $CO_{2captured}$ ($ktCO_2/y$) is the annual CO_2 that is captured (see formula 7). $CO_{2due\ to\ energy\ penalty}$ is the CO_2 emission by the energy production for the reboiler.

Total costs of post-combustion carbon capture depend for a large part on the configuration and the regeneration heat source. For different heat sources, different investments are required. Also the amount of required energy differs and thus influences the costs. An overview of all used data will be given in the following paragraph.

3.7 Input data

3.7.1 Emission factors

Table 5. Different emission factors used for calculations

Emission factor	Unit	Value
Fuel gas	$kgCO_2/GJ$	66.7
Natural gas	$kgCO_2/GJ$	56.7
Coal power plant electricity	$kgCO_2/GJ$	213.9[1]
Swedish grid electricity	$kgCO_2/GJ$	6.4[2]

To calculate emission reduction from fuel savings, the emission factor of natural gas is used. That is because when fuel use is reduced, the imports of natural gas are reduced first. It should be noted that when fuel consumption is reduced to the point that natural gas imports become unnecessary, the emission factor of fuel gas should be used for further reductions. However, for this study the emission factor of natural gas is used throughout.

For the emission factor of electricity it is assumed that a decrease in electricity demand leads to a reduced electricity production at coal power plants. This value will be used throughout the report. However, for comparison, the emission factor of the Swedish grid of electricity is also presented which is significantly lower. To put it in another perspective: the emission factor of Dutch electricity is 118 $kgCO_2/GJ$, almost 19 times higher (International Energy Agency (IEA), 2012). That is because Swedish electricity is generated for a very large part by hydropower and nuclear power. Using this value makes the CO_2 reduction potential of electricity reducing EEMs almost negligible as can be seen in Figure 3. Therefore the emission factor of coal power plant electricity is used.

3.7.2 Post-combustion capture

Calculating the mass and energy flows and all costs of post-combustion capture at the case refinery is mainly done by using data from the database of the case refinery and of Johansson et al. (2012). This latter study already calculated the avoidance costs for four different regeneration heat supply options and two different scenarios of heat requirement

[1] (International Energy Agency (IEA), 2012)
[2] (International Energy Agency (IEA), 2012)

(high and low) for a centralized configuration[3]. Table 6, 7 and 8 show the data and the results from Johansson et al. (2012) for eight possible scenarios. The data from table 7 are required for the calculation of a decentralized configuration because the investment costs for absorbers and ducting will change.

Table 6. General input data for post-combustion capture (Johansson et al., 2012)

	Unit	Value
Scaling factor		0.7
Capture ratio	%	85
Operation time post-combustion capture	h/y	8400
Discount rate	%	7
Lifetime post-combustion capture	y	25
Annuity factor		0.1

Table 7. Investment costs for the components Absorber and Ducting and operational costs for ducting as used in Johansson et al. (2012)

	NGCC		NB		BB		EH + HP	
Heat demand	2.8	4.7	2.8	4.7	2.8	4.7	2.8	4.7
Investment costs Absorber [M€$_{2010}$]	13.4	18.6	11.2	12.7	13.0	17.8	9.6	9.6
Investment costs Ducting [M€$_{2010}$]	6.2	8.6	5.2	5.9	6.0	8.2	4.5	4.5
Operational costs Ducting [M€$_{2010}$/]	0.3	0.5	0.2	0.3	0.3	0.4	0.2	0.2

Table 8. Summary of data used in Johansson et al. (2012) and results for 4 regeneration heat sources and 2 scenarios of energy demand

	NGCC		NB		BB		EH + HP	
Energy demand [MJ / kg CO_2]	**2.8**	**4.7**	**2.8**	**4.7**	**2.8**	**4.7**	**2.8**	**4.7**
Total CO_2 to capture plant from Refinery [M t/y]	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
CO_2 emissions from energy plant [Mt /y]	0.29	0.76	0.12	0.23	0.26	0.68	0.00	0.00
Captured amount of CO_2 emissions [Mt /y]	0.66	1.05	0.51	0.61	0.63	0.99	0.41	0.41
Avoided amount of CO_2 emissions [Mt /y]	0.37	0.30	0.39	0.38	0.41	0.41	0.41	0.41
Size of capture plant reboiler [MW_{th}]	61	164	47	95	58	153	38	64
Electricity consumption/production from energy plant [Gwh_{el}/y]	-659	-1774	-126	-255	-157	-412	0	17
Electricity consumption capture plant [Gwh_{el}/y]	110	176	85	102	105	164	69	69
Fuel demand [GWh_{Fuel}/y	1433	3745	577	1157	743	1952	0	0
Size of heat pump [MW_{th}]	0	0	0	0	0	0	0	10
Excess heat [MW_{th}]	0	0	0	0	0	0	54	54
Investment costs for the capture plant [M€]	99.7	138.8	83.5	94.6	96.8	132.4	71.8	71.8
Investment costs for NGCC/NB/BB/EH+HP [M€]	87.7	187.8	29.2	48.5	37.1	72.8	0	4.4

[3] This includes one absorber and one stripper for 2 stacks

Annualized investment costs for the capture plant [M€/y]	10	14	8	9	10	13	7	7
Annualized investment costs for the NGCC/NB/BB/EH+HP [M€/y]	9	19	3	5	4	7	0	0.1[4] + 0.4[5]
Total annualized investment costs [M€/y]	19	33	11	14	13	21	7	8
Annualized fixed costs [M€/y]	7	11	5	6	7	10	4	4
Fuel costs [M€/y]	47.6	124.5	19.2	38.5	25.9	68.1	0	0
Electricity costs [M€/y]	-36.1	-105.1	-2.8	-10.1	-3.4	-16.2	4.5	5.6
Avoidance costs [€/tCO_2]	101	211	83	127	106	200	38	41

3.7.3 Cost assessment EEMs

This study aims to perform a cost analysis of EEMs and post-combustion capture. In this section it is explained how the costs figures for EEMs are obtained.

In Berghout et al. (forthcoming), payback periods and lifetimes of general categories of EEMs are estimated by an expert. Examples of such categories are motors & pumps and steam distribution. A full overview is shown in table 9. Based on those estimations, annual costs of the EEMs of this study are calculated. How this is done is explained in the following steps:

- First the EEMs assessed in this study are subdivided in the general categories of Berghout et al. (forthcoming). This way, the assessed EEMs are appointed to the corresponding PBP from Berghout et al. (forthcoming).
- Then the subdivision in categories from the internship is included in the analysis. This means that the categories (A, B, and C) of the internship report influence the PBP of the EEMs. For example, there are two EEMs from Motors & Pumps, while one EEM is in category A and the other in category C. According to Berghout et al. (forthcoming) the PBPs for both EEMs are 3 years. Taking the categories from the internship report into account, the EEM from category A will probably have a slightly shorter PBP than 3 years, while the category C measure will have a longer PBP. It is tried to stay in the range of a 1 year shorter or longer PBP than the PBP estimated in Berghout et al. (forthcoming), depending on the category from the internship report. So, based on both categories (from Berghout et al. (forthcoming) and the internship report), an assumption is made for the PBPs for each EEM.
- Using the formulas as described in 3.6 and the assumptions for the PBPs of the EEMs, the investment costs can be calculated for the EEMs.
- When the investment costs are known, CAPEX and OPEX are calculated according to the formulas in 3.6. Next, the CO_2 avoidance costs, also marginal abatement costs, can be calculated in terms of €/tCO_2.
- Putting the EEMs in order of lowest marginal abatement costs to highest, resulted in a merit order for implementation. This is presented in a marginal abatement cost curve.

[4] Cost for heat exchanging of excess heat above 129 °C.
[5] Cost for heat pumping of excess heat above 90 °C.

Table 9. Estimations of PBPs and lifetimes for EEMs (Berghout et al., forthcoming)

	Estimated PBP (years)	Life time (years)
Directly available measures (<2020)		
Energy management & control	0.25	5
Heat integration distillation units	5	15
Motors & pumps	3	10
Steam distribution system	1	20
Heat integration & waste heat recovery	5	15
Fouling mitigation	1	10
Improved furnace performance	2.5	15
Hydrogen management & recovery	3	15
Flaring	2.5	20
Advanced measures (2020-2030)		
Advanced desulphurization	10	25
Advanced separation systems	7	25
Turbine pre-coupling	6	20

In the internship report, data on costs due to practical issues were not available, as these are very case specific. Therefore, no estimations were made in that report. However, when the marginal abatement costs are calculated for the EEMs, it can be calculated at what point practical issues change the order of implementation, namely, when the additional costs for an EEM exceed the difference with the next EEM, the implementation order is changed.

3.8 Scenario analysis

To make an estimation of the energy and CO_2 reduction potentials of the joint implementation of EEMs and post-combustion capture, a scenario analysis is done. In this analysis, multiple scenarios are analyzed and potentials are estimated based on optimistic and pessimistic assumptions. Also, the potential is presented when no interactions between EEMs and post-combustion capture are taken into account.

In this study, eight scenarios will be assessed. These scenarios will vary in implementation order, choice of regeneration heat supply and whether practical issues and interactions are taken into account or not. See figure 2 for a schematic overview of the scenarios.

