NTNU

Norwegian University of
Science and Technology

Eco-efficiency of Power Generation Options at a Refinery

Øystein Jerkø Kostøl

Master of Science in Energy and Environment
Submission date: June 2008
Supervisor: Edgar Hertwich, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

Problem Description

Conduct a life-cycle assessment of potential combined heat and power plants with CO2 capture and storage to be integrated into an oil refinery, suitable for Mongstad. Use this information to evaluate the eco-efficiency of the refinery and different solutions for the CHP. The thesis should rely on standard process-LCA data for the most important components and utilize hybrid analysis where appropriate.

The following questions should be considered in the thesis:

1. What is the current state of knowledge on the life-cycle impacts of CCS?

2. How does LCA deal with systems modelling and allocation of co-products?

3. What is the impact of producing the equipment to be installed at Mongstad?

4. What is the impact of operating this equipment?

5. What is the life-cycle impact of the various different configurations?

6. How can the impact be allocated to the different outputs? How do the alternatives compare in terms of the impacts they cause?

Assignment given: 24. January 2008
Supervisor: Edgar Hertwich, EPT

Preface

This report is the result of my master thesis, finishing five years of Energy and Environmental Engineering education at NTNU. I have written the thesis at Programme for Industrial Ecology, for Institute for Energy and Process Technology at NTNU.

The thesis has been a contribution to the cooperation project between Programme for Industrial Ecology and StatoilHydro, *Mongstad Pilot*. I hope the methodology, results and conclusions can be of interest to StatoilHydro staff working on environmental assessment of Energiverk Mongstad and the Mongstad refinery as such.

For me, the thesis has been an interesting learning experience, providing better insight in a topic which is a hot potato in Norwegian politics.

It has been very rewarding for me to be part of the Programme for Industrial Ecology this half year. It is a very inspiring and interesting group, working on important questions.

I would like to thank my supervisor, Edgar Hertwich. He has been supporting the whole process, but encouraging me to work independently, trusting my own decisions and assumptions. Christian Solli deserves big thanks for leading me through the more specific and detailed problems and considerations.

Thanks also go to Signy Midtbø Riisnes from StatoilHydro, for providing me with data on the Mongstad refinery.

_____

Øystein Jerkø Kostøl

Trondheim 12/06-2008

Sammendrag

Denne masteroppgaven undersøker miljøprestasjonen til tre ulike alternativer for kombinert kraft- og varmeproduksjon (CHP) fra naturgass (NG) ved Mongstad oljeraffineri. Et vesentlig mål er å evaluere CHP-anlegg med CO_2 fangst og –lagring (CCS), og miljøprestasjonen til slike anlegg sammenlignet med konvensjonelle CHP-anlegg uten CCS. Det benyttes livssyklusanalyse (LCA) for å gjøre miljøberegninger. LCA-resultatene benyttes for å undersøke endringer i øko-effektivitet ved raffineriet ved innføring av et naturgassfyrt CHP anlegg.

Det har foreligget detaljerte prosessmodellerings-resultater for CHP anleggene. Tre CHP-konfigurasjoner har blitt evaluert. Alle er designet for a levere 346 MW varme til raffineriet, men har ulik elektrisitetsproduksjon. De tre konfigurasjonene er:

1. Konvensjonell CHP med 343 MW elektrisk effekt
2. Konvensjonell CHP med Post-Combustion (PC) CCS, 493 MW elektrisk effekt
3. Autothermal Reforming (ATR) anlegg med pre-combustion CCS, 302 MW elektrisk effekt

De tre alternativene vil i det følgende bli omtalt som *Konvensjonell*, *PC* og *ATR*.

Dagens tilgjengelige metoder for CCS er energikrevende prosesser, som ofte involverer bruk av kjemikalier. Dette gjør det nødvendig å ha et bredt systemfokus for å sammenlikne livssyklus-utslippene fra et CCS system med et konvensjonelt kraftverk. Den totale reduksjonen i klimagasser (GWP) fra CCS systemene er et sentralt tema i denne oppgaven. Andre miljøeffekter som oppstår ved innføring av CCS er også vektlagt i undersøkelsene.

LCA-resultatene viser at den faktiske reduksjonen i GWP per enhet energi produsert fra PC-systemet er 82%, sammenliknet med det Konvensjonelle systemet. CO_2-rensegraden i karbonfangstanlegget er 90%. En sammenlikning av utslipp mellom PC og konvensjonell på basis av eksergiproduksjon eller produktverdi gir omtrent samme resultat som ved energibasis. ATR-anlegget har en CO_2-rensegrad på 78.6%, og gir er reduksjon i GWP på 71% sammenliknet med det konvensjonelle anlegget på energibasis. Respektive GWP utslipp per MWh eksergi produsert fra de tre CHP-ene er 56, 100 og 337 kg CO_2-ekvivalenter for PC, ATR og Konvensjonell.

En litteraturstudie viser at produksjon og transport av NG til gasskraftverkene i stor grad kan påvirke LCA resultatene for et gasskraftverk med CO_2-rensing. Resultatene som presenteres her viser at NG-verdikjeden forårsaker 22% av GWP-utslippene fra PC-systemet. 70% av totale GWP-utslipp forekommer imidlertid i drift av kraftverket. Det konkluderes dermed med at økte utslipp i opp- og nedstrøms systemer for kraftverket

ikke underminerer de totale miljømessige fordelene knyttet til reduksjon av klimagasser ved innføring av CCS.

CCS-systemene gir betydelig større miljøbelastning i form av toksiske stoffer (HTP), forsuring (AP) og overgjødsling (EP). Produksjonen av Monoetanolamin (MEA) som benyttes i CO_2-fangst står for en stor del av de økte toksiske utslippene, som er om lag 50% høyere for CCS-systemene som det konvensjonelle. Økte utslipp av NH_3 og NO_x er opphav til mye av økningen i AP og EP utslipp. I disse utslippkategoriene kan man se en 100-150% økning i utslippene ved innføring av CCS. Det anses som sannsynlig at bedret avgassrensing kan redusere en andel av AP og EP-utslippene. Det virker imidlertid uunngåelig at ikke innføring av CCS vil medføre ekstra miljøpåvirkning, relatert til de økte energistrømmene, samt innføring av nye prosesser relatert til karbonfangst og lagring.

Når utslippene fra kraftverkene evalueres i et utvidet system hvor alternative produksjonssystemer for varme og kraft evalueres, vil et konvensjonelt CHP-anlegg på Mongstad ikke nødvendigvis føre til globale CO_2-reduksjoner. Substitusjonen av dagens naturgassfyrte varmeproduksjon ved raffineriet gjør imidlertid av en CHP med CCS vil gi global reduksjon i klimagasser uavhengig av hva alternativet for elektrisitetsproduksjon ville være.

Den klimagassbaserte øko-effektiviteten på Mongstad, definert som de totale LCA GWP utslippene fra raffineriet dividert med den økonomiske verdien av raffineriproduktene estimeres til 64 ktonn CO_2-ekv/GNOK for 2007. Ved introduksjon av en CHP med CCS ville øko-effektiviteten bedres betraktelig; med mer enn 30% for PC-anlegget. Ved å installere et Konvensjonelt anlegg, ville imidlertid øko-effektiviteten reduseres med 12% til 72 ktonn CO_2-ekv/GNOK. Å installere kraftvarmeverk med karbonfangst og –lagring betraktes derfor som et betydelig steg i retning av en bærekraftig utvikling på Mongstad raffineri. Gitt forbedringer i avgassrensing av NH_3 og NO_x, ser det ikke ut til at andre miljøeffekter vil kunne rokke ved denne konklusjonen.

Summary

This master thesis is investigating environmental performance of three different alternatives for Combined Heat and Power (CHP) production from Natural Gas (NG) at Mongstad oil refinery. An important objective is to evaluate CHP plants with Carbon Capture and Storage (CCS), and the performance of these compared to a conventional CHP without such application. Life Cycle Assessment (LCA) is the applied methodology for environmental assessment. The LCA results are used to inspect changes in eco-efficiency at the refinery with introduction of a CHP plant.

Detailed process modelling work on CHP plants plant has been available for the thesis. Three CHP configurations have been assessed. All meet a design criterion of delivering 346 MW of heat to the refinery, but deliver different outputs of electricity. The three configurations are:

1. Conventional CHP with 343 MW electric power output
2. Conventional CHP with Post-Combustion (PC) CCS, 493 MW electric power output
3. Autothermal Reforming (ATR) plant; CHP with pre-combustion CCS, 302 MW electric power output

The three alternatives are denoted *Conventional*, *PC* and *ATR* in the following.

The current feasible applications of CCS are energy consuming processes, often involving chemical substances. This makes it necessary to apply a broad system focus to evaluate the life cycle environmental performance of the CCS systems compared to conventional power plants. The total reduction of Global Warming Potential (GWP) from the CCS systems is a central question discussed in the thesis. The emerging of other environmental problems when CCS is applied is also emphasized. This investigation is important in order to be aware of problem shifting issues that may rise from applying CCS.

A second objective for the thesis is to perform different analyses and contextualization of the LCA results. Producing different outputs of distinct energy products - heat, steam and electricity – the alternatives' environmental performance cannot be compared without choosing an allocation procedure. A system expansion is also performed, investigating emissions reductions or increases in a larger context, assuming alternative production systems for the CHP products. Finally, eco-efficiency at the refinery when constructing the different CHP options is assessed.

The LCA results show that actual GWP reduction from the PC system, having a carbon capture rate of 90%, is 82% on an energy basis compared to the conventional plant. This

means that system GWP impacts counted per MWh energy produced is 82% lower from the PC system than the conventional. Counting emissions per MWh exergy or per MNOK product value of heat and electricity only changes the result by 1 percentage point. The ATR has a capture rate of 78.6%, and gives a total system GWP reduction of 71% compared to conventional on energy basis. GWP emissions per MWh exergy produced from the three CHP's are 56, 100 and 337 kg CO_2-equvivalents for the PC, ATR and Conventional respectively.

A literature study shows that the production and transport of natural gas input to the power plant can strongly affect the LCA performance of a NG power plant with CCS. The results presented here show that the NG value chain is causing 22% of the GWP emissions from the PC system. 70% of total GWP from the PC system occurs in operation of the CHP, counting the increased energy needed for carbon capture and compression. It is concluded that up-and downstream emissions do not undermine the environmental benefit of applying CCS regarding GWP impacts.

The CCS systems have significantly higher impacts of Human Toxicity (HTP), Acidification (AP) and Eutrophication Potentials (EP). Production of Monoethanolamine solvent for carbon capture contributes largely to making HTP impacts over 50% higher for CCS systems compared to Conventional. Increased NH_3 and NO_x emissions make up much of the 100-150% rise in AP and EP impacts. It is considered possible that flue gas handling can mitigate a substantial fraction of the increased AP and EP impacts. However, it seems inevitable that CCS will induce extra environmental burdens in a LCA perspective due to increased energy flows and introduction of new processes is the product system.

The system expansion reveal that building a Conventional CHP at Mongstad will not lead to global CO_2 reductions if it substitutes renewable electricity production. The substitution of alternative heat production at the refinery makes the CCS systems unreservedly give net global CO_2 reductions, disregarding alternative electricity production technology.

The GWP eco-efficiency at Mongstad, defined as total LCA emissions from refinery output products divided by the economic value of the products, was estimated to 64 ktn CO_2-eq/GNOK for 2007. Introducing a CHP with CCS would significantly improve the eco-efficiency; by more than 30% for the PC plant. Installing a Conventional plant, however, would deteriorate eco-efficiency with 12% to 72 ktn CO_2-eq/GNOK. Installing a CHP with CCS is hence considered a significant step towards a sustainable development at Mongstad refinery, generating more value with less environmental impacts. Given improved flue gas handling of NO_x and NH_3, additional environmental effects are not considered to have potential of jeopardizing this conclusion.

Contents

Acronyms

AP	Acidification Potential
ASU	Air Separation Unit
ATR	Auto Thermal Reforming
BC	Base Case
CC	Carbon Capture
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
EP	Eutrophication Potential
EVM	Energiverk Mongstad
FCA	Foreground Contribution Analysis
GHG	Green House Gas
GWP	Global Warming Potential
HHV	Higher Heating Value
HTP	Human Toxicity Potential
I/O	Input/Output
IECM	Integrated Environmental Control Model
IGCC	Internal Gasification Combined Cycle
IPCC	International Panel on Climate Change
LCA	Life Cycle Assessment
LCE	Life Cycle Emissions
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquid Petroleum Gas
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
NG	Natural Gas
NGCC	Natural Gas Combined Cycle
NVE	Norges Vassdrags og Energidirektorat
PC	Post-Combustion
SCGT	Semi Closed Gas Turbine
SPA	Structural Path Analysis
TCM	Test Centre Mongstad
WBCSD	World Business Council for Sustainable Development

Symbols

1,4-DCB	1,4 Dichlorobenzene
CFC	Chlorofluorocarbons
CO_2	Carbon dioxide
GNOK	Billion Norwegian Kroner
Gton	Gigaton
H_2	Hydrogen
kWh	kilowatt hours
MNOK	Million Norwegian Kroner
Mton	Megaton
MWh	Megawatt hours
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NOK	Norwegian Kroner
NO_x	Nitrogen oxides
PO_4^{3-}	Phosphate
Sm^3	Standard
SO_2	Sulphur Oxide
TWh	Terrawatt hours

Chapter 1

Introduction

This chapter gives a short description of the objectives of the thesis, as well as the outline of this report.

This thesis is investigating environmental performance of a Natural Gas (NG) fired Combined Heat and Power (CHP) plant at the StatoilHydro oil refinery at Mongstad. Although construction of the actual CHP has started, this thesis is looking at different theoretical configurations for the plant, and compares environmental performance between the options. Special focus has been put on the application of Carbon Capture and Storage (CCS) on the plant. Process simulation work for relevant CHP's both with and without CCS has been available as a basis for the thesis.

Life Cycle Assessment (LCA) is the central methodology for the environmental assessment performed. LCA´s for the different CHP configurations are conducted in detail. The LCA methodology is combining both Input/Output analysis and process LCA, in what is called a Hybrid LCA methodology. This means that economic data are used to assess environmental effects of parts of the product system in which exact numbers for physical flows are not obtained.

Making an LCA of a natural gas fired power plant with CCS application is one central element of the thesis, seeking to investigate the importance of different parts of such a system to the overall environmental performance. The Global Warming Potential (GWP) of the complete system in an LCA perspective is interesting in order to assess the actual reduction in GWP impacts when CCS is applied. Looking into other environmental effects rising from the CCS value chain is also an important feature of this thesis. A literature study, reviewing studies of CCS systems in the LCA literature is also performed.

Being an integral part of an oil refinery, the results of the assessment are contextualized accordingly. Emphasis is put on illuminating the effect of applying different approaches for allocating the emissions from the CHP's to either the refinery or the CHP output products. System expansion, assuming alternative production systems for the CHP products is also applied, as a method for inspecting the environmental consequences of introducing the CHP. A central question is how different assumptions related to allocation procedures influence the conclusion of environmental performance of the CHP's. Some theory of allocation practices in LCA methodology is discussed to provide a backdrop for the experimentation on different allocation procedures.

The thesis has two more introductory chapters; Chapter 2 discusses the role of NG power plants and CCS at Mongstad, Norway and globally, briefly looking into technology status and the energy system context; Chapter 3 comprises the LCA literature study of CCS systems. Chapter 4 presents and discusses relevant LCA methodology. Challenges related to compiling the Life Cycle Inventory (LCI) using the hybrid technique is presented here, as well as methods for allocation of environmental impacts to products in multi output systems. Calculation of the Life Cycle Impacts Assessment (LCIA) and Eco-efficiency is also discussed. The detailed LCI is quantitatively described in Chapter 5. Chapters 6 and 7 comprise the results part of the thesis; LCIA results are presented in Chapter 6, and in Chapter 7, the results are used to calculate expanded system emissions and refinery eco-efficiency. Finally, a discussion of general trends and findings is performed in chapter 8, while conclusions are provided in chapter 9.

Chapter 2

Gas power and CO_2 – the Norwegian context

This chapter gives a briefing of the Norwegian power system, and the role of Natural Gas power plants in Norway. In this relation, the political status of CCS in Norway is also described. Further, the Mongstad refinery and the plans for establishing the CHP *Energiverk Mongstad* is put in a Norwegian context of energy and CO_2 emissions. Finally the technological status of CCS globally and in Norway is described.

2.1 Norwegian energy production and greenhouse gas emissions

In 2006 the Norwegian electric power production consisted of 119.8 TWh hydro power, 1.2 TWh thermal power and 0.7 TWh wind power (NVE 2008). Until 2007, new power production capacity of significance has not been built since the end of the 1980s. One reason has been that the potential for new large scale hydro power is small, requiring new types of power plants (small scale hydro, thermal power and wind power) to be built in the Norwegian system. Even if new production capacity has not been added, annual average consumption growth has been 1.2% in a ten year period from 1995 to 2005. Currently new capacity is under construction; 1.3 TWh hydro, 0.3 TWh wind and 4 TWh natural gas fired thermal power. Naturkrafts natural gas power plant at Kårstø started commercial operation late 2007, and can generate up to 3 TWh per year.

The two additional natural gas power plants under construction are StatoilHydros Snøhvit (1.9 TWh/year) in Finnmark and Mongstad CHP (2.2 TWh/year) at an existing refinery. In addition, license is given by the Norwegian Energy Directorate (NVE) for construction of three more NG power plants with a total production capacity of 16.5 TWh/year (Tjeldbergodden, Skogn and Kollsnes). Recent rise in natural gas prices have however substantially reduced the profitability of NG power plants, and in December 2007, it was reported in the press that the largest of the new planned plants, Tjelbergodden, no longer is profitable and that the plans are abandoned (Brockfield 2007). In March 2008, NVE rejected license for another gas power plant at Fræna arguing that the political climate no longer is positive towards gas power without CCS, and that applying CCS would make the plant non-profitable in a social economic perspective (NVE 2008). High gas prices and low electricity price has also already led Naturkraft to shut down operation of Kårstø non-CCS power plant at times when prices are unfavorable (TU 2008).

In the context of national CO_2 emissions, the newly planned NG power plants could have substantial impacts. In 2006, the total domestic greenhouse gas emissions were 53.5 $MtCO_2$-eq, before introduction of new thermal power production (SFT 2008a). Norwegian Kyoto obligations are by year 2012 to reduce emissions to 1% above 1990 level, meaning 50.2 $MtCO_2$-eq. The three NG power plants under current construction will emit additional 3.4 $MtCO_2$-eq if Carbon Capture and Storage (CCS) is not applied (SFT 2008b). The desire to mitigate this problem has led the Norwegian government to take responsibility for establishing full-scale CCS at Kårstø and Mongstad (Gassnova 2008). At Mongstad, the government, through the state-enterprise Gassnova SF, has formed joint project organization with industry actors to design, build and operate the Test Centre Mongstad (TCM) to test and improve CCS technology before investment on large scale CCS at Mongstad is decided in 2012. The test centre is due to be completed in 2011, and will capture 0.1 $MtCO_2$ which will be directly released to the atmosphere due to unreasonable high costs in transport and storage (Haga 2007). The full scale CCS at Mongstad is due to operate in year 2014. At Kårstø, Gassnova SF took over responsibility for the CCS project 1. January 2008, and will work on the project to support the governments investment decision on full scale CCS, which will be taken during fall 2009.

2.2 Mongstad refinery and power plant

This thesis is considering eco-efficiency improvements at Mongstad refinery when introducing a CHP plant. It is an objective to draw general conclusions on potential gains in eco-efficiency when considering alternative CHP plant configurations, including and excluding CCS application. Construction of the combined heat and power plant "EnergiVerk Mongstad" (EVM) began in January 2007, meaning that the configuration of the CHP plant is to a degree already decided. This chapter will therefore outline the status of the actual plans at Mongstad, giving a context for the more theoretical assessment of plant configurations that follows later. Data in the first paragraphs are based on a non-CCS solution. Since investment decision for CCS is not made before 2012, the plant will be made capture-ready, with the configuration outlined below.

The background for EVM was to improve energy efficiency at Mongstad refinery (Statoil 2005a). The refinery heat demand is currently met by combustion of refinery gas. The gas is combusted in outdated boilers and furnaces, representing an inefficient usage of the gas resources. The CHP will replace the furnaces and produce 350 MW heat to serve the refinery. In addition two gas turbines (130 MW) and a steam turbine will generate 280 MW electricity for internal use as well as export. The plant is being constructed by DONG Energy, and is scheduled to start operation in 2010 (StatoilHydro 2007).

The estimated electricity production from EVM is 2.3 TWh/year (Statoil 2005a). The refinery itself will require approximately 0.5 TWh/year. Additionally, electricity will be used offshore at Troll gas extraction plant and at Kollsnes for gas processing, whose demands are expected to amount about 2.0 TWh/year. The EVM project also includes construction of a NG pipeline from Kollsnes gas processing facility, which will supply the CHP with 0.5 GSm3/year of NG. The refinery gas amounts to about 0.2 GSm^3/yr and will be mixed with Kollsnes gas to fuel the plant. The EVM project, without CCS, is outlined in Figure 2-1.

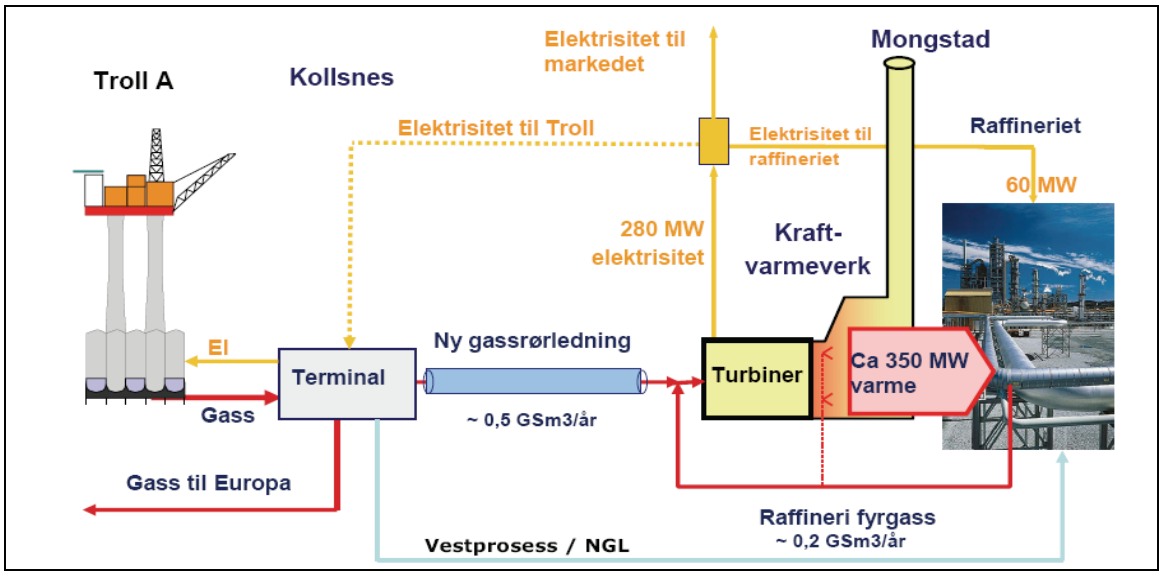

Figure 2-1 Flowchart of EVM, including upstream activities related to natural gas (Statoil 2005a)

The total CO_2 emissions from Mongstad refinery were 1.61 $MtCO_2$/year in 2005, and are expected to be 1.75 $MtCO_2$/year in 2008 due to increased flows in the refinery (Statoil 2005a). Emissions from the CHP without CCS are calculated to amount approximately 1.3 $MtCO_2$/year. However, shut-down of NG furnaces will induce emission reductions of 0.35 $MtCO_2$/year. In total, this makes emissions from the refinery when the CHP is built **2.7 $MtCO_2$/year**, compared to 1.75 $MtCO_2$/year without the CHP. This is based on 2008 prognosis, assuming that refinery activity will not further increase during the CHP construction period. It can be seen that Mongstad refinery with an integrated CHP will be a significant point source of CO_2 emissions, amounting 5% of the total domestic emissions in 2006. This makes the site interesting for exploring the CCS potential.

2.3 Carbon capture and storage – technology overview

In Norway, CCS is a central element in the national climate action plan. In addition to giving actual emission reductions at domestic point sources, this strategy aims at developing technology and establishing industry that can lead way in CCS globally. By the IPCC CCS is pointed out to be one of the major mitigation measures from the energy sector on a medium time horizon. An estimate indicates that from the baseline energy related CO_2 emissions in 2030 of 15.77 $GtCO_2$, 0.71 $GtCO_2$ could be mitigated by CCS technology, given CO_2 costs of 50-100 US$/$tCO_2$ avoided (IPCC; R.E.H. Sims and J. Torres-Martínez 2007). This is approximately 11% of the total mitigation potential from the whole energy sector at this CO_2 cost range. On a cumulative basis until year 2100, the IPCC special report on CCS operates with an economic potential of 15-55 % of total mitigation efforts worldwide (IPCC; Metz 2005). This potential implies installing several hundreds to thousands of capture systems over the coming century, each capturing some 1-5 $MtCO_2$ per year.

Detailed technology descriptions of carbon capture will not be provided here, as this is thoroughly covered in other sources, such as i.e. (IPCC; Metz 2005). Rather, some important parameters that affect the life cycle performance of the CCS systems will be presented, as well as expected technology choices for CCS implementation at EVM.

2.3.1 CO_2 Capture

It is common to divide CO_2 capture systems into three different main technology approaches; post-combustion, pre-combustion and oxy-fuel. A principal flowchart of the three technologies is given in Figure 2-2.

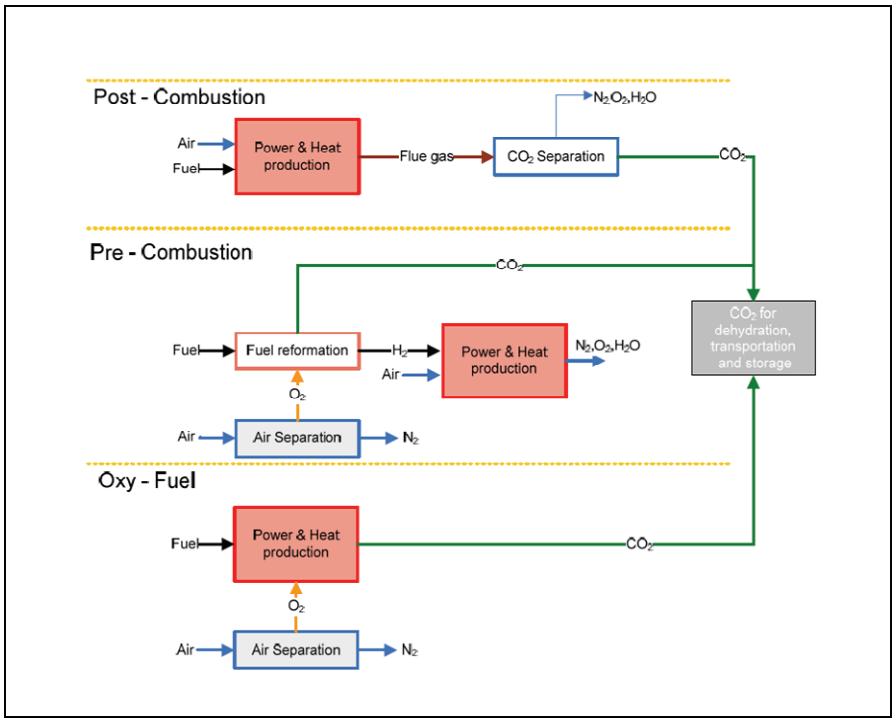

Figure 2-2 Three technology approaches to CO_2 capture (Aaberg 2006)

The dominant post-combustion separation method is using liquid solvents to bind CO_2 in the flue gas. The CO_2-saturated solvent is subsequently regenerated by heating, and CO_2 is released in a practically pure form. The solvents which receive most commercial interest are monoethanolamine (MEA), and methyldiethanolamine (MDEA). In addition to these, Mitsubishi Heavy Industries Ltd have developed an amine based solvent series called KS-1, KS-2 and KS-3, where KS-1 has been commercialized (IPCC; Metz 2005). The MEA solvent is cheaper than the MDEA, but the MDEA is preferred when CO_2 in present in high partial pressures (Aaberg 2006). KS-1 have never been in commercial use in a plant with as low CO_2 partial pressure as NG flue gas (NVE 2006). The typical energy requirement for regeneration of the amine used on NG flue gas is between 2.5 and 5 MJ/kgCO_2 with a capture rate of 90% (Solli 2008b). Energy requirement per kg captured carbon is an important parameter when LCA performance of the CCS system is evaluated.

In post-combustion carbon capture of flue gas from natural gas, the CO_2-concentration is very low (typically 3-4%). Increasing the CO_2-concentration can decrease the energy requirement for capture. An option to achieve this is to reform natural gas before combustion, converting the natural gas (mainly methane) into a gas mixture consisting mainly of hydrogen and CO_2. Capturing CO_2 from this gas mixture is what is referred to as pre-combustion carbon capture. In such a pre-combustion system, pure hydrogen (H_2) is subsequently combusted in the gas turbines, producing only water as flue gas. Using this method, the typical regeneration energy requirement lowers to the range 0.5 - 2 MJ/kgCO_2 (Solli 2008b). However, the reforming process itself requires energy, either via partial combustion of methane in the process or external firing of the reformer unit.

