

# LCA as an ecodesign tool for production of electricity, including carbon capture and storage - a study of a gas power plant case with post-combustion CO<sub>2</sub> capture at Tjeldbergodden

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## 1. Introduction

Statoil has worked for many years to develop technology and processes to meet the climate challenge associated with extraction and use of fossil-based energy carriers. The debate regarding CO<sub>2</sub> capture, transport and storage has mainly focused on technology and economy, and a complete environmental analysis for a Norwegian case has not been available. This is why Statoil in 2006 decided to make a Life Cycle Assessment (LCA) of a possible future Tjeldbergodden gas power plant case, including CO<sub>2</sub> capture, transport and storage (CCS). The project started in spring 2007, and in Phase I, two different gas power plant scenarios were compared. In Phase II, which started in September 2008, several additional scenarios have been analysed.

The strength of an LCA is the holistic perspective from 'cradle to grave', which means that the analysis includes all the activities through the whole value chain, and the inclusion of several environmental impact categories.

The project will give useful information regarding improvements of the design of the CCS system. The model made is now used in an iterative process and will provide information about the environmental improvements possible with suggested improvements in design, and is thus an useful ecodesign tool for StatoilHydro's CCS system development.

Ostfold Research is a private research company in Norway, with high level competence on holistic environmental assessments. Ostfold Research has previously carried out life cycle inventory studies of platform-based production of oil and gas in the Norwegian sector and LCAs of gas power plants at Kårstø and Kollsnes.

## 2. Aim and functional unit

The aim of the study is to compare the environmental impacts of four different gas power plant scenarios and by this give input to future strategic choices in StatoilHydro. The model developed is to be the basis for scenarios and will thus be an ecodesign tool for StatoilHydro in their CCS development process.

The functional unit is 1 TWh electricity generated at Tjeldbergodden gas power plant and delivered to the grid.

## 3. System boundaries and project design

The study was carried out using life cycle assessment (LCA) methodology based on the ISO-standards 14044-48. The following environmental impact categories were included: global warming potential, acidification potential, eutrophication potential, photochemical ozone creation potential and cumulative energy demand.

Four scenarios were analysed:

- Reference Gas power plant without CCS
- CCS-1 Gas power plant with CCS based on post-combustion CO<sub>2</sub> capture using MEA absorption, with a separate gas fuelled steam boiler for amine regeneration.

- CCS-2 Gas power plant with CCS based on post-combustion CO<sub>2</sub> capture using MEA absorption, with a separate biofuelled steam boiler for amine regeneration (four sub-scenarios with different transport modes and distances).
- CCS-3 Gas power plant with CCS based on post-combustion CO<sub>2</sub> capture using MEA absorption. Steam for amine regeneration is delivered from the low-pressure steam turbine in the power plant (process integration).

No integration between the CO<sub>2</sub> capture process and the power plant was included in the scenarios CCS-1 and CCS-2, except for the electricity consumption in the capture process, which was assumed to be delivered by the gas power plant. Due to the low integration between the power plant and the capture process, these scenarios were supposed to be 'worst case scenarios' for electricity production with CCS at Tjeldbergodden. In scenario CCS-3 the power plant and the CO<sub>2</sub> capture process were closely integrated by steam delivery from the power plant to the CO<sub>2</sub> capture plant.

In all four scenarios, natural gas from the Heidrun field is used in a combined cycle process. The CO<sub>2</sub> capture process is based on post-combustion decarbonisation using MEA (monoethanolamine) absorption. After the capture process, the CO<sub>2</sub> is transported in a 150 km pipeline to storage at the Heidrun licence area. A simplified flowsheet of the gas power plant scenarios is shown in Figure 1.

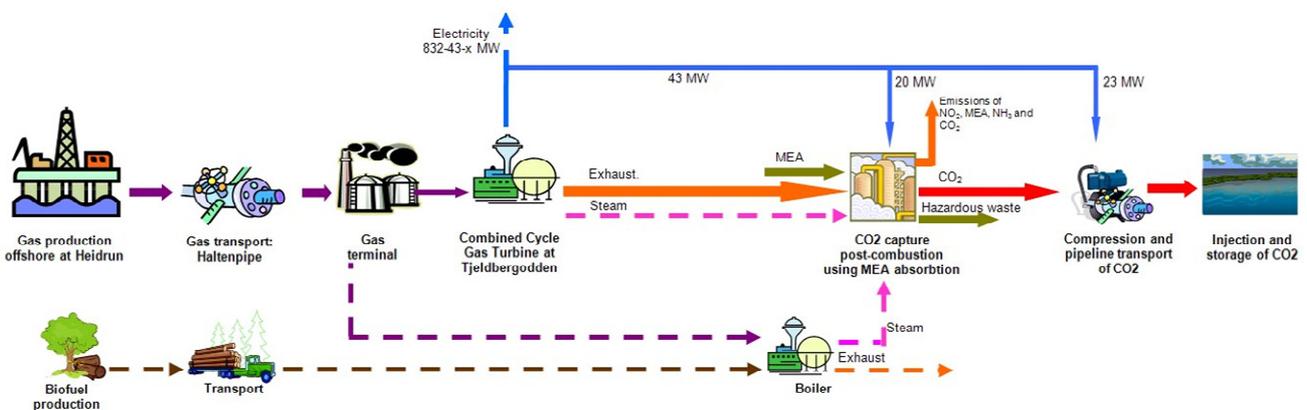


Figure 1 Simplified flow sheet of the Tjeldbergodden gas power plant case with CO<sub>2</sub> capture, transport and storage (four scenarios)