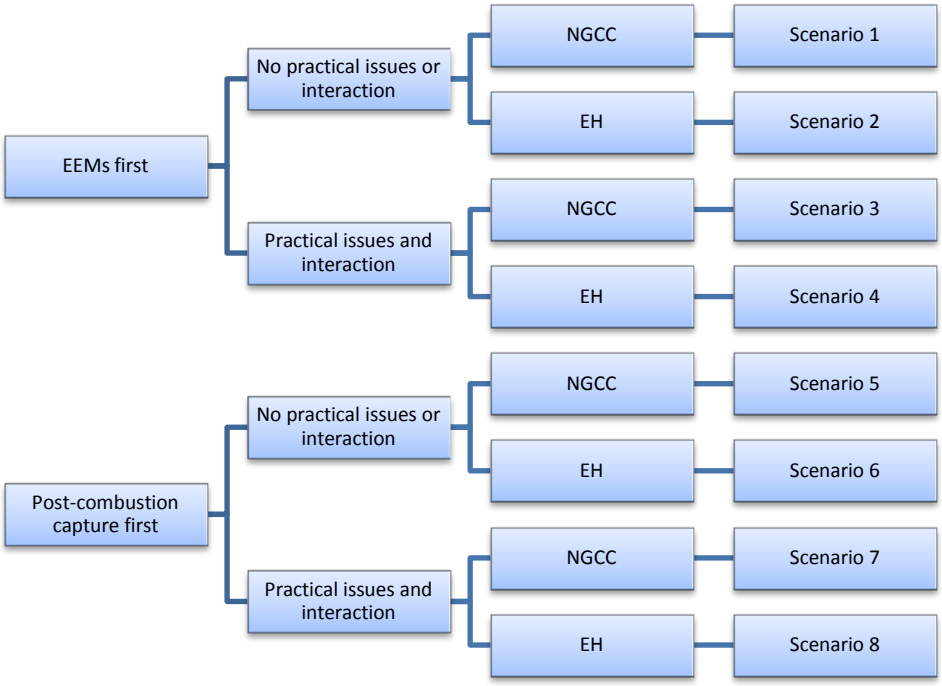

Figure 2. Schematic overview of assessed scenarios

The implementation order is divided in two options. The first option is that the EEMs are implemented first. When this is done, the efficiency measures will reduce energy use and CO_2 emission, which leaves a smaller amount of CO_2 to capture. While the investment costs for post-combustion capture will not decrease linear due to economies of scale, the specific avoidance costs of post-combustion capture will probably increase. The second option is that post-combustion capture is implemented first. This order can have an influence on which efficiency measures can be implemented and which measures are no longer available due to practical issues or interactions. This will have an influence on the total reduction potential of the case refinery.

Scenarios also differ in whether practical issues and interactions are taken into account or not. When practical issues and interactions are ignored, the reduction potentials of the EEMs and post-combustion capture are simply added up. It is assumed that all EEMs are implemented together with post-combustion capture and that these will not influence each other's potential. In the internship report a CO_2 reduction potential of the EEMs of 125 $ktCO_2/y$ was found when interactions are ignored. For the scenarios where interactions and practical issues are ignored, the result is a theoretical reduction potential. That is because these results are in fact not realistic. It is probably not possible for the case refinery to implement all EEMs, especially not without the occurrence of any interaction or practical issue. These theoretical results are useful because they can be compared with the other scenarios, in order to create insight in what the effect is of the interaction between EEMs and EEMs and post-combustion capture and practical issues.

When practical issues and interactions are not ignored, an optimistic perspective and a pessimistic perspective are used.

- With an optimistic perspective, interactions between EEMs and post-combustion capture are assumed to be minimal. This means that when EEMs tackle the same inefficiency, later implemented EEMs have a lower reduction potential than when they are implemented solely, because of the reduced energy use by the previous EEM. So to calculate the lower reduction potential of the second EEM, not the initial energy use is taken for the calculation, but the energy use after the implementation of the first EEM. This creates the lower reduction potential. Also, in an optimistic perspective, EEMs will probably not hamper each other's implementation, except for when EEMs are clear alternatives. When that is the case, the reduction potential of the EEM that cannot be implemented anymore is set to 0. For this scenario a reduction potential of 112 ktCO_2/y for the EEMs was found in the internship report. Also, it is assumed that the interaction between EEMs and post-combustion is minimal. Post-combustion and EEMs can mostly be implemented jointly.
- In a pessimistic perspective these interactions are assumed to be much stronger. This means that post-combustion capture and EEMs can influence each other's potentials by interaction or practical issues to such an extent that EEMs become economically unviable (PBP higher than 5 years) or that EEMs exclude each other due to practical issues. The reduction potential is than set to 0. Also, when a range was estimated by expert interviewees for reduction potential, the lower end of that range is used. Calculations for overlap are equal to the calculations for overlap in an optimistic perspective. In the internship report a CO_2 reduction potential was found of 82 ktCO_2 per year for the EEMs. Additionally, the interaction between post-combustion capture and EEMs is strong. This means that when post-combustion capture is implemented, it is assumed that many EEMs cannot be implemented due to practical issues. This mostly depends on the regeneration heat supply of post-combustion capture.

Finally two regeneration heat supply options can be chosen. Johansson et al. (2012) assessed four options; however, in this study only the options of NGCC and excess heat are assessed. That is because these options are the extreme heat supply options in terms of costs. In order to provide a range, these options must be looked at.

As will be shown in the results section, the difference between a centralized and decentralized configuration does not have a large influence on the costs of post-combustion capture for the case refinery. Therefore this difference is not taken into account for the different scenarios.

4. Results

4.1 Summary of results of the internship report

As said, the study continues the work that has been done for the internship report. The results of the internship report are used for this study. Therefore a summary of the results of the internship report is given.

Figure 3 shows the CO_2 reduction potentials of all assessed EEMs. The measures with an asterisk save electricity usage. Those measures have two bars to show the difference between two emission factors for electricity: coal power plant produced and Swedish grid electricity.

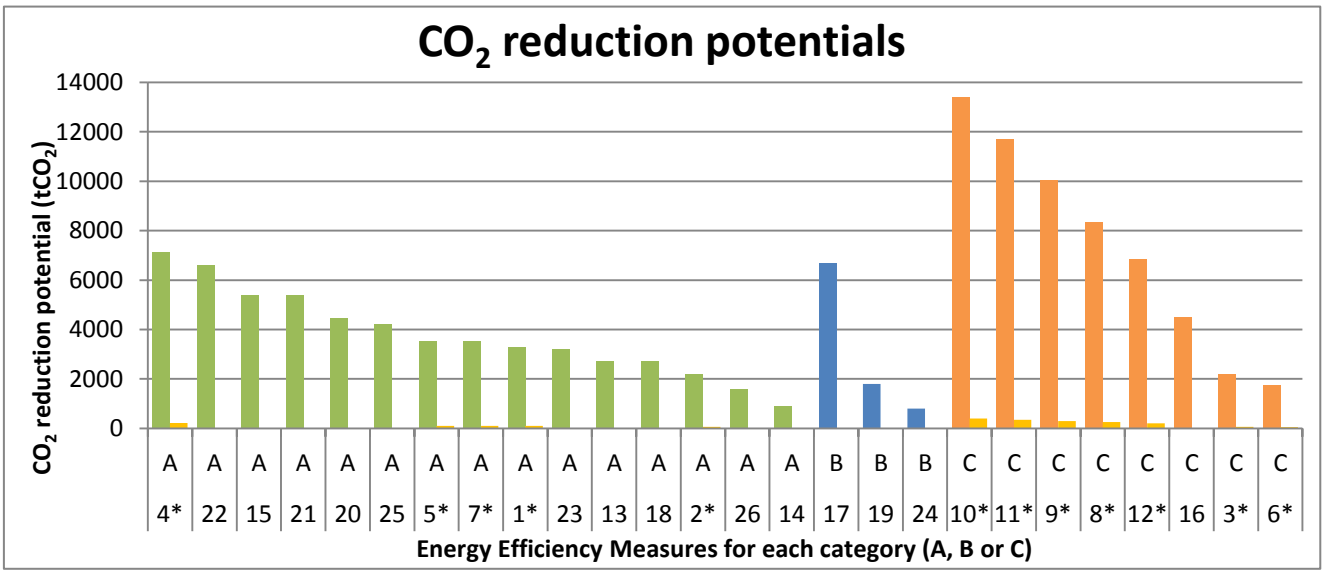

Figure 3. CO_2 reduction potential for each EEM at the case refinery. EEMs with an asterisk are measures that save electricity consumption. Electricity is bought and CO_2 reductions are therefore indirect.

