CO_2 capture in oil refineries – an evaluation of different heat integration possibilities for heat supply to the post-combustion process

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Abstract: This paper estimates the costs of CO_2 post-combustion capture for two refineries by comparing different alternatives for supplying the heat needed for the regeneration of the absorbent. The cost of capture ranges from 30 to 472 €/ tCO_2 avoided, depending on technology choice for heat supply and energy penalty for the CO_2 separation. In this study, it is concluded that process integration leads to a reduction in avoidance costs. However, the avoidance cost depends greatly on which system perspective is considered, i.e. whether CO_2 emission changes outside the refinery are included or not.

Keywords: *Carbon capture and storage, Post combustion, Oil refinery, Process integration*

1. Introduction

The oil refining industry generates large amounts of CO_2 emissions. Today and in the future, harder regulations (e.g. the EU ETS system and the Renewable Energy Directive) both on CO_2 emissions from the refinery process and on the refinery products will give new incentives for the oil refining industry to act towards CO_2 mitigation measures. However, the process structure of a refinery implies that even a perfect, energy-efficient refinery will continue to emit significant amounts of CO_2. Carbon Capture and Storage (CCS) is an alternative that can further reduce CO_2 emissions from the oil refining process. The interest in CCS has grown over the past years, among researchers as well as companies. Different capture technologies are possible: post-combustion, oxy-fuel combustion, chemical looping and pre-combustion. However, post-combustion is the most studied technology and is chosen in this paper as a promising technology since it does not require any extensive rebuilding of the existing refinery. Several previous studies have evaluated the costs for CCS at refineries [1-3], but none has been found that has investigated the costs with different heat supply options in combination with future energy market scenarios. Therefore, the aim of this paper is to examine how the avoidance costs for CO_2 in refineries are affected by different heat integration possibilities and future energy market scenarios.

In this paper, the CO_2 avoidance cost for post-combustion carbon capture, with mono-ethanolamine (MEA), is evaluated at two case refineries in the Skagerrak region. The oil refining industry is rather complex and therefore often offers opportunities for process integration which can facilitate substantial cost reductions for the heat supply. In this paper, possibilities to use excess heat from the main process to supply heat to the desorption unit, with or without the need of a heat pump, are evaluated as well as integration of a Natural Gas Combined Cycle (NGCC), a natural gas boiler and a biomass boiler. Also combinations of these alternatives are evaluated which is described in Section 2.1.

2. Studied systems and alternatives with related assumptions

The first case refinery is a hydroskimming refinery (Refinery no. 1) with a crude oil capacity of 6 Mt/y and ca. 0.5 Mt CO_2. The second is a complex refinery (Refinery no.2) with a crude oil capacity of 11.4 Mt/y and ca. 1.9 Mt CO_2. CO_2 emissions from the oil refining process originate from several sources. Only the largest CO_2 emission sources (89% of the total CO_2

emissions) have been selected for capture, resulting in 2 sources (totally 0.45 Mt CO_2/y) for Refinery no.1, and 4 sources (totally 1.7 Mt CO_2/y) for Refinery no. 2.

In this analysis the desorption column in the CO_2 capture unit has a working temperature of 120°C. After capture, the CO_2 is compressed to a pressure of ca. 75 bar with an absorber efficiency of 0.85. In order to generate the absorbent (MEA), large quantities of energy are needed. There are uncertainties regarding the heat demand needed per CO_2 emission captured, and therefore, to handle this discrepancy, two levels of desorption heat demand in the desorption are used, 2800 kJ/kg CO_2 and 4700 kJ/kg CO_2. The heat demand needed for desorption can be satisfied in different ways, and the alternatives used in this paper are described in more detail below. Key figures for the different alternatives are found in Table 1.