The power plant is designed with two gas turbines of 262 MW<sub>nominal</sub> each in addition to one steam turbine of 328 MW<sub>nominal</sub>. The nett power production will be 832 MW for the reference scenario and 789 MW for the scenarios CCS-1 and CCS-2. For scenario CCS-3 the net power will be 702 MW. The nett efficiency of the power plant is assumed to be 59.1% in the reference scenario and 44.8% in the CCS-1 scenario. It is assumed that the CO<sub>2</sub> capture fraction will be 90%, or 2.1 million tonnes per year. The capture facility will have emissions of CO<sub>2</sub>, NO<sub>2</sub>, MEA and NH<sub>3</sub> in addition to waste containing MEA, which is treated as hazardous waste. Construction and demolition of infrastructure such as pipelines, platform, terminal, buildings, turbines and process equipment are included in the analysis. The following environmental impact categories are included: global warming, acidification, eutrophication, photochemical ozone creation potential and cumulative potential energy demand.

#### 4. Data sources

Design information and technical specifications for a suggested StatoilHydro power plant, capture facilities and CO<sub>2</sub> transport system at Tjeldbergodden have been available for this study [1, 2]. In addition, data for a future capture facility at Naturkraft's power plant at Kårstø have been used [3]. Literature data from the IEA Greenhouse Gas R&D programme and Statistics Norway have also been useful [4, 5]. Details about the data used and the system boundaries are given in Modahl et al. 2009 [13].

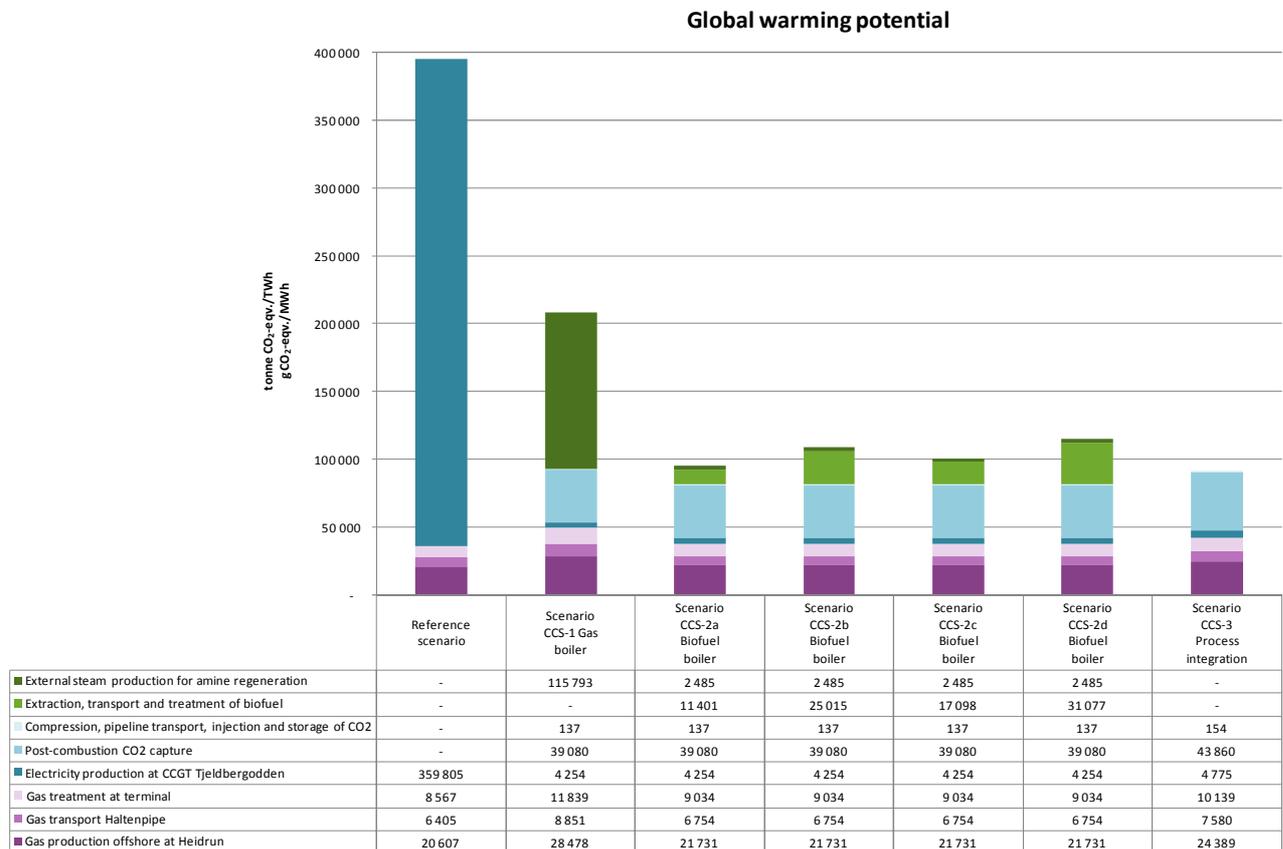
#### 5. Impact assessment results

The following environmental impact categories were assessed: global warming potential (GWP), acidification potential, eutrophication potential, photochemical ozone creation potential and cumulative energy demand. In order to show the different types of trends in results, the author's have chosen to show detailed results for GWP and eutrophication potential Modahl et al. [13] gives details of all of the results and figures illustrating