A completely different way of capturing CO_2 is to mix pure oxygen rather than air with the fuel. This produces a flue gas consisting of CO_2 and H_2O. The water can easily be separated by distillation at low energy requirements. Producing pure oxygen does however require energy. This technology is called oxy-fuel carbon capture.

Carbon capture at EVM will have to be post-combustion, because of the plant configuration. Two solvents will be tested in the TCM project. Aker Kværner or HTC Bechtel will deliver an MEA solvent based configuration, while the company Alstom will test ammonium carbonate, which is a lighter solvent that will require less heat in regeneration. It is assumed that the ammonium carbonate solvent also will enable flue gas handling from the refinery cracker, which contains about 12% CO_2. Information on carbon capture using ammonium carbonate is so far scarce, and the performance of the solvent is uncertain.

2.3.2 CO_2 transport and Storage

Basically, two options are feasible for CO_2 transport; ship transport and pipeline. Ship transport of gas is a technology that is known from Liquified Natural Gas (LNG) as well as Liquid Petroleum Gas (LPG). Experiences from this technology indicate that ship transport is more suitable for long-distance transport, while pipelines are preferred for shorter distances due to higher distance dependence of costs in pipeline transport. Low quantities of gas will also, naturally, favor ship transport before pipeline.

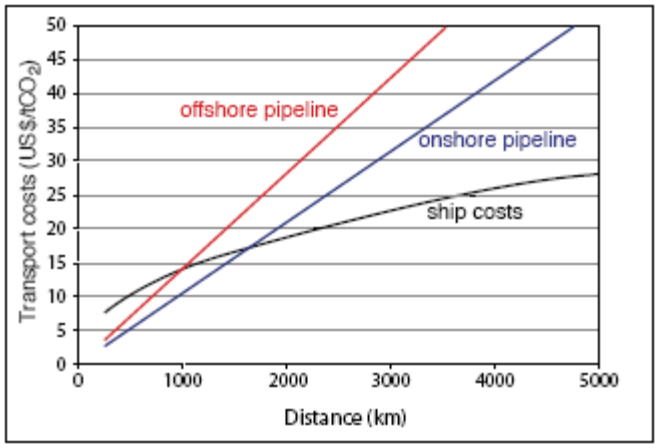

Figure 2-3 Transport costs with different technologies [$/tCO$_2$] for a 6 MtCO$_2$ annual CO$_2$ flow (IPCC; Metz 2005)

Pipeline transport of CO_2 will have to be based on transporting the gas in supercritical state to reduce energy requirements (NVE 2006). Compression work needed to achieve this state is a significant part of energy consumption in CCS. Under normal temperature conditions this means a pressure above 70 bars. The pressure drop occurring in transport may necessitate re-compression along the pipeline. Singh (2007) operates with a typical pressure drop of 10 bars / 100 km.

CO_2 storage can be done in geological formations of different types and depths. The IPCC concludes that it is *certain* that there is enough global potential for storing the low

end of the estimate for cumulative carbon capture through the century (200 $GtCO_2$) (IPCC; Metz 2005). Further, it is concluded to be *likely* that there is capacity for at least 2000 $GtCO_2$, which is the high end of the cumulative carbon capture potential (emphasis added). The most relevant geological formations for storing are oil and gas reservoirs, deep saline formations, and unminable coal beds. Storage in hydrocarbon reservoirs and saline formations is expected to take place at depths below 800 m, leaving the CO_2 in liquid or supercritical state. Given a required overpressure in order to inject the CO_2, injection at 800 m depth will typically require a pressure of 100-150 bars at injection site.

Another CO_2 storage option is deep ocean storage. There is no practical physical limit to what amount can be stored a deep ocean depths, but potential changes in pH as well as gradual release to the atmosphere are among the environmental challenges with this option.

An investigation of the transport and storage chain for CO_2 in Norway has been performed by request of the ministry for oil and energy, under the leadership of Gassnova (Gassnova 2007). The investigation considered handling of CO_2 from the two first Norwegian CO_2 sources, Kårstø and Mongstad. Baseline quantities of CO_2 used are 1.1 $MtCO_2$ from Kårstø and 2.2 $MtCO_2$ from Mongstad per annum. A possible increase in emissions by 100% at Mongstad and 200% at Kårstø is also considered.

Conclusions from the investigation are that a deep saline geological storage solution at either the Utsira or the Johansen aquifer should be pursued. The relevant Sleipner area of Utsira is located approximately 300 km away from both the CO_2 sources, while the Johansen formation is 100 km west of Mongstad and some 2-300 km north-west of Kårstø. The Utsira formation is at about 1000 m depth, while Johansen is at more than 2000 m. At the Sleipner field, there is already one existing well, probably able to handle approximately 1.1 $MtCO_2$/year. One new well at the Johansen formation is assumed to handle 3.5 $MtCO_2$/year, but it is planned to drill two wells in order to have backup capacity.

Pipeline transport is considered by far to be most cost-efficient for both storage alternatives.

Chapter 3

Carbon capture and storage in a life cycle perspective

This chapter provides a literature study of CCS in the LCA literature. Focus is put on GWP emissions and distribution of these in the value chain of a natural gas power plant with CCS.

The current feasible applications of CCS are energy consuming processes, often involving chemical substances. The increased energy demand for a fossil power plant installing CCS makes it necessary to apply a broader system focus in order to evaluate the full life cycle carbon reduction potential with this technology. Looking further into different environmental impacts arising from the use of chemicals in CO_2 capture is also desirable before concluding on the environmental performance of a CCS system.

3.1 Life cycle GWP for CCS systems

Some LCA studies have been conducted the recent years on CCS technologies. Most are focused on the greenhouse gas (GHG) emissions, excluding other environmental effects. The CCS literature to a large degree focus on coal fired power plants. In this literature briefing, however, emphasis is put on studies considering CCS from natural gas power plants. Often this is done in comparative studies, looking at life cycle impacts from different power generation systems with CCS applications. One recent such study is performed by Odeh and Cockerill (2008), comparing life cycle GHG emissions from different fossil fuel power plants with CCS. The authors have assessed GHG emissions from three types of fossil-fuel-based power plants, namely a supercritical pulverized coal (super-PC), natural gas combined cycle (NGCC) and an integrated gasification combined cycle (IGCC) coal power plant. All three systems with and without CCS are assessed and compared.

Firstly, it is interesting to note that the coal fired IGCC plant actually comes out with less life cycle GHG emissions than NGCC in this study. The IGCC and NGCC system applying CCS are respectively emitting 167 and 200 g CO_2/KWh. LCA emissions from NGCC without CCS are calculated to be 488 g CO_2/KWh.

Findings in Odeh and Cockerill (2008) show that when applying CCS to a NGCC system, emissions from up- and downstream activities strongly affect the overall GWP performance of the system. The Life Cycle Emissions (LCE) are divided by the authors into four categories: *1) Construction*, *2) CCS-Capture, Transport & injection*, *3) Indirect emissions related to the power plant* and *4) Direct combustion emissions* (see Figure 3-1). It can be seen from Figure 3-1 that for the NGCC system with CCS (red circle), the indirect emissions are actually the largest GHG source. Here indirect emissions refer to emissions from extraction and transport of natural gas, as well as production and transport of other input factors to the plant operation. The further decomposition of emissions in the value chain shows that emissions from the construction phase of the plant are negligible (Odeh and Cockerill 2008). Direct combustion emissions constitute the second largest emission source, followed by CO_2 capture, transport and injection emissions.

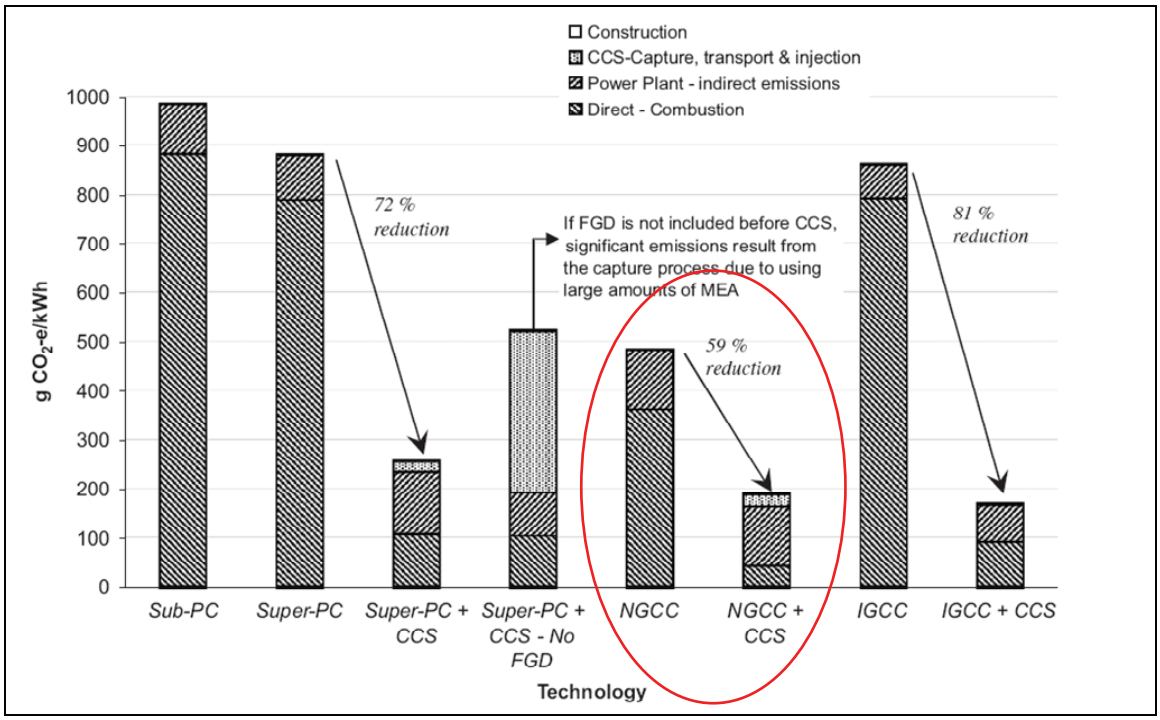

Figure 3-1 Comparison of GHG emissions from different technologies with and without CCS (Odeh and Cockerill 2008)

The authors use another parameter, manifesting the importance of the up- and downstream processes for the NGCC system, namely the "life cycle efficiency". The life cycle efficiency is "the energy output throughout the lifetime of the power plant divided by all sources of energy input from the life cycle system over the same period of time." Odeh and Cockerill state that "The percentage reduction of life cycle efficiency from the actual power plant efficiency […] is an indication of how significant energy use in upstream, downstream, and construction processes is." For the NGCC system, life cycle efficiency is much lower than power plant efficiency. This reflects that the up- and downstream activities are energy intensive. The efficiencies calculated in the study are shown in Figure 3-2.

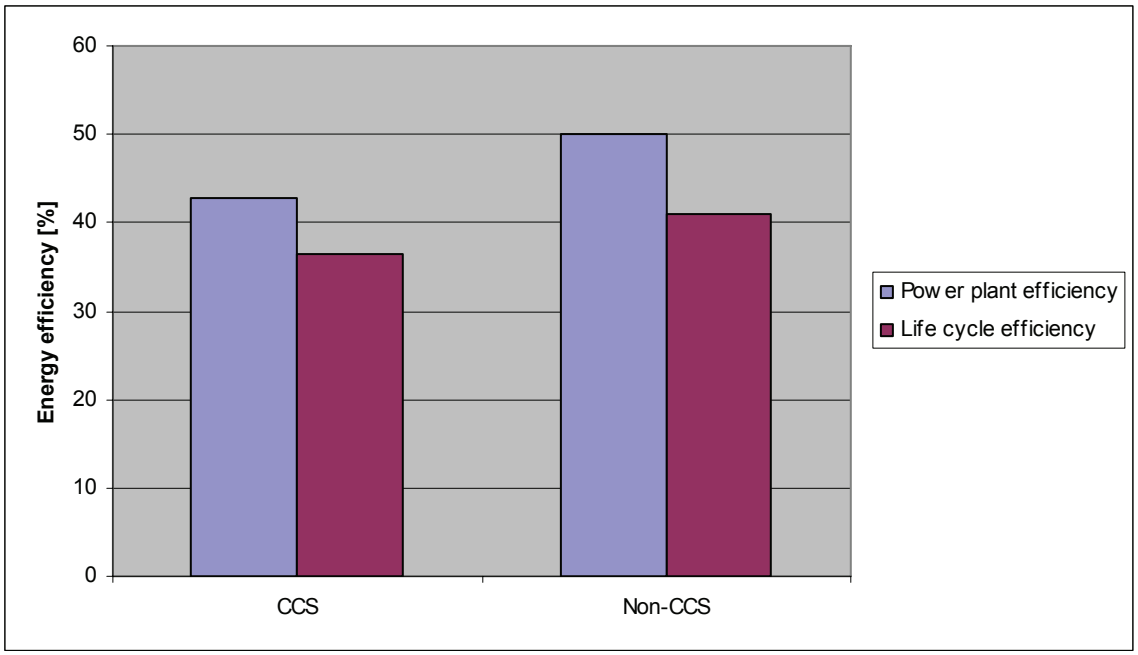

Figure 3-2 Energy efficiencies in power plant and value chain for NGCC system with and without CCS. Numbers from (Odeh and Cockerill 2008).

As seen above, the authors find upstream emissions from the NG value chain to be significant. A key assumption leading to this result is the modelling of NG extraction and transport technology. Odeh and Cockerill (2008) assume a 1% methane leakage from the extracted volume of NG offshore. A sensitivity analysis of this parameter is performed, inspecting the effects of assuming a 3% methane leakage from natural gas extraction pipes. The finding is that GHG emissions rise with 33.2% for the CCS system when changing this assumption. Data on methane leakage rates are based on a study by Kirchgessner et al. (1997) which inspects US average production in 1992. Whether these data are relevant in other parts of the world and 15 years later is not discussed further by Odeh and Cockerill. Nevertheless, the sensitivity analysis highlights the importance of methane production technology to the overall LCE's from NG power production with CCS.

Sensitivity analysis is also performed on parameters affecting transport and storage of CO_2. In their analysis, Odeh and Cockerill (2008) assumes the length of CO_2 transport pipes to be 300km. An increase of this length by 100km does not affect the life cycle GWP notably (+0.07%).

Viebahn *et al.* (2007) reaches results that are somewhat more favourable to the NGCC technology compared to coal powered plants. Firstly, the non-CCS power plant efficiency is assumed higher by Viebahn (60%) than by Odeh and Cockerill (50.1%), leading to less emissions from the whole system. Secondly, in their results, the NG fuel chain does not emit as much as the model by Odeh and Cockerill (2008). Details about assumptions in NG value chain are not available, but the comparison of emissions from different fossil fuel power options with and without CCS is illustrated in Figure 3-3. The study by Viebahn *et al.* gives specific attention to methane emissions in coal mining, and it can be

seen by comparing Figure 3-1 and Figure 3-3 that Viebahn operates with higher numbers for these emissions than Odeh and Cockerill.

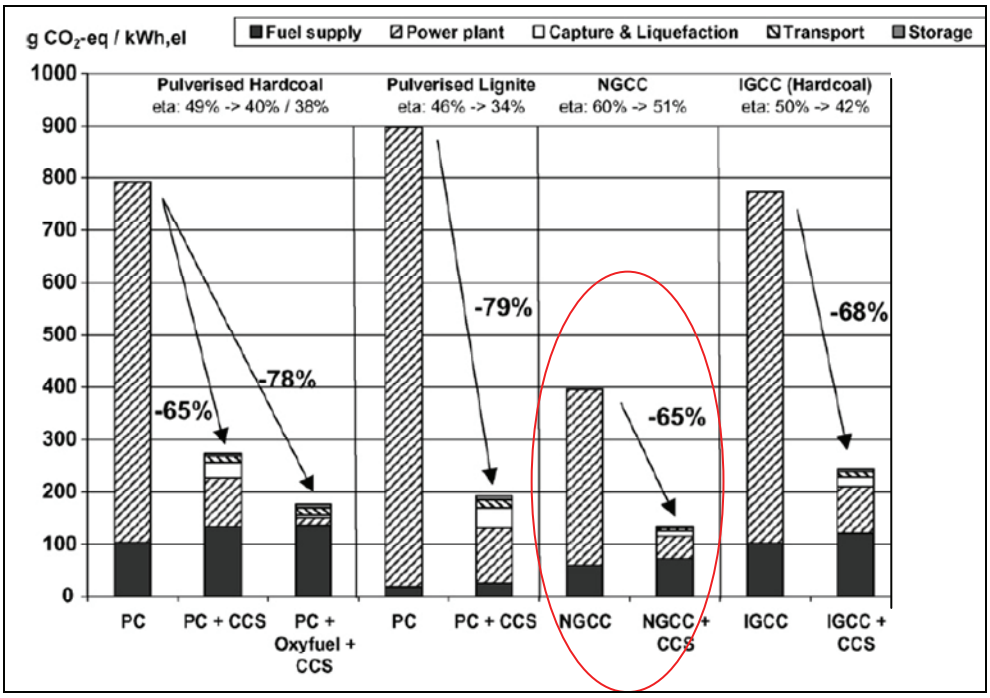

Figure 3-3 Life cycle GWP from different fossil fuel power plants with and without CCS (Viebahn et al. 2007)

Spath and Mann (2004) have conducted a study of similar scope as the two previous, comparing a conventional coal fired power plant, a NGCC plant and three different biomass fired power plant configurations. Life cycle GWP is compared for all systems with and without CCS application. Life cycle GHG emissions from the NGCC system and the coal fired system are calculated to be almost identical; 245 and 247 g CO_2-eq/kWh respectively. One possible reason why this study concludes with 22% larger GHG emissions from the NGCC system than Odeh and Cockerill (2008) is the system setup. The power generation capacity of the plants examined by Spath and Mann is kept constant at 600 MW for all configurations. The authors further choose not to scale up the capacity of the modelled plants when CCS is introduced, but rather to import electricity over the system border to compensate power loss in CCS. The study assumes that this compensating power comes from a NGCC system without CCS, because this technology dominates new investments in current and future US power generation (Spath and Mann 2004). It can be questioned, however, if not a more realistic modelling choice would be to use electricity from the plant in scope as long term marginal electricity to balance power loss in CCS. This would lead to less life cycle emissions from the CCS systems, since the compensating power would have carbon capturing.

Looking deeper into the LCA results of Spath and Mann (2004), stack emissions from the coal fired plant and NGCC are 76 and 37 g CO_2-eq/kWh respectively. It is the life cycle perspective for the two technologies that alter the picture, and makes emissions from the NGCC almost similar to the coal fired plant. The relative increase in life cycle emissions

for NGCC compared to coal is also in this study due to large upstream emissions from the NGCC technology counting up to 25% of total GHG emissions. The upstream emissions from the NGCC plant are primarily a result of the fugitive methane emissions from natural gas production and distribution. The fugitive methane emissions are taken from an earlier LCA of NGCC by Spath and Mann (2000), where a leakage rate of 1,4% is used based on US data from the 90´s. In addition to the fugitive methane, the upstream processes of the NG value chain are energy intensive, consuming 21 percent of the total fossil energy consumption in the life cycle. Of all the steps required in natural gas production (extraction, separation and dehydration, sweetening and pipeline transport), the study concludes that the natural gas extraction and transport steps require the most energy.

The modelling choice made by Spath and Mann makes their results somewhat complex to analyse. As a result of importing electricity over the system border for CCS configurations, a substantial fraction of life cycle GHG emissions from these alternatives stem from this power compensation. The breakdown of the emissions from NGCC with CCS is illustrated in a simple flowchart in Figure 3-4. It can be seen that from the 600MW plant (red circle to the left part of the figure), 37 g CO_2-eq/kWh is emitted through the stack. The blue circle to the right of the figure illustrates the NGCC plant compensating lost power in CCS. This plant does not have CCS itself, and needs to produce 97 MW to supply sequestration and storage of CO_2 from the 600MW plant. This results in 60 g CO_2-eq/kWh additional pipe emissions. Upstream activities add up to 147 g CO_2-eq/kWh for the two plants; emissions that can not be captured. As Odeh and Cockerill and Spath and Mann conclude that the additional emissions from pipeline construction and recompression for CO_2-transport do not add significantly to the overall GWP. In Figure 3-4, the emission from power production for recompression work in the 600km pipe transport of CO_2 is illustrated as a separate emission of 1 g CO_2-eq/kWh. All in all this sums up to 245 g CO_2-eq/kWh life cycle emissions from electricity production from the NGCC-plant.

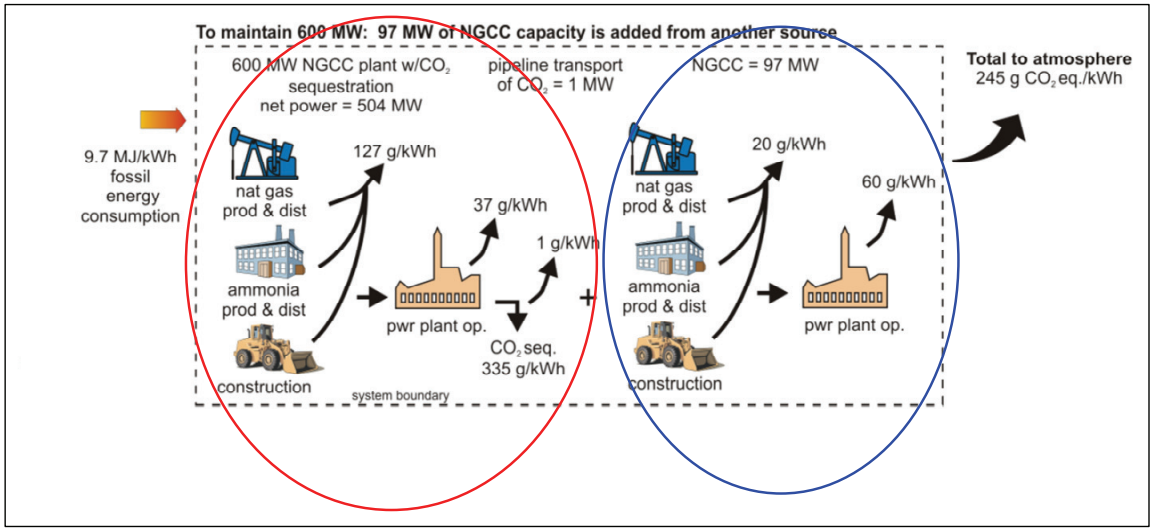

Figure 3-4 Flowchart of 600 MW power production from NGCC plant with CCS (Spath and Mann 2004)

A parameter that is not explicitly examined in the two previous studies is the value chain of the CO_2 capture agent. Lombardi (2001) discusses this parameter in an LCA of a semi-closed gas turbine combined cycle (SCGT/CC) power plant of 230 MW. The studied plant is equipped with an amine based carbon sequestration plant for post combustion CO_2 capture. The semi-closed technology allows increasing of the CO_2 concentration in the flue gas, compared to a regular NGCC, something which leads to a potential for constructing a more compact carbon capture plant. The lifetime of the plant is set to 15 years. Upstream emissions related to natural gas extraction as well as production of materials for construction are included also in this study. Demolition of the plant is modeled by an optimistic recycling scenario, actually leading to small negative emissions from this life phase.

Due to lack of data, Lombardi (2001) has no accurate calculations on GWP impacts from the amine production chain. To assess a "worst case scenario" for energy consumption in amine production, the amount of amines used in the process is substituted with the same amount of another chemical whose production process is taken from a non specified database in SimaPro rel. 4.0. The selected chemical is toluene-diisocyanate (TDI I), the chemical among those in the database with the highest production energy requirement with a production energy input of 145 MJ/kg. The reasoning behind this modeling choice is to have an idea of the potential influence of the amine production to the life cycle CO_2-emissions given a high production energy requirement of the chemical.

Lombardi (2001) has only performed an LCI, looking only at CO_2-emissions. The total CO_2 emissions from the system amount to 137 g CO_2/kWh. The emissions distribution in the value chain is shown in Table 3-1. The emissions from the amine production process is here sorted under the process "maintenance CCS", which also covers maintenance of heat exchangers and consumption of activated carbon. It can be seen that the imaginary amine process counts no more than 3% of total CO_2 emissions. Another interesting conclusion is that emissions from processes related to construction of both power plant and carbon capture unit counts only 1%. Lombardi concludes that the life cycle CO_2 emission reduction with CCS is about 85% compared to a similar non-CCS plant. Regarding the amounts of CO_2 avoided, extra emissions from construction of carbon capture facilities does hence not seem to be significant when assessing carbon reduction potential from CCS.

% of CO2-emissions	
Construction	1 %
Demolition	0 %
Maintenance CCS	3 %
Operation and Maintenance SCGT	96 %

Table 3-1 Distribution of CO_2 emissions in NG power plant value chain. Data from (Lombardi 2001)

Lombardi (2001) conducts an Exergetic Life Cycle Analysis (ELCA) as well. The findings from the ELCA still show that maintenance and operation by far contributes

most to the life cycle exergy destruction. Considering the exergy destruction occurring in the construction phase of the power plant and CCS, a breakdown on a material basis is performed. Results are shown in Figure 3-5, and it is the seen that steel (blue circle) and concrete (red circle) contributes most to exergy production (to the right in the figure). Even though clearly the concrete is the material consumed in largest amounts (left part of figure), the steel is consuming most exergy due to high values of exergy per unit mass. For LCA, this information can be useful when construction of plant is modeled.

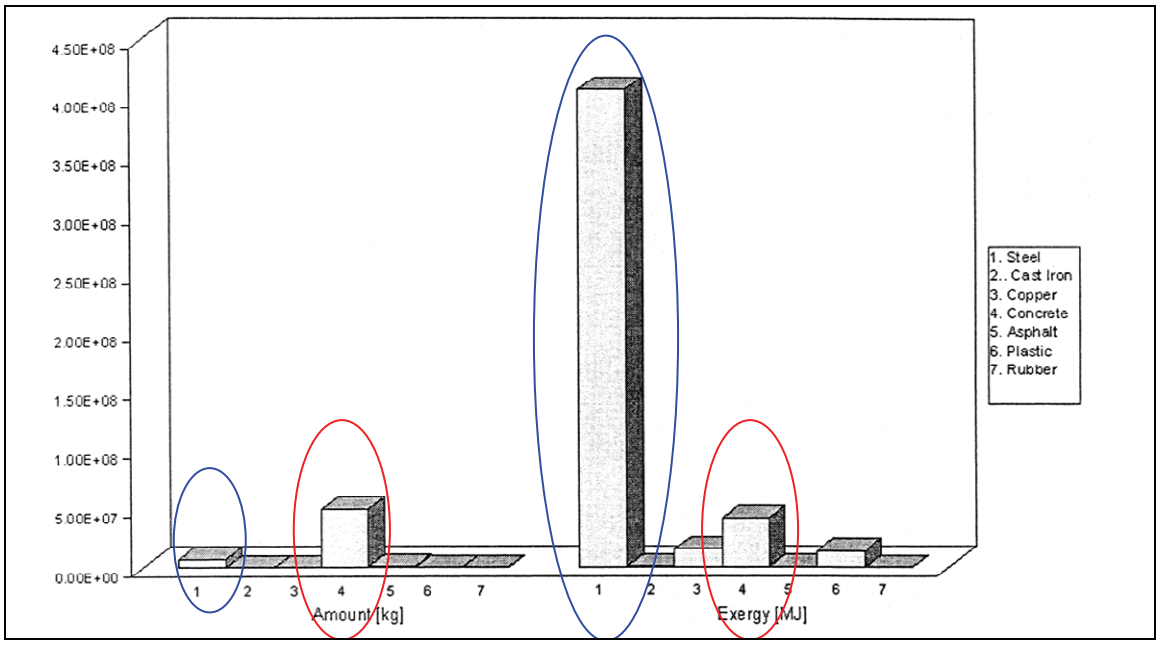

Figure 3-5 Amount and exergy of materials for construction of NG SCGT/CC plant (Lombardi 2001)

In Table 3-2, the key data from the LCAs above is systemized. The green field on top of the table is data on the non CCS plants, which the authors use as reference scenarios in their work. The yellow field contains data on power output, energy efficiency, and life cycle GWP emissions (given in [g CO_2/kWh]) for the plants with post-combustion MEA-based CCS installed. Further, the capture rate of the MEA-plant is given, as well as the percentage reduction of specific emissions when CCS is applied ("Specific GWP reduction"). Finally, the CO_2 pipeline length is given for each of the studies. For Lombardi *et al.* the reference power and efficiency is not stated, but numbers are here assumed in order to get results for the Specific GWP reduction. In the case of Spath and Mann, an adjustment of their results is made in order to get comparable results with the other studies. Red numbers in parentheses represent the original numbers used by Spath and Mann, while the other numbers are using reduced power output as basis for calculating emission intensities, leaving out the right part of the flowchart in Figure 3-4.

			Odeh & Cockerill	Viebahn et al	Spath & Mann	Lombardi et al.
Non CCS	P	[MW]	500	700	600	270 (assumed)
	Efficiency	[%]	50%	60 %	54%[1]	53% (assumed)
	Emissions	[g CO2-eq/kWh]	488	393	499	535
CCS	P	[MW]	432	600	504 (600)	230
	Efficiency	[%]	42,80 %	51 %	41 %	45 %
	Emissions	[g CO2-eq/kWh]	200	138	150 (247)	137
	Capture rate	[%]	90 %	88 %	90 %	85 %
	Specific GWP reduction	[%]	59 %	65 %	70% (41%)	74 %
	CO2 transport distance	[km]	300	300	300	None

Table 3-2 Summary of LCA literature on NG power plants with CCS

Figure 3-6 inspects further the specific emissions from the plants applying CCS by comparing the distribution of emissions in the value chains. For Spath and Mann, the emissions in "power plant" also include carbon capture related emissions, while only emissions from CO_2 transport and storage is allocated to "CCS". The same is valid for Lombardi et al, but here transport and storage emissions are not at all included. In addition, Lombardi et al only count direct CO_2-emissions, not GWP.