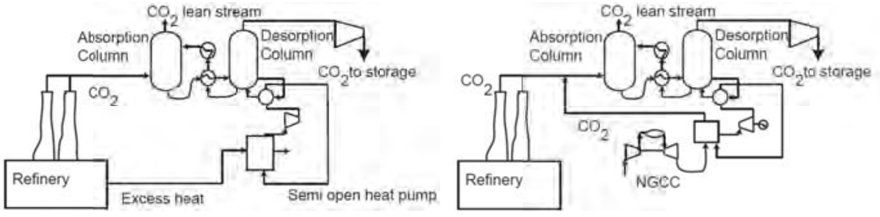
2.1. Process integration, utilization of excess heat (EH)

In this alternative the excess heat available above 129°C (EH) has been investigated in order to produce steam for the desorption unit. Two cases are used in Refinery no. 1. First, all excess heat is assumed to be available, presented as EH[1]&HP in Table 1. In the alternative with low heating demand (2800kJ/kgCO_2) enough heat above 129°C is available. However, in the alternative with high heating demand (4700kJ/kg CO_2) a heat pump must be used for supplying the additional heat needed. Second, due to contract regulations the amount of excess heat delivered to the current district heating network is assumed to be reserved. In this case only remaining excess heat is available for heat supply, and additional heat is supplied by a NGCC (EH[2]&NGCC), Biomass boiler (EH[2]&BB) or a Natural gas boiler (EH[2]&NB). Hence, the latter alternatives are a combination of excess heat above 129° (heat left after district heat delivery) and NGCC, BB and NB.

The prerequisites for Refinery no. 2 are different. The current district heat delivery is only a few percent of the excess heat, compared to over 50 percent for the first refinery. According to this fact, the alternative where the current level of district heat is reserved is not examined in Refinery no.2. On the other hand Refinery no.2 has the opportunity to increase the capacity of the current boilers. When evaluating Refinery no.2, the excess heat above 129°C is not enough to cover the whole heating demand for any of the levels of heating demands. Here, several alternatives to supply the additional energy needed are explored. First, a heat pump is used to supply the extra energy, presented as EH[1]&HP. Second, the capacity of the current steam boiler is increased (SP) and a biomass boiler, a natural gas boiler or a NGCC is used to supply the rest of the steam needed, presented as EH[3]&BB, EH[3]&NB and EH[3]&NGCC respectively. In both alternatives the available excess heat above 129°C has been used.

2.2. Heat pump (HP)

The heat pump uses heat available above 90°C at the refinery to produce LP steam (2.3 bar). The configuration is shown in Fig. 1. It is assumed that the temperature drop of available heat, related to the collection of heat from process streams, is 5°C. The heat pump is a semi-open cycle Mechanical Vapour Recompressor (MVR) using water vapour as working fluid [4].



Figs. 1 & 2. The design of the capture unit using a HP (Fig. 1) or a NGCC (Fig. 2) for heat supply.

2.3. Natural gas combined cycle (NGCC)

The NGCC alternative is designed so that the heat recovery steam generator (HRSG) produces enough HP steam (80 bar) to cover the demand of LP steam (2.3 bar) needed for capturing CO_2 generated from both the refinery process and the NGCC; see Fig. 2.

2.4. Biomass and natural gas boilers (BB and NB)

In the biomass boiler alternative, a boiler (with efficiency 0.9) is installed. The boiler produces HP steam (80 bar) that is expanded in a back-pressure steam turbine to produce LP steam (2.3 bar). The boiler capacity is adjusted to produce enough LP steam to cover the heat demand for CO_2 capture from both the current process and the biomass boiler; see Fig 3. The natural gas boiler follows the design of the biomass boiler, except from the efficiency (0.94).

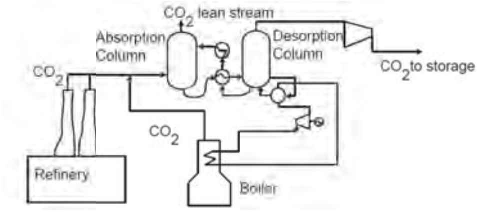


Fig. 3. The design of the capture unit using a biomass boiler or a natural gas boiler for heat supply.