which parts of the life cycle contribute most to the different impacts. For the purposes of this paper the results of this analysis of which life cycle elements are important are included in text form only. A summary of the relative results (compared to the reference scenario) is included in the form of a radar chart. A note of caution about interpretation of this radar chart is also included at the end of the summary.

### Global Warming Potential

Figure A shows the contribution to the global warming potential (GWP) in tonnes CO<sub>2</sub>-equivalents per TWh (tCO<sub>2</sub>-eqv./TWh) electricity delivered to the grid by the different power plant scenarios at Tjeldbergodden.



**Figure A** Global warming potential for electricity from different power plant scenarios (tCO<sub>2</sub>-eqv./TWh delivered to the grid).

Figure A shows that in the reference scenario, the global warming potential is 395.000 tonne CO<sub>2</sub>-eqv./TWh electricity delivered to the grid. In the CCS-1 scenario (gas boiler), the global warming potential is 208.000 tCO<sub>2</sub>-eqv./TWh. The global warming potential for the CCS-2 scenarios (biofuel boiler), varies between 95.000 – 115.000 tCO<sub>2</sub>-eqv./TWh and in the CCS-3 scenario (process integration) the result is 91.000 tCO<sub>2</sub>-eqv./TWh. This means that the best result is achieved by the CCS-3 scenario where the global warming potential has decreased by 77% compared to the reference scenario. The next best result is achieved by use of biofuel for amine regeneration (scenarios CCS-2a/b/c/d) where the global warming potentials have decreased by 76% - 71%, while use of gas for amine regeneration (scenario CCS-1) only reduces the global warming potential by 47%.

In the reference scenario, the dominant phase is the electricity production at CCGT Tjeldbergodden, which contributes with approximately 91% of the global warming potential. This burden is caused by CO<sub>2</sub> emissions from the combustion of gas. Gas production offshore at Heidrun contributes with 5% and gas transport through the Haltenpipe and gas treatment at the terminal contribute with 2% each.

In the CCS-1 scenario, the most important phase is the external steam production for amine regeneration, which contributes with 56% of the global warming potential. The flue gas from combustion of gas in the steam production phase is not captured, hence the high CO<sub>2</sub> emissions. The CO<sub>2</sub> capture phase contributes with 19% and the gas production offshore at Heidrun 14%. In the CO<sub>2</sub> capture phase, the global warming potential is due to the fact that only 90% of the CO<sub>2</sub> emissions from the power plant are captured (100% capture is not practicable). Production and transport of chemicals used (for example MEA) does not

contribute much to the total. The small amount of greenhouse gases from the electricity production phase is caused mostly by emissions of CH<sub>4</sub> (and CO) from the combustion process. Gas treatment at the terminal and gas transport in the Haltenpipe contribute 6% and 4% respectively. The compression, pipeline transport, injection and storage phase is almost negligible.

In the CCS-2 scenarios, the most important phase is CO<sub>2</sub> capture (34% - 41%), followed by gas production offshore (19% - 23%), but also extraction, transport and treatment of biofuel plays an important role (12% - 27%). It is the transportation part which dominates this phase. The burden is less in the scenario with Norwegian biofuel transported a short distance (Scenario 2a), then comes the scenario with biofuel from the Baltic states (Scenario 2c) and Norway/long distance (scenario 2b), while the scenario which uses biofuel from Canada (Scenario 2d) has the highest burdens when it comes to global warming potential.

In the CCS-3 scenario, the most important phase is also CO<sub>2</sub> capture (48%), followed by gas production offshore (27%). Gas transport, gas treatment and electricity production contribute with 8%, 11% and 5% respectively.

The global warming potential from gas production offshore at Heidrun, gas transport in the Haltenpipe and gas treatment at the terminal have all increased by 38% in the CCS-1 scenario when compared to the reference scenario. There are two reasons for this:

- the efficiency penalty in the electricity production phase due to consumption of electricity for the CO<sub>2</sub> capture process and for compression/pipeline transport of CO<sub>2</sub>, which means that more gas is needed to produce the same amount of electricity to the grid (5.5% points), and
- extra gas has to be produced, transported and treated for steam production for amine regeneration (32.5% points).

In the CCS-2 scenarios, the global warming potential for the same three phases (gas production, gas transport and gas treatment) have increased by 5% compared to the reference scenario. This is because of the efficiency penalty in the electricity production phase due to the electricity consumption for the CO<sub>2</sub> capture and compression/pipeline transport of CO<sub>2</sub>.