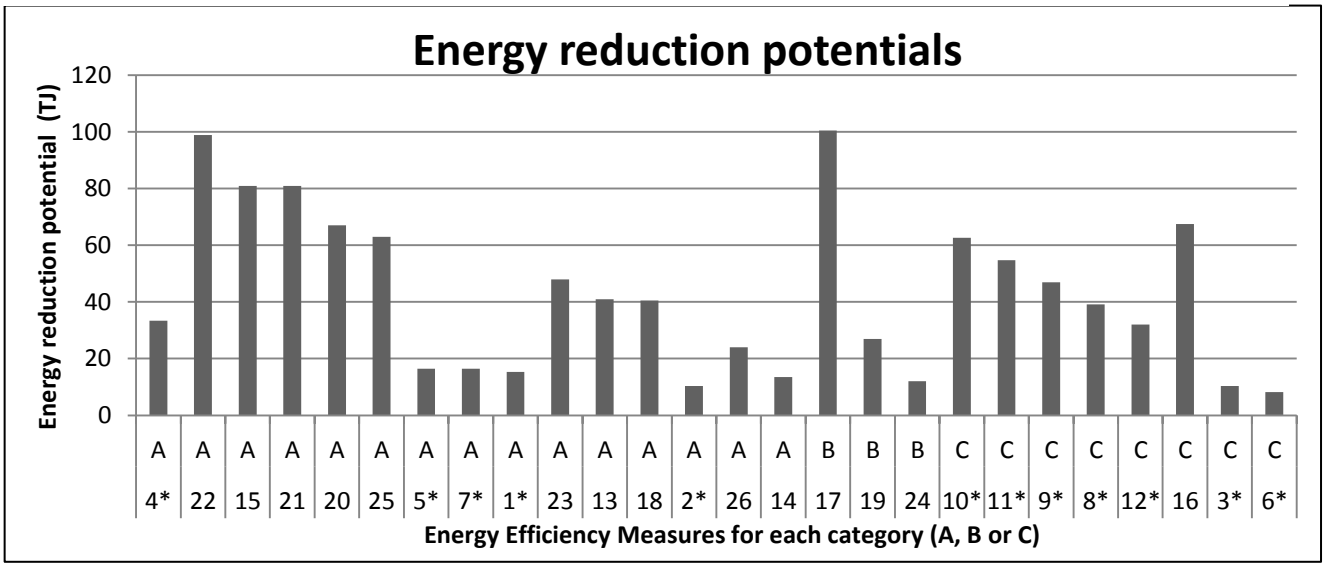

Figure 4. Energy reduction potential for each EEM at the case refinery when implemented separately. The order of presentation of EEMs is kept the same as in Figure 2 to show that CO_2 reduction is not only dependent on the energy reduction but also on the emission factor of the reduced energy.

Table 10. Overview of practical issues for each EEM

	FANS				PUMP SYSTEM								STEAM PRODUCTION/DISTRIBUTION							DISTILLATION PROCESSES						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Retrofitting	0	0	-	-	0	0	0	-	0	-	0	0	0	0	0	0	-	0	-	0	-	-	0	-	0	-
Layout	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	0	-	0	-	0	0	-	0	0
Space availability	0	0	0	-	0	0	-	-	0	- -	-	0	0	0	-	0	- -	0	-	0	0	0	0	0	0	0
Controllability	0	0	0	0	0	0	0	0	0	0	0	-	-	0	0	0	-	0	-	0	0	0	0	0	0	0
Reliability core process	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reliability unit	0	0	0	0	0	0	0	0	-	0	0	-	-	0	0	0	-	0	-	0	0	0	-	0	0	0
Flexibility	0	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	-	0	-	0	0	0	0	0	0	0
Startup/shutdown time	0	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	-	0	-	0	0	0	0	0	0	0
Maintenance	0	0	0	0	0	0	0	0	0	-	0	0	0	0	0	-	-	0	-	0	0	0	-	0	0	-

Figure 4 shows the energy reduction for each EEM. Table 10 shows the identified practical issues. For a more detailed analysis, we refer to the internship report. Table 11 shows the annual reduction potential of the EEMs when category A measures are implemented first, then B and then C. The reduction potentials are presented with an optimistic perspective, pessimistic perspective and when interactions and practical issues are ignored, as described in paragraph 3.8.

Table 11. Annual reduction potentials of a scenario with all category A measures implemented first, then B and then C.

	Without interactions		Optimistic		Pessimistic	
	Energy (TJ)	CO_2 (kt)	Energy (TJ)	CO_2 (kt)	Energy (TJ)	CO_2 (kt)
Subtotal A	650	57	635	55	488	44
Subtotal B	139	9	121	8	98	7
Subtotal C	321	59	299	55	178	33
Total	1111	125	1054	118	756	81

4.2 Energy efficiency measures costs assessment

With the help of the estimations for payback periods and lifetime from Berghout et al. (forthcoming), indications of investments are made as explained in paragraph 3.7.3. Based on these estimations, the marginal carbon abatement costs are calculated and shown in table 12. It can be seen that the EEMs with the lowest (most negative) abatement costs, are not necessarily the EEMs with the lowest payback periods. That is because of the difference in reduction potential, investment costs and operational costs for each EEM.

The marginal abatement cost curve for EEMs is shown in figure 5. The first half of the total reduction potential rises steeply while the second half is leveled out. Also, 13 out of 26 EEMs are responsible for about the first half of the total reduction potential. It is therefore noteworthy that the second half of the EEMs are more expensive but can add up to a significant amount of CO_2 reduction.

In these estimations, no additional costs for practical issues are taken into account. As said, there was no data available for these extra costs. However, it can be calculated at what point these extra costs start having influence on the implementation order. For example, EEMs 5 and 24 are close in terms of marginal abatement costs. EEM 5 is slightly cheaper, namely -9.7

€/tCO_2 whereas EEM 2 is -9.5 €/tCO_2. When practical issues concerning EEM 5 add extra costs to an amount of more than 0.2 €/tCO_2, the implementation order changes. Because the reduction potential of EEM 5 is 3.5 ktCO_2 per year, these additional costs would be €700 per year. Comparing this with the initial annual costs (of €31,500) it becomes clear that when practical issues add only 2.2% to the annual costs of EEM 5, the implementation order changes. So these additional costs due to practical issues are important to consider.

Table 12. Cost assessment overview of EEMs 1-26

EEM #	Type[6]	Type (Berghout et al.)[7]	Category[8]	CO_2 Reduction potential (kt CO2/y)	Energy Reduction potential (TJ/y)	Cost reduction (k€/y)	PBP (y) (Berghout et al.)[9]	Lifetime (y) (Berghout et al.)[10]	α	Investment (k€)[11]	CAPEX (k€/y)	OPEX (k€/y)	PBP (years)	Annualized costs (k€/y)	Savings (k€/y)	Marginal CO2 abatement costs (€/t CO2)
1	FANS	Fouling Mitigation	A	3.3	15	91	1	10	0.16	60	8.5	30.0	1.1	38.5	52.7	-4.3
2	FANS	Motors & Pumps	A	2.2	10	61	3	10	0.16	65	9.3	19.5	2.0	28.8	32.6	-1.8
3	FANS	Motors & Pumps	C	2.2	10	61	3	10	0.16	125	17.8	12.5	4.0	30.3	31.1	-0.4
4	FANS	Motors & Pumps	A	7.1	33	199	3	10	0.16	300	42.7	30.0	2.4	72.7	125.8	-7.5
5	PUMP	Motors & Pumps	A	3.5	16	98	3	10	0.16	130	18.5	13.0	2.0	31.5	66.3	-9.9
6	PUMP	Motors & Pumps	C	1.7	8	48	3	10	0.16	70	10.0	14.0	2.9	24.0	24.3	-0.2
7	PUMP	Motors & Pumps	A	3.5	16	98	3	10	0.16	160	22.8	16.0	2.7	38.8	59.0	-5.8
8	PUMP	Motors & Pumps	C	8.4	39	233	3	10	0.16	470	66.9	47.0	3.9	113.9	119.2	-0.6
9	PUMP	Motors & Pumps	C	10.1	47	280	3	10	0.16	560	79.7	56.0	3.9	135.7	144.5	-0.9
10	PUMP	Motors & Pumps	C	13.3	62	371	3	10	0.16	750	106.8	75.0	4.0	181.8	189.0	-0.5
11	PUMP	Motors & Pumps	C	11.7	55	327	3	10	0.16	660	94.0	66.0	4.0	160.0	166.7	-0.6
12	PUMP	Motors & Pumps	C	6.9	32	191	3	10	0.16	320	45.6	48.0	3.3	93.6	97.8	-0.6
13	STEAM	Steam Distribution system	A	2.7	41	500	1	20	0.12	490	46.3	98.0	1.4	144.3	355.3	-77.2
14	STEAM	Steam Distribution system	A	0.9	14	164	1	20	0.12	190	17.9	38.0	1.8	55.9	108.6	-58.4
15	STEAM	Steam Distribution system	A	5.4	81	987	1	20	0.12	1800	169.9	180.0	2.8	349.9	637.1	-53.2
16	STEAM	Steam Distribution system	C	4.5	68	822	1	20	0.12	2000	188.8	200.0	4.6	388.8	433.7	-10.0
17	STEAM	Steam Distribution system	B	6.7	100	1223	1	20	0.12	2800	264.3	280.0	4.1	544.3	679.1	-20.1
18	STEAM	Steam Distribution system	A	2.7	41	493	1	20	0.12	550	51.9	110.0	1.7	161.9	331.6	-62.8
19	STEAM	Steam Distribution system	B	1.8	27	329	1	20	0.12	750	70.8	75.0	4.1	145.8	183.2	-20.8
20	DIST	Heat integration distillation units	A	4.5	67	816	5	15	0.13	800	87.8	80.0	1.2	167.8	648.6	-107.6
21	DIST	Advanced separation systems	A	5.4	81	987	7	25	0.11	2400	240.0	240.0	4.7	480.0	507.0	-5.0
22	DIST	Heat integration & waste heat recovery	A	6.6	99	1206	5	15	0.13	2500	274.5	250.0	3.7	524.5	681.8	-23.8
23	DIST	Improved furnace performance	A	3.2	48	585	2.5	15	0.13	1100	120.8	110.0	3.1	230.8	354.1	-38.5
24	DIST	Heat integration & waste heat recovery	B	0.8	12	146	5	15	0.13	330	36.2	33.0	4.3	69.2	77.0	-9.7
25	DIST	Improved furnace performance	A	4.2	63	768	2.5	15	0.13	1400	153.7	140.0	3.0	293.7	473.9	-42.9
26	DIST	Improved furnace performance	A	1.6	24	292	2.5	15	0.13	500	54.9	50.0	2.7	104.9	187.5	-51.6
TOTAL				124.9	1110.2	11379				21280	2300	2311		4611	6767	

[6] The four types of EEMs used in the internship report
[7] The subdivision using types of EEMs used in Berghout et al. (forthcoming).
[8] Subdivision in categories based on economic profitability from the internship report
[9] Estimations of Payback Periods by Berghout et al. (forthcoming)
[10] Estimations of lifetimes by Berghout et al. (forthcoming)
[11] Own estimations based on a combination of the findings in the internship report and estimation of Berghout et al. (forthcoming).