Table .1 Key figures for the case refineries and the studied alternatives. Numbers within parentheses indicate figures for the high desorption heating demand (4700 kJ/kg CO_2). Ref. indicates the current figures for the refinery. In the current refinery (ref.) excess heat used refers to district heat delivery.

Refinery no.1	**Ref.**	**EH[1] &HP**	**NGCC**	**BB**	**NB**	**EH[2]& NGCC**	**EH[2] & BB**	**EH[2] NB**
Natural gas (MW)	19	19 (19)	178 (458)	19 (19)	86 (153)	142 (397)	19 (19)	70 (134)
Biomass (MW)	-	-	-	86 (195)	-	-	58 (195)	-
Excess heat used (MW)	120	37 (62)	-	-	-	129	129	129
CO_2 captured (t/h)	48	48	75 (123)	73 (114)	59 (71)	84 (113)	65 (105)	56 (67)
Electricity import (MW)	21	29 (30)	-39 (-157)	15 (-8)	16 (3)	-21 (-132)	19(-3)	19 (6)
Refinery no.2	**Ref.**	**EH[1] & HP**	**EH[3]& NGCC**	**EH[3] &BB**	**EH[3] &NB**	**NGCC**	**BB**	**NB**
Natural gas (MW)	-	-	118(843)	67 (67)	88 (304)	470(1420)	67(67)	236 (480)
Biomass (MW)	-	-	-	28 (400)	-	-	218 (697)	-
ΔSP[1] (t/h)	-	-	80	80	80	80	80	80
Excess heat used (MW)	27	136 (227)	82	82	82	-	-	-
CO_2 captured (tone/h)	174	174 (174)	195(319)	194 (303)	189 (226)	255 (418)	250 (391)	215 (257)
Electricity import (MW)	654	683 (704)	650(331)	668 (596)	668 (623)	637 (586)	631 (539)	638 (587)

[1] Increased capacity of the current boiler

3. Methodology

The main methodology in this work is to combine knowledge from process integration in the refinery industry with knowledge about the CCS technology (similar methodology is used in [5]). The methodology and data collection are described by the following steps:

- The potential for steam savings and usage of excess heat from the refinery process are investigated using Pinch analysis. A thorough description of the methodology can be found in several editions; one of the most recently updated is [6]. Heat exchanger cost calculations for collection of excess heat are taken from [7], and used also for calculations for collection of excess heat streams for heat pumping.
  The data regarding the CO_2 capture unit are taken from previous studies of the MEA absorption process [3, 5, 8, 9]. The cost for the capture plant (excluding costs for the energy plant) has originally been taken from studies by Tel-tek [8] and adjusted to fit the refineries studied by using cost information in [9].
- The SGT-800 is assumed to be representative for gas turbines and data are taken from [10]. The size of the gas turbine is scaled to fit the applications studied in this paper, and economic scaling is based on price levels for different NGCC sizes in [11].
- The heat pump is designed using the software IEA Annex 21[4]. Using the chemical engineering plant cost index from 2010, updated investment cost is provided by the software.
- Economic data for the biomass boiler case are taken from [12], including installation and engineering costs, and data for the natural gas boiler are taken from [5].
- To include costs for installation and engineering, the budget prices for all equipment are scaled using a factor 2 (in cases when this is not already included), which is a mean value from [11] and [13]. For the heat exchangers, however, a factor of 3.5 is used [7]. Data for economic calculations for the steam turbines are taken from [14].
- Finally, to evaluate the costs for the different cases, future energy market scenarios are used. The scenarios are based on an energy market model adapted for evaluation of long-term investments in the process industry; a thorough description is found in [15].