In the CCS-3 scenario, the global warming potential for these three phases (gas production, gas transport and gas treatment) have increased by 18% compared to the reference scenario due to the efficiency penalty in the electricity production phase, which is caused by:

- The electricity consumption for the CO<sub>2</sub> capture process and compression/pipeline transport of CO<sub>2</sub> (5.5% points)
- The loss of thermal work due to withdrawal of low pressure steam for regeneration of solvent (12% points)

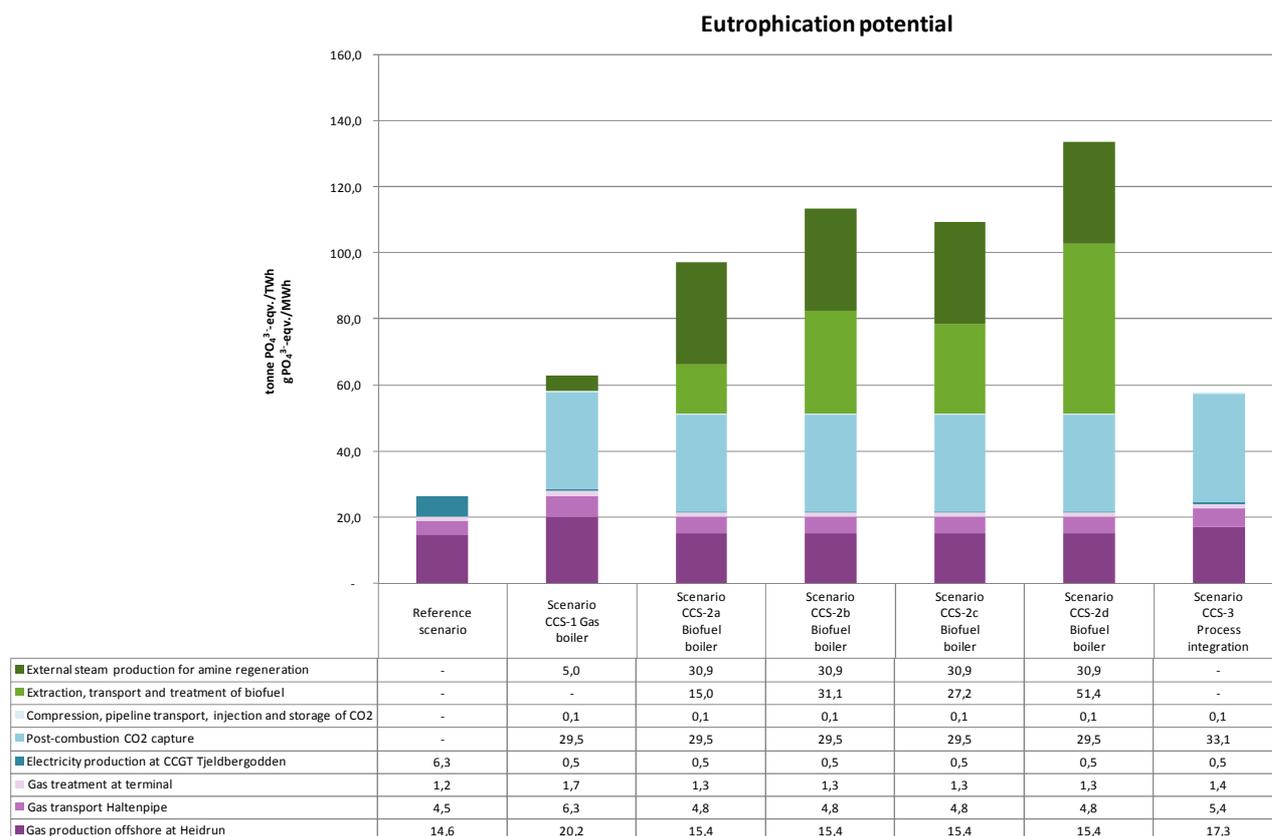
The loss of thermal work due to withdrawal of low pressure steam is also the reason why the CCS-3 scenario has higher global warming potential than the scenarios CCS-1 and CCS-2 in the electricity production phase, the CO<sub>2</sub> capture phase and the compression/pipeline transport of CO<sub>2</sub> phase.

The results from the LCA analysis also show that the global warming potential is completely dominated by emissions from operation, and that production, transport and waste treatment of infrastructure is almost negligible.

The authors have also used the results to calculate the In Table 14 the 'CO<sub>2</sub> avoidance efficiency' for for the different scenarios are calculated. The CO<sub>2</sub> avoidance efficiency is defined as the amount of CO<sub>2</sub>-eqv. avoided compared to the amount of CO<sub>2</sub> stored [20]. The calculations for this are presented in Modahl et al. [13]. The average CO<sub>2</sub> avoidance efficiency in the analysed scenarios is 80%, which means that storing one tonne of CO<sub>2</sub> does not equal one tonne of CO<sub>2</sub> avoided.