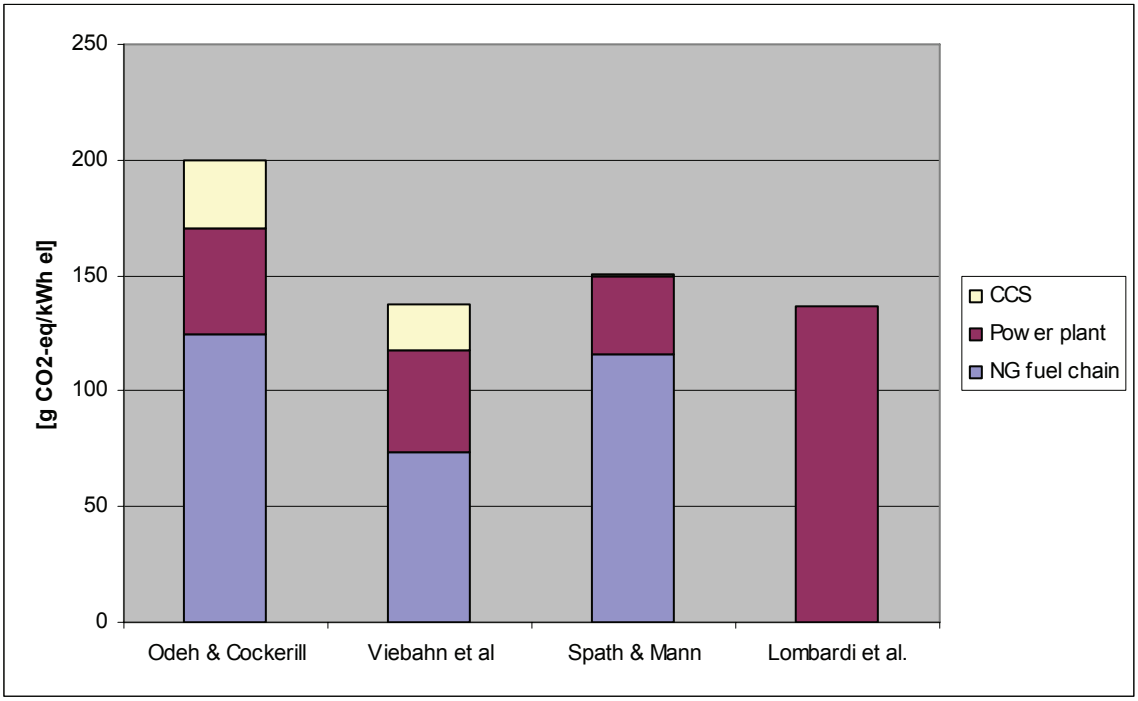

Figure 3-6 LCA literature comparison of GWP from MEA-cleaned NG power plants

[1] Heating value of Spath and Mann is modified from HHV to LHV basis

3.2 Other environmental impact categories

Nazarko *et al.* (2007) have inspected extra environmental burdens from applying CCS in other impact categories than GWP. A study presented at Risø International Energy Conference 2007 analyses impacts from coal power plants with three different technology assumptions, and compares conventional configurations with MEA carbon capture configurations. The three technologies are supposed to reflect technology improvements from year 2005; to 2010, and 2020. LCI results show that except for CO_2 and SO_2, all environmental flows increase. This increase is both due to increased use of chemicals and to reduced plant efficiency, giving increased flows through the systems. SO_2 emissions decrease due to an expected improvement of desulphurization if MEA is used.

Impact assessment is performed using CML 2001 characterization model. The normalized impact assessment results are envisaged in Figure 3-7. In the figure, the three bars to the left in an impact category represent the non-capture coal plant of respectively 2005, 2010 and 2020 technology, while the three left bars represent impacts from the same plants utilizing MEA carbon capture. Reduction in greenhouse gas potential for the carbon capture plants are obviously large, and the lowered SO_2-emissions give approximately 50% reduction in photochemical oxidation potential. In contrast to this, acidification and human toxicology potentials are slightly increasing due to ammonia emissions in air and heavy metal emissions to water respectively. Eutrophication impacts are substantially increased due to increased emissions of NOx and ammonia. The impact assessment method used does not have an impact factor to assess impacts from MEA emissions to air, a problem that is not discussed in the paper.

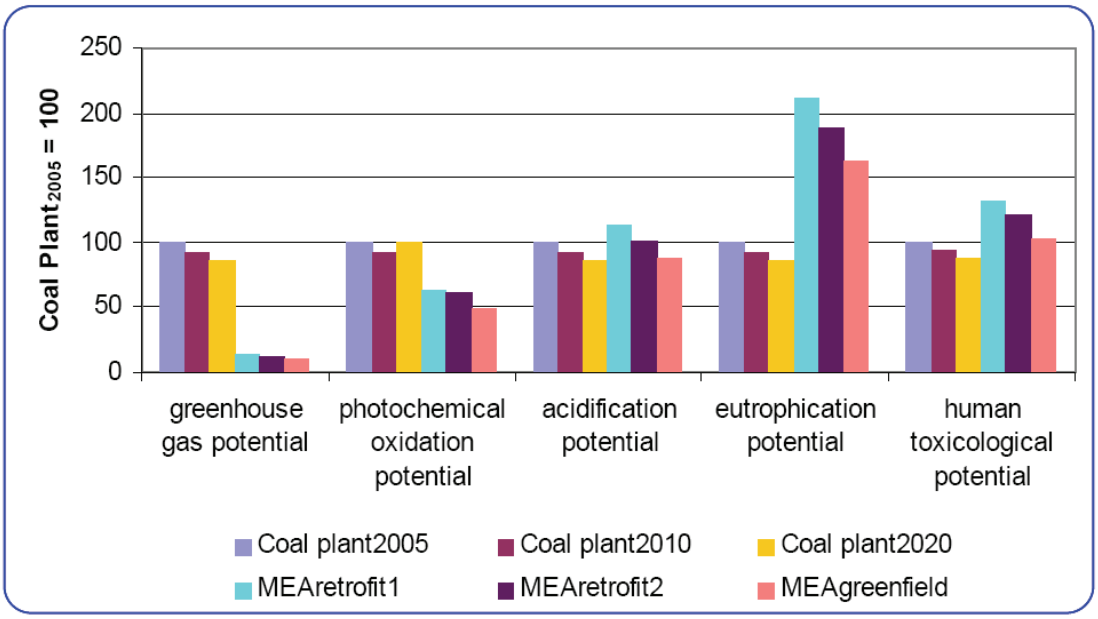

Figure 3-7 Impact assessment of coal power plants with and without MEA carbon capture

The environmental impacts of carbon capture solvent emissions are discussed by Gijlswijk et al. (2006). In their study they list different sources for solvent releases to the environment including mechanical losses, evaporation losses, degradation, absorber losses, and formation of solids. Mechanical losses can, as the authors argue, be controlled through "good housekeeping". Evaporation losses, degradation, and absorber losses gives origin to MEA and NH_3 contents in the flue gas, and will be quantitatively assessed later in this thesis. The formation of solids due to solvent reaction with other components in the flue gas represents a source of hazardous waste, which must be handled accordingly. Giljswijk et al. (2006) addresses the lack of impact factors for MEA, and provide calculations of toxicity potentials for such emissions. In this thesis, these toxicity potentials are used. A discussion of Acidification Potential or Eutrophication Potential from MEA emissions is however not available, and are assumed zero.

Odeh and Cockerill (2008) also discuss qualitatively additional environmental impacts (other than GWP) from CCS systems. The authors conclude that impacts in eutrophication, acidification, and human toxicity are likely to increase with CCS options. They have documented a rise in NO_x from 0.140 to 0.160 g/KWh from the NGCC when applying CCS, leading to increased impacts in EP and AP. HTP is "expected to increase due to increased emissions of heavy metals in water and due to the MEA hazardous waste".

Viebahn *et al.* (2007) looks at additional environmental effects from the pulverized hard coal plant when post combustion MEA capture is applied (with 88% capture rate). It is concluded that the 34% increased energy consumption make impacts in all categories increase about 40% as shown in Figure 3-8. In addition, the MEA production process leads to 60% increase in photo-oxidant formation, making impacts in this category rise by 96%. The authors comment that a reduction of some flue gas emissions (SO_2, dust, HCL) can be expected due to reaction with the MEA solvent. This is, however, not modelled in this study.

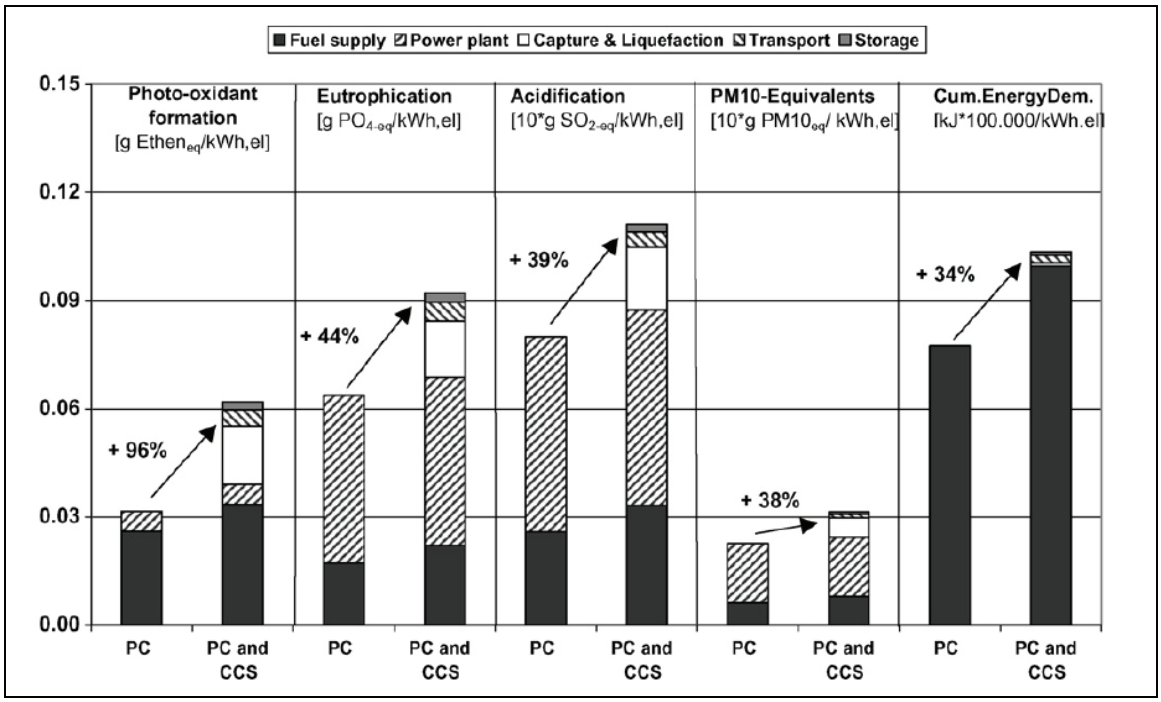

Figure 3-8 Further environmental impacts from pulverized hard coal plant with and without CCS (88% capture rate) (Viebahn et al. 2007)

Chapter 4

LCA methodology

Here, methodology for assembling a Life Cycle Inventory and calculating life cycle environmental impacts is described. Emphasis is put on describing theory and background for the Hybrid Life Cycle Inventory compilation. The chapter also revises the methodological development of allocation procedures in LCA methodology literature. The ISO standard for allocation of environmental loads is discussed, as well as different interpretations and critical opinions of this. Normative implications of different approaches to allocation are also discussed. Finally, the term eco-efficiency is introduced as an alternative way of handling data from an environmental assessment.

4.1 Hybrid Life Cycle Inventory

Life Cycle Analysis is a method for evaluating environmental impacts of a product holistically, including both direct and indirect impacts. A brief LCA methodology outline is provided in Appendix I. The phase of the LCA where system model is built by gathering data and systemizing environmentally relevant flows is called the Life Cycle Inventory (LCI) analysis. Two main approaches exist for compiling an LCI, namely the *process analysis* and the *input-output analysis* (Suh et al. 2004). The process analysis uses a physical approach, seeking to describe resource use and environmental releases from the main production processes, as well as some important contributions from other suppliers of input products. In principle, a complete process LCI, describing environmental flows from all suppliers and their respective sub-suppliers, is impossible in a complex economy, and cut-offs are therefore necessary.

The input-output (I/O) analysis represents a more aggregated approach, applying sectoral monetary transaction matrices that describe interlinkages in the economy on a national, regional, or global level. These data are coupled with data on emission intensities from the respective economic sectors, providing a consistent data set where environmental flows can be allocated to economic activity related to a product system. The disadvantage of the input-output analysis is that the detail level is not high enough to provide specific information on environmental performance of specific technologies, as one I/O-sector often covers different technologies and production practices.

Methodological work has been done, aiming to combine the completeness of an I/O analysis with the detailing of a process analysis. This methodology is referred to as *hybrid LCA*. There are different techniques for performing hybrid LCA, and Suh et al. (2004) groups them into three; tiered hybrid analysis, I/O based hybrid analysis and integrated hybrid analysis. The method that is used in this thesis is the tiered hybrid analysis, which describes the foreground process-based system with a technology matrix using physical units. This foreground system is linked to an I/O based background system, using monetary units.

Solli et al. (2006) provide an extended version of the tiered hybrid LCA in an article assessing two different routes for hydrogen production. In addition to linking the foreground system to an I/O- based background economy, the authors also include a process LCA database to model background processes needed as inputs to the foreground system. This provides an improved detailing level on the physical inputs to the foreground system that are known by the modeler. Finally, the I/O data are used to assess the remaining impacts. Typically, the difference between the price of a unit of equipment and the cost of its material inputs will be modeled as a purchase from an I/O sector. In a matrix representation, the data are arranged as shown in equation (1). Here, *Aff* is the foreground inventory matrix, *App* is the process database matrix and *Ann* is the I/O matrix, describing interindustry demands. Each of the three inventories are associated with corresponding emission matrices describing environmental flows per unit outputs;

Ff, *Fp* and *Fn*. The process inputs to the foreground system from the process LCA database are specified in *Apf*, while the purchases from the I/O sectors are given in *Anf*.

$$A = \begin{pmatrix} Aff & 0 & 0 \\ Apf & App & 0 \\ Anf & 0 & Ann \end{pmatrix} \quad (1)$$

Solli et al. (2006) compares environmental impacts from hydrogen production via nuclear assisted thermochemical water splitting and natural gas steam reforming with CO_2 sequestration. Emphasis is put on inspecting the effects of methodology choices to the results. Figure 4-1 show where emissions of different categories originate; in foreground, background, or input-output systems. It can be seen that there are significant differences between the production systems regarding the fraction of emissions originating from the foreground, background, and input-output processes.

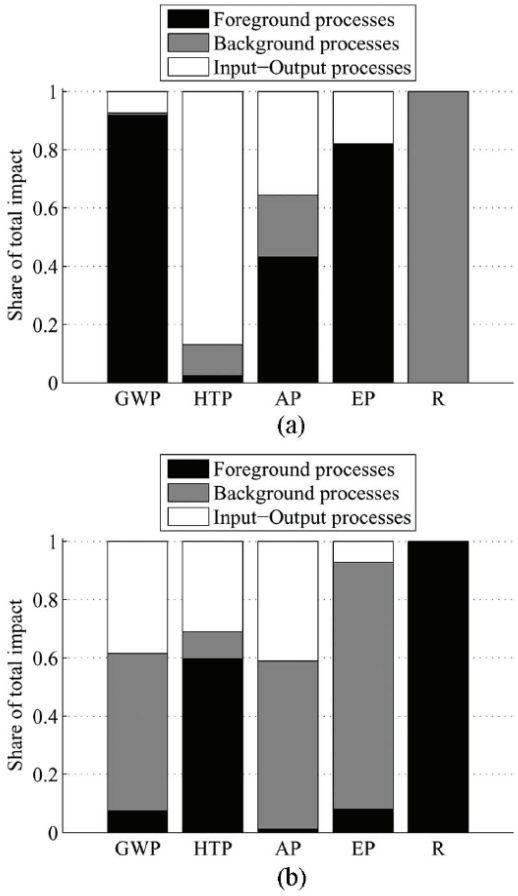

Figure 4-1 Impacts from hydrogen production stemming from different parts of system. (a) Natural gas reforming. (b) Nuclear thermochemical.

The authors conclude that in a comparative assessment, a significantly larger fraction of impacts may be accounted for in one product system than another if only process LCA is used. This may give misleading results in a comparative LCA based solely on a process

LCA. By including inducted economic activity through hybrid LCA techniques, the system boundary expands, giving a better basis for comparison.

However, the findings of Solli et al. (2006) for the natural gas reforming case reveal that on global warming, the foreground processes are dominant, accounting for over 90% of GHG emissions from the system. More than 80% of emissions in eutrophication occur in the foreground system. This might indicate a high importance of the foreground system for the CHP's at Mongstad, assuming that these two product systems will be quite similar.

4.2 Calculation

The hybrid LCI approach described above is applied to a foreground matrix, which is compiled in Chapter 5. Data sources for the background process (*App*) and the Input-Output database (*Ann*) is also briefly described in Chapter 5. The data are compiled in an Excel-matrix, and calculations are performed in Matlab. Below follows a description of the calculation procedure.

4.2.1 Inventory compilation

The foreground system *Aff* is defined in Excel, describing relevant flows and interlinkages. Emissions from the foreground system are described in a matrix *Ff*. Furthermore, requirements of substances, such as natural gas, monoethanolamine, and building materials are defined as inputs to the foreground system from the Ecoinvent database v1.1 (Frischknecht et al. 2005), *App*. The stressor matrix of Ecoinvent, *Fp*, contains 4345 stressors, and stressors matrices from the foreground and I/O systems, *Ff* and *Fn*, are merged into this as described in Equation (2).

$$F = \left[Ff, \quad Fn, \quad Fp \right] \tag{2}$$

Finally, purchases from the I/O sectors are modeled. Here, a Norwegian I/O table from year 2000 is used, *Ann*. All prices are adjusted to price year 2000 by use of consumer price index provided by Statistics Norway. The purchases made in basic prices, meaning that value added is subtracted from all modeled purchases. The values of goods that are modeled as inputs from the Ecoinvent database are also subtracted from the purchases to avoid double counting of any inputs.

4.2.2 Impact assessment

The *A* matrix is compiled by assembling *Aff*, *App*, and *Ann*, as shown in Equation (1). Then, the Open Leontief Model is applied, giving the requirement matrix, *x*, as shown in Equation (3). *y* is the external demand vector (Strømman 2008).

$$x = \left(I - A \right)^{-1} y \tag{3}$$

The requirement matrix is in the next step used to calculate environmental stressors, *e*, by the following relation.

$$e = Fx \tag{4}$$

Finally, impacts, *d*, are calculated by multiplying the stressor vector with the categorization matrix, *C*. This matrix contains the CML baseline 2000 v2.1 method for categorizing stressors into environmental impact categories

$$d = Ce \tag{5}$$

4.2.3 Contribution analysis

In order to analyze the systems and inspect how and where emissions occur, several calculating techniques have been applied.

A process contribution analysis provides information about impacts caused by each of the processes in the system. To obtain this, the requirement matrix, *x*, is diagonalized. Below, the hat ^, symbolizes diagonalized vectors. The process contribution matrix, accounting impacts from all processes, is denoted Dpro.

$$Dpro = CF\hat{x} \tag{6}$$

It can be useful also to obtain information of what stressors that give rise to the different environmental impacts in order to understand the system better. A stressor contribution analysis is performed by diagonalizing the stressor matrix, *e*. The stressor contribution matrix is denoted Dstr.

$$Dstr = C\hat{e} \tag{7}$$

Finally, it can be important to attribute the emissions to the different processes in the foreground system. This is performed through a Foreground Contribution Analysis (FCA). The FCA provides information of the impacts caused directly by a foreground process plus the impacts generated by the other upstream processes it induces activity in. It is important here to note that if a foreground process A induces activity in another foreground process B, it is process B that is attributed the direct and indirect impacts caused by the A's demand for B. The matrix calculation of foreground contribution analysis can be found in Strømman (2008).

4.2.4 Structural Path Analysis (SPA)

An SPA provides information of what single processes stand out as most polluting in the system. It also gives information about the value chain that gives rise to the polluting process, enabling insight in causal relationships in the system. The calculation procedure

for performing an SPA is not presented here. The SPAs are used only as supporting information to the contribution analysis in order to identify the drivers for different emissions in the value chain when this is not obvious.

4.3 Allocation of impacts

An LCA assesses environmental impacts of processes related to the production, use, and disposal of products. When a production system is related to more than one product, environmental burdens will have to be partitioned between the products in some way. The methodology for allocating environmental burdens to different co-products is referred to as simply *allocation*, and has caused significant controversy in the development of LCA methodology. Allocation can significantly influence the results of an LCA, and several approaches exist.

4.3.1 Definition and standards in allocation

In the ISO standard 14044 the term allocation is defined as ”partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.” (ISO14044 2006). In the standard, three steps for performing an allocation is outlined.

Step 1 of the standard says that allocation should, wherever possible, be avoided by dividing into sub-processes or by expanding the system to include the functions of the co-products. System expansion is done to achieve a fair comparison of different product systems which have different outputs of co-products, and is done by including alternative product system for co-products.

Where allocation cannot be avoided, it should be done in a way that reflects the “underlying physical relationships” between the different products or functions (ISO14044 2006). This is Step 2 of the ISO procedure, and means more precisely that the allocation should “reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system”. If a physical relationship can not be clearly established, inputs and outputs should be allocated according to other relationships between the products, like for instance economic value (Step 3).

In order to analyze the issue of choosing allocation procedure, it is interesting to look deeper into the theoretical debate on LCA methodology. One important concept for determining if system expansion should be performed is the distinction between prospective and retrospective LCA´s. Ekvall et al. (2005) applies theory from normative ethics to explain the two methodological approaches to LCA methodology and the differences in ethical fundamentals behind them.

4.3.2 Prospective and retrospective LCA

What Ekvall et al. (2005) define as a retrospective LCA is an LCA aiming at describing actual environmental impacts from a product system, using average data. A prospective LCA, on the other side, focuses on describing how environmental impacts will change in response to a change in product system. Key differences in methodology for the two LCA types are choice of process data and allocation procedure. A retrospective LCA will use average data for subsystems in the life cycle, while a prospective LCA uses marginal data. For a retrospective LCA, allocation problems are typically solved through partitioning of environmental burdens to a property of the product such as economic value, energy, mass, etc. Without further reasoning, Ekvall et al. consider economic value to be the most objective basis for allocation. In a prospective LCA, allocation problems are avoided by applying system expansion.

It can be seen above that the two methodological approaches reflect different study foci: the retrospective seeks to generate environmental information on the life cycle investigated, while the prospective investigate the consequences of changes. Ekvall et al. (2005) argue that "the retrospective LCA is valid to an (hypothetical) audience that wants to avoid [environmentally undesirable] product systems and subsystems. Likewise, the prospective LCA is valid if the audience considers changes of a product system "good" if consequences for the total environment are good." Furthermore they argue that the retrospective LCA has most relevance "if the ethical rule is to avoid being associated with systems that have undesirable environmental impacts", and that such a rule without reference to its consequences is an example of deontological rule ethics, such as the categorical imperative evolved by Immanuel Kant. The prospective LCA, judging environmental performance based on particular consequences, is on the other side an example of teleological situation ethics, such as the utilitaristic theories of Jeremy Bentham.

According to Ekvall et al., there are drawbacks using both the methodology approaches. Since the retrospective LCA does not reflect the consequences in the surroundings of an action, there is a risk that the environment can be harmed by something which is recommended by the retrospective LCA. On the other hand, a prospective approach might give unfair conclusions in a local perspective, leading to sub-optimal systems.

(Ekvall et al. 2005) does not conclude on what methodology that suits different LCA studies, but stress the importance of stating clearly in an LCA whether the purpose of the study is to "describe environmental burdens of a system, or to describe the consequences on the environmental burdens of changes that can be made in the system". The statement should also be accompanied by an understanding of the normative implications this choice has.

4.3.3 Classification of allocation situations

Frischknecht (2000) makes a critical review of the ISO standard, and proposes a new method for classification of allocation situations. A decision tree is made in order to support the choice of allocation procedure based on the presented classification. It is interesting to look into Frischknechts classification in order to systemize the allocation choices that are present in the Mongstad case.

Frischknecht's main point is that choice of allocation procedure is highly context dependent, and that value judgements in allocation are inevitable. The author highlights three distinctive features for an allocation problem that together constitute the nature of the problem. The first feature is whether there is *joint* or *combined* production of a product. If the case concerns combined production, then physical causalities in product output and emissions can be identified and allocation factors is determined through inspecting these. In joint production, however, such causal relations can not be identified because changing the output of one product can not be done without changing the other product outputs. The second distinctive feature is whether the co-products are produced simultaneously or successively. The example of a CHP can by use of these features be classified as a *simultaneous joint production* case.

The third feature is whether one or several decision-makers are involved. It is by emphasizing this third distinctive feature that Frischknecht brings in a new dimension to classification of allocation problems from what is already discussed in the ISO. This dimension reflects the important point of the context being decisive in allocation methodology. If several decision stakeholders are involved in a joint production, the allocation of burdens (economic and environmental) will be subject to what Frischknecht calls "multiobjective negotiation". This is not further pursued here. If, on the other side, the joint production is done by one single company (decision maker), it is claimed that the market conditions will decide the allocation procedure.

The market condition is in the paper simplified to a question of whether there is a perfect market. If there is such a perfect market, it is argued that these may determine the allocation factors. Looking at economic and environmental burdens of the competitors' single-output products can be a way of determining allocation factors for the joint product. Such an approach can determine a range of allocation factors within which both joint products perform better than the competitors' single output products. Following such an allocation procedure implies looking into alternative production technologies for the joint products, and Frischknecht points out that an allocation factor in this approach actually can correspond to the "avoided burden" approach. In that way, he concludes that this form of system expansion actually is just a special case of an allocation factor, based on a competitiveness approach to a joint production allocation problem.

Weidema (2001) supports the ISO 14044 procedure, stating that system expansion should be favored wherever possible. Further, he argues that the steps of the ISO-procedure actually can be replaced by more specific classifications of allocation cases. Step 1, system expansion, is always applicable for cases of joint production in prospective LCAs. Step 2, determining physical causalities, is done for cases of combined production in

prospective studies. And finally, step 3, allocation according to relative economic value of products, is only relevant for retrospective (status quo) studies. Regarding the latter case, Weidema actually questions the relevance of retrospective LCA studies, as he claims that the ultimate goal of an LCA always is to improve the studied systems. If the audience of an LCA is interested in avoiding products with undesirable environmental effects, then the product choice ideally should be based on the environmental consequences of his choice, not on historical impacts caused by the product.

4.4 Eco-efficiency

Eco-efficiency is a way to measure environmental performance in relation to economic value of a process, product, or service. The World Business Council for Sustainable Development (WBCSD) define eco-efficiency as being a parameter bringing the dimensions of economy and ecology together, for instance through the following ratio (WBCSD 2000):

$$\text{Eco-efficiency} = \frac{\text{Environmental Influence}}{\text{Product Value}} \tag{8}$$

The indicator can also be inverted, providing the same information[2]. Both product value and environmental influence can be counted in different ways, and often they are characterized by different indicators that cannot be merged into one number. The product value can be interpreted as the price of the product. It is common practice in Input – Output analysis to define the price as being the sum of the price of the input products and the value added:

$$\text{Price} = \text{price of inputs} + \text{value added} \tag{9}$$

This representation of price can be seen as analogous to how emissions from a product system can be split up into direct and indirect emissions:

$$\text{Total Emissions } (TE) = \text{Indirect } (IE) + \text{Direct } (DE) \tag{10}$$

Equations (9) and (10), are useful in understanding what eco-efficiency expressions that are meaningful. To obtain a consistent expression, the same terms from equation (9) and (10) should be chosen for eco-efficiency calculation; for instance, the total emissions divided by product price, or the direct emissions divided by the value added.

The purpose of eco-efficiency calculations was, when invented by the WBCSD in 1991, to find a single concept to sum up the business approach to sustainable development; namely to create more goods and services with less use of resources and pollution

[2] The WBCSD definition is actually Product Value over Environmental Influence

(WBCSD 2000). Eco-efficiency is considered a helpful tool for evaluating different options for heat and power production at the Mongstad refinery, due to the ability of the concept to compare systems that give different economic outcomes and have different environmental impacts. Eco-efficiency will in this thesis be used as a tool for economic allocation of environmental impacts in order to inspect and compare environmental performance of different parts of the system when different configuration for heat and power production is introduced; all with different flows of in- and outputs.

Chapter 5

Life Cycle Inventory (LCI) modeling

This chapter shows the assumptions behind the compilation of the three life cycle inventories for alternative CHP plants at Mongstad. A system flowchart is provided, to visualize the system boundaries of the CHP systems. Critical parameters for the environmental performance of the plants are discussed and quantified.