3.1. Pinch analysis at the refineries

The pinch analysis only includes streams that are not already integrated (i.e. streams that are heated and cooled with utility, e.g. air). It shows that a significant amount of excess heat is available at Refinery no.1. Theoretical, 54 MW is available above 129°C, and 53 between 90° & 129°C. In the case when the current excess heat used for district heating delivery is inaccessible (EH[2]) the available excess heat is less: 9 MW above 129°C, and 15 MW between 90°C & 129°C. In Refinery no.2 the result shows a theoretically potential of 82 MW available excess heat above 129°C and 145 MW between 90°C & 129°C.

3.2. Economic calculations

In order to evaluate the above-described alternatives, the cost of each avoided tonne of CO_2 emitted is calculated from both a company and a society point of view, in Eqs. (1-5).

$$C_{avoided,company} = \frac{C_{annual}}{CO_{2\_avoided,company}} \quad \textbf{or} \quad C_{avoided,society} = \frac{C_{annual}}{CO_{2,\_avoided,society}} \quad [€/\text{tonne } CO_2] \quad (1,2)$$

$$CO_{2\text{ avoided, company}} = CO_{2\text{ before capture}} - CO_{2\text{ after capture}} \quad (3)$$

$$CO_{2\text{ avoided, society}} = CO_{2\text{ before capture}} - CO_{2\text{ after capture}} + CO_{2\text{ reduced by replacing electricity production}} \quad (4)$$

Where: $C_{annual} = \Delta C_{inv} + \Delta C_{running\ costs} + \Delta E * p_e + \Delta F * p_f - \Delta n_{biomass} * p_{Co2}$ [€/year] (5)

ΔC_{inv} = Annualised investment costs (including installation costs)

$\Delta C_{running\ costs}$ = Annual change in running costs except for energy (e.g.MEA costs)

ΔE= Annual change in electricity

ΔF= Annual change in fuel use

$\Delta n_{biomass}$ = Annual captured CO_2 from biomass (from BB)

p_{Co2} = Price of CO_2 permits

p_f = Fuel price

p_e= Electricity price

The avoided amount from a society point of view also includes the CO_2 emissions saved from replacing marginal electricity production, as shown in Fig. 4. In all calculations an annuity factor of 0.1 and operation time of 8000h are used. All costs are calculated in 2010 prices levels. In this paper, CO_2 emissions generated from biomass are evaluated as not included in the EU ETS system. However, since capturing CO_2 emissions from the biomass boiler leads to a reduction of CO_2, and since alternative use of biomass – for example combustion for heat and power production – would otherwise release this CO_2, revenues related to the price of the CO_2 emissions (p_{CO2}) are allocated to the captured CO_2 emissions from the biomass.

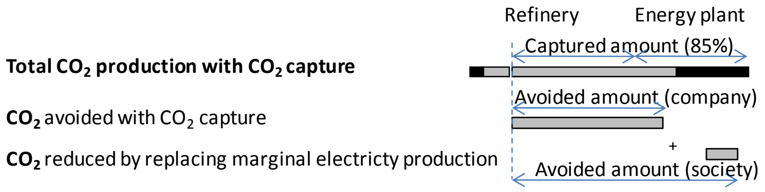


Fig. 4. Description of the avoided amount of CO_2.

3.3. Future energy market scenario

The performance of the CO_2 capture investments is evaluated by using consistent energy market scenarios based on the tool ENPAC [15]. The scenario data are shown in Table 2.