## Eutrophication potential

Figure B shows the contribution to the eutrophication potential in tonnes PO<sub>4</sub><sup>3-</sup> equivalents per TWh (tPO<sub>4</sub><sup>3-</sup>-eqv./TWh) electricity delivered to the grid by the different power plant scenarios at Tjeldbergodden.



**Figure B** Eutrophication potential for electricity from different power plant scenarios (tPO<sub>4</sub><sup>3-</sup>-eqv./TWh delivered to the grid).

The figure shows that in the reference scenario, the eutrophication potential is 26,6 tPO<sub>4</sub><sup>3-</sup>-eqv./TWh electricity delivered to the grid. In the CCS-1 scenario (gas boiler), the eutrophication potential is 63,1 tPO<sub>4</sub><sup>3-</sup>-eqv./TWh. The eutrophication potential for the CCS-2 scenarios (biofuel boiler), varies between 97,4 – 133,9 tPO<sub>4</sub><sup>3-</sup>-eqv./TWh and in the CCS-3 scenario (process integration) the result is 57,8 tPO<sub>4</sub><sup>3-</sup>-eqv./TWh. This means that the best result is achieved by the reference scenario, and that the 'least bad' CCS scenario is scenario CCS-3 where the eutrophication potential has increased by 117% compared to the reference scenario. In scenario CCS-1 the eutrophication potential has increased by 137% and in the scenarios CCS-2a/b/c/d the eutrophication potentials have increased by 266% - 403%.

In the reference scenario, the dominating phase is gas production offshore at Heidrun, which contributes with 55% of the eutrophication potential. Gas transport in the Haltenpipe and the electricity production phase contributes with 17% and 24% respectively, while gas treatment at the terminal contributes with 5% only.

In the CCS-1 scenario, the two most important phases for eutrophication potential are the CO<sub>2</sub> capture phase and gas production offshore at Heidrun, which contributes with 47% and 32% respectively. In the CO<sub>2</sub> capture phase, the eutrophication potential is mostly caused by the emissions of NO<sub>x</sub> (10% of the total), ammonia/NH<sub>3</sub> (16 % of the total) and MEA (10% of the total). These NO<sub>x</sub> emissions come originally from the combustion process in the electricity production stage (assumed unchanged), and the ammonia and MEA emissions are due to the capture process itself. Gas transport in the Haltenpipe contributes with 10% of the eutrophication potential, external steam production for amine regeneration 8% and the gas treatment at terminal phase is responsible for 3%. The small eutrophication potential connected with the electricity production phase is caused by the NO<sub>x</sub> cleaning process (emission of ammonia) and production of power plant infrastructure. The contribution from compression, pipeline transport, injection and storage phase is almost negligible.

In the CCS-2 scenarios, the eutrophication potentials are dominated by the use of biofuel for amine regeneration (the extraction, transport and treatment of biofuel phase and the external steam production for amine regeneration phase). In the scenario with shortest transportation distance (CCS-2a), these two phases together contribute with 47% of the eutrophication potential, and it is the external steam production phase (combustion of wood) that is largest. The longer the distance for transporting biofuel, the larger the eutrophication potential, and in scenario CCS-2d these two phases together contribute with as much as 61%

of the total eutrophication potential. The total eutrophication potential of scenario CCS-2d is 37% higher than scenario CCS-2a.

In the CCS-3 scenario, the most important phase is CO<sub>2</sub> capture (57%), followed by gas production offshore (30%). Gas treatment at terminal, gas transport and electricity production contribute with 9%, 2% and 1% respectively.

As for the global warming and acidification potentials, the eutrophication potential from gas production offshore at Heidrun, gas transport in the Haltenpipe and gas treatment at the terminal have all increased by 38% in the CCS-1 scenario compared to the reference scenario. There are two reasons for this:

- the efficiency penalty in the electricity production phase due to consumption of electricity for the CO<sub>2</sub> capture process and for compression/pipeline transport of CO<sub>2</sub>, which means that more gas is needed to produce the same amount of electricity to the grid (5.5% points), and
- extra gas has to be produced, transported and treated for steam production for amine regeneration (32.5% points).

In the CCS-2 scenarios, the eutrophication potentials for the same three phases (gas production, gas transport and gas treatment) have also increased by 5% compared to the reference scenario. This is because of the efficiency penalty in the electricity production phase due to the electricity consumption for the CO<sub>2</sub> capture process and for compression/pipeline transport of CO<sub>2</sub>.

In the CCS-3 scenario, the eutrophication potential for these three phases (gas production, gas transport and gas treatment) have increased by 18% compared to the reference scenario due to the efficiency penalty in the electricity production phase, which is caused by:

- The electricity consumption for the CO<sub>2</sub> capture process and compression/pipeline transport of CO<sub>2</sub> (5.5% points)
- The loss of thermal work due to withdrawal of low pressure steam for regeneration of solvent (12% points)

The loss of thermal work due to withdrawal of low pressure steam is also the reason why the CCS-3 scenario has a higher eutrophication potential than the scenarios CCS-1 and CCS-2 in the electricity production phase, the CO<sub>2</sub> capture phase and the compression/pipeline transport of CO<sub>2</sub> phase.