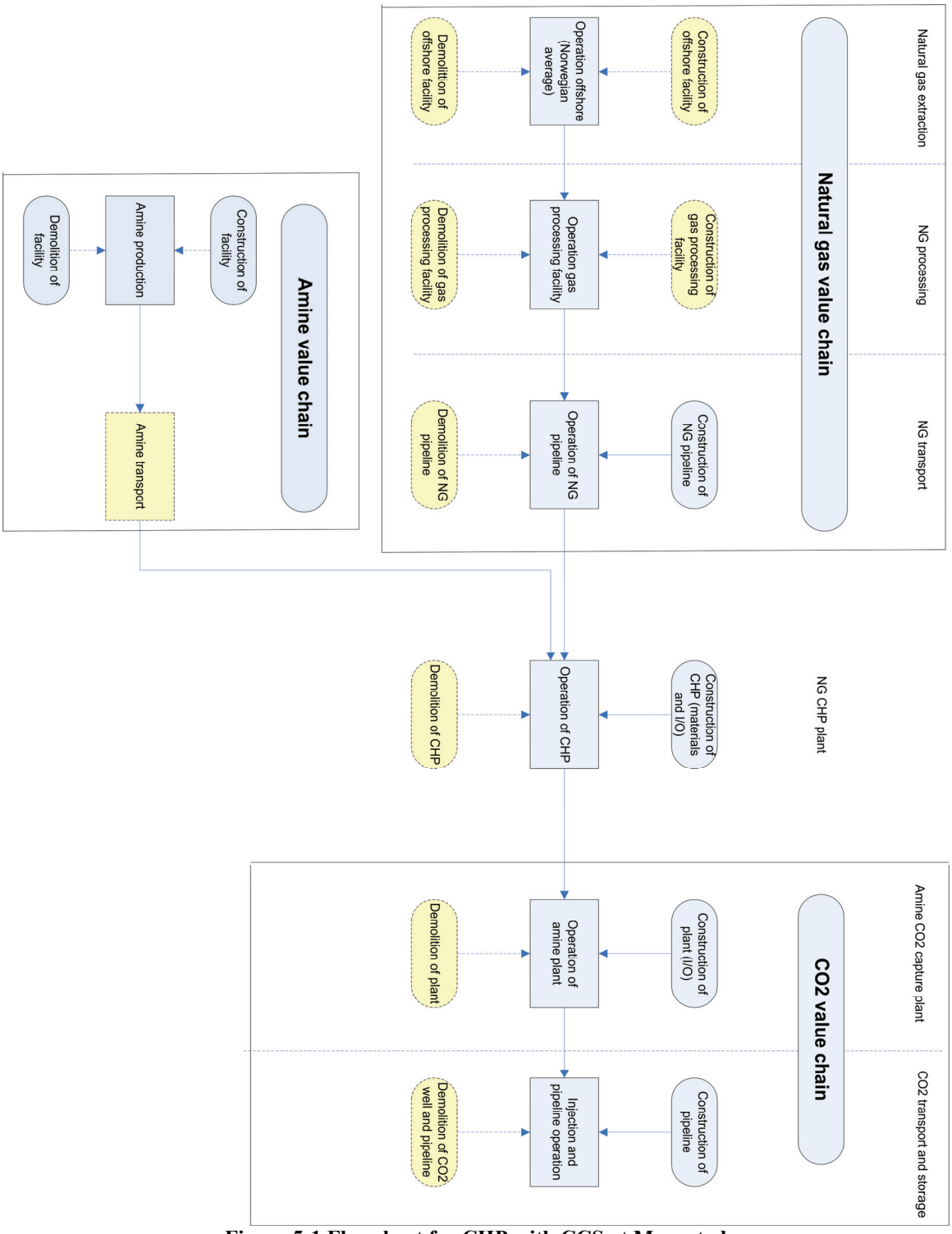

Figure 5-1 Flowchart for CHP with CCS at Mongstad

The flowchart in Figure 5-1 shows the environmentally relevant processes in a CHP at Mongstad using a CCS application. Naturally, the amine and CO_2 value chains are not part of the non-CCS CHP. Processes marked yellow are excluded from the LCI due to lack of data in combination with an assumption of lower environmental relevance.

Regarding the NG value chain, the yellow processes actually are included when an Ecoinvent process is decided to describe NG production; see chapter 5.3. In the following chapters, the LCI data on the different processes are accounted for. Three inventories are made, describing different CHP and CCS configurations. However, much of the data input to the different inventories are based on generalizations, meaning that numbers are scaled to describe different configurations. One of the full inventory matrices can be found in appendix II, as a detailed sample of the methodology that can be read in accordance with chapters 4.1and 4.2.

5.1 Data sources used in the analysis

Inventory analysis
In this thesis the process database Ecoinvent 1.1 is used as the *App* matrix, following the notation of chapter 4.1. This database is the result of a Swiss project to harmonize and update life cycle inventory data for use in LCA (Frischknecht 2005). The database version 1.1 is completed in 2004 and contains more than 2500 products and services and more than 4000 environmental stressors. Mainly the process descriptions represent Swiss averages from the year 2000. However the Swiss economy is closely linked to the rest of Europe, so many of the processes are classified as being valid as European averages. The system boundary for the database comprises the entire world, meaning that all up- and downstream emissions are modelled, independent of geography.

The Norwegian Input-Output (I/O) database for year 2000 is used as matrix *Ann*. This database contains 56 sectors and 20 stressors, and is hence on a quite aggregated level.

Impact assessment
The CML 2000 baseline is used for characterization of environmental impacts (Guinée 2002). Nine of the ten standard categories are used, as shown in Table 5-1. An addition is made on the standard CML 2000 characterization matrix for emissions of MEA. A characterization factor of 0.64 kg 1,4-DCB-eq/kg MEA is included to assess toxicity effects from MEA emissions.

Impact category	Indicator unit
Global Warming (GWP100)	kg CO2-eq
Ozone Layer Depletion	kg CFC-11-eq
Human Toxicity	kg 1,4-dichlorobenzene-eq
Fresh Water Aquatic Ecotox.	kg 1,4-dichlorobenzene-eq
Marine Aquatic Ecotoxicity	kg 1,4-dichlorobenzene-eq
Terrestrial Ecotoxicity	kg 1,4-dichlorobenzene-eq
Photochemical Oxidation	kg ethylene-eq
Acidification	kg SO2-eq
Eutrophication	kg PO43- eq

Table 5-1 Selected CML 2000 baseline impact categories

5.2 Power plant and CO_2 capture

Three CHP configurations are evaluated in this thesis, based on process modeling results by Solli (2008b). The framework from Mongstad refinery as described in chapter 2.2 has been used as a basis for configurations. To serve the refinery heat consumptions the CHP's are dimensioned to deliver 270 MW of high pressure steam as well as 76 MW of heat for pre-heating crude oil. This is the only fixed design criteria, making electricity output variable in the different plant configurations. The configurations are:

1. Conventional CHP with 343 MW electric power output
2. Conventional CHP with post-combustion CCS, 493 MW electric power output
3. Autothermal reforming (ATR) plant; CHP with pre-combustion CCS, 302 MW electric power output.

In the following, system alternative 1, 2 and 3 will be referred to respectively as *Conventional*, *PC* and *ATR.*

The systems are set up with gas turbines with 92% adiabatic efficiency and inlet temperature of 1370 ºC. Adiabatic efficiency of the air compression is 88%, and a pressure rate of 1:17.6 is assumed. The most LCA-relevant process parameters for the three plant configurations are listed in Table 5-2 below.

The conventional plant is schematically visualized in Figure 5-2. For the post-combustion CCS option, the carbon capture plant is shown in with dashed lines to the right in the figure.

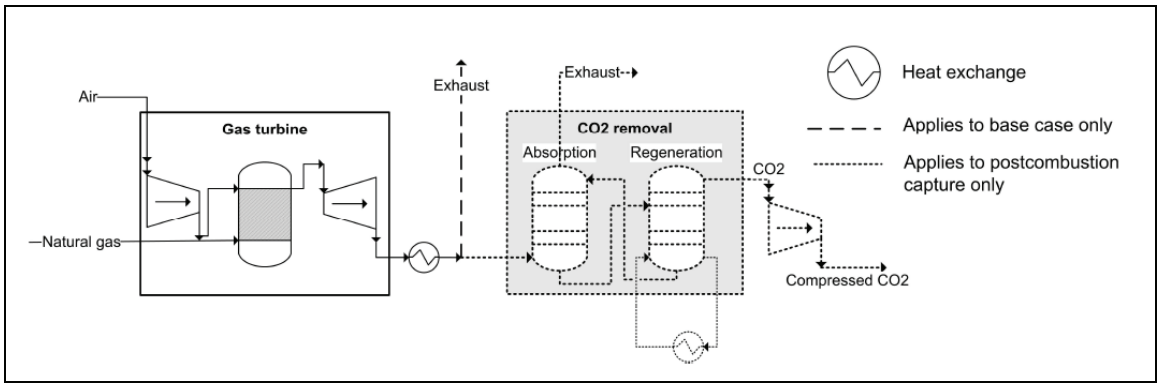

Figure 5-2 Simplified flowchart of conventional CHP and carbon capture plant (Solli 2008b)

The ATR configuration is shown in Figure 5-3. First natural gas and steam is fed to a pre-reformer, converting longer hydrocarbons to methane, hydrogen, CO, and CO_2. The gas from the pre-reformer subsequently enters the autothermal reformer (ATR) together with oxygen. The oxygen is produced in an Air Separation Unit (ASU). In the ATR, the methane is reformed into syngas, consisting of hydrogen (H_2), CO, and CO_2. The reforming is an endothermic reaction, and the heat required is provided by partial combustion of methane. The reactor has hence no need for external firing; therefore the process is called *autothermal reforming*. After reforming, the syngas is fed to high and low temperature shift reactors (HTS, LTS), where CO reacts with water to form CO_2 and

H_2. A gas mixture consisting mainly of CO_2 and H_2 is then ready for CO_2 removal in the carbon capture plant.

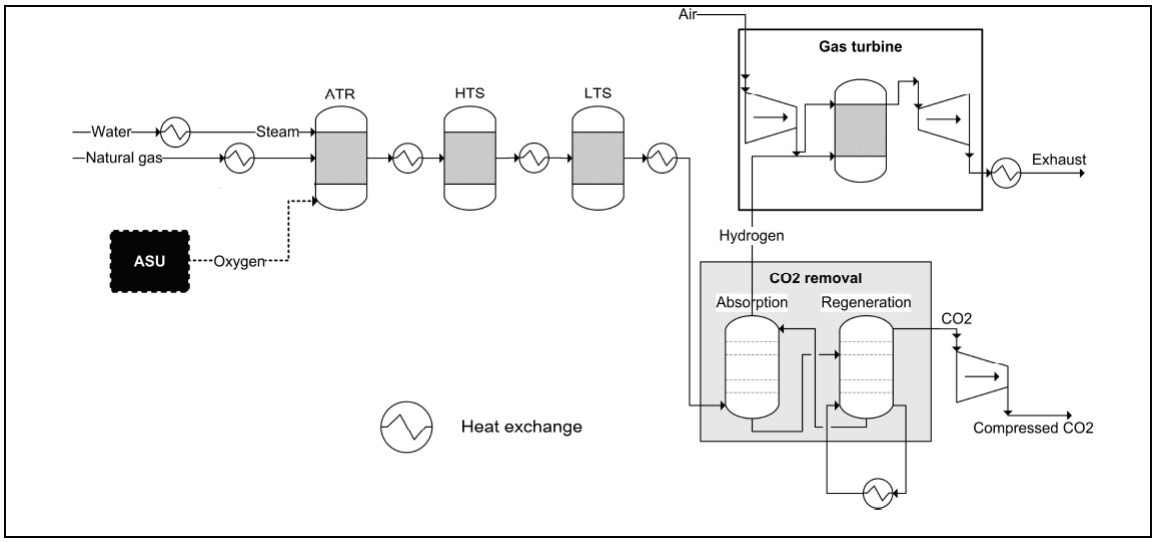

Figure 5-3 Autothermal reforming CHP with pre-combustion CO_2 capture

	Conventional	Post-combustion	ATR
Natural gas input [MW]	807	1367	889
Electricity output [MW]	343	493	302
Heat output [MW]	346	346	346
Energy efficiency [%]	85,3	66,2	72,8
CO2 emissions [Mt/yr]	1,42	0,22	0,33
CO2 captured [Mt/yr]	0	2,01	1,23
Capture rate [% of fuel carbon]	0	90	78,6

Table 5-2 Key parameters for the three CHP configurations

Other operation emissions

The process modeling results above only specify CO_2 emissions. Different sources have been used to assess other operation emissions from the power plants. A modeling tool called Integrated Environmental Control Model (IECM), assessing costs and emissions from fossil power plant with CCS, is developed at Carnegie Mellon University (Rubin et al. 2007). The model applies fundamental mass and energy balances together with empirical data, quantifying overall plant performance, resource requirements and emissions. The IECM is publicly available, and has been used to assess reasonable emissions coefficients for the CHP plants. The gas fed to the CHP is in the process modeling simplified to be pure natural gas of the composition shown in Table 5-3. The fact that refinery gas is used as feedstock is hence neglected in the further modeling.

Molar %	Compound
93,28 %	Methane
0,29 %	CO2
1,69 %	N2
3,60 %	Ethane
0,57 %	Propane
0,32 %	i-butane
0,08 %	n-butane
0,06 %	i-pentane
0,02 %	n-pentane
0,11 %	n-hexane

Table 5-3 Composition of natural gas feedstock (LHV 48 MJ/kg)

A report by NVE assesses expected emissions of NO_x, amines, ammonia and wastes at the planned post combustion capture plant at Kårstø, and has been used as a data basis for releases of the three latter compounds (NVE 2006). Emissions from power generation and carbon capture are in Table 5-4 shown as kg per hour operation of the three CHP alternatives.

	Conventional	PC	ATR
Power plant			
NO2	1,08	1,27	35,63
NO	13,4	21,0	14,7
CO_2 capture			
MEA	-	23,9	0
NH3 to air	-	14,36	0
NH3 to water	-	10,34	6,32
Special waste	-	1581	1332

Table 5-4 Operation emissions from power and CO_2 capture plant [kg/hour operation]

The figures are obtained by scaling the data from the different data sources after power output of the CHPs and CO_2 capture duty of the CC units. For the ATR plant, it should be noticed that there are no releases of MEA solvent or ammonia to air due to combustion of these compounds in the turbine (Gijlswijk 2006; Svendsen 2008). The nitrogen content is, however, assumed to be emitted as NO_2, causing substantially larger emissions of NO_2 from the ATR in this inventory. Whether the NO_x cleaning system would capture these increased NO_2 emissions is not discussed further.

To improve completeness of the inventory, costs in operation are also sought included in this hybrid inventory. All cost data used in the inventory are basic prices, excluding value added such as labor. Remaining costs in operation are typically related to maintenance and insurance. On the power plant, a cost estimate made by Fluor on the Tjeldbergodden plant has been taken from Aaberg (2006). NVE (2006) assesses operation costs for the carbon capture plant. Yearly operation costs are shown in Table 5-5, scaled after power and CO_2 removal capacity.

	Unit	Price year	Value
Power plant	NOK/yr (per GW gas input)	2004	**82 386 364**
Capture plant	NOK/yr (1MtnCO2/yr)	2006	**83 809 524**

Table 5-5 Calculated operation costs at Mongstad

Construction of power plant equipment
Emissions related to construction of the power plant were indicated by the literature study in chapter 3.1 above as not being crucial to the overall LCA-emissions of the plant. A full process LCA approach on plant construction has therefore not been performed. The hybrid approach is applied, by assessing costs as well as finding data on average material consumption in construction of NG power plants. Cost data has been scaled according to the rated power input of natural gas for the different configurations. Average data on material requirements has been taken from Spath and Mann (2000).

The costs of constructing the carbon capture plant are assessed and discussed by NVE (2006). These data are scaled after CO_2 removal duty for the different alternatives. Table 5-6 summarizes important input data on power and carbon capture plant construction.

	Unit	Reference	Price year	Value
Power plant				
Construction costs	[NOK/GW gas input]	Aaberg (2006)	2004	**2 982 954 545**
Concrete	[kg/MW power output]	Spath & Mann (2000)	-	**97 749**
Steel	[kg/MW power output]	Spath & Mann (2000)	-	**31 030**
Iron	[kg/MW power output]	Spath & Mann (2000)	-	**408**
Aluminum	[kg/MW power output]	Spath & Mann (2000)	-	**204**
CO2 capture plant				
Construction costs	[NOK/Mtn CO2 per year]	NVE (2006)	2006	**3 295 238 095**

Table 5-6 Construction costs and material requirements at power plant

A lifetime of 30 years is assumed for all power plant and carbon capture equipment. Decommissioning of the equipment has not been modeled.

5.3 Natural gas value chain

Extraction and processing of NG
It was desirable to utilize an Ecoinvent process describing Norwegian natural gas production, 'Natural gas, at production offshore/NO U', to consistently quantify all categories of emissions as well as resource use in the whole NG value chain. However, due to the fact that extraction, transport and processing of natural gas contributed to large amounts of the GWP emissions in some of the literature studies in chapter 3.1, special effort was put down into cross-checking GWP from the Ecoinvent process with real data for Mongstad.

The natural gas for use at Mongstad will be transported in pipeline from Kollsnes gas processing plant. CO_2 emissions at Kollsnes were retrieved by mail correspondence with

Tormod Spangelo, Gassco (Spangelo 2008). Most of the gas supply at Kollsnes is from the Troll platform. However, Norwegian average figures were used here to assess offshore GWP emissions related to natural gas extraction. Data on total greenhouse gas emissions as well as production of oil and gas for the Norwegian offshore sector are reported by the Norwegian Environmental Agency, Sft, to the European Environmental Agency and made publicly available (EEA 2008).

The Ecoinvent process includes exploration and production of natural gas on the Norwegian continental shelf. Processing data has been collected from Kårstø and Kollsnes for year 2000. The GWP values for the Ecoinvent process are compared to the gathered data in Table 5-7, where emissions are categorized into GWP and divided by MWh LHV gas delivered. It can be seen that the Ecoinvent process reports 44% higher GWP emissions than the collected data. This difference is not unexpected, due to the fact that the system border is wider for the Ecoinvent process. For instance, only CO_2 and methane are included in the Sft and Gassco estimates, whereas Ecoinvent includes other stressors counting 0.08 kg CO_2-eq/MWh LHV. Processes related to supply of chemicals etc., the offshore installations, as well as welding and disposal of wastes, are also included by Ecoinvent. The total evaluation is that the Ecoinvent process seems to be a good description of the natural gas supply for Mongstad.

	Reference	[kg CO2-eq/MWh LHV]
Reported numbers		
Offshore emissions	Sft (2008)	4,45
Gas processing	Gassco (2008)	0,22
Sum		**4,67**
Ecoinvent		**6,74**

Table 5-7 Comparison of GWP emissions in NG production from different data sources

Transport of NG

A 62 km long pipeline from Kollsnes to Mongstad is part of the EVM project (Statoil 2005b). In the impact study for this pipeline, Statoil assesses emissions as well as costs in laying of such a pipe. A 10 inch pipe with a pressure resistance of 200 bars, is chosen. Material consumption has been calculated by geometry, and life time is assumed to be 30 years. Costs, emissions, and material consumption are listed in Table 5-8 on a yearly breakdown.

	Unit	Value
Steel	[tn/year]	**79**
Concrete	[tn/year]	**3431**
Construction cost	[MNOK 2000/yr]	**31**
Opeartion cost	[MNOK 2000/yr]	**9**
CO2	[tn/year]	**107**
SO2	[kg/year]	**133**
NOx	[kg/year]	**233**

Table 5-8 NG pipeline Kollsnes – Mongstad; emissions, costs and material requirements

Compressor work needed to transport the NG is assumed similar to energy consumption per tkm of pipeline transport of CO_2, which is stated below. The electric energy for compression is served by the EVM plant itself.

5.4 CO_2 transport and storage

The transport and storage of CO_2 from Mongstad is discussed by Gassnova (2007). An estimate of the costs related to joining the CO_2 from Kårstø and Mongstad at Utsira has been used in this hybrid inventory. The pipe distance is approximately 300 km, and costs for building a pipe with capacity of 3,3 MtnCO_2/year has been allocated between Mongstad and Kårstø after the size of CO_2 flow. This gives a cost of approximately 100 MNOK/yr with a 30 year lifetime for 300 km pipe plus offshore welding in the Utsira formation.

Material requirements for CO_2 pipe are assumed to be the same as for the NG pipeline. Energy requirement in recompression of the CO_2 has been given to be 0.0056 kWh/tkm (Singh 2007). The process data by Solli (2008) includes a compression of the dry CO_2 product to 200 bars. At the Utsira formation, the CO_2 can be stored at a depth of 900 – 1000 m below sea level. Calculations by Singh (2007) indicated that for an 800 m deep reservoir, an injection pressure of about 140 bars is required. This indicates that further power supply for injection at Utsira will not be necessary.

5.5 Amine value chain

The solvent used for CO_2 capture is chosen to be *Monoethanolamine* (MEA) for both the PC and the ATR. However, the so called tertiary amine *Methyldiethanolamine* (MDEA) is more suitable for pre-combustion capture (Gijlswijk 2006), and should ideally be used to model the CC for the ATR. The choice of MEA is done based on data availability in the Ecoinvent database. The database contains a process description of MEA assessing environmental loads from the production of the solvent, but lack data on MDEA. The MEA production process description is theoretically based on stoechiometry, and uses average European processes for raw materials, transport, and electricity inputs. Transport of the MEA itself has not been assessed, as it is not clear where production will occur and it is assumed not to have significant importance to the calculations. The amount of MEA needed for CO_2 capture is stated by Mitsubishi Heavy Industries to be around 0.35 kg

MEA/tn CO_2 captured (Yasuyuki Yagi 2004). The amount of solvent needed per ton CO_2 captured is likely to be smaller for pre-combustion capture, but this is neither pursued further here.

Chapter 6

Results

The results of the Life Cycle Impact Assessment (LCIA) and the contribution analysis are provided in this chapter. A comparison of the environmental performance of the three systems is performed, using different allocation methods for the impacts. Relevant environmental impacts categories for further inspection are selected based on global normalization of impacts, among other criteria. Possible weaknesses with the inventory models that have appeared when processing the results are discussed at the end of the chapter.

6.1 Overall results

6.1.1 Functional units

The environmental impacts from operating the three CHP configurations have to be calculated in relation to a comparable functional unit. The functional unit should take into account that the composition of energy products and the total energy flow rate differs between the three plants. Three different functional units are chosen, all representing different ways of allocating environmental impacts to the products, namely by energy content, exergy content and product value. Calculating emissions per MWh energy delivered as heat and electricity is very transparent and easy to comprehend. It also makes results comparable to the results in the literature study in Chapter 3. However, this allocation approach does not reflect the thermodynamic difference in quality between the two products, and therefore a calculation of emissions per MWh exergy is also performed. Finally, a calculation of emissions per MNOK product value from the CHP's is also estimated. This monetary functional unit is calculated by assigning prices to steam, heat, and electricity. Nord Pool's system price for January 2008 is used for electricity; 0.364 NOK/kWh (NordPool 2008). A typical relation between heat and electricity price is obtained from StatoilHydro, making a corresponding heat and steam price 0.216 NOK/kWh. These prices are merely estimates on probable internal prices for the products. The actual internal prices StatoilHydro uses at Mongstad are neither officially available nor fixed over time.

The production of energy and exergy from the CHP's to generate 1 MNOK product value using the prices above is listed in Table 6-1.

System alternative	Energy production	Exergy production
Post-combustion	3301	2556
ATR	3509	2483
Conventional	3452	2503

Table 6-1 Energy and exergy production per monetary functional unit [MWh / MNOK]

The thermodynamic fundamentals behind the exergy calculations are provided in Appendix III. It is the different product composition with regard to heat and electricity that causes the energy and exergy production to vary by some percentage between the different alternatives. The PC, for instance, has a larger fraction of electricity than the two other options, requiring less quantity of energy generation to achieve 1 MNOK product value. It can hence be expected that the PC will come out more beneficial, relative to the other options, using a monetary allocation than an energy allocation. As for exergy allocation, the PC will have even more relative benefit, since it is the alternative with largest exergy output per product value as shown in Table 6-1.

6.1.2 System GWP impacts

The Global Warming Potential (GWP) from the three system alternatives are shown for all three allocation methods in Figure 6-1. The red and blue bars are energy and exergy allocations, giving emissions in kg CO_2-eq/MWh. The yellow bars show monetary allocation and use the secondary y-axis, with units tons CO_2-eq/MNOK.

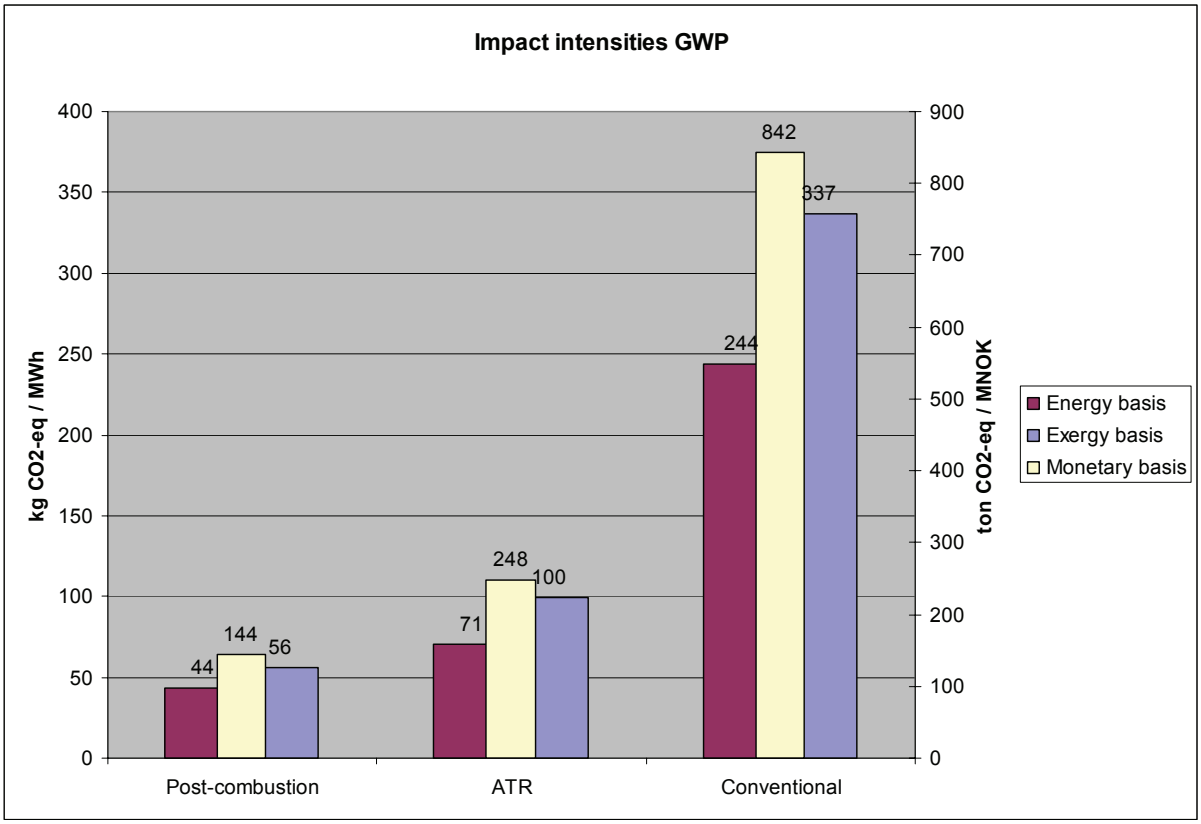

Figure 6-1 GWP impacts from the three CHP's applying three different allocation methods. Yellow bars use the secondary y-axis

A substantial emission reduction can be observed from the two system alternatives with CCS application. The total reductions in system GWP for the PC and ATR compared to the conventional plant are summarized in Table 6-2. Here, it can be seen that allocation on an exergy basis for the PC plant results in the largest emission reductions (83.3%), while energy allocation result in less emission reductions (82.2%), for reasons discussed above. However, the table shows that choice of allocation method does not radically alter conclusions regarding the ranking of the different system alternatives. The variance is only around one percentage point, and this indicates that further analysis of emissions will not be dramatically affected by choice of functional unit.

	System GWP reductions	
	PC	ATR
Monetary	83,0 %	70,6 %
Energy	82,2 %	71,1 %
Exergy	83,3 %	70,4 %

Table 6-2 Reduction of system GWP from CCS systems compared to conventional plant, using different allocation methods

6.1.3 Other environmental impacts

Looking at the whole environmental picture, impacts in nine important impact categories of CML baseline 2001 are in Table 6-3 and Figure 6-2 compared for the different power plant alternatives on a monetary basis.

Impact category	Impact unit (per MNOK)	Postcombustion	ATR	Conventional
Global Warming (GWP100)	kg CO2-eq	1,44E+05	2,48E+05	8,42E+05
Ozone layer Depletion	kg CKC-11-eq	2,55E-03	2,45E-03	1,99E-03
Human Toxicity	kg 1,4-dichlorobenzene-eq	5,51E+04	5,04E+04	3,31E+04
Fresh Water Aquatic Ecotox.	kg 1,4-dichlorobenzene-eq	4,76E+03	4,29E+03	3,90E+03
Marine Aquatic Ecotoxicity	kg 1,4-dichlorobenzene-eq	7,03E+06	6,51E+06	5,52E+06
Terrestrial Ecotoxicity	kg 1,4-dichlorobenzene-eq	1,31E+02	1,25E+02	9,25E+01
Potochemical Oxidation	kg ethylene-eq	9,89E+00	1,48E+01	6,90E+00
Acidification	kg SO2-eq	2,84E+02	2,82E+02	1,36E+02
Eutrophication	kg PO43- eq	7,56E+01	7,69E+01	2,97E+01

Table 6-3 Environmental impacts per MNOK turnover in 9 categories for the three system alternatives

Figure 6-2 provides a normalization of impacts within all categories. This gives an easy visualization of which system alternative has the largest impact in each category, and how large the difference in impacts is between the three alternatives within a category.