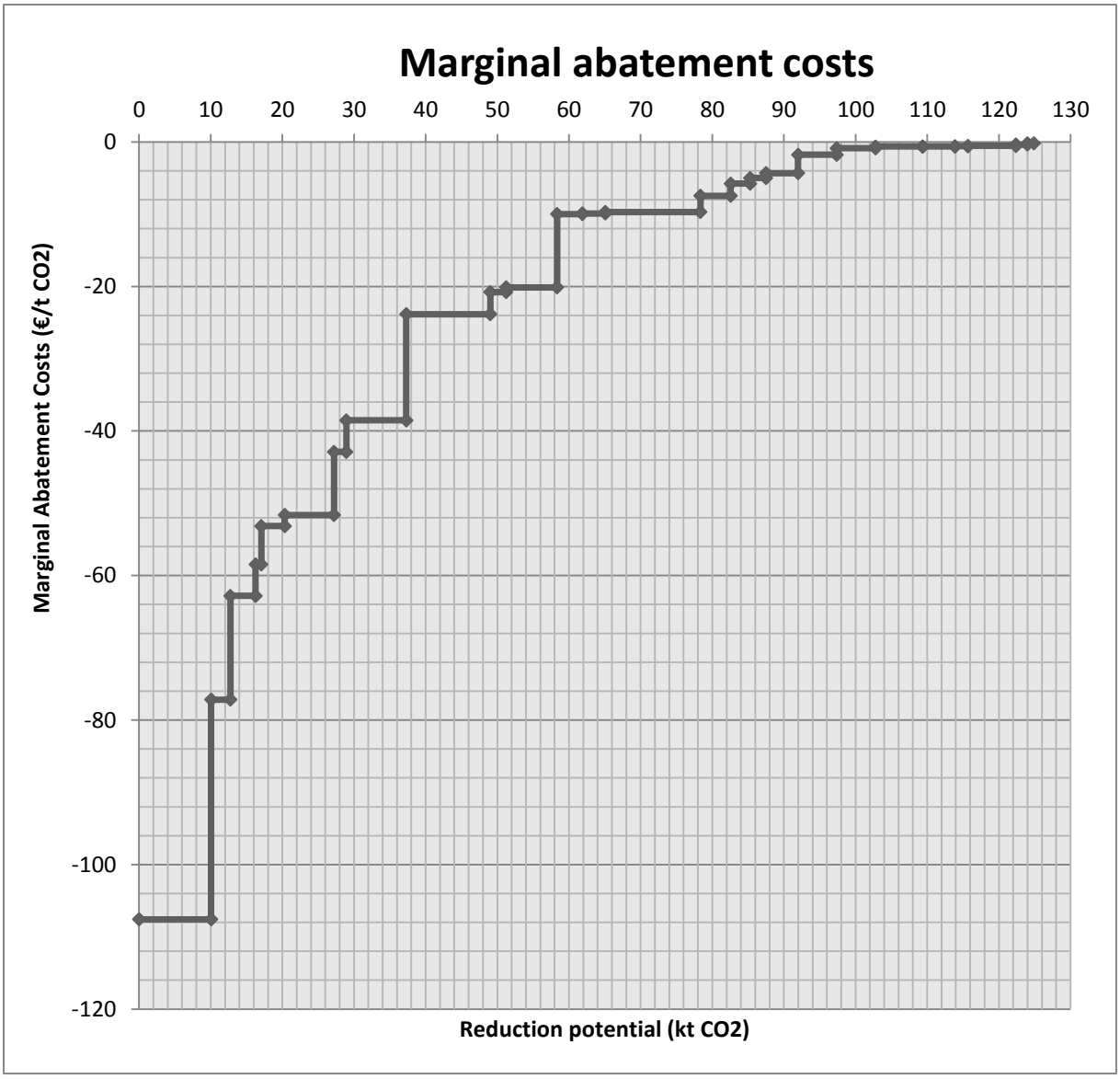

Figure 5. Marginal abatement cost curve of EEMs

4.3 Post-combustion capture

In this section the investment costs for post-combustion carbon capture at the case refinery is calculated. Johansson et al. (2012) did this already for a centralized configuration. In this paragraph it is analyzed whether a decentralized configuration study can make a large difference.

In table 7 the costs for the absorber and ducting are shown because when a decentralized configuration is chosen, these cost figures will change.

At the case refinery, carbon capture will be installed at 2 stacks. So for a decentralized configuration, 2 absorbers will be needed. Because of the scaling factor, investments costs for the absorbers will rise, while less ducting is required so those costs will decrease.

The 2 stacks are responsible for 192 $ktCO_2/y$ and 292 $ktCO_2/y$ which sums up to 484 $ktCO_2/y$. For calculating the investment costs of the absorbers, they are scaled to the emission of the two stacks, using the scaling factor of 0.7. The sum of the two absorbers gives the new total investment costs for the absorbers. Comparing these costs with the costs from table 7, it can be seen that due to economies of scale the investment for absorbers is now higher.
For the investment costs of ducting an assumption was made because of the lack of available data. It is assumed that investment costs for ducting will decrease with 30%. The operational costs of ducting will also decrease because distances are shorter. This leads to smaller pressure drops and therefore requires less pump duty. The 30% lower costs assumption is also used for the operational costs of ducting. This gives the results from table 13.

Table 13. Investment cost for the components Absorber and Ducting and operational costs of Ducting for a decentralized configuration and difference with centralized configuration

Costs [M€$_{2010}$]	NGCC		NB		BB		EH + HP	
Heat demand	2.8	4.7	2.8	4.7	2.8	4.7	2.8	4.7
Investment Absorber	14.0	19.5	11.7	13.3	13.6	18.6	10.1	10.1
Investment Ducting	4.3	6.1	3.6	4.1	4.2	5.8	3.1	3.1
Operational Ducting [M€$_{2010}$/y]	0.2	0.3	0.2	0.2	0.2	0.3	0.1	0.1
Difference	-1.33	-1.92	-1.03	-1.27	-1.30	-1.74	-0.99	-0.99

This difference between a centralized and a decentralized configuration leads to the results in table 14.

Table 14. Investment and avoidance costs for a centralized (Johansson et al., 2012) and decentralized configuration

Regeneration heat source	NGCC		NB		BB		EH + HP	
Heat demand	2.8	4.7	2.8	4.7	2.8	4.7	2.8	4.7
Total investment costs centralized [M€$_{2010}$]	98	137	82	93	96	131	71	71
Total investment costs decentralized [M€$_{2010}$]	97	135	81	92	94	129	70	70
Avoidance costs centralized [€/tCO_2]	101.34	213.36	83.86	130.40	69.81	113.12	38.59	42.42
Avoidance costs decentralized [€/tCO_2]	101.01	212.79	83.60	130.09	69.52	112.72	38.37	42.20

Looking at the avoidance costs for both configurations, it can be concluded that it does not make a large difference in terms of costs. That is mainly because at the case refinery there are only two stacks where is captured from. For refineries with more capture points, the choice of configuration would have a larger influence. Because of the relatively small influence of configuration at the case refinery, this is ignored in the scenario analysis of this study.

4.4 Scenario analysis

4.4.1 Scenario 1

In the first scenario, the EEMs are implemented first. Post combustion capture is implemented with the regeneration heat supplied by a NGCC. Also, practical issues are ignored. This means that the outcome of this scenario is only a theoretical reduction potential.

In the internship report, we found a CO_2 reduction potential of 125 ktCO_2 per year and an energy reduction potential of about 1100 TJ per year when the EEMs are implemented and practical issues and interactions are ignored. Then post-combustion capture is implemented with a NGCC as heat supply option. Johansson et al. (2012) found a CO_2 reduction potential of 300-370 ktCO_2 per year, depending on the level of heat demand. However, this is based on annual emissions of 0.48 MtCO_2/y. In 2012, the emissions were 0.55 MtCO_2/y. Scaling the capture plant to the proper size leads to the results of table 15. The avoidance costs are lower than in Johansson et al. (2012) because of the higher emission and relatively lower investment costs due to scaling.