Table 2. Energy market parameters for the different scenario

Scenario	1	2	3	4	5	6	7	8
Fossil fuel price	Low	Low	Low	Low	High	High	High	High
CO_2-price [€/tCO2]	15	27	45	85	15	27	45	85
RES-E support[1] [€/MWh$_{el}$]	20	20	20	20	20	20	20	20
El price [€/MWh-el]]	56	66	81	87	62	72	87	95
CO_2 from el [kg/MWh$_{el}$]	679	679	679	129	679	679	679	129
Marginal technology for electricity production	Coal	Coal	Coal CCS	Coal CCS	Coal	Coal	Coal	Coal, CCS
Price of biomass [€/MWh$_{fuel}$]	26	31	39	56	29	34	42	60
Natural gas price [€/MWh$_{fuel}$]	33	33	33	33	51	51	51	51

[1] Premium paid to producers of renewable electricity from combustible renewable

By using a number of different scenarios that outline possible cornerstones of the future energy market, robust investments can be identified and the climate benefit can be evaluated. Since CO_2 capture is a technology under development and will most likely not be implemented before 2030, scenarios for 2030 are used. This case consists of eight scenarios which are a result of combining two levels of fossil fuel and four levels of CO_2 prices.

4. Results

The results of the calculated avoidance costs are presented in Figs. 5 and 6, together with the price of the CO_2 emission certificates. The CO_2 price can be viewed as an estimate of the possible income from performing these measures at the refinery.

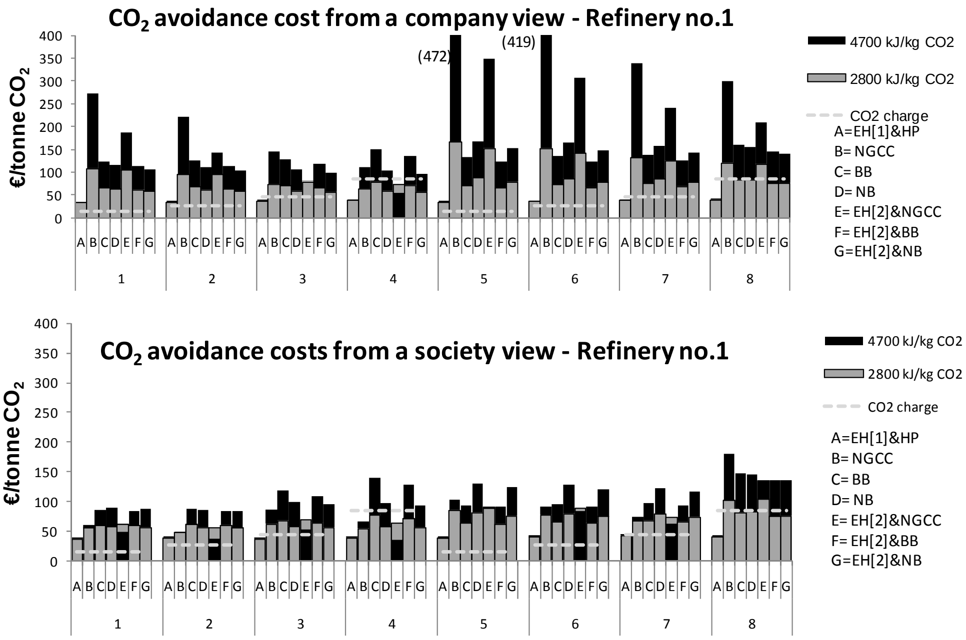


Fig. 5. The avoidance costs (from a company and a society view) for the different alternatives in Refinery no.1. Black bars lower than grey bars indicate that the high heating demand causes lower avoidance costs. Only one bar indicates that the avoidance costs for the two energy levels are similar.