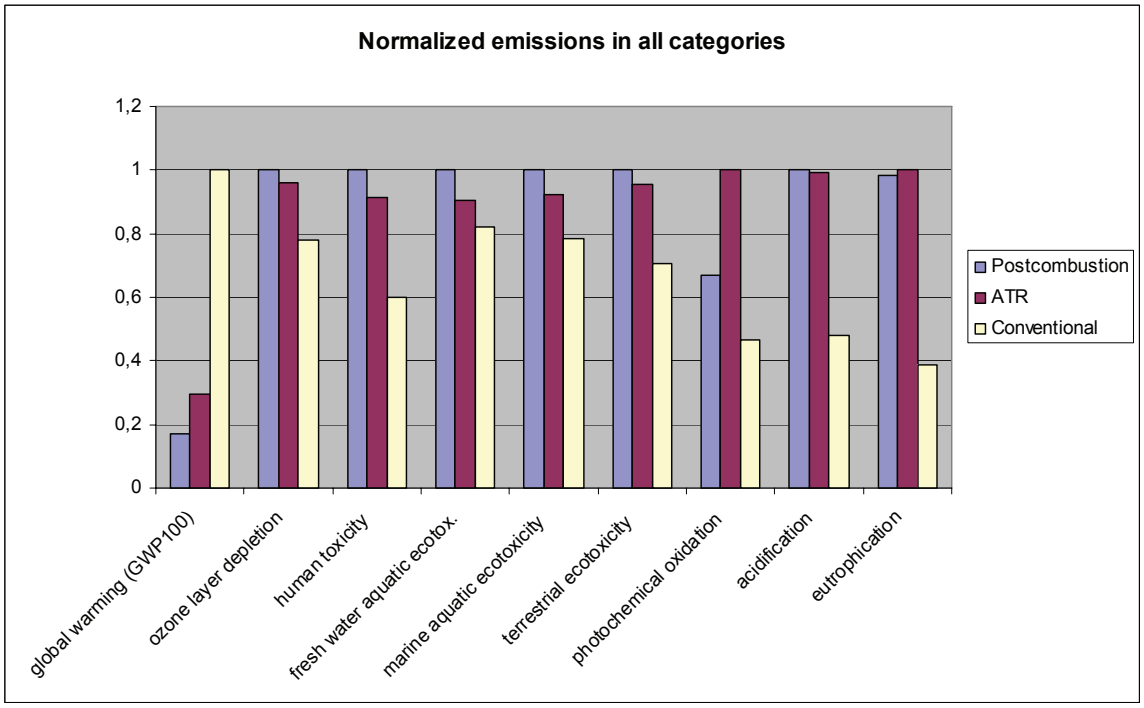

Figure 6-2 System performance comparison within nine impact categories using monetary allocation

In Figure 6-3 four impact categories are selected, and normalization similar to Figure 6-2 is compared for all three allocation procedures. It can be seen that the GWP emissions are more robust with regard to choice of allocation procedure than the other selected impact categories. It is because the GWP emissions differ so much between the alternatives, the allocation procedure here become of less importance when assessing the relative emission difference. Furthermore, it can be noticed that it is the ATR that is most sensitive to allocation method. The ATR is more sensitive because it has the largest output of energy, and the smallest output of exergy per product value, due to a low electricity fraction.

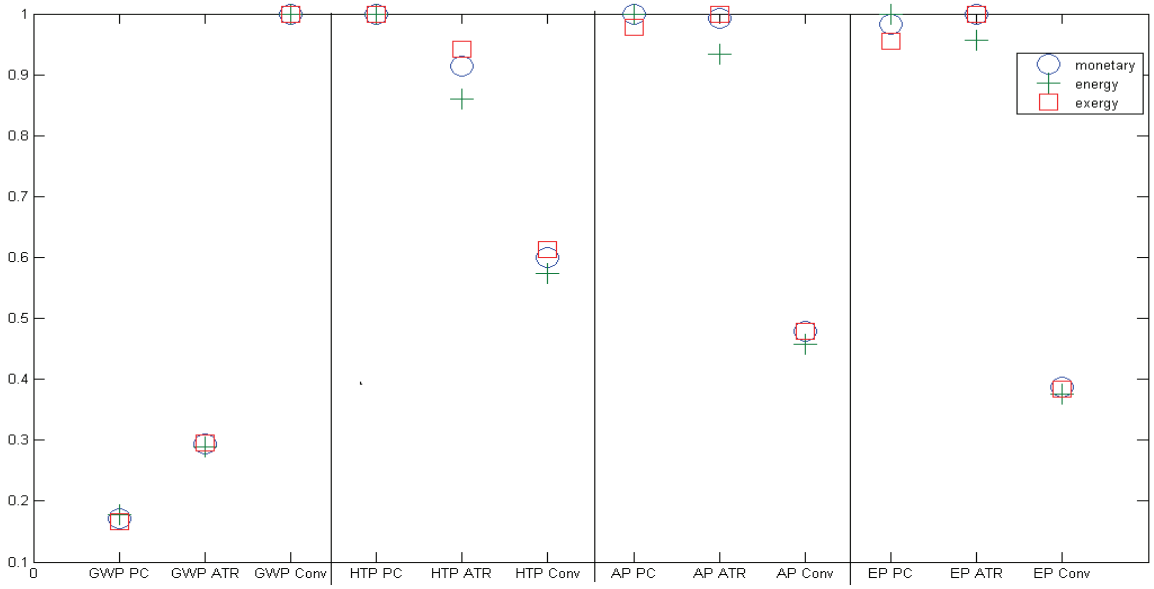

Figure 6-3 System performance comparison within four impact categories using three different allocations

It can be seen that when using an energy allocation, the PC has worst performance in all selected non-GWP impact categories, whereas the ATR has largest AP and EP impacts on an exergy basis. The monetary basis seems to represent a median value between the two extremities. The graph nevertheless indicates that in order to grasp the big picture of environmental performance of the different systems, allocation method does not have decisive impact on the conclusions. Hence, even if the allocation procedure affects how the different alternatives perform, it is seen most practical to operate mainly with one allocation method in the following impact assessment and contribution analysis. The monetary allocation will be preferred below.

6.2 Choice of impact categories

As already discussed, the conventional plant has GWP impacts almost six times as large as the PC and more than three times larger than the ATR, irrespective of allocation procedure. The GWP impacts are central in this report, and a contribution analysis of GWP impacts are provided in chapter 6.4 below.

Interestingly, the impacts in all other categories are lower for the conventional CHP, than the CCS cases. Figure 6-4 shows the relative impacts from the PC and ATR plants compared to the conventional plant in non-GWP impact categories on the monetary basis. As seen in the figure, the PC has the highest impacts in ozone layer depletion, toxicities, and eutrophication, while the ATR has larger impacts of photochemical oxidation. Acidification impacts are almost identical from the PC and ATR systems.

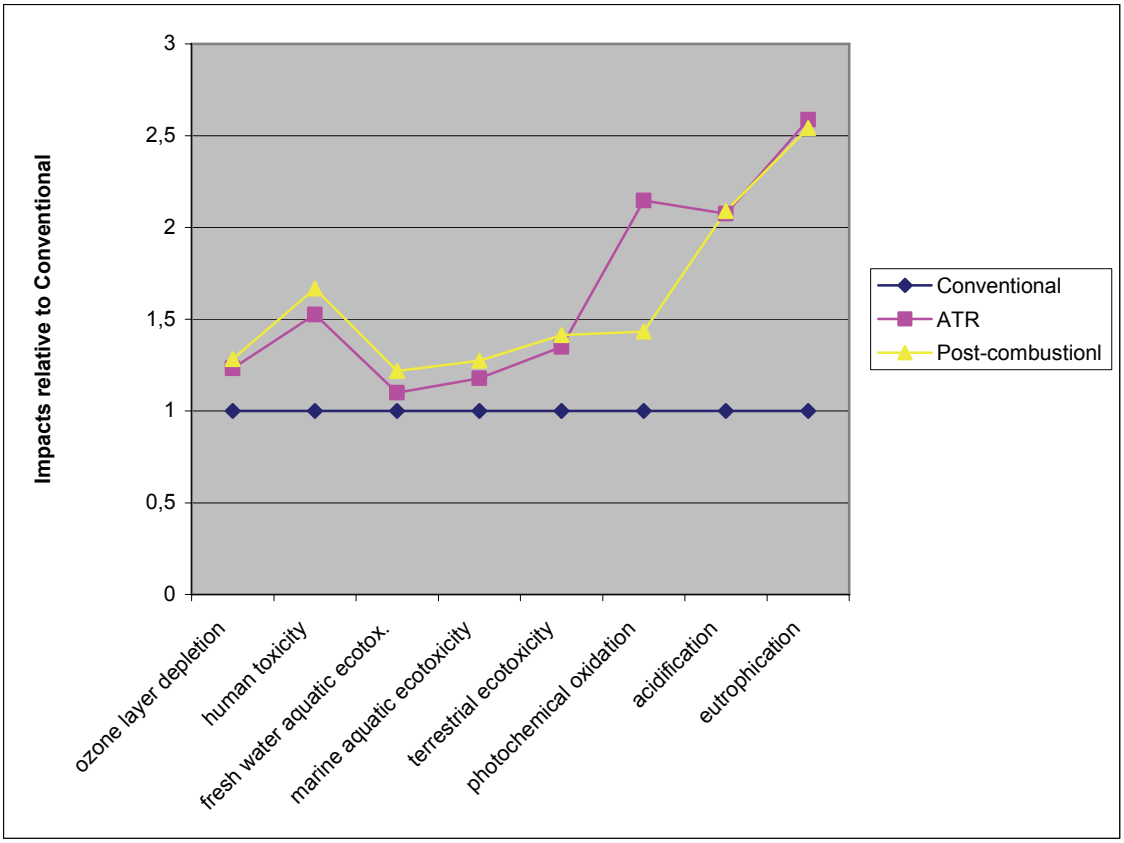

Figure 6-4 Impacts relative to conventional plant in non-GWP impact categories

It can be seen that emissions in categories Human Toxicity Potential (HTP), Acidification Potential (AP), and Eutrophication Potential (EP), stand out as being much higher for both CCS options than the conventional CHP. Also impacts of Photochemical Oxidation Potential (PCOP) are large for the ATR compared to the conventional. Table 6-4 shows how much larger impacts from the CCS plant are, compared to the conventional.

Impact category	PC / conventional	ATR / conventional
Ozone layer Depletion	28 %	23 %
Human Toxicity	**67 %**	**52 %**
Fresh water aquatic ecotox.	22 %	10 %
Marine aquatic ecotoxicity	27 %	18 %
Terrestrial ecotoxicity	41 %	35 %
Photochemical Oxidation	43 %	**115 %**
Acidification	**109 %**	**107 %**
Eutrophication	**154 %**	**159 %**

Table 6-4 Increase in impacts for CCS systems compared to conventional plant

Considering what impacts to inspect further, a normalization of impacts can be helpful. This is performed using CML baseline 2000 normalization factors for global 1995 emissions. This method relates the emissions to the global emissions of this year, in order to have an idea of the internal relevance of the different impacts in a global perspective.

The normalization is shown in Figure 6-5, and confirms that GWP is important. Further, the marine and fresh water ecotoxicities stand out as being of high relative importance. However, the ecotoxicity impact categories are excluded from further analysis, as the difference in impacts is small between the system alternatives (Figure 6-4), and that there are some problems with normalization factors for these impacts (Solli 2008a). It comes out clear that the ODP impacts are small in a normalized scale. The same can be said for the photochemical oxidation potential (PCOP), although emissions here are of some relevance.

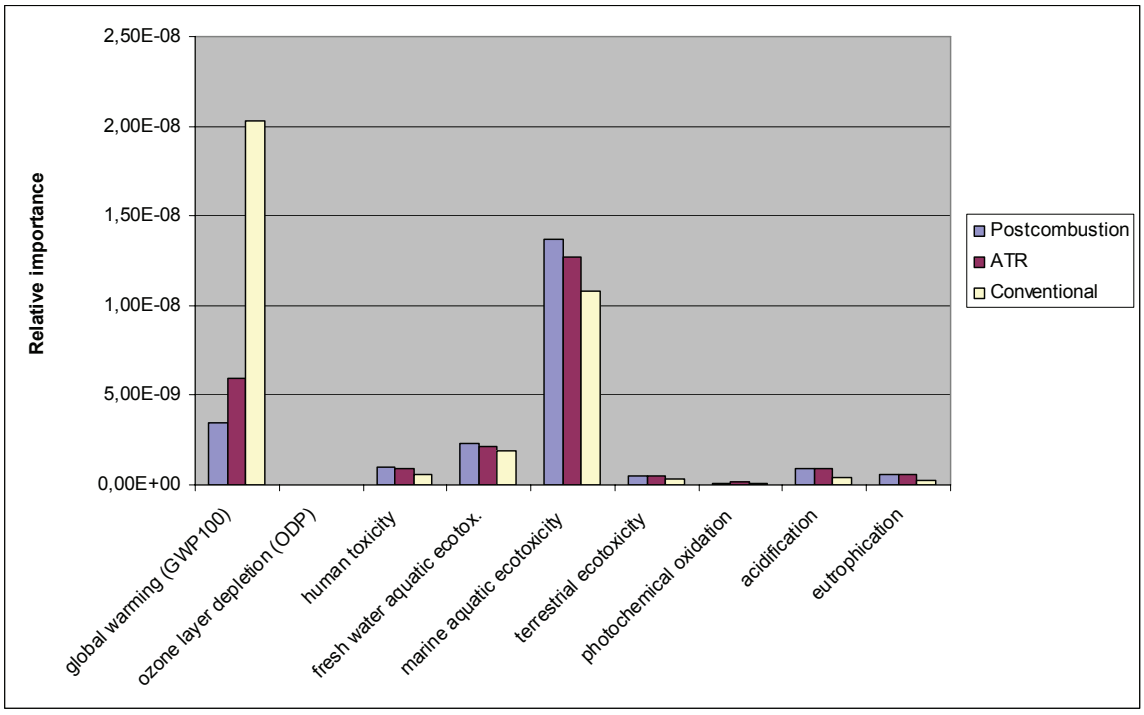

Figure 6-5 Normalized environmental impacts from different power plant configurations

The ratio between CCS and conventional plant impacts (Figure 6-4), together with normalization results and reliability in impact assessment, makes HTP, AP, and EP stand out as interesting impacts categories in addition to GWP. Leaving out GWP and ecotoxicities from the figure above gives Figure 6-6 which defends the choice of excluding ODP and PCOP in further analysis.

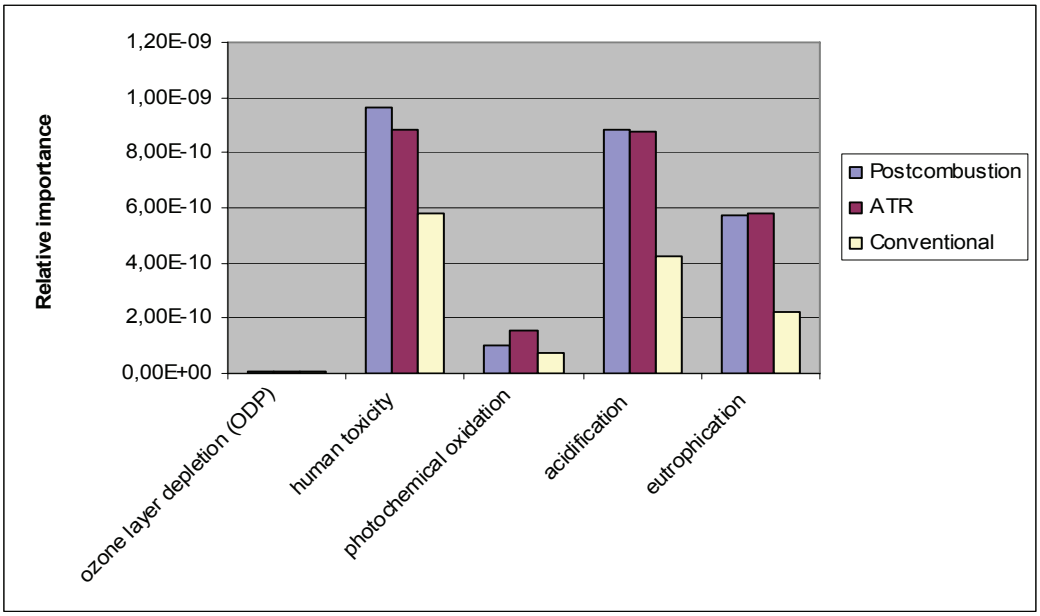

Figure 6-6 Normalized impacts in selected impact categories

The methods for contribution analysis described in chapter 4.2.3 have been applied to inspect the four selected impact categories further. The Foreground Contribution Analysis (FCA) provides important insight on the emission distribution in the value chain. However, an issue that does not come out very clear from this analysis is emissions related to energy consumption in different parts of the system. The energy required both for pumping natural gas to Mongstad from the refinery, and CO_2 into the reservoir is modeled to stem from Mongstad CHP itself. The same is done with energy consumption for carbon capture, in the process simulation work of Solli (2008b). This modeling choice makes environmental effects from all the mentioned energy consumption attributed to the operation of the CHP in the FCA. However, the data show that the pump work generates only 0.06% additional activity in the CHP operation, serving required energy for pumping CO_2 and natural gas. Energy consumption in carbon capture and CO_2 compression, however, is not transparent, as this is integrated in the process simulations described in chapter 5.2. The foreground processes comprised by the FCA are shown in Table 6-5.

Construction:
-Natural gas infrastructure (from refinery to CHP)
-CHP plant
-Carbon Capture (CC) plant
-CO_2 infrastructure
Operation:
-Natural gas (offshore infrastructure, extraction, processing)
-CHP plant (including emissions related to the described foreground energy demands)
-Operation CC plant (excluding energy use)

Table 6-5 Foreground processes used in contribution analysis

6.3 Non-GWP impact categories

6.3.1 Human toxicity potential

The FCA results for HTP impacts are visualized in Figure 6-7. It can be seen that impacts in constructing the CHP plant, have the largest contribution in all system setups. For the post-combustion case, these construction related impacts count 39% of total HTP impacts. The Structural Path Analysis (SPA) reveals that it is production of steel that mainly give rise to the HTP impacts occurring in the CHP construction phase. Steel used in pipes for NG and CO_2 also is the main cause of impacts in the foreground processes for construction of NG- and CO_2 infrastructure, respectively. The large difference in impacts from construction of CHP plant compared to construction of the CC plant (process number two and three from the right) is partly related to modeling inconsistencies, and will be discussed in chapter 6.5, Uncertainties.

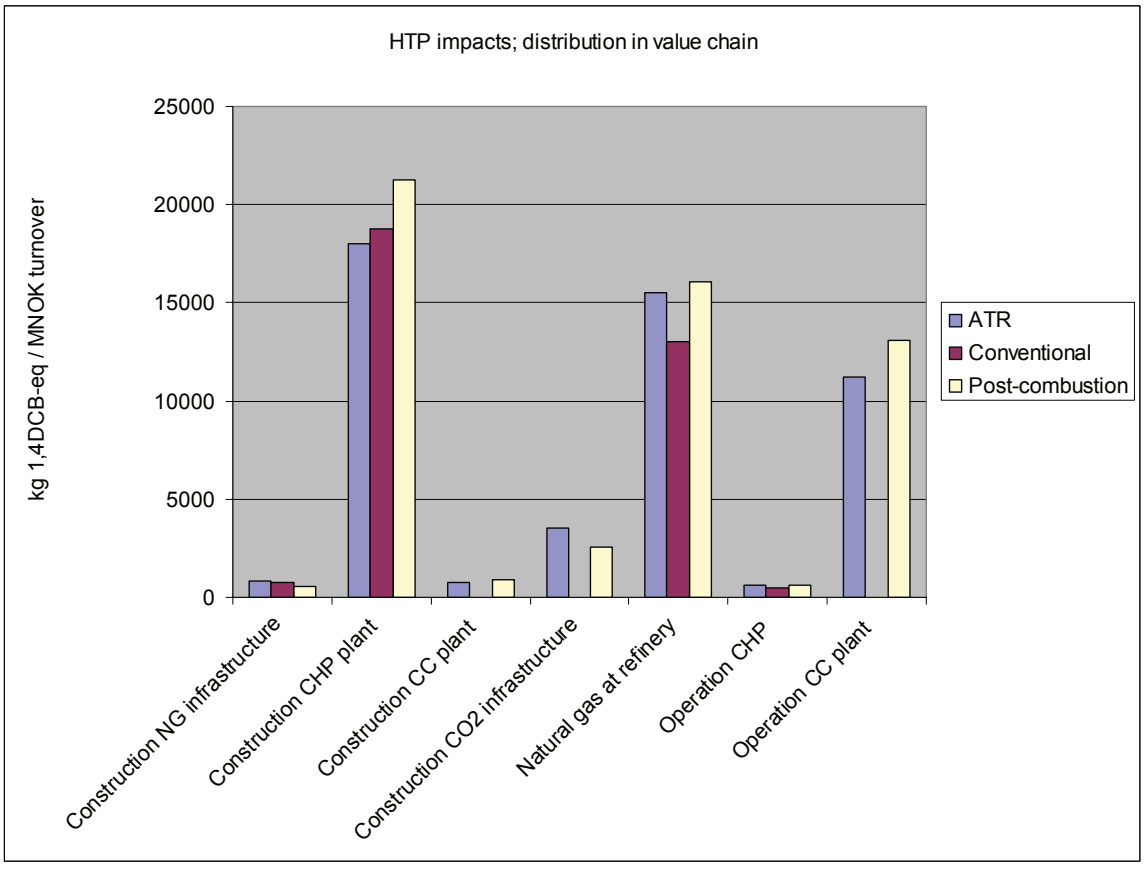

Figure 6-7 Foreground Contribution Analysis for HTP impacts; comparison of system alternatives

Operation of the CC plant (leftmost in the figure) represents a significant HTP impact in the two CCS system; 24% of total HTP impact from the PC system. These impacts are almost exclusively related to the production process of MEA; production of MEA makes up 22% of total system HTP impacts. Impacts from MEA released in CC operation at

Mongstad are not at all significant, using the given characterization factor for these emissions. Emissions in operation of the CHP itself are also of minor importance to HTP; impacts count only 1% of total and are constituted by NO_x emissions as well as indirect emissions related to operation and maintenance activity.

The natural gas value chain counts for 29% of HTP emissions in the PC case, but here no single process stands out as having especially high impacts. A significant fraction of these impacts are also related to production of steel used in the production processes. The upstream value chain for NG production is modeled equally for all system alternatives, and differences in emission intensities are only caused by differences in efficiencies. This is further discussed below in chapter 6.3.4.

A look at the process and stressor contribution reveal that the five of the six most polluting processes all are related to steel production, counting 70% of the HTP impacts. The main stressors emitted in steel production are Dioxins and Chromium VI (hexavalent chromium), each causing over 30% of the total HTP impacts from the PC system. The direct emissions of Ethylene Oxide in Monoethanolamine production contribute to 22% of the total HTP impacts. Polycyclic Aromatic Hydrocarbons and Arsenic respectively cause 8% and 2% of the impacts, some of it also emitted in steel production.

6.3.2 Acidification Potential

Total AP impacts per monetary unit are 109% larger for the PC system, and 107% larger for the ATR system, than impacts from the conventional system. Figure 6-8 show the FCA for AP impacts. It can be seen that the CC plant contributes significantly to the increased emissions from the CCS systems, with direct emissions of NH_3 counting 90 kg SO_2-eq from the PC system. Emissions related to MEA production account for 5 kg SO_2-eq, while other indirect emissions from operation and maintenance add 5 additional kg SO_2-eq. This makes impacts related to operating CC plant 100 kg SO_2-eq; 35% of the total as shown in Figure 6-8. For the ATR system, it is interesting to note that elimination of NH_3 emissions to air, do not eliminate AP impacts from operation of the CC plant. To the contrary, conversion of MEA and NH_3 to NO_2, actually make the ATR a larger polluter of acidificating substances than the PC. The second largest *direct* emission source is NO_x-emissions from the CHP plant, counting 44 kg SO_2-eq in the PC plant, and 42 kg SO_2-eq from the ATR.

It can be seen that impacts from operating the conventional CHP are slightly lower than from the CHPs applying CCS. This is in spite of the fact that CCS application will result in slightly lower NO_x concentration in the flue gas, according to the IECM process software used (Rubin et al. 2007). The superior energy efficiency of the Conventional plant outweighs this effect, and makes operation of the conventional plant less polluting.

Indirect emissions from operating the CHP are 6 kg SO_2-eq for the PC plant, almost the same value as for operating the CC plant.

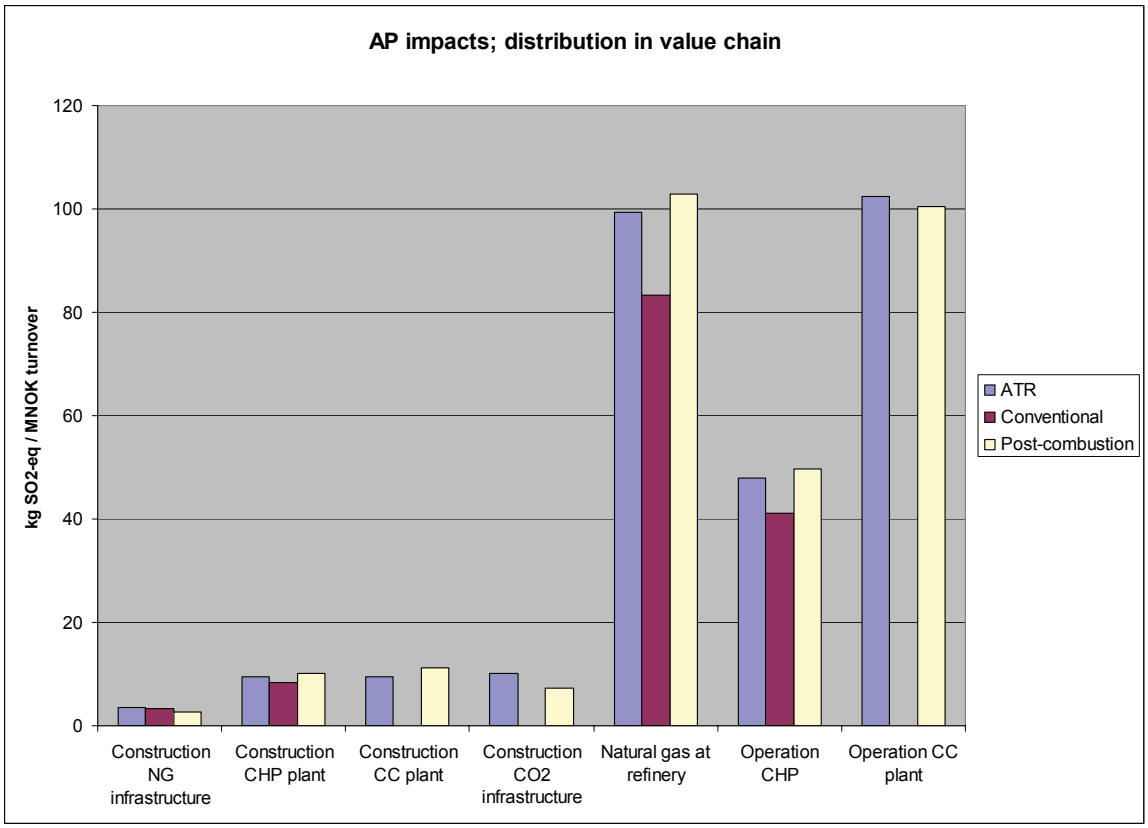

Figure 6-8 Foreground contribution analysis for AP impacts; comparison of system alternatives

The foreground process that generates largest AP impacts is the natural gas value chain. One third of impacts from the PC system, and more than half of impacts from the conventional system are related to this activity. It is emissions of nitrogen- and sulfur oxides in combustion of fossil fuels through the value chain that mainly causes these impacts. Total impacts related to construction of infrastructure and plant equipment count for 11% of system emissions from the PC and 9% of impacts from the conventional system.

6.3.3 Eutrophication Potential

Qualitatively, the FCA for EP impacts (Figure 6-9) is very similar to the one for AP. As seen in Figure 6-4, the relative increase in impacts from the CCS systems is, however, even bigger than for AP compared to the conventional system. The PC and ATR systems generate respectively 154% and 159% more eutrophication impacts per monetary unit than the conventional system. The main driver for these increased impacts is ammonia emissions from the capture plant for the PC case, and NO_2 emissions from the ATR. Operation of this plant is causing 48% of EP impacts from the PC system, out of which 45 percentage points are direct NH_3 emissions. For the ATR, CC operation generates exactly half of system EP impacts. The same effect as for AP is seen also here; conversion of MEA and NH_3 to NO_2 has a slight negative environmental effect.

Energy efficiency considerations do also in this impact category make CCS options more polluting in CHP operation than a conventional plant. The Stressor Contribution analysis shows that 49% of impacts are caused by nitrogen oxides and 46% by NH_3 to air and water for the PC. The emissions from the natural gas chain are mostly related to NO_x from combustion.