Table 15. Results for post-combustion capture of scenario 1

NGCC	No interactions	
Energy demand [MJ / kg CO_2]	**2.8**	**4.7**
Total CO_2 to capture plant from Refinery [M t/y]	0.55	0.55
CO_2 emissions from energy plant [Mt /y]	0.33	0.87
Captured amount of CO_2 emissions [Mt /y]	0.75	1.21
Avoided amount of CO_2 emissions [Mt /y]	0.42	0.34
Investment capture plant [M€]	109.03	153.08
Investment energy plant [M€]	87.70	187.80
Investment costs for the capture plant [M€/y] (CAPEX)	10.90	15.31
Investment costs for the NGCC [M€/y] (CAPEX)	8.77	18.78
Total investment costs [M€/y] (CAPEX)	19.67	34.09
Fixed costs [M€/y] (OPEX)	7.00	11.00
Fuel costs [M€/y]	54.54	142.66
Electricity costs [M€/y]	-41.36	-120.43
Avoidance costs [€/tCO_2]	**95**	**200**

Because no practical issues and interactions are taken into account, these reduction potentials can be added up. This results in a total CO_2 reduction potential of 465-545 ktCO_2 per year. In 2012 the case refinery emitted 550 ktCO_2 which therefore means that this scenario has a theoretical CO_2 reduction potential of 85-99%.

4.4.2 Scenario 2

The second scenario is similar to the first scenario, except for the heat supply for the stripper. In this scenario excess heat is used for regenerating the absorbent in the stripper. Johansson et al. (2012) found available excess heat at the case refinery of 54 MW_{th}. The

temperature of this heat is above 129 °C. With a low heating demand (2800 kJ/kgCO_2), 38 MW_{th} is required and the available excess heat would suffice. However, for a high heating demand (4700 kJ/kgCO_2), 64 MW_{th} is required. In this case an additional heat pump must be installed (Johansson et al, 2012). This heat pump uses heat between 90-129 °C. 53 MW_{th} of this heat is available at the case refinery and would therefore suffice.

Without any practical issues and interactions, the CO_2 emission reduction potential of the EEMs remains the same as in scenario 1. For post-combustion capture with using excess heat as heat supply, Johansson et al. (2012) found a CO_2 reduction potential of 410 ktCO_2/y. Using the emission level of 2012, the CO_2 reduction potential would become 470 ktCO_2 as can be seen in table 16.

Table 16. Results for post-combustion capture of scenario 2

EH + HP	No interactions	
Energy demand [MJ / kg CO_2]	**2.8**	**4.7**
Total CO_2 to capture plant from Refinery [Mt/y]	0.55	0.55
CO_2 emissions from energy plant [Mt /y]	0.00	0.00
Captured amount of CO_2 emissions [Mt /y]	0.47	0.47
Avoided amount of CO_2 emissions [Mt /y]	0.47	0.47
Investment capture plant	78.71	129.16
Investment energy plant	0.00	4.40
Investment costs for the capture plant [M€/y] (CAPEX)	7.87	12.92
Investment costs for the EH+HP [M€/y] (CAPEX)	0.00	0.44
Total investment costs [M€/y] (CAPEX)	7.87	13.36
Fixed costs [M€/y] (OPEX)	4.00	4.00
Fuel costs [M€/y]	0.00	0.00
Electricity costs [M€/y]	5.16	6.42
Avoidance costs [€/tCO_2]	**36**	**51**

Together with the reduction potential of EEMs and ignoring practical issues and interactions, this adds up to an emission reduction of 595 ktCO_2 per year. Obviously this is a theoretical reduction potential. When practical issues and interactions are taken into account, this reduction potential will be much lower.

4.4.3 Scenario 3

In this scenario EEMs are implemented first and the heat for post-combustion capture is supplied by a NGCC. Also, practical issues and interactions are taken into account. This means that the reduction potential of EEMs is reduced as was shown in the internship report. Also practical issues regarding post-combustion itself will be assessed. But more importantly, the interaction between EEMs and post-combustion capture will lead to a reduced potential for post combustion capture and thus different specific costs.

The internship report found a reduction potential for EEMs, with practical issues and interactions, of 81-112 ktCO_2 (from pessimistic and optimistic perspectives, respectively).

Post-combustion capture will not have any practical issues itself at the case refinery (Interviewee 4, 2014). Also, because a NGCC is used as heat supplier, the implementation of post-combustion capture is not hampered by the implementation of any of the EEMs.
So, implementing the EEMs first leaves a CO_2 emission of 432-469 ktCO_2 per year at the case refinery. Because of the reduced emission, a smaller capture plant is required and new costs are calculated accordingly. It is assumed that the emission from the energy plant is reduced linear. The investment costs for the energy plant remain the same. Fuel and electricity costs (or income in the case of the NGCC) also decline linear. This leads to the results in table 17.

Table 17. Results for post-combustion capture of scenario 3

NGCC	EEMs optimistic		EEMs pessimistic	
Energy demand [MJ / kg CO_2]	**2.8**	**4.7**	**2.8**	**4.7**
Total CO_2 to capture plant from Refinery [M t/y]	0.43	0.43	0.47	0.47
CO_2 emissions from energy plant [Mt /y]	0.26	0.68	0.28	0.74
Captured amount of CO_2 emissions [Mt /y]	0.59	0.95	0.64	1.03
Avoided amount of CO_2 emissions [Mt /y]	0.33	0.26	0.36	0.29
Investment capture plant [M€]	92.07	129.28	99.52	136.93
Investment energy plant [M€]	87.70	187.80	87.70	187.80
Investment costs for the capture plant [M€/y] (CAPEX)	9.21	12.93	9.75	13.69
Investment costs for the NGCC [M€/y] (CAPEX)	8.77	18.78	8.77	18.78
Total investment costs [M€/y] (CAPEX)	17.98	31.71	18.52	32.47
Fixed costs [M€/y] (OPEX)	7.00	11.00	7.00	11.00
Fuel costs [M€/y]	42.84	112.05	46.51	121.65
Electricity costs [M€/y]	-32.49	-94.59	-35.27	-102.69
Avoidance costs [€/tCO_2]	**108**	**227**	**103**	**217**

The avoidance costs in scenario 3 are in most cases higher than in the reference scenario, especially with an optimistic perspective on the reduction potential of the EEMs. This is mainly because less CO_2 will be captured while the total investment costs will not decrease as much. However, in this scenario a total of 371-448 ktCO_2 could be avoided, which corresponds to an emission reduction of 67-81%.

4.4.4 Scenario 4

In the fourth scenario, again EEMs are implemented first. When post-combustion is implemented, the heat for regenerating the absorbent is supplied by excess heat. Practical issues and interactions are taken into account.
The interaction between EEMs and post-combustion capture is in this scenario possibly relatively strong, because of the use of excess heat. In the internship report, several EEMs are based on the usage of this excess heat. Because EEMs are implemented first in this scenario, the excess heat is already used before implementation of post-combustion capture. It is therefore questionable whether this scenario is possible.

This is depending on the temperatures and amount of the excess heat that is used by EEMs. Johansson et al. (2012) found available excess heat at the case refinery of 54 MW_{th} with temperatures above 129 °C and 53 MW_{th} with temperatures between 90-129 °C. When (too much of) this excess heat is used by EEMs, it cannot be used for post-combustion capture anymore.

However, according to Worrel (2014), excess heat below 130 °C is not used for refinery processes anymore. When this is assumed, the excess heat can be used for post-combustion capture. The EEMs are implemented first, followed by post-combustion with excess heat. This gives the results as in table 18.

Table 18. Results for post-combustion capture of scenario 4

EH + HP	EEMs optimistic		EEMs pessimistic	
Energy demand [MJ / kg CO_2]	**2.8**	**4.7**	**2.8**	**4.7**
Total CO_2 to capture plant from Refinery [Mt/y]	0.43	0.430	0.470	0.470
CO_2 emissions from energy plant [Mt /y]	0.00	0.00	0.00	0.00
Captured amount of CO_2 emissions [Mt /y]	0.37	0.37	0.40	0.40
Avoided amount of CO_2 emissions [Mt /y]	0.37	0.37	0.40	0.40
Investment capture plant [M€]	66.25	66.25	70.51	70.51
Investment energy plant [M€]	0.00	4.40	0.00	4.40
Investment costs for the capture plant [M€/y] (CAPEX)	6.63	6.63	7.05	7.05
Investment costs for the EH+HP [M€/y] (CAPEX)	0.00	0.44	0.00	0.44
Total investment costs [M€/y] (CAPEX)	6.63	7.07	7.05	7.49
Fixed costs [M€/y] (OPEX)	4.00	4.00	4.00	4.00
Fuel costs [M€/y]	0.00	0.00	0.00	0.00
Electricity costs [M€/y]	4.03	5.34	4.29	5.65
Avoidance costs [€/tCO_2]	**40**	**44**	**39**	**43**

The avoidance costs are higher when there is an optimistic perspective on the reduction potential of EEMs. That is because EEMs reduce more and therefore less CO_2 remains for capture. Due to economies of scale, the avoidance costs are higher.

As said, excess heat below 130 °C is not used for refinery processes. This means that these heat fluxes are cooled by fans. It is contradictory to implement EEMs first which will improve cooling fans, followed by installing heat exchangers for post-combustion capture. When post-combustion capture with excess heat is implemented, these cooling fans will be used much less.

Also, there is currently enough space available for the implementation of post-combustion capture (Interviewee 4, 2014). But when EEMs are implemented first, it is uncertain whether there will be enough plot space left for heat exchangers and piping for post-combustion capture. This is however hard to quantify because there is too little information and data on these issues.

4.4.5 Scenario 5

In this scenario, post-combustion capture is implemented first with a NGCC as heat supply. But because practical issues and interactions are ignored in this scenario, the different implementation order will not lead to different results. The reduction potential is therefore equal to the theoretical reduction potential of scenario 1, namely 465-545 ktCO_2 per year.