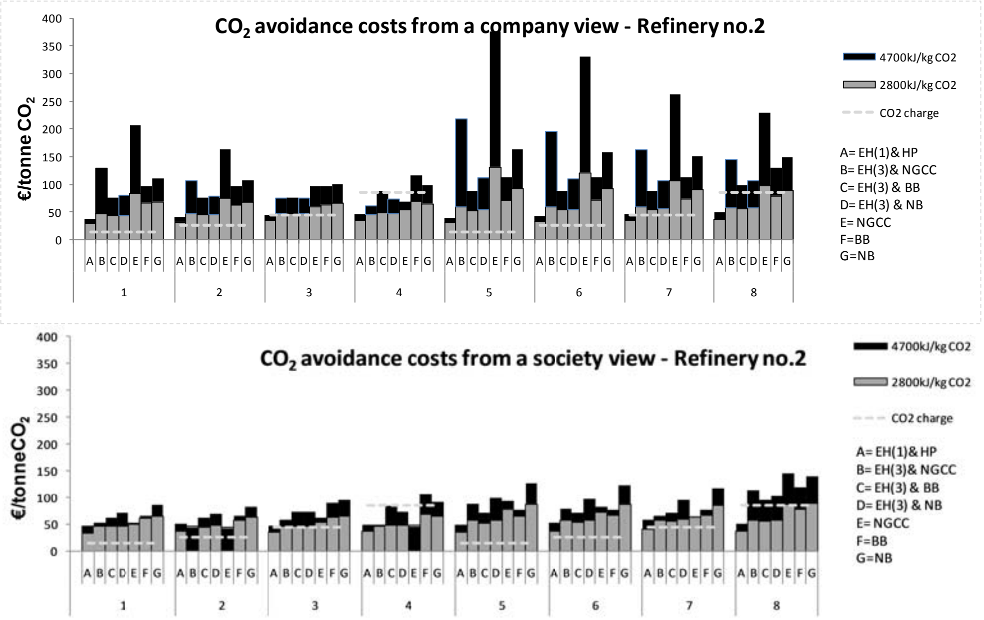


Fig. 6. The avoidance costs (from a company and a society view) for the different alternatives in Refinery no.2. Black bars lower than grey bars indicate that the high heating demand causes lower avoidance costs. Only one bar indicates that the avoidance costs for the two energy levels are similar.

The avoidance costs from a company view are for both refineries, in most scenarios, lowest for the alternatives using excess heat and heat pump. The avoidance costs for these alternatives are also robust with respect to changes in scenario data, which is due to the relatively small amount of electricity used and the fact that no additional fuel is necessary. Figs. 5 and 6 show that only if the price of CO_2 emissions will become high (85 €/tCO_2), and if excess heat is used to supply the heat demand, could investing in a capture unit be a robust and promising alternative. If the fossil fuel price is low at this level of CO_2 price, several more alternatives could be promising. Moreover, the results from Refinery no. 2 show lower avoidance costs for almost all alternatives compared to Refinery no.1. This can be explained by cheaper investment costs (in relative terms) and the fact that Refinery no. 2 has the opportunity to increase the capacity of current boiler.

When evaluating the costs from a society view, meaning that CO_2 changes outside the refinery are considered, most alternatives will have much lower avoidance costs compared to the results from a company view; see Figs. 5 and 6. The largest impact can be seen for the NGCC alternative. The large generation of electricity from the NGCC implies large CO_2 savings from marginal production of electricity, especially in Scenarios 1, 2, 5, 6 and 7 when marginal electricity producers are coal power plants without CCS. The benefits from including the reduction of CO_2 emissions from electricity production result in a lower avoidance cost for the high heating demand in almost all cases for the NGCC alternatives. The NGCC alternatives (in both refineries) with high heating demand (4700kJ/kg CO_2) have the lowest avoidance costs.

5. Conclusions and discussion

The main conclusion from this study is that process integration of the capture process at the refinery, i.e. use of excess heat and heat pumping, can significantly reduce the avoidance costs for CO_2 capture at a refinery and be a robust and promising alternative at high CO_2 price levels. However, the avoidance cost depends greatly on which system perspective is considered, i.e. including CO_2 changes in marginal electricity production or not. The alternatives with NGCC could be competitive if high heating demand is needed in combination with a high CO_2 price and low fossil fuel prices (an unlikely combination).