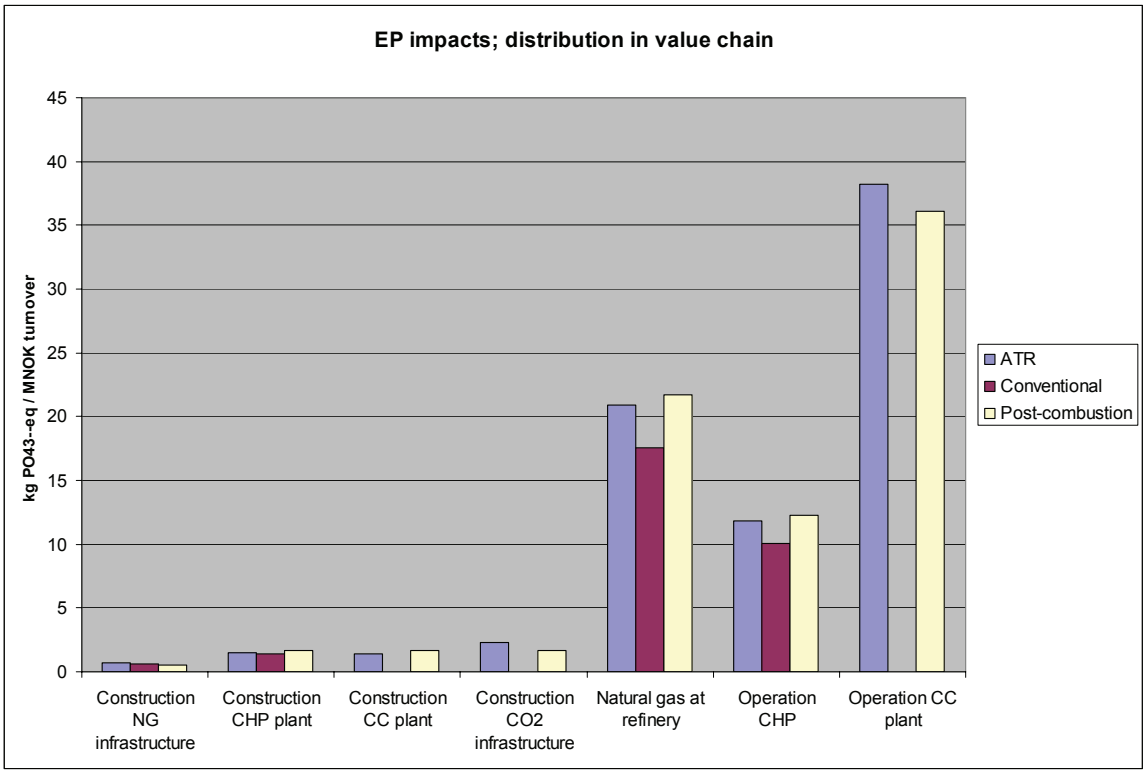

Figure 6-9 Foreground contribution analysis for EP impacts; comparison of system alternatives

6.3.4 General remarks

The analyses of the three selected non-GWP impacts show that the two CCS systems, Post-Combustion (PC) and Autothermal Reforming (ATR) have higher environmental impacts per monetary unit. One reason is the need for increased energy flows through the system to generate the same amount of energy. This makes emissions in the NG value chain higher for CCS systems in all categories when analyzed per monetary unit as above. More important to increased emissions from the CCS system options is the introduction of a new process unit; the Carbon Capture (CC) unit. Both construction of this, with associated CO_2 infrastructure, and operation of it generate extra impacts compared to a conventional plant. Regarding the difference in environmental performance between the ATR and the PC options, the FCA show that for most of the processes in the foreground system, the ATR performs slightly better than the PC. This is also related to better energy efficiency, in addition to the fact that the carbon capture plant is smaller and has a lower capture rate. This leads to lower emissions in construction of the plant. Operation of the CC plant is however more polluting in

categories AP and EP due to the assumption of high NO_2 emissions. Emissions related to construction of CO_2 and NG infrastructure are also higher for ATR than PC. The reason for this difference is that a fixed size of the infrastructure is assumed, independent of the product flows. This assumption makes the emissions intensity from constructing the infrastructure higher for the ATR than the PC due to smaller product flows to which infrastructure emissions can be allocated. However, the conventional plant actually has lower NG infrastructure emissions per monetary unit than the ATR (7% lower for all impact categories), even with a lower NG consumption per hour (9% lower than ATR). This is because superior energy efficiency for the conventional plant makes the turnover larger, neutralizing the allocation issue occurring due to smaller product flow of natural gas in the infrastructure.

6.4 Global Warming Potential

Total GWP of the three systems is presented in Figure 6-10, together with direct CO_2 emissions from the respective CHP's. The total reduction in system GWP per monetary unit for the PC system compared to the conventional is 83%. The same figure for the ATR is 71%. Considering only direct CO_2 emissions in combustion the corresponding figures is 88% reduction for PC and ATR 75%. It can be seen that emission reduction in the whole system is not as big as emissions reduction from the flue gas. This is due both to increased energy flows through the system per monetary unit and to the need for investment in more equipment to handle the CO_2, both factors leading to upstream emissions.

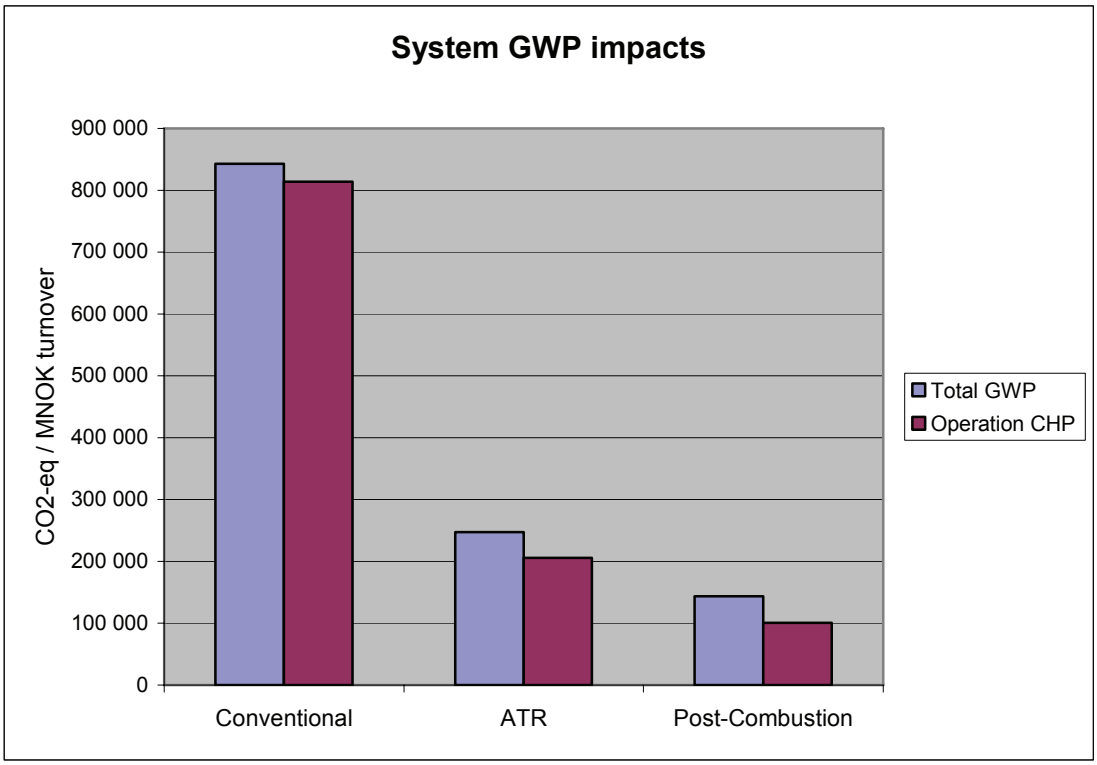

Figure 6-10 Total system GWP impacts per MNOK turnover from different plant configurations

Regarding the value chain distribution of GWP impacts, the figure above, as well as the FCA, show that emissions from operation of the CHP plant is by far the most significant. In the conventional system, 97% of impacts are related to operation of CHP. For ATR and PC, the corresponding fractions are 83% and 70%. Figure 6-11 shows the contribution analysis in the same outline as the chapters above. It can be seen that emissions from operating the CHP, especially the conventional, bring the other emissions of scale.

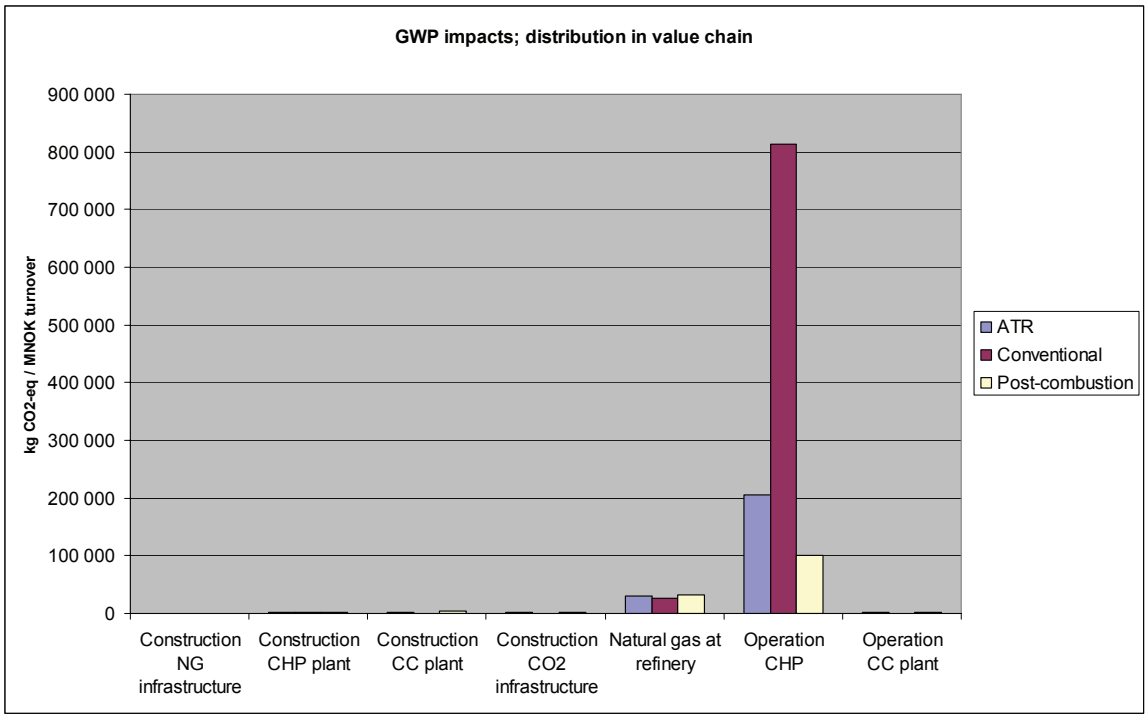

Figure 6-11 FCA of GWP emissions

The foreground process "operation CHP" is dominated by direct CO_2 emissions in combustion. For the PC system, 69 percentage points of these impacts are caused by direct emissions. The one remaining percentage point is related to other operation and maintenance inputs to the power plant. For the other two systems (ATR and conventional), the fraction of direct emissions are even higher due to higher operation emissions and approximately equal operation and maintenance requirement.

The natural gas value chain is the second largest process causing GWP impacts. The fraction of these impacts to the total system impacts vary greatly between the systems, as shown in Figure 6-13. For the PC system, these emissions account for 22% of GWP, ATR 12% and for the conventional, only 3%. The absolute figures of emissions in NG value chain per monetary unit (as seen in the small bars in Figure 6-11) are on the other side quite comparable, with the conventional having the lowest score, followed by ATR and PC highest. This quantity of specific emission from the respective NG value chains are a direct implication of the different energy efficiencies, making the fuel input per monetary unit larger for the CCS systems with lower efficiencies. Obviously, the reason

why the NG value chain contributes so differently in terms of fraction of total impacts is the large differences in total impacts between the three systems.

In order to inspect further the parts of the system that contributes relatively less, emissions from natural gas value chain and CHP operation are removed in Figure 6-12, providing information of all construction impacts plus impacts from operation and maintenance of the CC plant. Notice that the scale of Figure 6-11 is more than two orders of magnitude larger than Figure 6-12.

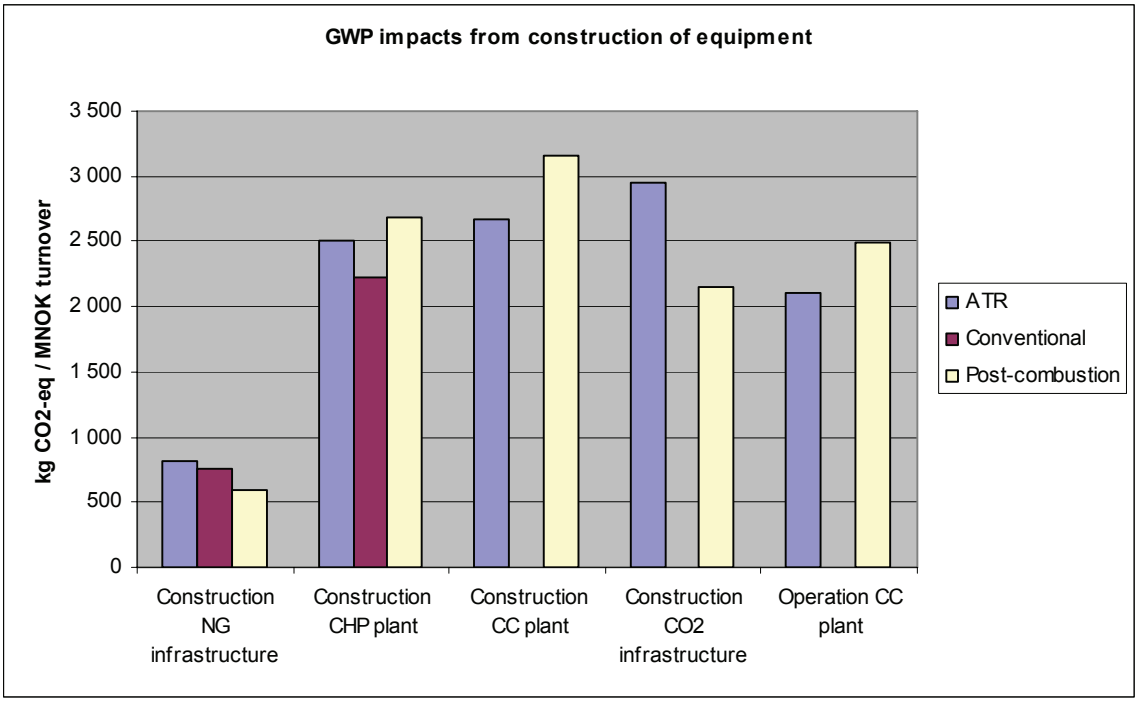

Figure 6-12 FCA of GWP from selected foreground processes

Impacts caused by constructing NG and CO_2 infrastructure are discussed above for other impact categories, and are subject to the same considerations for GWP emissions. Further, it can be seen that impacts from constructing the CHP plant and the CC plant are of similar magnitudes, with the CC plant having slightly larger emission intensity. A discussion on the differences in modeling methodology related to impact from construction of these two plants is provided in chapter 6.5 below.

Operating the CC plant causes lower emissions per monetary unit in the ATR case, due to the lower capture rate of ATR than PC, generating lower activity in this process.

Figure 6-13 provides a detailed picture of the fraction of different emissions in the value chain to the total emissions for the three different CHP systems. For the PC system, all activity related to constructing system infrastructure and components cause 6% of the total GWP impacts generated per monetary unit turnover in the power plant. The corresponding number for the conventional plant is 0.3%, and for the ATR, 4%.

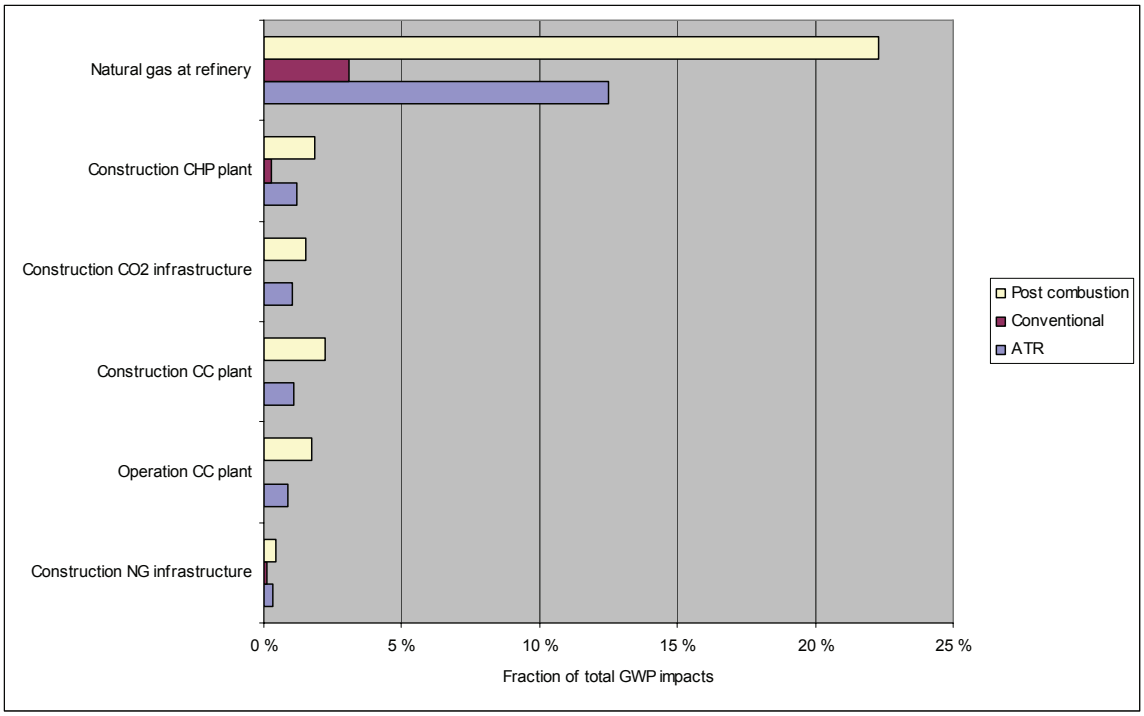

Figure 6-13 Fraction of total GWP impacts caused by different foreground processes in the three systems

6.5 Uncertainties

Some issues related to the system boundaries and weaknesses in the hybrid inventory model that has been made should be discussed. The HTP impacts in construction of the CC plant show weaknesses in the I/O model that has been used. As described in chapter 5.2, detailed data on construction of power plant and capture plant has not been available for this LCA. The construction of the CHPs has been modeled by using average numbers for material consumption, combined with I/O data. The I/O data are assumed to provide supplemental data on emissions that due to lack of detail level has not been as by physical flows. When the CHP construction was modeled, the values of materials consumed were subtracted from the I/O purchases. For the CC plant, no data on material consumption was assumed, as the technology is not so widely used, and data are more uncertain. However, the costs for constructing the carbon capture plant were quite similar to the costs of the CHP, and it would hence be reasonable to assume a similar material consumption, with accordingly similar environmental impacts. When results indicate emissions rising from CC plant construction to be 92% less than CHP construction, the emission data achieved from using the I/O database does not seem to cover HTP related emissions satisfactorily. A reason for this can be found when looking at the stressor contribution to HTP impacts, where Chromium VI and Dioxins account for more than 80% of the impacts related to CHP construction. The stressors that are covered by the Norwegian I/O table include Chromium, but not Chromium VI. In the characterization matrix, *C*, Chromium is not assigned with any environmental impacts. Chromium VI, however, has a characterization factor of 3.4E+6 kg 1,4DCB-eq/kg Chromium VI. Using the Norwegian I/O table will hence not provide information of impacts related to

Chromium IV emissions. Concerning the second important stressor causing HTP impacts, Dioxines, these emissions are traced to mainly stem from Sinter plants in the iron industry. According to the European Commission's *European Dioxine Inventory* (Quass 1997), Norway is one out of five European countries not having any sinter plants. As the analysis show that this process is the main emitter of Dioxins in the CHP systems, it seems reasonable that Dioxin emissions neither will be quantified correctly from the Norwegian I/O based environmental assessment. Excluding these two stressors will bring HTP impacts from CHP construction down by 83%, and to a level comparable to the I/O calculated impacts from constructing the CC plant.

Also for describing other impacts there seem to be some system boundary weaknesses in the hybrid assessment. GWP impacts from constructing the CC plant are assed to be 18% larger than constructing the CHP plant in the PC system. When inspecting the inventory for the PC system, construction costs for the CC plant, scaled after CO_2 removal duty are approximately 213 MNOK annualized. The construction of the CHP is modeled to need 117 MNOK of annualized purchases. The CC plant is hence 82% more costly, but gives rise to only 18% larger impacts. There is no reason why the CC plant should have less emission intensity in construction; hence the difference in this intensity seems to be due to the fact that material usage is modeled explicitly for the CHP, but not for the CC. Based on this, it seems that impacts from material consumption modeled through Simapro are assigned with disproportionately large impacts compared with the impacts from I/O purchases. A reason for this might be that the Simapro processes used are based on European averages, meaning that inputs of electricity are much more carbon intensive that the Norwegian domestic electricity mix. This is an example of system boundary and consistency challenges that arise in the hybrid methodology applied here.

Chapter 7

Contextualizing the results

Here, the CHP emissions are seen in relation to the surrounding energy system, as well as the rest of the refinery. A system expansion is performed to inspect what emission reductions or –increases that can be expected as a consequence of the CHP investment. Furthermore, changes in refinery emissions due to introduction of a CHP are discussed, and calculation of the eco-efficiency of the refinery is performed. To conduct this, a base case refinery is compared with a CHP integrated refinery. Regarding the three CHP configurations, this makes four different eco-efficiency scenarios. Eco-efficiencies of four different impact categories are performed, but emphasis is put on describing GWP eco-efficiency.

7.1 System expansion

Being a prospective LCA study, seeking to investigate the environmental effects of the suggested changes at Mongstad refinery, the allocation methods applied in Chapter 6 are not sufficient to conclude on environmental performance, following the logics of Weidema (2001), presented in chapter 4.3.3. Most of the arguments for constructing the CHP at Mongstad relates to wanting to improve energy efficiency at the refinery, with an underlying assumption that this will imply positive change in environmental impacts for the society as a whole. Hence the study is prospective, and system expansions should be performed to inspect the effects of the suggested changes at Mongstad.

System expansion enables a more holistic assessment of the consequences of change, and is done by including alternative production systems for co-products, as outlined in chapter 4.3 on allocation. Modeling alternative production systems for energy necessitate some assumptions. For heat and steam production, the alternative to the heat production in the CHP is clearly refinery boilers and furnaces. A process for this is modeled in Simapro, using average Norwegian natural gas input. More on the refinery and substitution processes is discussed below in relation to eco-efficiency at the refinery. For electricity production, two alternative production systems scenarios are chosen; 1) a Natural Gas Combined Cycle without CCS, but using best available technology, and 2) wind energy from a Danish offshore installation. These two energy production technologies both represent probable long-term marginals for Norwegian electricity production. The assumed GWP emission intensities of the NGCC and the wind power are 361 and 14.7 kg CO_2/MWh electricity, respectively. GWP emission intensity for heat production at the refinery boilers is assumed 240 kg/MWh heat.

Calculation of emissions in the expanded system is merely done by subtracting emissions from the production systems which are substituted from the actual emissions of the CHPs. In that sense, zero emissions represent no change in environmental performance of the system. Since the EVM is a hot topic in the political debate around Norwegian electricity supply, it is chosen to look at the emissions from the expanded system on an exergy basis. This perspective makes the heat production in the CHP's become comparable to electricity production. Results for GWP impacts are shown in Figure 7-1.

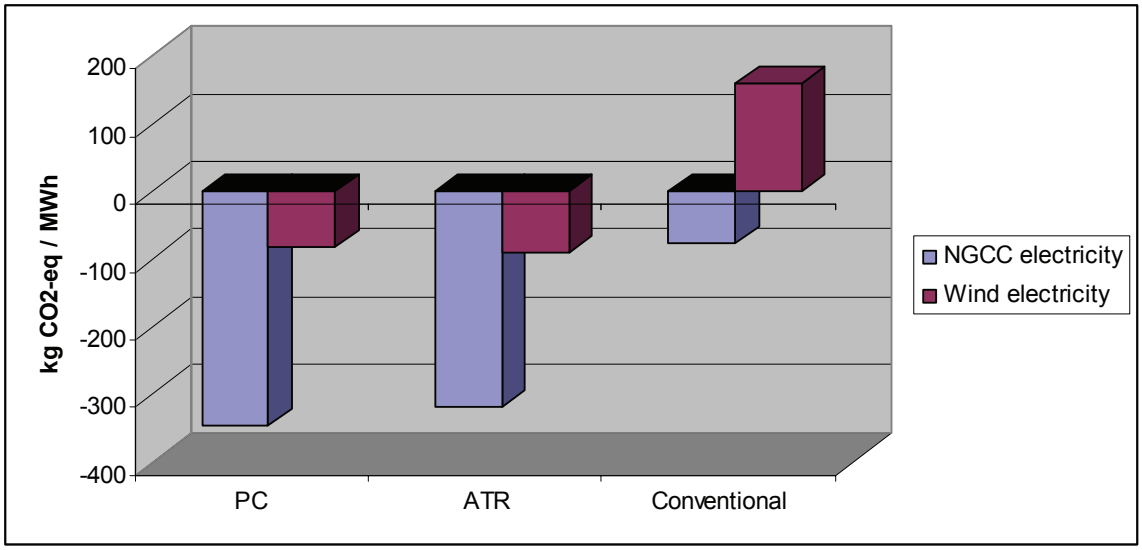

Figure 7-1 GWP emissions per MWh exergy from two system expansion alternatives

The figure shows that for both the CCS options, the energy production at EVM will have positive environmental effects (negative emissions) when assessed in an expanded system. When substituting NGCC the emissions are -345 kg CO_2/MWh for PC and -319 kg CO_2-eq/MWh for ATR. It is interesting to note that also when assumed that the electricity production at EVM will substitute wind energy, emissions still are negative; -83 kg CO_2/MWh for PC and -91 kg CO_2-eq/MWh for ATR. This is due to the fact that heat production from the CHPs will substitute refinery boilers with high CO_2 emissions.

The conventional plant has a positive environmental effect if alternative electricity supply is assumed to be NGCC (-78 kg CO_2-eq / MWh). If the alternative electricity production is assumed to be wind power, the environmental consequence of building the CHP is negative; the CHP will emit 160 kg extra CO_2 per MWh of exergy produced, than would be the case using the alternative energy production system (refinery boilers plus wind power).

For other impact categories, the system expansion reveals that all three CHP implementations will lead to reduction in HTP impacts, irrespective of choice of alternative electricity production. The avoided impacts range from 42 to 56 kg 1,4 DCB-eq/MWh exergy produced.

For AP impacts, the calculations show larger impacts from wind electricity than the NGCC, leading to larger impact reductions when wind is chosen as alternative electricity source. The CCS options are here having negative environmental effect, while the Conventional leads to reductions in total emissions (Figure 7-2).

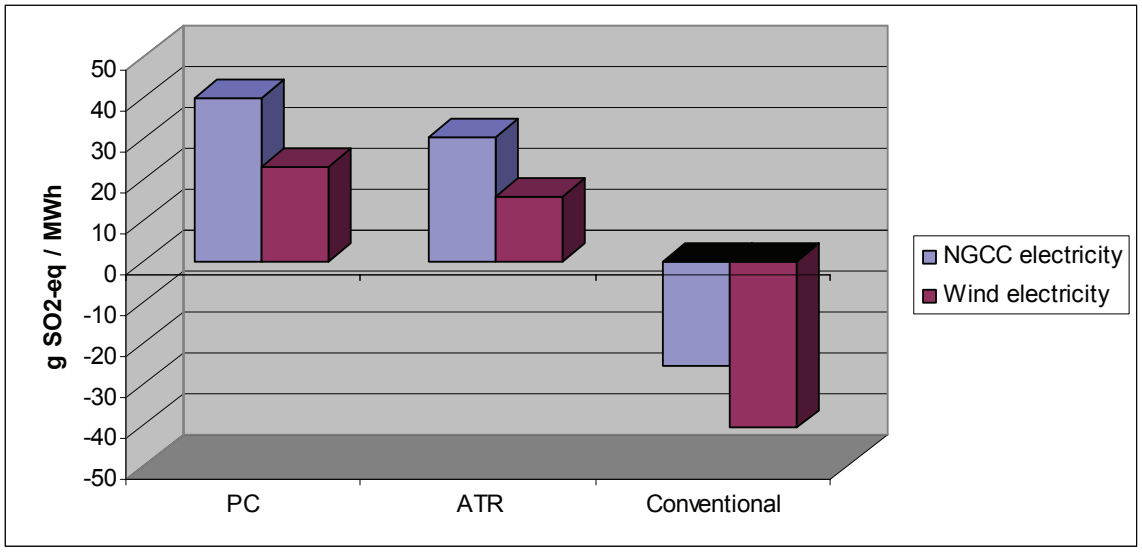

Figure 7-2 AP impacts per MWh exergy produced in expanded system

EP impacts are practically identical for the two alternative power production technologies, and also here the CCS options show negative environmental performance, while the Conventional plant induces emission reductions. This is shown in Figure 7-3, where only results for wind energy are provided, due to almost identical data for the two sources.