4.4.6 Scenario 6

The same goes for the sixth scenario. Post-combustion is implemented first with excess heat as heat supply. Because interactions and practical issues are ignored, the theoretical reduction potential of scenario 6 is equal to the reduction potential of scenario 2: 595 ktCO_2 per year.

4.4.7 Scenario 7

In scenario 7, post-combustion is implemented first with an NGCC as heat supply. Practical issues and interactions are taken into account in this scenario and will therefore have a different reduction potential and avoidance costs.

When post-combustion capture is implemented first, the case refinery still emits the initial amount of CO_2 per year. Therefore the capture plant that is installed is the same size as in scenario 1 and thus has the same investment costs. Subsequently the EEMs are installed. Because EEMs make the refinery more efficient, the emission level is reduced. This leads to a capture plant that is too large for the remaining CO_2 emission and results in a less efficient CO_2 capture. This makes post-combustion more expensive, as can be seen in table 19. Comparing the avoidance costs of scenario 7 with scenario 3 (the same scenario, except for the implementation order), shows that when post-combustion capture is implemented first, the avoidance costs are higher. The difference ranges between 1 and 4 €/tCO_2. The difference is larger for an optimistic perspective on the EEMs. This is correct because then EEMs reduce more emission which makes the already installed capture plant even less efficient.

Table 19. Results for post-combustion capture of scenario 7

NGCC	EEMs optimistic		EEMs pessimistic	
Energy demand [MJ / kg CO_2]	**2.8**	**4.7**	**2.8**	**4.7**
Total CO_2 to capture plant from Refinery [M t/y]	0.43	0.43	0.47	0.47
CO_2 emissions from energy plant [Mt /y]	0.26	0.68	0.28	0.74
Captured amount of CO_2 emissions [Mt /y]	0.59	0.95	0.64	1.03
Avoided amount of CO_2 emissions [Mt /y]	0.33	0.26	0.36	0.29
Investment capture plant [M€]	99.70	138.80	99.70	138.80
Investment energy plant [M€]	87.70	187.80	87.70	187.80
Investment costs for the capture plant [M€/y] (CAPEX)	9.97	13.88	9.97	13.88
Investment costs for the NGCC [M€/y] (CAPEX)	8.77	18.78	8.77	18.78
Total investment costs [M€/y] (CAPEX)	18.74	32.66	18.74	32.66

Fixed costs [M€/y] (OPEX)	7.00	11.00	7.00	11.00
Fuel costs [M€/y]	42.84	112.05	46.51	121.65
Electricity costs [M€/y]	-32.49	-94.59	-35.27	-102.69
Avoidance costs [€/tCO_2]	**110**	**231**	**104**	**218**

4.4.8 Scenario 8

In the final scenario, post-combustion is implemented first with excess heat as heat supply to the stripper. Practical issues and interactions are taken into account.

In scenario 4 it became clear that the excess heat use of EEMs and post-combustion capture will probably not overlap. So the excess heat below 129 °C is used for post-combustion capture. However, because post-combustion capture with excess heat usage is implemented first, some EEMs are probably not implemented anymore. These are especially the measures regarding cooling fans. When the excess heat is used for capturing, these fluxes will not be cooled anymore by fans. Therefore the emission reduction potential of EEMs is adjusted to levels without the EEMs regarding cooling fans. This is shown in table 20.

Table 20. Annual reduction potentials of EEMs in different options of scenario 8

	Old potential	Potential for scenario 8
Optimistic perspective	118 ktCO_2/y	103 ktCO_2/y
Pessimistic perspective	81 ktCO_2/y	66 ktCO_2/y

With these reduction potentials by EEMs, the results in table 21 are found.

Table 21. Results for post-combustion capture of scenario 8

EH + HP	**EEMs optimistic**		**EEMs pessimistic**	
Energy demand [MJ / kg CO_2]	2.8	4.7	2.8	4.7
Total CO_2 to capture plant from Refinery [M t/y]	0.447	0.484	0.447	0.484
CO_2 emissions from energy plant [Mt /y]	0.00	0.00	0.00	0.00
Captured amount of CO_2 emissions [Mt /y]	0.38	0.41	0.38	0.41
Avoided amount of CO_2 emissions [Mt /y]	0.38	0.41	0.38	0.41
Investment capture plant [M€]	71.80	71.80	71.80	71.80
Investment energy plant [M€]	0.00	4.40	0.00	4.40
Investment costs for the capture plant [M€/y] (CAPEX)	7.18	7.18	7.18	7.18
Investment costs for the EH+HP [M€/y] (CAPEX)	0.00	0.44	0.00	0.44
Total investment costs [M€/y] (CAPEX)	7.18	7.62	7.18	7.62
Fixed costs [M€/y] (OPEX)	4.00	4.00	4.00	4.00
Fuel costs [M€/y]	0.00	0.00	0.00	0.00
Electricity costs [M€/y]	4.19	5.22	4.50	5.60
Avoidance costs [€/tCO_2]	**40**	**41**	**41**	**42**

As can be seen, this scenario has similar avoidance costs as scenario 4. That is because in scenario 4 the investment costs are lower (because EEMs are implemented first), but the

amount of captured CO_2 is larger in scenario 8. Because efficiency measures regarding cooling fans are not implemented in scenario 8, the effect of a too large capture plant is weakened.

However, similar to scenario 4, space limitation might become an issue for implementing EEMs when post-combustion with excess heat is already implemented. The total CO_2 reduction potential is in the range of 446-513 $ktCO_2/y$.

4.5 Analysis

Figure 6 shows the results of the scenario analysis. As said, scenarios 1, 2, 5 and 6 are theoretical scenarios because practical issues and interactions are ignored. Comparing these with other scenarios shows the effect of interactions and practical issues. Therefore the reduction potentials of scenarios 3, 4, 7 and 8 are lower.

The error bars represent the range of reduction potential for the scenarios. These ranges occur due to the different perspectives on the reduction potential of EEMs (which subsequently influences the reduction potential of post-combustion capture).

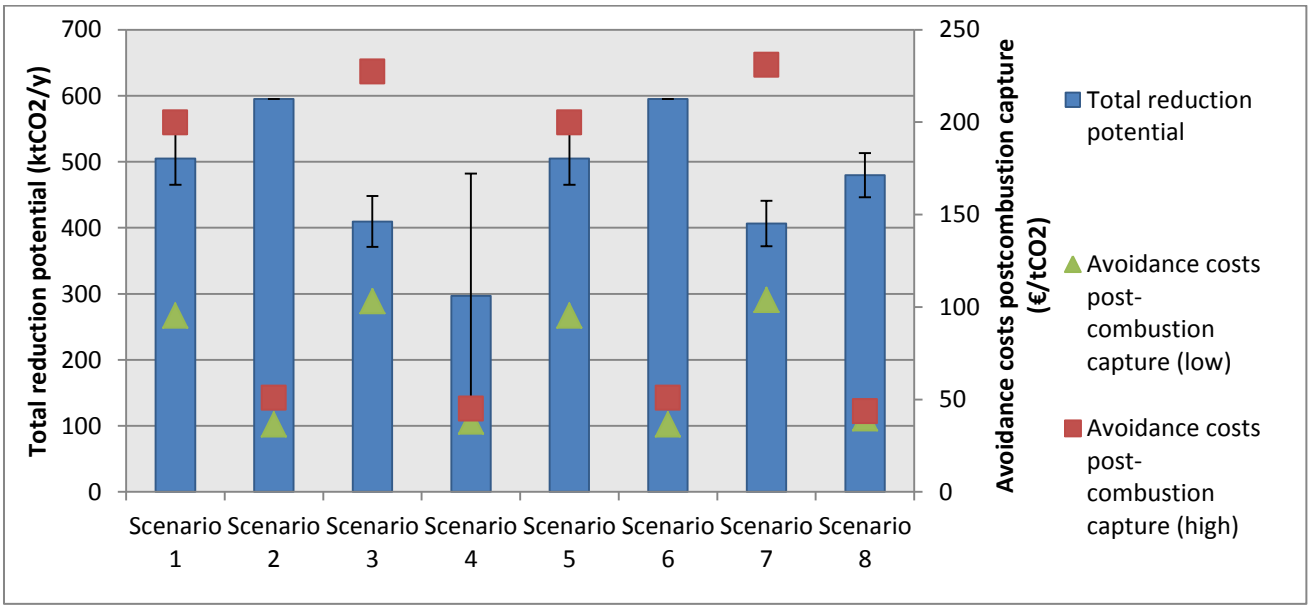

Figure 6. Results of scenario analysis

Scenario 4 has a large error bar. That is because it shows when post-combustion capture can be implemented or not. As said, according to Worrel (2014), excess heat usage of EEMs and post-combustion capture does not overlap in terms of temperatures. This would mean that post-combustion capture is possible and the upper range of the error bar applies.

It is important to mention that when EEMs regarding cooling fans are installed, those EEMs will probably become obsolete when post-combustion capture with excess heat is installed. Therefore a variation of scenario 4 is assessed as well. In this scenario, the only difference with scenario 4 is that EEMs regarding cooling fans are not installed. When this is done, the post-combustion capture plant is properly sized and more CO_2 is avoided. This leads to even lower avoidance costs. Also the investment costs for the EEMs regarding cooling fans are not

necessary anymore. The result is that the same amount of CO_2 is avoided as in scenario 8, with slightly lower avoidance costs for post-combustion capture (about 1€/tCO_2 lower than scenario 8). This would mean that this variation of scenario 4 would be the best option.
It must be noted however, that when the NGCC is chosen as heat supplier, excess electricity is produced. This can be sold to the grid. The income that it generates is taken into account, but the indirect CO_2 reduction elsewhere is not. Therefore the global reduction potential for the scenarios with a NGCC is actually higher. In fact, when it is assumed that due to the electricity production of the NGCC, electricity production at a coal power plant is avoided, global emission reductions are much higher than the global emission reduction of the scenarios with excess heat. This is calculated by Johansson et al (2012) and is presented in table 22.