Previous research by [1], [2] and [3] examining CO_2 capture at refineries reported capture costs in the range 50-120 €/tCO_2. This study's estimates range between 30 and 472 €/ tCO_2 avoided. However, the previous studies have all used natural gas CHP to supply the extra energy needed, and in this study that alternative ranges from 45 to 168 € /tCO_2 avoided. It should be noted that the estimated costs in other studies arise from different assumptions and the costs can be calculated per CO_2 captured or CO_2 avoided (as in this study and in [1] and [3]). First, different values for the desorption heat are used in the different studies: 2800 kJ/kg CO_2 in [3] , 4700 kJ/kg CO_2 [2] and undefined in [1]. Second, the values for the different costs (e.g. investments and fuel) also arise from different assumptions. In this study, for example, fuel and electricity costs are calculated from future energy market scenarios. Moreover, in this study the transport costs are not included: however, studies by [16] indicate that the costs for transport and storage are around 15-25 €/t CO_2.

Before CCS becomes a commercial technology, a lot can occur with the available excess heat levels and demands at a refinery. This is to be investigated in more detail in other studies. Finally, to improve the cost estimations of the post-combustion capture process, future work would also include a comparison of the avoidance costs for other absorbents, e.g. ammonia.

Acknowledgement

This work has been carried out within the Energy Systems Programme, which is primarily financed by the Swedish Energy Agency, and within the project *CCS in the Skagerrak/ Kattegat region*, which is an intraregional CCS project partly funded by the EU. The work has also been co-financed by Preem AB. Finally, the authors would also like to thank Preem AB for valuable inputs.

References

[1] MT. HO, GW. Allison, DE. Wiley, Comparison of MEA capture cost for low CO2 emissions sources in Australia, International Journal of Green Gas Control.2011;5(1), pp. 49-60

[2] Tel-Tek, CO_2 capture from industrial facilities, Tel-Tek, 2009, Tel-Tek Porsgrunn, Norway, 2009

[3] J. Van Straelen, F. Geuzebroke, N. Goodchild, L. Mahony, CO2 capture for refineries, a practical approach. Energy Procedia. 2009, pp.179-185

[4] IEA Annex 21, Industrial heat pump screening program, IEA Heat Pump Centre c/o SP Technical Research Institute of Sweden, 1997

[5] E. Hektor, Post-Combustion CO_2 Capture in Kraft Pulp and Paper Mills – Technical, Economic and System Aspects, PhD thesis, Chalmers University of Technology, Sweden, 2008

[6] Kemp I, Pinch Analysis & Process Integration – A user guide on process integration for the efficient use of energy, 2nd ed., Butterworth-Heinemann, Oxford, UK, 2007

[7] R. Sinnot, G. Towler, Chemical engineering design, 5th ed., Elsevier Ltd, 2009

[8] Personal communication with Stefan Nyström and Christina Simonsson, Refinery Development, Preem AB, 2010-12-08

[9] Sherif A, Integration of a Carbon Capture process in a chemical industry – Case study of a steam cracking plant, Master Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2010

[10] Siemens SGT-800 brochure, available online 2010-12-3:http://www.energy.siemens.com

[11] Gas Turbine World Handbook, Performance Spec, 2007

[12] E. Pihl, Integrating biomass in existing natural gas-fired power plants – a techno-economic assessment, Lic. Thesis, Chalmers University of Technology, Sweden, 2010

[13] J. Strömberg, P.Å Franck, T. Berntsson, Learning from experiences with Gas-Turbine-Based CHP in Industry, CADDET Analyses Series No.9, 1993

[14] E. Axelsson, Energy Export Opportunities from Kraft Pulp and Paper Mills and Resulting Reductions in Global CO2 Emissions, PhD thesis, Chalmers University of Technology, Sweden, 2008

[15] E. Axelsson, S. Harvey, Scenario assessing profitability and carbon balances of energy investments in industry, The AGS report: 2010: EU1, 2010

[16] McKinsey & Company, Carbon Capture & Storage: Assessing the Economics, 2008