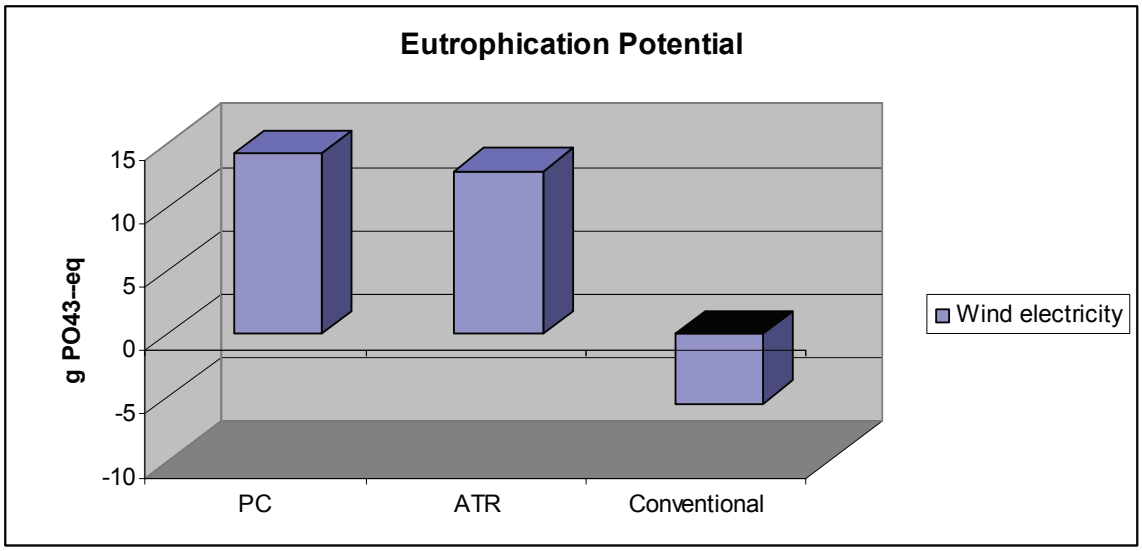

Figure 7-3 EP impacts per MWh exergy produced in expanded system

7.2 Eco-efficiency

Because the CHP at Mongstad will be an integrated part of the StatoilHydro refinery facility, it is useful to contextualize environmental performance of the different CHP options into the framework at Mongstad refinery. Evaluating eco-efficiency of the output products from a system including both the refinery and the CHP is considered a meaningful basis for comparison of different system alternatives. Four system alternatives will be compared; one base case which represent the current refinery with heat production from boilers and furnaces, and three versions of a modified refinery taking heat and electricity input from the respective three CHP options assessed earlier in the thesis, and exporting additional electricity from the system border. The four cases will be referred to as; *Base Case (BC)*, *Conventional*, *PC* and *ATR*, following the terminology from chapter 5.2.

Basically, there are only two qualitatively different refinery system alternatives compared here; the base case and the CHP cases. A simple flowchart of the two alternatives is provided in Figure 7-4. There are three different alternatives for CHP integrated refineries (right side of the figure), but the only variable on a gross energy basis is, however, the input of natural gas and the output of electricity (stippled).

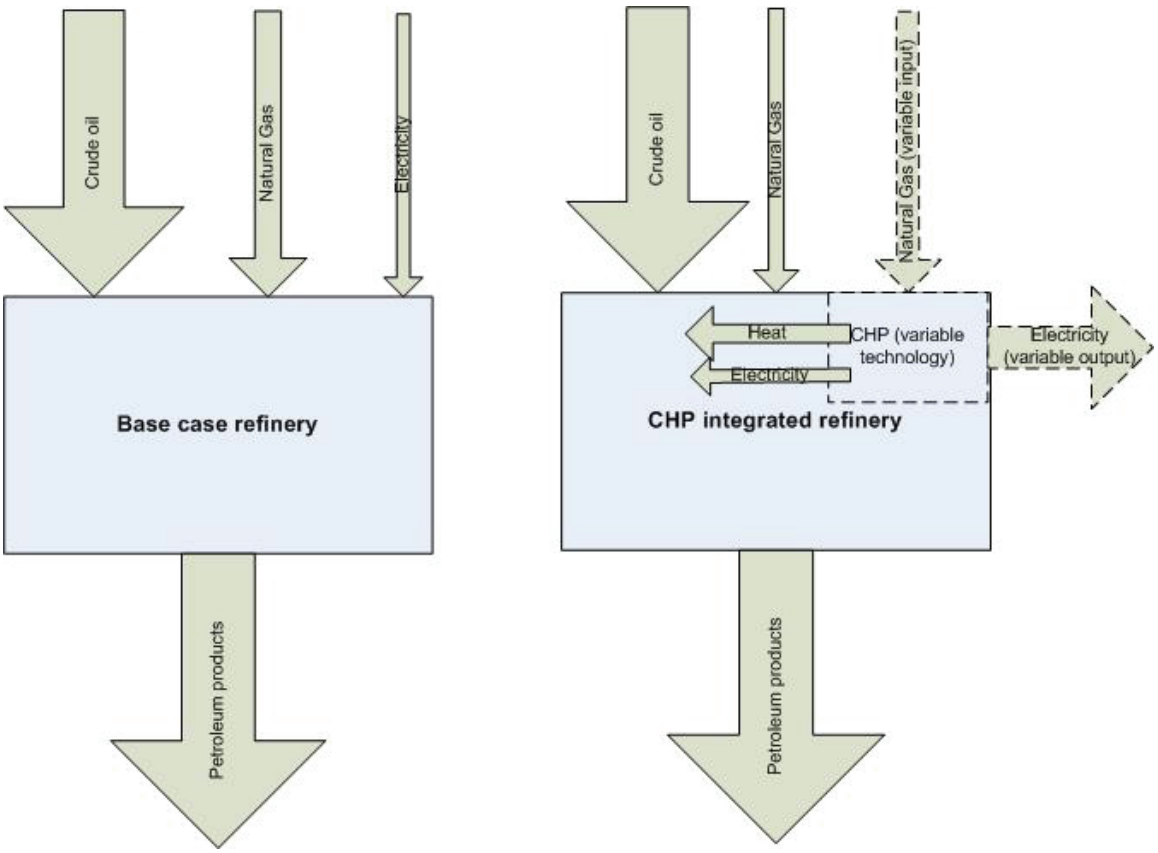

Figure 7-4 Main energy flows in two refinery configurations

When eco-efficiency is calculated here, it is sought to be done on an LCA basis. An environmental assessment of the refinery is performed, primarily based on figures from StatoilHydro's annual report (StatoilHydro 2008). A coarse LCA is set up in Simapro, calculating impacts from the refinery, as well as its upstream processes.

Following the theory of eco-efficiency given in chapter 4.4, four parameters are important to get a picture of the refinery eco-efficiency. These are shown in a matrix in Table 7-1.

	Upstream	Refinery
Economic	Cost of inputs	Value creation
Environmental	LCA impacts of inputs	Direct emissions

Table 7-1 Important data for assessing eco-efficiency at the refinery

Below, data used to describe the two different refinery configurations are described.

7.3 The Base Case alternative

The refinery models in the thesis are, as indicated in Figure 7-4 strongly simplified representations of an oil refinery. Retrieving complete data of all four parameters in Table 7-1 is not possible, due both to confidentiality and lack of data at StatoilHydro, and hence simplifications are necessary. One simplification is that only energy input is taken into account in the economic analysis. Capital expenses and inputs of services and non-energy flows are not accounted for when calculating value added at the refinery. Secondly, simplifications with regard to input products have been made. In 2007, the refinery processed 8.53 Gtons of crude oil and 2.92 Gtons of "other process inputs" (StatoilHydro 2008). It has not been successful to bring to light what the last category represents, and hence it is also modeled as crude oil in the LCA analysis. Economically, the cost of "other" products is assumed to be half the cost of crude oil, due to assumed lower quality. The internal heat requirement at the refinery is also subject to a simplified modeling approach. In practice, refinery gas is used for this purpose. Refinery gas is a by-product from the refinery processes, and the energy content is hence originating from the crude oil. In calculations here, it is chosen to disregard this fact, and model the heat input as input of natural gas. The corresponding NG energy content is further subtracted from the crude oil input, in order to obtain the right energy balance. Total annual inputs to the refinery of crude oil and natural gas, as modeled in Simapro are respectively 128.9 TWh (10.9 Gtons) and 6.9 TWh. Impacts related to both these inputs are modeled by standard Norwegian continental shelf processes in Simapro.

A range of different petroleum products, counting 10.86 Gtons, were produced at Mongstad in 2007. The composition of refinery products is taken from 2003 data, since 2007 data were not available. Both costs of energy inputs and prices of output products are taken from EIA, the official energy statistics from the US government. The prices are all average January 2008 prices. For crude oil, the "Refiner Acquisition Cost" is used, counting 88.6 USD/barrel (EIA 2008). A weighted average of the refinery output product

prices, using data from the same source is 3880 NOK/ton. The price of Natural Gas is estimated using average relation between crude oil and gas prices, taken from StatoilHydro (0.193 NOK/kWh).

Electricity input amounts to 0.49 TWh per year for the refinery. Price of electricity is the Nord Pool monthly average system price for January 2008 (0.46 NOK/kWh). For the base case this is assumed to be produces from a Nordic power mix (NORDEL). A sensitivity analysis on the origin of the electric input is also performed, using both Norwegian power mix and electricity from a non-CCS gas fired power plant.

In the refinery LCA, input of various chemicals and disposal of wastes is also included using numbers from the annual report (StatoilHydro 2008). Construction of the refinery is also accounted for by the use of a predefined Simapro process for this.

Direct emissions from the refinery are taken from (StatoilHydro 2008), and listed in Table 7-2 below.

Emissions to air [annual]	
CO2	1,64Mton
nmVOC	11,40kton
Metane	2,85kton
NOx	1,93kton
SO2	0,73kton
HC-gas	4,70ton
Emissions to water [annual]	
Oil	379,00ton
Phenol	1,20ton
Ammonium	37,60ton

Table 7-2 Direct emissions from Mongstad refinery 2007

7.4 CHP integrated refinery

When introducing one of the three CHP alternatives outlined earlier in this thesis, some changes will occur both in input and output structure of the refinery as well as the emission profile of the refinery installation. If the CHP is considered as an integral part of the refinery, a new product – electricity – is produced by the CHP integrated refinery, as shown in Figure 7-4. This also involves that the external electricity input is avoided. Apart from this, the petroleum output products will remain the same, as will also the crude oil input to the refinery. The heat production from the CHP is 346 MW. Assuming energy efficiency in the refinery boilers of 90%, this will replace 3.37 TWh of natural gas input to the refinery annually. Reduced CO_2 emissions related to this are found by stoichiometric considerations to be 0.69 Mton CO_2. NO_x emissions will also be reduced. A NG boiler process is set up in Simapro, indicating that NO_x emissions related to the

avoided heat production at the refinery would be 0.22 ktons. The NO_x emissions from the CHP integrated refinery is hence estimated to 1.71 kton.

Input of natural gas, as well as output of electricity varies between the three CHP configurations. This makes the total value creation different between all four refinery options. Direct and indirect emissions related to heat and power production are of course taken from the LCA calculations in Chapter 6 above. In order to apply similar approach to the eco-efficiency representation both for the refinery and the CHP, upstream emissions related to the energy fuel chain is separated from the total emissions from the CHP.

7.5 GWP eco-efficiency

Below, the eco-efficiencies of the four options are shown graphically with different level of detail. First, GWP is used as environmental indicator. Later eco-efficiencies using other environmental impact categories will also be discussed. Figure 7-5 separate only between inputs of energy products and production at the refinery. What is referred to as "refining and power production" represent value of products minus value of energy inputs. On the emission side, "refining and power production" are all LCA emissions not related to the upstream activity in the energy product value chain.

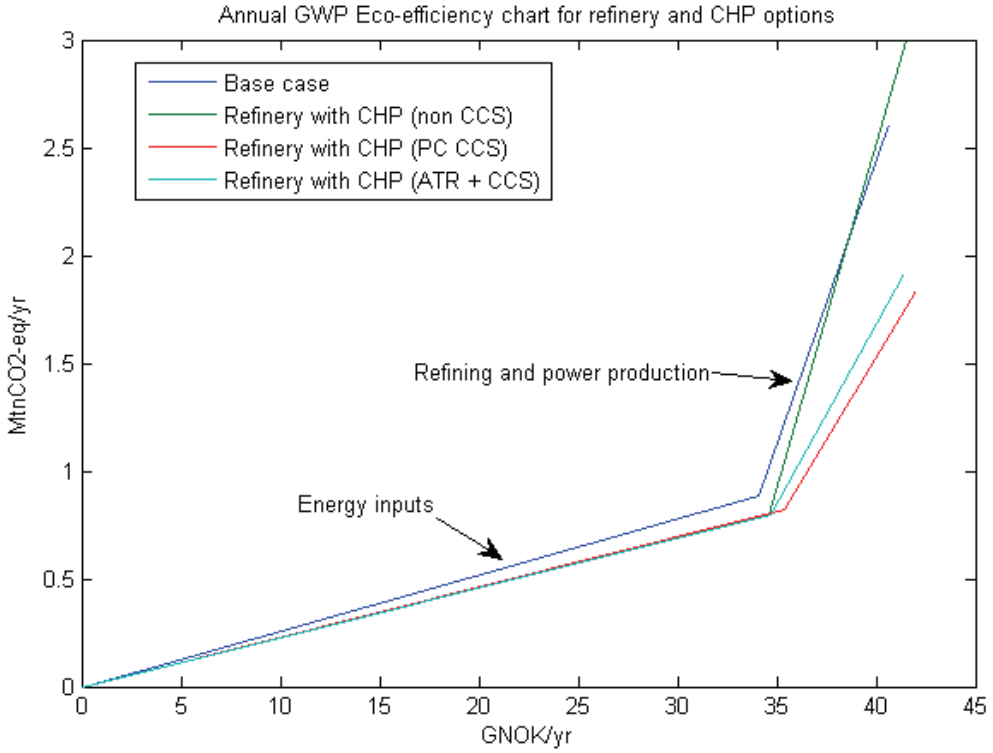

Figure 7-5 Eco-efficiency of refinery products; energy inputs separated from total

In Figure 7-5 a steep curve represents a low eco-efficiency (high impacts per monetary value produced). The alternative with the lowest eco-efficiency is actually the

conventional CHP integrated refinery, with overall emission intensity of 72 ktnCO_2-eq/GNOK. Life cycle emissions per product turnover from the Base Case refinery are 64 ktnCO_2-eq/GNOK, followed by the ATR with 46 and the PC emitting 44 ktnCO_2-eq/GNOK. It should further be noted that all three CHP integrated refinery options have larger product values, naturally due to the electricity production. Total product value for the Base Case is 40.6 GNOK, the ATR 41.4 GNOK, conventional 41.5 and the PC plant 42.0. Another interesting result is that input of products to the base case is more emission intensive than for the other three cases. This is due to electricity import, modeled as Nordic average. The eco-efficiencies of the different energy input products are inspected further in Figure 7-6.

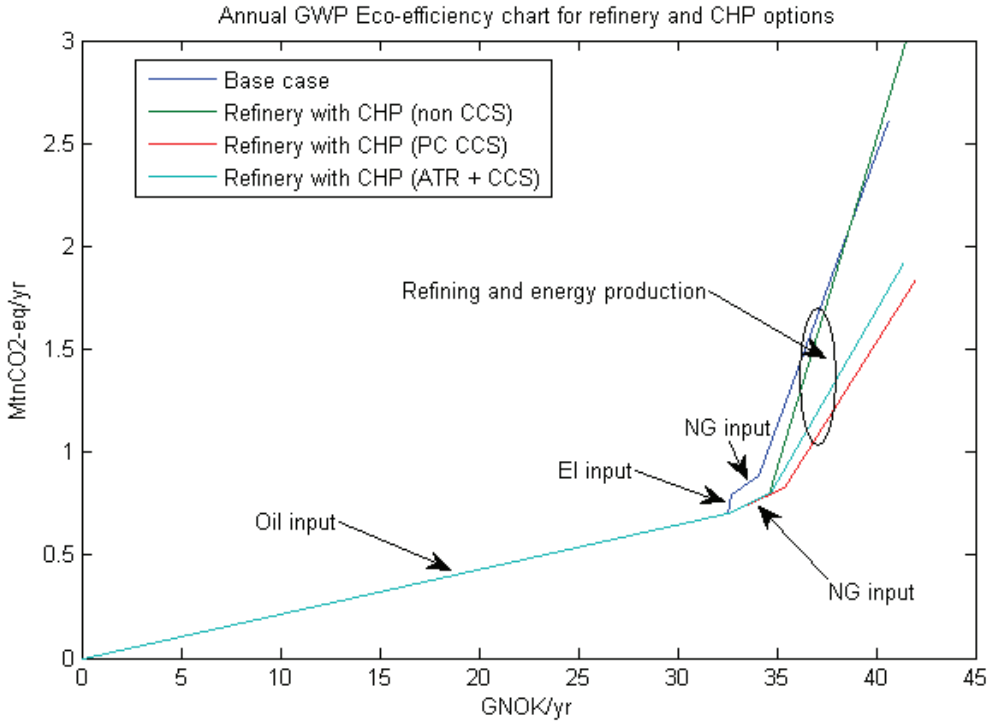

Figure 7-6 Eco-efficiency of refinery products; different energy products evaluated

It is interesting to see that electricity is the input product of far worst eco-efficiency, followed by natural gas, and crude oil having the best eco-efficiency. This is, of course, disregarding end-use. What is not easily read from Figure 7-6 is that the input of NG is different from the different alternatives, which is the reason why Figure 7-5 shows slightly different eco-efficiency in energy inputs between the three CHP integrated alternatives. When the conventional CHP integrated refinery come out at least eco-efficient, it is important to keep in mind that the activities of combusting fossil fuels for power generation is qualitatively different than processing fossil fuels for later end-use. The fact that the conventional CHP case has worst eco-efficiency is due to this.

Even if it might give a misleading picture of the causes of emissions in the system, Figure 7-7 gives a detailed picture of where different emissions occur. In this figure, the NG input to refinery and CHP is split up, as is also direct emissions from refining and power

production. In this figure, the CHP-plants are not credited for the heat and power delivered to the refinery. This makes eco-efficiency of the refinery very high in the integrated cases, while the value creation in electricity production only represents the value of electricity export minus NG expenses. This actually results in negative values for electricity generation. However, the figure shows clearly that electricity generation from fossil fuels is a very emission intensive activity, especially without CCS application.

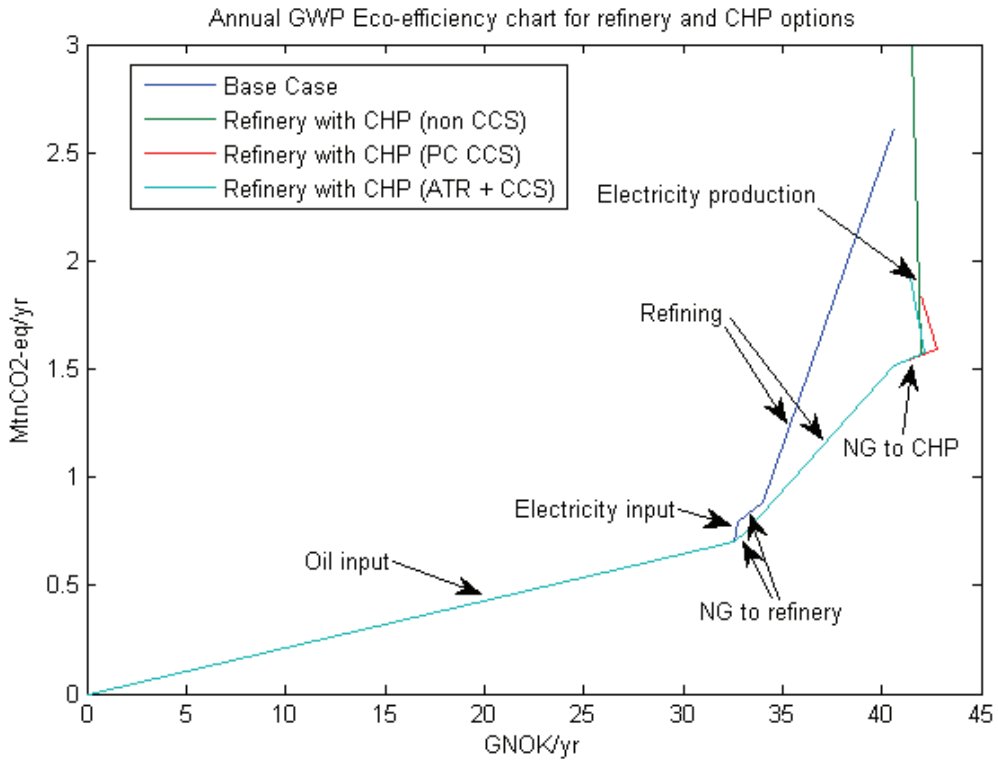

Figure 7-7 Eco-efficiency of refinery products; CHP and refinery split up

7.6 Other impact categories

Results show that HTP impacts occurs predominantly in production of the energy inputs, making choice of refinery type less important to overall eco-efficiency (Figure 7-8).

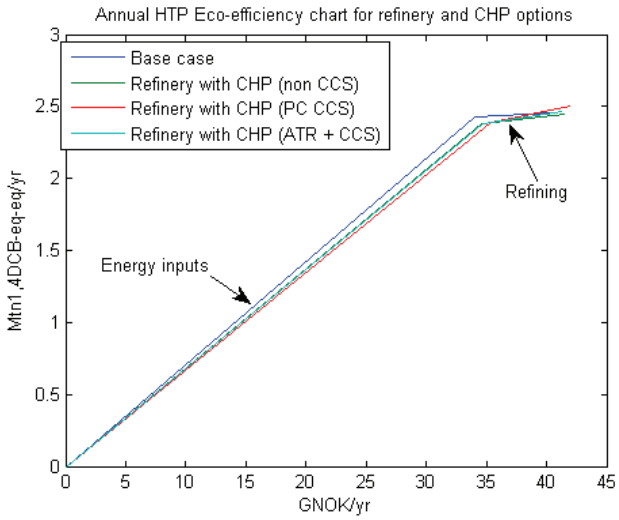

Figure 7-8 HTP eco-efficiency

The AP and EP eco-efficiencies are shown in Figure 7-9.

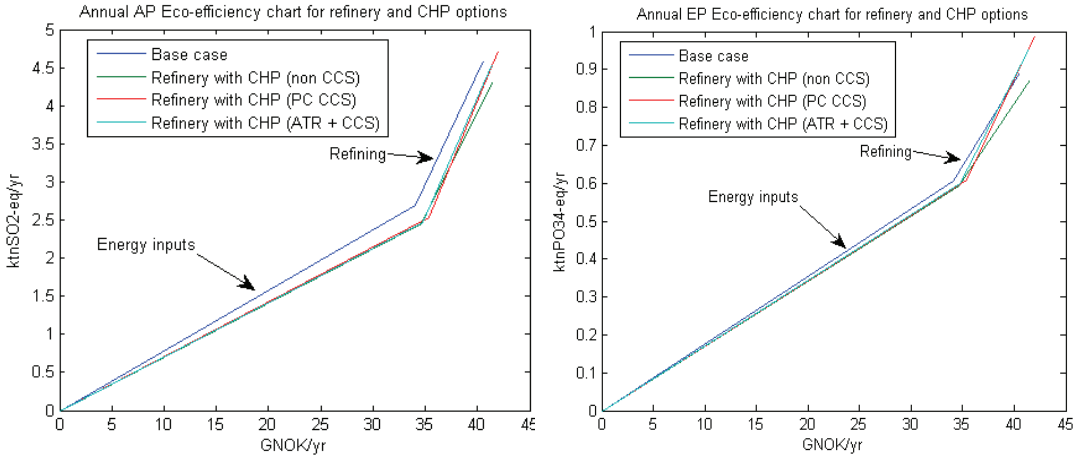

Figure 7-9 AP and EP eco-efficiencies

It can be seen that the Conventional CHP integrated refinery has the highest eco-efficiency in both impact categories; 104 ton SO_2-eq and 21 ton $PO_3$4-eq per GNOK. For EP, the PC integrated refinery has lowest eco-efficiency (24 ton $PO_3$4-eq/GNOK), followed by the ATR integrated. For AP impacts, the Base case refinery has the worst eco-efficiency, generating 113 ton SO_2-eq/GNOK. Even if the PC integrated has higher total emissions, eco-efficiency is slightly better; 112 ton SO_2-eq/GNOK.

Chapter 8

Discussion

Important findings in the three previous chapters are here summarized and commented. It is sought to find some general trends, bringing light to the objectives of the thesis; environmental performance of CCS and refinery eco-efficiency when introducing a CHP.

8.1 Environmental performance of the CCS alternatives

An important task in this thesis has been to determine life cycle impacts of different CHP configuration, with emphasis on investigating the performance of CCS systems compared to a conventional CHP. Considering CCS being a measure to reduce GHG's, the GWP performance of the systems is of central interest. This has made it natural to divide the environmental assessments into GWP and non-GWP impacts. The non-GWP impacts are also important, in to order to be aware of any cases of problem shifting that might occur when applying CCS.

8.1.1 GWP impacts

The CO_2 capture rate of the PC and ATR were 90% and 78.6%, respectively. The actual reductions of GWP arising from the whole product system comprising the CHP are however calculated to be significantly less. It has further been shown that since the plants compared have had different outputs of energy products, allocation method of environmental impacts to these products influence the conclusion of what actual emission reduction that is achieved from one system to another. A further discussion regarding allocation and the contextualization of the CHP emissions is provided in chapter 8.2 below. Whether the GWP impacts are calculated on a monetary, energetic, or exergy basis, the conclusions point in the same direction. For the PC plant, life cycle GWP reductions are around 82-83% compared to the conventional plant. The ATR achieve reductions of 70-71%. For both plants it can hence be said that actual GWP reduction is 7-8 percentage points less than the capture rate in the CC plant.

Two main reasons why actual emissions reductions are lower than the carbon capture rate a significant: 1) energy consumption in the CC gives larger consumption of NG as well as larger amount of exhaust; 2) introduction of new facilities and infrastructure has an environmental impact in both construction and operation. The analysis revealed that increased exhaust flow reduced the CO_2 end-of-pipe emission reduction to 88% for the PC and 75% for the ATR. Bringing in the life cycle perspective will hence subtract additional 4-6 percentage points from the end-of-pipe emission reduction rates to achieve a number for total GWP reduction rate.

The importance of constructing equipment has been given some attention in the analysis. It is important to include these emissions, regarding the fact that they are impossible to mitigate, and that they actually increase due to construction of CC plant and CO_2 infrastructure. The emissions from construction are actually 3.6 times higher in absolute figures for the PC and ATR cases compared to the conventional. As discussed, model inconsistencies might even have caused an underestimation, bringing CC construction emissions even higher. However, when construction only account for 6% of total emissions from the PC plant, and 0.3% for the conventional, construction emissions do not significantly affect conclusions on overall environmental performance.

Compared to the emissions from the CCS based NGCC systems that were inspected in the literature study, results in this thesis are significantly lower. To obtain a fair basis for comparison of emission factors between the NGCC's and the CHP's, emissions per exergy can be used. The literature sources all reported GWP impacts of 100-200 g CO_2-eq/kWh electricity, while the PC CHP emitted 56 g CO_2-eq/kWh exergy. Exergy efficiency for the PC is 51%; within the rage of electric efficiency for the literature sources. A key reason seems to be the emissions from the NG value chain. Three of the main literature sources used here, (Odeh and Cockerill 2008; Spath and Mann 2004; Viebahn et al. 2007) all operate with NG value chain emissions higher than total system GWP from the PC system inspected here. Also from the PC system, results indicate that the NG value chain is the most important source of GWP impacts apart from CHP operation. However, both in absolute and relative numbers, the dimension of these emissions are far from those found by many of literature sources. There is reason to question the conclusions by the mentioned sources, as they seem to be based on old data sources, and nonetheless, they are based on a different geography than this thesis. The validity of the Simapro process used here is considered more justifiable, but regarding the importance of emission data from NG extraction to the conclusions, ideally a LCA should be dedicated to oil and gas extraction in the North Sea to obtain updated, site specific information.

Counted on an exergy basis, the ATR emits 78% more GHG's compared to the PC. The low capture rate is causing this. On an energy basis, the ATR has an advantage, due to very good energy efficiency and has only 62% higher emissions. Nevertheless, improving the capture rate seems necessary for the ATR to be compatible with the PC on emissions intensity.

8.1.2 Other impacts

All impact categories show increased impacts from the CCS alternatives. However it was chosen to focus on three categories. For EP and AP impacts, there seem to be significant rise in impacts (100-160%) from the CCS systems. For the PC system, this is due to ammonia emissions from the CC plant, whereas from the ATR, ammonia and MEA are combusted to NO_2, which causes the impacts. There might be reason to question mark the probability of whether an ATR would actually have this large emission increase of NO_2, or whether it rather would have been captured by a NO_x cleaning facility. With regard to the ammonia emissions in the PC plant, the NH_3 emission factors are taken from the impact study of NVE, and are in that sense more credible. If numbers are correct, NH_3 emissions from PC plant will cause a significant rise in AP and EP pollution, affecting the environmental performance of such a plant.