Table 22. Additional CO_2 reduction in a global perspective

	NGCC		EH+HP	
Energy demand	2.8	4.7	2.8	4.7
Additional CO_2 reduction [ktCO_2/y]	**373**	**1.086**	**-47**	**-58**

The global CO_2 reduction for excess heat is negative because it requires electricity, which must be bought from the grid. When the global CO_2 reduction is calculated for the scenarios (i.e. adding the values of table 22), it becomes clear that the NGCC scenarios could have almost a three times larger global CO_2 reduction than the excess heat scenarios. Therefore the NGCC is in a global perspective more attractive. It could become more attractive for the case refinery as well, when regulations on green certificates (for indirect savings) play a more important role or when electricity prices increase in the future.

5. Discussion

The main objective of this study was to examine the techno-economic performance of post-combustion capture and EEMs for different implementation possibilities and to provide insight in the effect of practical issues and interactions between EEMs and carbon capture on the reduction potential. This has led to interesting results. However, the study's methodology has several weaknesses.

5.1 Data limitations

The data that is used applies only on the case refinery of this study. The plant-specific data dates from 2012, while the data from Johansson et al. (2012) on post-combustion capture is based on 2010. On the long term, core processes in refineries may change. This can influence the energy use, CO_2 emission, the possibility for implementation of EEMs, but also the availability of excess heat and or space availability. Also, on the long term, new mitigation options might become available. This could include more advanced EEMs, or new or improved technologies for carbon capture (e.g. pre-combustion and oxyfuel combustion capture). Next to that, energy prices and emission certificate prices are uncertain factors on the long term. Therefore, the results of this study might change considerably when it is done for the long term.

This study did not fully focus on the accuracy of the cost figures for post-combustion and EEMs. The data for costs of post-combustion capture at the case refinery originate from only 1 study and are therefore uncertain. The costs for EEMs are based on the internship report and Berghout et al., (forthcoming). Also, the calculated avoidance costs are based on many assumptions, and are therefore uncertain.

This could be dealt with by doing a sensitivity analysis. A sensitivity analysis could give insight in how this inaccuracy influences the results. An uncertainty range for the results could be given which makes the results more reliable. Nevertheless, future studies are required to analyze the costs of post-combustion capture and EEMs at refineries more thoroughly so more reliable (pilot plant) data are generated.

This study performed a case study. More case studies should be performed, because each refinery is site specific and can lead to different results. For example, at the case refinery the configuration of post-combustion capture did not have a large influence on the avoidance costs and are therefore neglected in this study. For refineries on larger scales, the configuration could play a large role because the effect of economies of scale will be larger. Other plant-specific factors that could have an effect on the results are fuel use and differences in products. That is because these can influence the CO_2 concentration of the fuel gas. A lower concentration requires a more expensive capture plant. Also the location of the refinery has an influence, e.g. seasonal differences can lead to the requirement of more heat. This should be investigated more by doing case studies with varying refineries.

5.2 Capture technologies

Other technologies for carbon capture, e.g. pre-combustion and oxyfuel combustion capture, require more investigation. Whereas this study looked at the interaction between post-combustion and EEMs, it should also be analyzed how pre-combustion capture and oxyfuel capture interact with EEMs. Berghout et al. (2012) gave a first overview of remaining challenges related to the implementation of these technologies. Next to that, the interaction with EEMs should also be analyzed, especially because pre-combustion capture and oxyfuel capture are not commercially available yet. Implementing EEMs at refineries now which might hamper or delay the implementation of pre-combustion capture and oxyfuel capture is not desirable. Therefore, these interactions are important to investigate.

5.3 Feasibility of scenarios

During the internship report it became clear that EEMs are probably not implemented when they have a PBP that is longer than 5 years. This is mainly because it is never certain how long the refinery will stay operational. This is for example due to the competition of larger scale refineries or more sustainable fuels. Also because of the legislative regulations, refining becomes more expensive. Therefore, the refinery does not want to invest in mitigation options with a PBP longer than 5 years. From the results of this study, only post-combustion capture with excess heat could become economically viable, depending very strongly on energy prices and emission certificate prices. Otherwise, the required investments are currently too large.

Required investments are an issue that also should be taken into account. Because of the lack of available capital, the case refinery will most probably not implement all EEMs and post-combustion capture. Lack of available capital is therefore a serious issue that is not taken into account in this study. Future studies should assess scenarios where post-combustion capture (or other capture technologies) is implemented in combination with only the cheap EEMs; low hanging fruit. This would be a more realistic scenario and the total reduction potential will probably not decrease by much because more CO_2 can be captured.

Also, other economic factors for post-combustion capture require more investigation. These include for example the transportation of liquid CO_2, storage and legal regulations that must be arranged. These can be large barriers for the implementation of carbon capture. Also, the social acceptance of on- and off-shore storage is a factor that can hamper or delay the implementation of carbon capture.

5.4 Next step

The next step for studies on this field would be to include other capture technologies in the analysis. Also, quantifying the additional costs of practical issues should be included in future studies. This way, a better insight into the effect of practical issues on avoidance costs can be provided.

6. Conclusion

This study did a techno-economic analysis of post-combustion capture at a case refinery in combination with EEMs. Two heat supply options for post-combustion capture were analyzed, namely a NGCC and excess heat.

The results show that a CO_2 reduction potential of 482 ktCO_2 per year is achievable. This corresponds to a reduction of 87%. This is the case when EEMs are implemented together with post-combustion capture and regeneration heat is supplied by excess heat (scenario 4 and 8). When a NGCC is used, the reduction potential is smaller because the NGCC emits CO_2 itself. Therefore, in a refinery perspective, the scenarios with excess heat are preferable. However, the NGCC produces excess electricity that can be sold to the grid. Assuming that electricity production at coal power plants is reduced, this could lead to an additional (indirect) reduction of 373-1086 ktCO_2/y. This could lead to an almost three times larger global CO_2 reduction for the NGCC than the excess heat scenarios. From a global perspective, the NGCC is therefore preferable.

Avoidance costs of post-combustion capture are between 39 and 227 €/tCO_2. The avoidance costs of the scenarios with excess heat are significantly lower than the scenarios with a NGCC. That is because the investment costs for the NGCC scenarios are much larger than for excess heat scenarios, while the excess heat avoids more CO_2 (from a refinery perspective).

Comparing the scenarios 1, 2, 5 and 6 with scenarios 3, 4, 7 and 8 shows the effect of practical issues and interactions between EEMs and post-combustion capture. The scenarios where these are neglected (1, 2, 5 and 6) all have a reduction potential that is about 100 ktCO_2/y higher than the scenarios where these issues are not neglected. Also, when practical issues and interactions are neglected, the avoidance costs of post-combustion capture are lower for the scenarios with a NGCC, especially when a high heat demand is assumed (difference is about 28 €/ktCO_2) . For the scenarios with excess heat the difference is much smaller.

Scenarios 3 and 7 are the scenarios with NGCC and interactions taken into account. They differ in implementation order. Comparing these scenarios shows that it is better to implement EEMs first. That is because when post-combustion is implemented first, followed by EEMs, the size of the capture plant becomes too large. Because of the large investment and smaller amount of captured CO_2, avoidance costs will be higher. A difference of 1-4 €/tCO_2 was found. That is a significant difference when large amounts of CO_2 are captured each year. This effect is smaller for the scenarios with excess heat. That is because when post-combustion capture with excess heat is implemented first, some EEMs are not implemented. Also, the investment costs of post-combustion with excess heat are much smaller and thus the effect is smaller.

From the perspective of the refinery, the scenario where EEMs are implemented first and the heat for post-combustion capture is supplied by excess heat (scenario 4), might be the most profitable scenario. That is because of the large CO_2 reduction potential and low avoidance costs. Especially when the cooling fans EEMs are not implemented, the amount of CO_2 captured increases and avoidance costs of post-combustion capture decrease. These

EEMs become (nearly) obsolete when post-combustion capture with excess heat is implemented and can therefore be disregarded.
Currently space availability is not a practical issue at the case refinery. However, this might change when EEMs are implemented first. Also, this is a site-specific issue which means that other refineries should consider the implementation of post-combustion capture first when space is limited.

7. Acknowledgements

This study is a master thesis that is done at Utrecht University. First of all, I would like to thank Niels Berghout for all his support and input. It is very much appreciated. Also thanks to Andrea Ramirez for all the valuable comments.
I would also like to thank Elin Svensson for all the help during the internship. And of course thanks to all the interviewees from the case refinery.

8. References

Anderson, K., & Bows, A. (2008). Reframing the climate change challenge in light of post-2000 emission trends. Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences, 366(1882)

Andersson, V., Franck, P.-åke, & Berntsson, T. (2013). Temperature Dependence of Heat Integration Possibilities of an MEA Scrubber Plant at a Refinery. Energy Procedia, 00, 9.