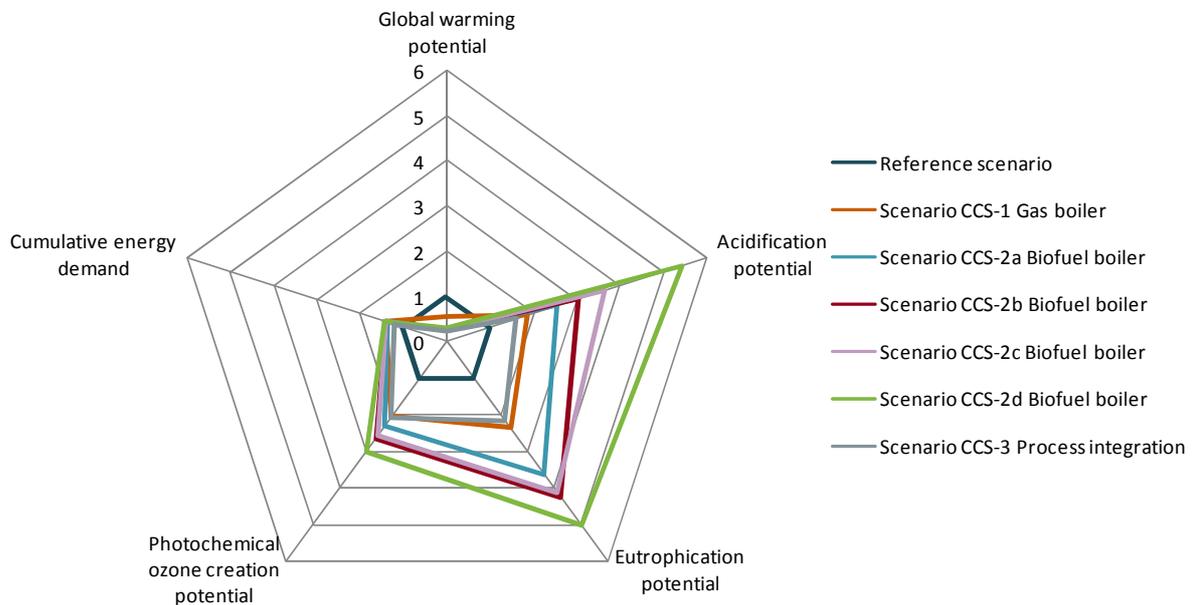
The total eutrophication potential is completely dominated by emissions from operation, but that in the electricity production phase of the CCS scenarios, infrastructure causes over 45% of the eutrophication emissions. The eutrophication potential of the infrastructure life cycle phase is, however, negligible compared to the other phases and the total eutrophication emissions.

### **Summary of impacts analysed**

The main impact assessment results are shown in Table A and the relative impacts for the different power plant scenarios are shown in Figure C.

**Table A:** Impact assessment results for the analysed power plant scenarios

Scenario	tonne CO <sub>2</sub> -eqv./TWh	tonne SO <sub>2</sub> -eqv./TWh	tonne PO <sub>4</sub> <sup>3-</sup> -eqv./TWh	tonne C <sub>2</sub> O <sub>4</sub> -eqv./TWh	TWh LHV/TWh
	g CO <sub>2</sub> -eqv./MWh	g SO <sub>2</sub> -eqv./MWh	g PO <sub>4</sub> <sup>3-</sup> -eqv./MWh	g C <sub>2</sub> O <sub>4</sub> -eqv./MWh	kWh LHV/kWh
	Global warming potential	Acidification potential	Eutrophication potential	Photochemical ozone creation potential	Cumulative energy demand
Reference scenario	395 384	148	26,6	42,3	1,62
Scenario CCS-1 Gas boiler	208 433	275	63,1	87,1	2,26
Scenario CCS-2a Biofuel boiler	94 875	379	97,4	98,8	2,23
Scenario CCS-2b Biofuel boiler	108 489	453	113,6	112,4	2,29
Scenario CCS-2c Biofuel boiler	100 572	543	109,6	108,3	2,25
Scenario CCS-2d Biofuel boiler	114 552	806	133,9	127,5	2,31
Scenario CCS-3 Process integration	90 897	240	57,8	87,4	1,93



**Figure C** Relative impacts of the CCS scenarios in relation to the Reference Scenario.

The trend is clear: the CCS scenarios have reduced impacts for the global warming potential category only. The total reduction in CO<sub>2</sub> equivalent emissions is 47% for the CCS-1 scenario (gas boiler), 71% - 76% for the CCS-2 scenarios (biofuel boiler) and 77% for the CCS-3 scenario (process integration) when compared with the reference scenario. These results are in line with LCA results found in literature for CCS of a combined electricity and H<sub>2</sub> production plant using natural gas as fuel [19].

The average CO<sub>2</sub> avoidance efficiency in the analysed scenarios are 80%, which means that storing one tonne of CO<sub>2</sub> does not equal one tonne of CO<sub>2</sub> avoided.