A rise in HTP impacts is also observed from the CCS plants. If the characterization factor used for MEA emissions is corrects, results are however promising with regard to toxicity impacts from solvent emissions; these emissions have no significant HTP impacts in this study. The production of the MEA solvent, on the other side, proves to have substantial impacts; 22% of total system HTP impacts from PC system. In all CHP alternatives, the key driver of HTP impacts is identified to be production of metals for construction of the production system (CHP plus infrastructure). In a sense, this might indicate that the HTP

impacts from the CHP's are not decisive. High HTP impacts from metal production should rather be regarded as a problem in the metal industry than in the power production sector. Anyway, the increased HTP impact from MEA production reveals a problem shift issue with CCS application. It has also been observed that due to system boundary issues in the I/O analysis, the CC plants seem to come out with disproportionately small HTP impacts in construction. Given the high impacts from metal production, the CCS alternatives are hence actually not debited for all relevant HTP impacts, and would perform even worse using consistent data.

8.2 CHP emissions in a larger context

The fact that the CHP plants assessed are located at a refinery, substituting heat production at the refineries strongly affects the conclusions on environmental performance. Emissions are analyzed through a system expansion and through an eco-efficiency perspective for the whole refinery to illustrate how different assumptions and contexts change the outcome of the assessment.

8.2.1 System expansion

When alternative production systems for heat and electricity are considered, it is shown that environmental performance of the conventional power plant is dependent on assumption of marginal Norwegian electricity production. Arguing that building a CHP at Mongstad will reduce CO_2 emissions globally proves not to be correct if the alternative electricity supply in the region is wind power. The positive effects from substituting inefficient heat production at Mongstad refinery can not up weigh the increased emissions generated from electricity production in the CHP. Emissions intensity of producing heat by refinery boilers and electricity by wind turbines is 177 kg CO_2-eq/MWh exergy using the energy product mix from the conventional plant. Emission intensity for the exergy produced in the conventional plant is 337 kg CO_2-eq/MWh, making the conventional plant a poorer solution. If the alternative electricity production system is an NGCC plant, emission intensity is 415 kg CO_2/MWh exergy, and the conventional plant is environmentally beneficial. However, arguing that building a NG fired power plant in Norway is environmentally beneficial if the alternative is building another NG fired power plant can be seen as an invalid argument, regarding that the Norwegian power system until this year has not had any of these plants. A perspective that might be more relevant is that if the alternative to electricity production at Mongstad is no additional electricity production in Norway. Under this assumption the Mongstad power plant most likely has positive environmental effect, given that the north-European fossil thermal power plants supply balancing marginal power to the Norwegian market.

Through introduction of CCS, the CHP at Mongstad has significantly better environmental performance considering GWP emissions. Even an alternative system based on wind power electricity would have larger emissions than both the PC and ATR CHP's. Considering the plans of applying CCS at Mongstad, this result is very encouraging. Assuming NGCC based alternative energy production or other conventional fossil thermal power production, the PC and ATR plants will have significantly less

emissions than alternative production systems; a reduction of -345 kg CO_2/MWh exergy from the PC when NGCC electricity is the alternative. The ATR system performance is not lagging too far behind the PC, in spite of significantly higher specific emissions.

In all three non-GWP impact categories, the conventional plant gives emission reductions, compared to the alternatives. For the CCS alternatives, eutrophication and acidification impacts increase compared to the alternative systems. For EP, the alternative systems generate a little more than half of the impacts from the ATR or the PC. The AP impacts from the alternative system using wind based energy are approximately 20% lower than the ATR and PC alternatives. If NGCC is used as alternative, the emissions are 60-70% lower. With lower emission factors of NH_3 and NO_x from the CC plants, AP and EP impacts would probably come down to levels equal to or below the alternative production systems, considering the large fraction of total impacts caused by these emissions. HTP emissions are reduced by all three CHP applications compared to the alternatives.

8.2.2 Refinery eco-efficiency

Looking at eco-efficiency for the refinery also reveals that a conventional CHP is not especially environmentally beneficial. Introducing the CHP will represent more GWP impacts per product value. The combustion of NG for electricity production represents a far more GWP intensive activity per product value, than does oil refining. If a conventional CHP is introduced at Mongstad, the eco-efficiency actually is reduced by more than 12% compared to today's refinery.

A combination of increased product value and reduced total emissions at the refinery can be achieved through integrating CHP's with CCS application. This makes a big difference in refinery eco-efficiency for both PC and ATR integrated alternatives; up to more than 30% improvement.

For both HTP and AP impacts, eco-efficiency improves for all CHP system alternatives. Margins between the system alternatives are quite low, and impacts are not considered to have potential for significantly influencing Mongstad total eco-efficiency. The EP eco-efficiency will however be deteriorated with introduction of either the PC or the ATR. As much as a 7% decrease in eco-efficiency is expected to result from introducing the PC plant, showing the importance of addressing NH_3 and NO_x emissions from CCS activity at the CHP.

8.3 General considerations

Results of system expansion, eco-efficiency assessments, and all calculations of environmental performance show a large difference in the performance of the conventional system compared to the CCS systems. The performance of the ATR compared to the PC is however not very large. Generally, the ATR performs poorer than the PC for GWP calculations, due to lower carbon capture rate, and the increased energy efficiency does not help on this. However, the potential for improvements in the pre-

combustion technology with regard to improvements in energy consumption, capture rate and other emissions is present.

Chapter 9

Conclusion

The findings of the thesis are here seen in a broader context. Strategic recommendations for selection of CHP at Mongstad refinery are made, based on a broader contextualization of the thesis results.

The calculations of GWP from CHP's with CCS application are quite encouraging both for post- and pre-combustion technology. The total system GWP reductions were significant, and analysis showed that up- and downstream emissions did not undermine the environmental benefit of applying CCS regarding GWP impacts.

Impacts from other categories are increasing significantly in this analysis. A tendency towards problem shifting with regard to increased construction activity, chemical production and emissions of different nitrogen compounds is observed. The additional environmental problems do not seem insuperable, as a lot can be improved with additional flue gas cleaning of NO_x and NH_3 emissions. Problems related to increased activity in the upstream economy of construction, gas extraction, and chemical industry are not as easy to address, and will inevitably make the CCS systems to have a larger environmental impact in most impacts categories.

The system expansion perspective revealed that building a CHP at Mongstad without CCS is not necessarily a measure to reduce global CO_2 emissions. Analysis showed that assuming the possibility for alternatively producing electricity from wind power, the CHP actually will cause increased CO_2 emissions. If the alternative to investing in electricity generation capacity at Mongstad was to build non-CCS NGCC elsewhere in Norway, or importing balancing fossil fuled electricity from neighbouring countries, then the CHP will support a global CO_2 reduction. Emissions in all other impact categories would decrease with construction of a non-CCS CHP.

Applying CCS to the CHP alters the picture, and makes the CHP contribute to global CO_2 reduction irrespective of what alternative electricity generation it would replace. It is the replacement of NG fired boilers and furnaces at Mongstad that ensures the GWP benefit. For other impact categories, except HTP, the CCS alternatives as modelled here will induce increased environmental problems. It is, however, considered likely that improved flue gas handling will bring the CCS emissions down to or below the levels of emissions from the alternative systems.

The eco-efficiency of Mongstad refinery on a GWP basis is defined as GWP emissions per product value of refinery products and electricity. A significant deterioration of the eco-efficiency is observed if the CHP is constructed without CCS. In a global context calling for CO_2 reductions, it will be crucial that new economic activity is able to reduce emissions related to value creation. Sustainable development can only be achieved trough generating more value with less impact on the global environment. The petroleum industry is from before generating a substantial fraction of CO_2 emissions in Norway. Introducing new economic activity at Mongstad refinery, deteriorating GWP eco-efficiency seems to be a step in the wrong direction.

Applying CCS on the Mongstad CHP will on the other side improve GWP eco-efficiency at Mongstad by contributing both to substantial GWP impact reductions at the refinery as well as increased value creation. An installation of such a plant can hence be seen as a significant step towards sustainable development at the refinery and for the Norwegian economy at large.

References

Baumann, H. 2004. The hitch hiker's guide to LCA: an orientation in life cycle assessment methodology and application, edited by A.-M. Tillman. Lund: Studentlitteratur.

Brockfield, J. 2007. Dropper gasskraftverk på Tjeldbergodden. http://www.aftenposten.no/klima/article2161966.ece. Accessed.

EEA. 2008. European Environmental Agency, Central Data Repository. Reporting for offshore discharges. http://cdr.eionet.europa.eu/no/ospar/Offshore%20installations/envryosa/Reporting__for_Offshore_discharges_for_2006.xls/manage_document. Accessed 29/02 2008.

EIA. 2008. Refiner Acquisition Cost of Crude Oil. http://tonto.eia.doe.gov/dnav/pet/pet_pri_rac2_dcu_nus_m.htm. Accessed 04. may 2008.

Ekvall, T., A.-M. Tillman, and S. Molander. 2005. Normative ethics and methodology for life cycle assessment. *Journal of Cleaner Production* 13(13-14): 1225-1234.

Ertesvåg, I. S. 1997. Litt om energi, varme, temperatur og eksergi. Trondheim: NTNU.

Frischknecht, R. 2000. Allocation in Life Cycle Inventory Analysis for Joint Production. *International journal of Life Cycle Assessment* 5(2): 10.

Frischknecht, R., N. Jungbluth, H. J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, and M. Spielmann. 2005. The ecoinvent database: Overview and methodological framework. *International journal of Life Cycle Assessment* 10(1): 3-9.

Frischknecht, R., |Frischknecht,R,. 2005. The ecoinvent database: Overview and methodological framework. In *The international journal of life cycle assessment*.

Gassnova. 2007. *Beslutningsgrunnlag knyttet til transport og lagring av CO2 fra Kårstø og Mongstad*. Gassnova, Gassco, NVE, OD.

Gassnova, S. 2008. TCM - Test Centre Mongstad. http://www.gassnova.no/wsp/gassnova/frontend.cgi?func=publish.show&func_id=1110&table=PUBLISH&site=tcm. Accessed 10/3 2008.

Gijlswijk, R. v. F., Paul; Oonk, Hans; Brouwer, J. P. 2006. *Environmental impact of solvent scrubbing of CO2*. Apeldoorn: TNO science and Industry.

Guinée, J. B. 2002. Handbook on life cycle assessment: operational guide to the ISO standards, edited by J. B. Guinée. Dordrecht: Kluwer.

Haga, Å. 2007. Status på CO2-fangst og -lagring på Mongstad, edited by M. f. o. a. energy: Ministry for oil and energy.

IPCC; Metz, B. D., O. de Coninck, H. C. Loos, M. and Meyer, L. A. 2005. *Special Report on Carbon Dioxide Capture and Storage*. Cambridge, United Kingdom and New York, USA: Working Group III of the Intergovernmental Panel on Climate Change.

IPCC; R.E.H. Sims, R. N. S., A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, and C. T. J. Torres-Martínez, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, X. Zhang,. 2007. Intergovernmental Panel on Climate Change, Fourth Assessment Report, Working group III, Chapter 4: Energy Supply. http://www.mnp.nl/ipcc/pages_media/AR4-chapters.html. Accessed 05.10 2007.

ISO14044. 2006. Environmental management - Life cycle assessment - Requirements and guidelines.

Kirchgessner, D. A., R. A. Lott, R. Michael Cowgill, M. R. Harrison, and T. M. Shires. 1997. Estimate of methane emissions from the U.S. natural gas industry. *Chemosphere* 35(6): 1365-1390.

Lombardi, L. 2001. Life cycle assessment (LCA) and exergetic life cycle assessment (ELCA) of a semi-closed gas turbine cycle with CO2 chemical absorption. *Energy Conversion and Management* 42(1): 101-114.

Moran, M. S., Howard. 1998. *Fundamentals of engineering thermodynamics*. 3rd ed. West Sussex: John Wiley & Sons Ltd.

Nazarko, J., A. Schreiber, W. Kuckshinrichs, and P. Zapp. 2007. Environmental Analysis of the Coal-based Power Production with Amine-based Carbon Capture. In *Risø International Energy Conference 2007*, edited by L. S. P. a. H. Larsen. Risø National Laboratory DTU, Roskilde, Denmark.

NordPool. 2008. Elspot Monthly Prices.

NVE. 2008. Energiproduksjon - statistikk og analyser. http://webb.nve.no/modules/module_109/publisher_view_product.asp?iEntityId=10082. Accessed 10/3 2008.

NVE. 2006. *CO2-håndtering på Kårstø - Fangst, transport og lagring*. 13.2006. Oslo: Norges vassdrags- og energidirektorat.

Odeh, N. A. and T. T. Cockerill. 2008. Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. *Energy Policy* 36(1): 367-380.

Quass, U. F., Michael; Bröker, Günter 1997. *European Dioxin Inventory*. ISSN 0947-5206. European Commission.

Rubin, E. S., C. Chen, and A. B. Rao. 2007. Cost and performance of fossil fuel power plants with CO2 capture and storage. *Energy Policy* 35(9): 4444-4454.

SFT. 2008a. Miljøstatus i Norge. http://www.miljostatus.no. Accessed 10/3 2008.

SFT. 2008b. Gasskraftverk med konsesjon. http://www.sft.no/seksjonsartikkel____41549.aspx. Accessed 10/3 2008.

Singh, B. 2007. Life cycle assessment of carbon dioxide capture and storage: Post-combustion capture from natural gas fired power plant. Trondheim: NTNU.

Solli, C. 2008a. Personal Communication with Solli, C., Normalization factors in CLM 2000 baseline. 2008a.

Solli, C., A. H. Stromman, and E. G. Hertwich. 2006. Fission or fossil: Life cycle assessment of hydrogen production. *Proceedings of the Ieee* 94(10): 1785-1794.

Solli, C. A., Rahul. Strømman, Anders. Zhang, Xiangping, Hertwich, Edgar. 2008b. Evaluation of different CHP options for refinery integration in the context of a low carbon future.

Spangelo, T. 2008. Personal Communication with Spangelo, T., Emissions in gas prosessing at Kollsnes. 2008.

Spath, P. L. and M. K. Mann. 2000. Life Cycle Assessment of a Natural Gas Combined Cycle Power Generation System.

Spath, P. L. and M. K. Mann. 2004. Biomass Power and Conventional Fossil Systems with and without CO2 Sequestration -- Comparing the Energy Balance, Greenhouse Gas Emissions and Economics.

Statoil. 2005a. *Energiverk Mongstad - Kraftvarmeverk med tilhørende ombygginger i raffineriet. Konsekvensutredning*. Statoil.

Statoil, A. 2005b. *Energiverk Mongstad, Gassrørledning Kollsnes - Mongstad. Konsesjonssøknad med konsekvensutredning*.

StatoilHydro. 2007. Energiverk Mongstad. http://www.statoilhydro.com/no/TechnologyInnovation/ProtectingTheEnvironment/CarbonCaptureAndStorage/Pages/TheMongstadCPHstation.aspx. Accessed 11/3 2008.

StatoilHydro. 2008. *Sterkere sammen - StatoilHydros Årsrapport 2007*. Stavanger: StatoilHydro ASA.

Strømman, A. H. 2008. Methodological Essential of Life Cycle Assessment. Trondheim: NTNU.

Suh, S., M. Lenzen, G. J. Treloar, H. Hondo, A. Horvath, G. Huppes, O. Jolliet, U. Klann, W. Krewitt, Y. Moriguchi, J. Munksgaard, and G. Norris. 2004. System boundary selection in life-cycle inventories using hybrid approaches. *Environmental Science & Technology* 38(3): 657-664.

Svendsen, H. F. 2008. Personal Communication with Svendsen, H. F., Emissions of MEA and NH3 in CO2 capture. 30. April 2008.

TU. 2008. Billig strøm stanser gasskraftproduksjon. http://www.tu.no/energi/article131290.ece. Accessed 16.01 2008.

Viebahn, P., J. Nitsch, M. Fischedick, A. Esken, D. Schuwer, N. Supersberger, U. Zuberbuhler, and O. Edenhofer. 2007. Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany. *International Journal of Greenhouse Gas Control* 1(1): 121-133.

WBCSD. 2000. *Eco-efficiency - creating more value with less impact*.

Weidema, B. 2001. Avoiding Co-product Allocation in Life-Cycle Assessment. *Journal of Industrial Ecology* 4(3): 22.

Yasuyuki Yagi, T. M., Masaki Iijima. 2004. *IMPROVEMENTS OF CARBON DIOXIDE CAPTURE TECHNOLOGY*. KEPCO&MHI.

Aaberg, M. 2006. Life Cycle Assessment of Carbon dioxide Capture and use for Enhanced Oil Recovery in the Draugen Fieldthesis, Department of Energy and Process Engineering, NTNU, Trondheim.

Appendices

Appendix I

Life Cycle Assessment methodology

An environmental Life Cycle Assessment seeks to quantitatively describe natural resource use and pollutant emissions from a product's life cycle, from cradle to grave. However LCA is also a term describing a procedure for conducting such studies. Figure 9.1 below illustrates this procedure. The procedure is standardized in the ISO standard 14040 (Baumann 2004).

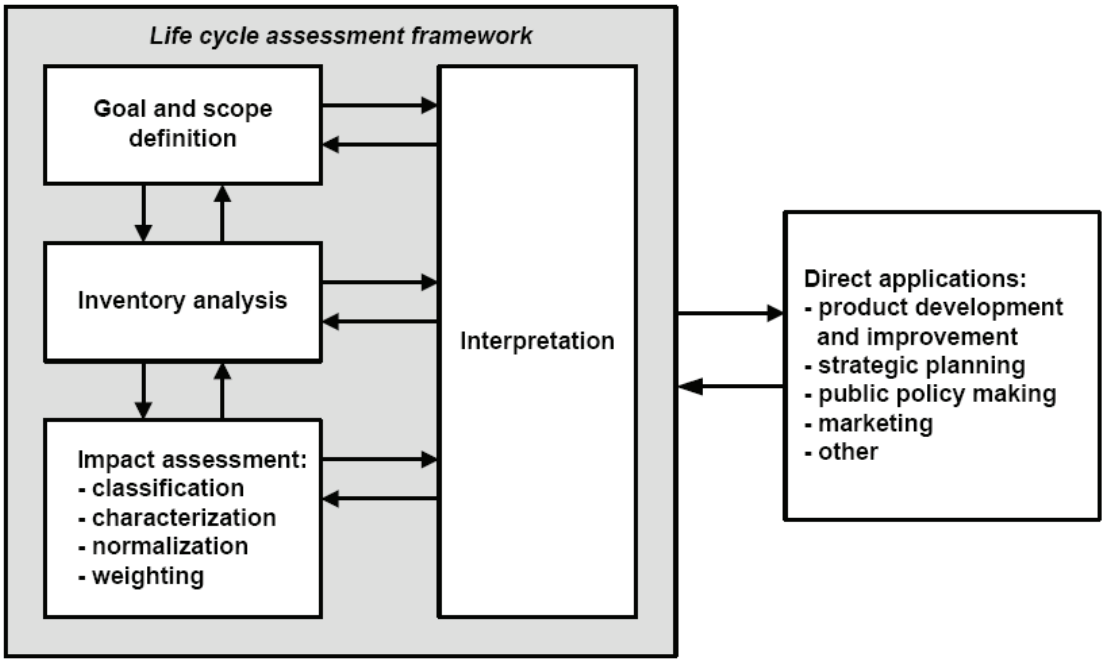

Figure 9.1 ISO 14040 framework for LCA

The **goal and scope** definition is stating the intended application of the study. Modelling issues such as the system boundaries, definition of relevant environmental impacts and level of detail of the system models are also discussed. Ideally all choices and specifications should be done in this phase, leaving no or at least very few value choices to the subsequent LCA phases (Baumann 2004). An important quantity in the goal and scope definition is the functional unit. This unit represents the function the product system is supposed to fulfil, and environmental impacts are related to this quantity. The **inventory analysis** is where the models of the product systems are built. The physical

flows of resources and emissions are quantified in this phase. The environmental impacts are determined in the **impact assessment** phase. This is done by *classifying* relevant environmental flows into different impact categories, and *characterizing* the contribution from different emissions to the impact in scope. **Interpretation** of results and implications of different assumptions is lying behind the whole process. The phase should secure that the results answer questions that correspond to what is posed in the goal and scope phase. The **direct application** of the LCA will affect choices in all the other phases. Usually, the LCA procedure is to an extent iterative, sometimes requiring the practitioner to go through the same phases several times, as the key questions might change when results are interpreted.

The main strength of the LCA tool is that it addresses a multitude of environmental problems, and applies a large system perspective. When addressing environmental problems, there is a risk of solving one environmental problem by creating another; a phenomenon referred to as “problem shifting”. When stakeholders promote nuclear energy as being emission free, this is an example of problem shifting. LCA assess environmental hazards in a broad range of impact categories to avoid this. The importance of the system border can be illustrated by another example, for instance the use of hydrogen for transport. Looking only at end use, hydrogen cars are emission free. Expanding the system border, current technologies for producing hydrogen often involves fossil fuel, and have large emissions. LCAs are supposed to consider such “hidden” emissions, by applying system borders wide enough to identify all relevant emissions occurring in a product system.

Appendix II

LCI for PC alternative

			Construction Amine plant [p]	Construction CHP plant [p]	Construction CO2 pipe [km]	Construction CO2 infrastructure [p]	Construction CO2 infrastructure operation	Operation CHP [hr]	Operation CHP + CCS [1 MNOK]	Operation CCS plant [1hr]	Natural gas at refinery [MWh]	Natural gas infrastructure construction [km annual]	Compressor work for gas transport [MWh]	Natural gas transport [MWh]	Natural gas at Mongstad [MWh]
		Construction Amine plant [p]	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,0001142	0	0,00	0	0,00	0
		CHP plant construct [p]	0,00	0,00	0,00	0,00	0,00	0,0001142	0,00	0,00	0,00	0,00	0,00	0,00	0,00
		CO2 pipe [km annual]	0,00	0,00	0,00	300	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
		CO2 infrastructure construction [p]	0,00	0,00	0,00	0,00	0,0001142	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
		CO2 infrastructure operation [hr]	0,00	0,00	0,00	0	0	0	3,93409602	0,00	0,00	0,00	0,00	0,00	0,00
		Operation CHP [1hr]	0,00	0,00	0,00	0	0	0	3,93409602	0,00	0,00	0,00	0,00	0,00	0,00
		Operation CHP + CCS [1 MNOK]	0,00	0,00	0,00	0	0	0	0,00	0,00	0,00	0,00	0,000364	0,00	0,00
		Operation CCS plant [1hr]	0,00	0,00	0,00	0	0	0	3,93409602	0,00	0,00	0,00	0,00	0,00	0,00
		Natural gas at refinery [MWh]	0,00	0,00	0,00	0	0	0	0	0,00	0,00	0,00	0,00	0,00	1
		Natural gas infrastructure construction [km annual]	0,00	0,00	0,00	0	0	0	0,00	0,00	0,00	0,00	0,00	5,586E-06	0,00
		Compressor work for gas transport [MWh]	0,00	0,00	0,00	0	3,85E-01	0	0,00	0,00	0,00	0,00	0,00	2,604E-05	0,00
		Natural gas transport [MWh]	0,00	0,00	0,00	0	0,00	0	0,00	0,00	0,00	0,00	0,00	0,00	1
		Natural gas at Mongstad [MWh]	0,00	0,00	0,00	0	0	1267	0	0,00	0,00	0,00	0,00	0,00	0,00
		Processes	Row												
	2083	Reinforcing steel at plant:RER U [kg]	0	0	1 523,20	0	0	0	0	0	0	1 523,20	0	0	0
	603	Drawing of pipes, steel:RER U [kg]	0	0	0	0	0	0	0	0	0	0	0	0	0
	251	Concrete, normal, at plant:CH U [m3]	0	674,933571	0,9102173	0	0	0	0	0	0	0,910217265	0	0	0
	210	Chromium steel 18 8, at plant:RER U [kg]	0	509926,333	0	0	0	0	0	0	0	0	0	0	0
	175	Cast iron, at plant:RER U [kg]	0	6704,8	0	0	0	0	0	0	0	0	0	0	0
	65	Aluminium, primary, at plant:RER U [kg]	0	3352,4	0	0	0	0	0	0	0	0	0	0	0
	1665	'Natural gas, at production offshore:NO U' [m3]	0	0	0	0	0	0	0	0	102,597771	0	0	0	0
	1646	Monoethanolamine [kg]	0	0	0	0	0	0	0	8,03E+01	0	0	0	0	0
	493	Disposal, hazardous waste, 0% water, to underground deposit:DE U' [kg]	0	0	0	0	0	0	0	1581,5066	0	0	0	0	0
		F-matrix [kg]	ROW												
	808	CO2	0	0	0	0	0	2,51E+04	0	0,00E+00	0,00	1,72E+03	0	0	0
	612	CO	0	0	0	0	0	0	0	0	0,00	0	0	0	0
	1142	CH4	0	0	0	0	0	0	0	0	0,00	0	0	0	0
	1230	NO2	0	0	0	0	0	1,27136	0	0	0,00	0	0	0	0
	1231	NO	0	0	0	0	0	21,01400	0	0	0,00	3,76E+01	0	0	0
	1447	SO2	0	0	0	0	0	0	0	0	0,00	2,15E+00	0	0	0
	1208	N2O	0	0	0	0	0	0	0	0	0,00	0	0	0	0
	1151	MEA	0	0	0	0	0	0	0	23,92857	0,00	0	0	0	0
	676	NH3 to air	0	0	0	0	0	0	0	14,35714	0,00	0	0	0	0
	1653	NH3 to water	0	0	0	0	0	0	0	10,33714	0,00	0	0	0	0
	1234	NMVOC	0	0	0	0	0	0	0	0	0,00	0	0	0	0
		Cooling water (waste heat [MJ])	0	0	0	0	0	0	0	0	0,00	0	0	0	0
I/O		**Annual NOK 2000**													
CAPEX		Planning, materials, construction	25	1,39E+08	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
		Pipes, digging, infrastructure	37	2,76E+07	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
		Storage, logistic, labour, eq rent ++	49	5,53E+06	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
		Adm, organization	49	7,99E+06	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
CO2 capture Plant		Unforseen, uncertainty	48	3,26E+07	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
		Staff, maintenence	49	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	1,85E+04	kr 0,00	kr 0,00	kr 0,00	kr 0,00
OPEX		Chemicals etc.	17	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
CAPEX		Construction costs	25	kr 0,00	1,17E+08	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
CHP Plant		Staff	49	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
OPEX		Insurance	48	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 573,91	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
		Maintenence	25	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	1,05E+04	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
CO2 infrastruc, CAF		Pipeline + well	5	kr 0,00	kr 0,00	kr 0,00	9,95E+07	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
NG pipeline, CAPEX			37	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 500 621,62	kr 0,00	kr 0,00
OPEX			42	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 150 186,49	kr 0,00	kr 0,00

Above is provided the Life Cycle Inventory for the CHP with post-combustion CCS. Following the nomenclature of chapter 4.1, the pink part at the top is the *Aff*-matrix, The blue part following is the *Apf*, while the bottom orange, yellow, grey and mint part is *Anf*. The green part in the middle is *Ff*, following chapter 4.2.1.

Explanation of foreground processes in the LCI

Construction Amine plant [p]	Construction of the CC plant; only economic data
CHP plant construct [p]	Mixed data; physical inputs and investment cost
CO2 pipe [km annual]	Pipe from Mongstad to offshore injection; material inputs per km and year
CO2 infrastructure construction [p]	Offshore installations related to CO_2 sequestration, CO_2 well. Costs taken from (Gassnova 2007)
CO2 infrastructure operation [hr]	Energy requirement for pump work; recompression.
Operation CHP [1hr]	Inputs, outputs and costs related to CHP operation
Operation CHP + CCS [1 MNOK]	The functional unit in this inventory.
Operation CCS plant [1hr]	Inputs, outputs and costs related to CC plant operation
Natural gas at refinery [MWh]	Conversion factor between Sm3 gas from Simapro and MWh gas input to CHP
Natural gas infrastructure construction [km annual]	Materials, emissions and costs associated with construction and laying of NG pipe from Kollsnes to Mongstad
Compressor work for gas transport [MWh]	Pump work for NG transport Kollsnes – Mongstad
Natural gas transport [MWh]	Aggregated unit
Natural gas at Mongstad [MWh]	Aggregated unit

Appendix III

Emission intensity on exergy basis

A calculation of exergy in the heat and steam flow from the CHP is provided below. Formulas are retrieved from Ertesvåg (1997).

Heat
All three CHP configurations will deliver 76 MW of heat for pre-heating crude oil. The oil enters the refinery at a temperature of 250ºC, and is heated to 370ºC. The exergy in a heat transfer is given by the following formula:

$$E^{Q} = Q\left(1 - \frac{T_0}{T}\right) \tag{0.11}$$

Here E^Q is the exergy, and Q the energy transferred. T_o is the ambient temperature, while T is the temperature at the heat exchange surface. Temperature T is chosen to be the middle temperature between inlet and outlet crude oil, 310ºC. The exergy that is transferred to the crude oil is then 39 MW

Steam
270 MW of steam is also delivered to the refinery. The steam leaves the CHP superheated at 335ºC, 31 bar. The return flow from the refinery is saturated water at 125ºC. In order to find the ratio between exergy, E, and energy, Q, delivered by the steam flow, a flow exergy analysis is performed. The exergy transfer, E, can be found by inspecting the difference in flow exergy for the in- and outflow in steam in the refinery:

$$E = \left(h_2 - h_1\right) - T_0\left(s_2 - s_1\right) \tag{0.12}$$

The enthalpies $h_{1 \text{ and } 2}$, and the entropies $s_{1 \text{ and } 2}$ are found through thermodynamic tables (Moran 1998). The energy transfer in terms of heat is merely the enthalpy difference:

$$Q = h_2 - h_1 \tag{0.13}$$

The ratio E/Q, giving the fraction of exergy to the energy delivered to the steam, becomes 0.435. 118 MW exergy is hence transferred through the steam.