Bergh, C., & Cohen, B. (2012). Energy Efficiency in the South African Crude Oil Refining Industry: Drivers , Barriers and Opportunities MSc Sustainable Energy Engineering, (May).

Berghout, N., van den Broek, M., & Faaij, A. (2013). Techno-economic performance and challenges of applying CO2 capture in the industry: A case study of five industrial plants. International Journal of Greenhouse Gas Control, 17, 259–279.

Berghout et al. (forthcoming)

Chew, K. H., Klemeš, J. J., Wan Alwi, S. R., & Abdul Manan, Z. (2013). Industrial implementation issues of Total Site Heat Integration. Applied Thermal Engineering, 61(1)

Det Norske Veritas. (2010). Global Technology Roadmap for CCS in Industry Sectoral Assessment: Refineries (p. 37). Vienna, Austria.

Holmgren, K., & Sternhufvud, C. (2008). CO2-emission reduction costs for petroleum refineries in Sweden. Journal of Cleaner Production, 16(3), 385–394.

Integrated Pollution Prevention and Control (IPPC). (2003). Reference Document on Best Available Techniques for Mineral Oil and Gas Refineries. UE BREF, February (p. 518).

Intergovernmental Panel on Climate Change (IPCC). (2005). Special Report on Carbon dioxide Capture and Storage (p. 74).

International Energy Agency (IEA). (2011). Technology Roadmap Carbon Capture and Storage in Industrial Applications (p. 52). Paris, France.

International Energy Agency (IEA). (2012). CO2 emissions from fuel combustion (p. 138). Paris, France.

Johansson, D., Franck, P.-Å., & Berntsson, T. (2013). CO2 capture in oil refineries: Assessment of the capture avoidance costs associated with different heat supply options in a future energy market. Energy Conversion and Management, 66, 127–142.

Johansson, D., Rootzén, J., Berntsson, T., & Johnsson, F. (2012). Assessment of strategies for CO2 abatement in the European petroleum refining industry. Energy, 42(1), 375–386.

Kuramochi, T., Ramírez, A., Turkenburg, W., & Faaij, A. (2012). Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes. Progress in Energy and Combustion Science, 38(1), 87–112.

Richels, R., & Edmonds, J. (1995). The economics of stabilizing atmospheric CO2 concentrations. Energy Policy, 23(4-5), 373–378.

Rootzén, J., Kjärstad, J., & Johnsson, F. (2011). Prospects for CO_2 capture in European industry. Management of Environmental Quality: An International Journal, 22(1), 18–32.

Saygin, D., Patel, M. K., Worrell, E., Tam, C., & Gielen, D. J. (2011). Potential of best practice technology to improve energy efficiency in the global chemical and petrochemical sector. Energy, 36(9)

Saygin, D., van den Broek, M., Ramírez, a., Patel, M. K., & Worrell, E. (2013). Modelling the future CO2 abatement potentials of energy efficiency and CCS: The case of the Dutch industry. International Journal of Greenhouse Gas Control, 18, 23–37.

Stockle, M., Carter, D., & Jones, L. (2008). Optimising refinery CO2 emissions. Petroleum Technology Quarterly, 1–17.

Van Straelen, J., Geuzebroek, F., Goodchild, N., Protopapas, G., & Mahony, L. (2009). CO2 capture for refineries, a practical approach. International Journal of Greenhouse Gas Control, 4(2), 316–320.

Worrel, E., Corsten, M., & Galitsky, C. (2013). Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries. Energy Star Guide.

Worrell, E., & Galitsky, C. (2005). Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries. Energy Star Guide, (February).

Worrel (2014) Personal conversation

Interviewee	Field of expertise	Date	Topic
Interviewee 1	Process Engineer, Hydrotreating and Distillation	04-03-2014	Changing internals and other EEMs
Interviewee 2	Process Engineer, Catalytic Reforming and Distillation	13-02-2014	Energy efficiency at Reformer
Interviewee 3	Environmental Engineer, Emissions to Air	04-02-2014	Fuel consumption and CO2 emission
Interviewee 4	Controlling Manager, Emission Credit Accounting	03-03-2014	EU ETS
Interviewee 5	Control Engineer, Advanced Process Control	10-03-2014	EEMs at isomerization processes
Interviewee 6	Control Engineer, Advanced Process Control	12-02-2014	Energy efficiency at distillation units
Interviewee 7	Mechanical Engineer, Fired equipment	05-02-2014	Energy efficiency of fired heaters and boilers
Interviewee 8	Mechanical Engineer, Rotating equipment	04-02-2014	Energy efficiency of pumps and fans
Interviewee 9	Process Engineer, Hydrotreating and Isomerization	10-03-2014	EEMs at isomerization processes
Interviewee 10	Development Engineer, Refinery and Renewables	14-02-2014	Post-combustion capture

9. Appendix

Table 23. Assessed EEMs in the internship report

EEM	Description	EEM	Description
	Cooling fans		**Steam prodution and distribution**
1	Improve maintenance	13	Improve process control
2	Leakage repair	14	Leakage repair
3	High efficiency belts	15	Improve insulation
4	Adjustable speed drives	16	Return condensate
	Pump system	17	Preheat boiler combustion air wiht flue gases
5	Improve maintenance	18	Steam trap maintenance
6	Monitoring	19	Shut down existing low pressure boiler
7	Control systems		**Distillation processes**
8	High efficiency pumps	20	Preheat train optimization
9	Replace oversized pumps	21	Pre-flash drum
10	Multiple pumps for vaiable loads	22	Replace tube and shell heat exchangers
11	Adjustable speed drives	23	Exchanging internals of colums
12	Avoid throttling valves	24	Install waste heat recovery unit at naphta splitter
		25	Reduce pressure in the Penex stabilizer
		26	Raffinate column and extract column

Table 24. First inventory of EEMs with reasons for pre-selection

Process	Energy Efficiency Measure	Comments
Distillation	Energy Management	A well-organized energy management system is already implemented (interviewee 1, 2014)
	Process (heat) integration	Already implemented to a very large extent (interviewee 6, 2014)
	Install heat recovery at naphtha splitter	Included in analysis
	Reduce pressure Penex stabilizer	Included in analysis
	Seasonal operating pressure adjustments	Already implemented
	Upgrade column internals: replacing trays, adding high performance packing	Included in analysis
	Stripper optimization	Included in analysis
	Advance process control	Included in analysis (for Molex only)
	Progressive crude distillation	Only interesting on the long term: alternative is pre-flash drum (interviewee 6, 2014)
	Dividing wall-column	Too expensive to retrofit (interviewee 6, 2014). Interesting for a newly built refinery.
	Liquid-ring vacuum pump	No vacuum distillation at case refinery
	Replace heat exchangers	Included in analysis
	Install pre-flash drum	Included in analysis
Hydrotreatment	Process (heat) integration	Already implemented
	Hydrogen integration (pinch)	No hydrogen plant
	Hydrogen recovery (e.g. using membranes)	Only for long term (interviewee 1, 2014)
	Desulfurization alternatives: oxidative	Not interesting for short term, maybe long term (interviewee 1, 2014)
Other	Process (heat) integration	Already implemented to a large extent

	Adiabatic pre-reformer (using waste heat)	No steam reforming at case refinery (L. Norberg, 2014)
Flaring	Improved recovery systems: compression and storage	Almost no flaring at case refinery, very small potential (interviewee 1, 2014)
Fans	Maintenance	Included in analysis
	Properly sized fans	Too large investment to retrofit (interviewee 8, 2014). Interesting for new refinery
	Leakage repair	Included in analysis
	Replace with high efficiency belts	Included in analysis
	Adjustable speed drives	Included in analysis
Steam production / distribution	Feed water preparation: reverse osmosis (RO)	Only for long term, not interesting now (interviewee 7, 2014)
	Improve boiler process control	Included in analysis
	Leakage repair	Included in analysis
	Improve insulation	Included in analysis
	Return condensate	Included in analysis
	Preheat boiler air with flue gases	Included in analysis
	Minimize boiler blowdown: automatic blowdown control system	Already implemented
	Steam distribution controls: install control system and set standby boilers to zero steam production	No standby usage so no reduction potential
	Insulation maintenance	Already implemented
	Improve steam traps	Hundreds of steam traps, too large investment (interviewee 7, 2014)
	Steam trap maintenance	Included in analysis
	Monitor steam traps automatically	Hundreds of steam traps, too large investment (interviewee 7, 2014)
	Shut down existing low-pressure boiler	Included in analysis
Process heaters	Draft control (minimize excess air)	Already implemented
	Preheat air	Only interesting for just a few burners (interviewee 7, 2014)
	Replace burners	Too large investment (interviewee 7, 2014)
Pump system	Improved maintenance	Included in analysis
	Monitoring	Included in analysis
	Control systems	Included in analysis
	Replace with high-efficiency pumps	Included in analysis
	Replace oversized pumps	Included in analysis
	Use multiple pumps for variable loads	Included in analysis
	Adjustable Speed drives: better match speed to load requirement	Included in analysis
	Avoid throttling valves	Included in analysis
	Proper pipe sizing	Size of pipes calculated very well already (interviewee 8, 2014)
	Surface coating (reduce fricition)	Already implemented
	Improve sealings	Too small potential (interviewee 8, 2014)
Other	Power recovery at FCC	No FCC at case refinery
	Improve lighting efficiency	Negligible potential compared to other EEMs (interviewee 1, 2014)
	Switch lights of when not needed/use daylight	Negligible potential compared to other EEMs (interviewee 1, 2014)