It is possible to improve the global warming potential for scenario CCS-1 by capturing the flue gasses from the external steam production for amine regeneration, but the result could never be as good as scenario CCS-3, which is the 'process integration limit' for this scenario. The global warming potential results for the CCS-2 scenarios could possibly be even better than the CCS-3 scenario if the biological CO<sub>2</sub> in the flue gas from the external steam production also was captured.

The impacts for the CCS scenarios are higher than for the reference scenario for all the other impact categories analysed (acidification potential, eutrophication potential, photochemical ozone creation potential and cumulative energy demand). This is in line with findings in literature. The effect is caused by:

- Emissions from the capture process itself (ammonia, MEA and acetaldehyde).
- The efficiency penalties due to:
  - Consumption of electricity for the CO<sub>2</sub> capture process and for compression/pipeline transport of CO<sub>2</sub>, which means that more gas is needed to produce the same amount of electricity to the grid (this applies to all of the CCS scenarios).
  - Withdrawal of low pressure steam for regeneration of solvent, which leads to loss of thermal work in the power plant (scenario CCS-3).
- Production, transport, treatment and combustion of:
  - Gas (scenario CCS-1)
  - Biofuel (scenario CCS 2a/b/c/d)
 to produce steam for amine regeneration.

The 'least bad' CCS-scenario for the impact categories acidification potential, eutrophication potential, photochemical ozone creation potential and cumulative energy demand is scenario CCS-3. Regarding photochemical ozone creation potential, scenario CCS-1 has the same result as scenario CCS-3.

Construction of the infrastructure, including production of materials and waste treatment of these at their 'end-of-life' is generally insignificant for both the reference scenario and the CCS scenarios. This is in line with findings for previous fossil fuel systems. Compression, pipeline transport, injection and storage of CO<sub>2</sub> has also almost negligible impacts for all of the impact categories analysed.

The increase in hazardous waste is not assessed here, but the CCS scenarios will produce hazardous waste that is not present in the reference scenario (solvent waste and MEA).

It is important for the reader to note that Figure C can easily lead to the misunderstanding that each of the environmental impacts assessed are equally important. However, this is not necessarily the case. Figure C should thus be interpreted with care. The normalisation and weighting work performed in this study is an attempt to establish which impacts are most important in order to provide focus for filling data gaps and where efforts to improve design will be most important.

## 6. Normalisation

In order to see how significant the emissions from the different power plant scenarios are, the results are compared to the national emissions of greenhouse and acidifying gases. National emissions data are provided by Statistics Norway [16, 17, 18]. Some of the emissions given also contribute to eutrophication and photochemical ozone creation, but since several other emissions that also contribute to these impact categories are not given by SSB, only the global warming potential and the acidification potential are calculated. The national data and corresponding global warming and acidification potentials are given in Table B and the normalisation results are shown in Figure D. The impact assessment methods for the global warming and acidification potentials are the same as have been used for the analysis of the power plant cases

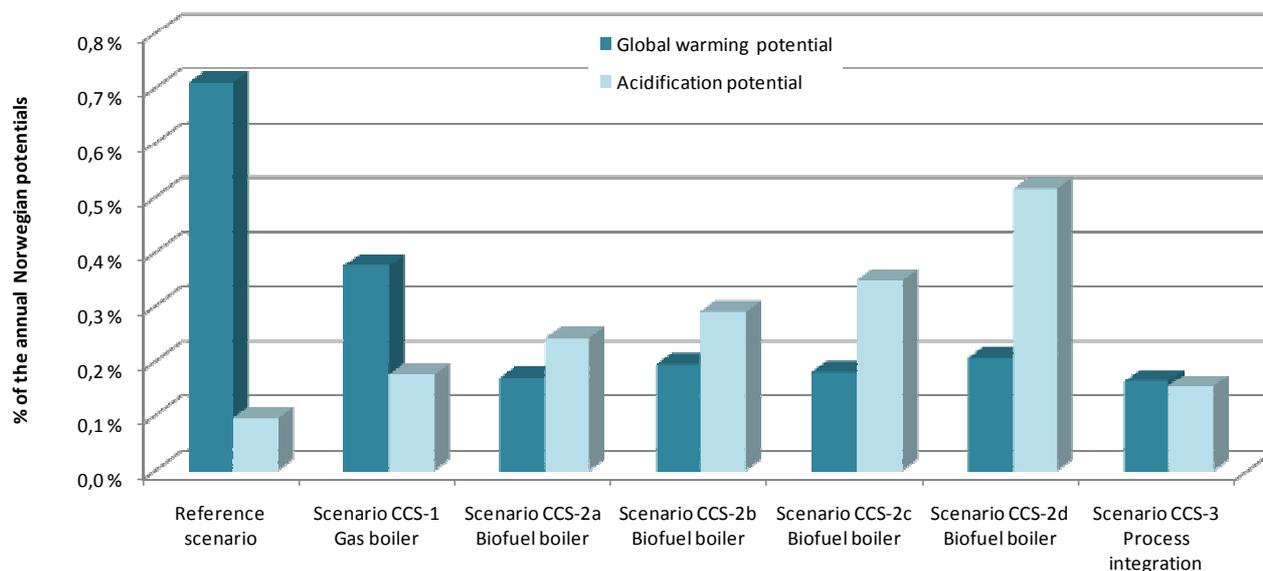
**Table B** Annual emissions of greenhouse and acidifying gases in Norway (2007)

National emission of	Annual emission <sup>1</sup>	Reference	Global warming potential and acidification potential
CO <sub>2</sub>	45.0 Mill tonne	SSB (2007b) [16]	55.7 mill tonne CO <sub>2</sub> -eqv./year
CH <sub>4</sub>	210.1 Ktonne	SSB (2007b) [16]	
N <sub>2</sub> O	13.7 Ktonne	SSB (2007b) [16]	
HFK	330.7 Tonne	SSB (2007b) [16]	
PFK	119.0 Tonne	SSB (2007b) [16]	
SF <sub>6</sub>	3.2 Tonne	SSB (2007b) [16]	
GWP (not including CO)	55.1 Mill tonne	SSB (2007b) [16]	
CO	398.9 Ktonne	SSB (2007c) [17]	157 Ktonne SO <sub>2</sub> -eqv./year
SO <sub>2</sub>	19.7 Ktonne	SSB (2007d) [18]	
NO <sub>x</sub>	193.5 Ktonne	SSB (2007d) [18]	
NH <sub>3</sub>	22.6 Ktonne	SSB (2007d) [18]	

<sup>1</sup> Only domestic flights and ship transport are included in the Norwegian statistics.

## Normalisation

1 TWh electricity produced by the reference scenario and the CCS scenarios in relation to the annual Norwegian global warming and acidification potentials



**Figure D** The global warming and acidification potentials per 1 TWh of electricity produced by the different scenarios analysed, compared to the annual Norwegian potentials.

Normalisation shows that per TWh electricity produced and delivered to the grid by the different power plant scenarios, the Norwegian global warming potential will increase by 0.2% - 0.7%. The Norwegian acidification potential will be increased by 0.1 % - 0.5%.

Since the planned annual production of these power plant scenarios are 5.6 - 6.7 TWh/year, the annual increase in the Norwegian global warming potential will be 0.9% - 4.8% and the total annual Norwegian acidification potential will increase by 0.6% - 3.2%.

## 7. Weighting results

Weighting is a part of LCA methodology that is useful when the results for different impact categories give contrary indications (like in this study), making it necessary for decision makers to decide which impact categories are more important. The weighting models used were the EDIP/UMIP [6, 7] (updated in 2002 by Pré Consultants [8]) EPS 2000 [9, 10] (last updated Pré Consultants August 2004 [8]) and IMPACT 2002+ methods [11] (last updated April 2008, Pré Consultants [8]). Weighting is based on value choices, and the methods are based on different principles like the 'distance to target method' (EDIP/UMIP 96), 'damage values' given in monetary units (EPS 2000) and combinations of several principles (IMPACT 2002+) in damage values or other units. The models used in this study are all implemented in the software SimaPro 7.1.8., and are for European conditions and political targets, not specific to Norway.

As mentioned above, weighting is based on value choices, and since weighting never can give an exact answer, we have chosen to use three different weighting methods to see the robustness of the weighting results. All the fundamental input data regarding emissions and use of energy and other resources are included, and not only the data associated with the environmental impact categories shown earlier in this paper.

The main findings from weighting are:

- Scenario CCS-3 has lowest score, and hence has the best result, for all three weighting methods used in this study.
- In the EDIP/UMIP method, toxic effects are strongly in focus, while in the EPS 2000 and IMPACT 2002+ methods, use of non-renewable energy is dominant for most of the scenarios.

This study has chosen not to include impact categories concerning toxic effects due to the large uncertainties regarding toxic emissions in the input data material. Now that we see that toxicity is important for the weighting results from one of the three methods used, and we know that the degradation reactions from emission of MEA are not yet fully understood, except that the degradation products could have toxic effects, toxicity should be stronger focused in the data gathering of future analysis of these CCS systems. In literature, toxicity is also found to be one of the most notable trade-offs.

Since we know that potentially important data regarding toxicity are missing, the weighting results should be used with care.

## 8. Further work

The results presented in this paper and the references it is based upon [12, 13, 14, 15] show that it is still important that the CCS system design continues to find more optimal design options. Focus should be on the CCS-3 scenario (process integration), since this scenario has proved to be the best of the CCS scenarios analysed, but also CCS-2 (biofuel boiler) with capture of the biological CO<sub>2</sub> in the flue gas from the external steam production should be analysed, even if this scenario is found not to be economically feasible today.

Sensitivity analysis should be made for the CO<sub>2</sub> capture rate and the steam consumption since these parameters have shown to be of vital importance for the results in other studies. Sensitivity analysis should also be made for the MEA emission, after the degradation reactions and degradation products are more understood. Experiments are being performed to understand what degradation products are being produced from MEA, to what extent they are made and whether they are carcinogenic. Experiments are also in progress to understand more about use and emissions of amine inhibitors, amine promoters and antifoam agents. The results from these studies should also be included in future analysis of these CCS systems.

Regardless of what kind of CCS scenario is chosen, one obvious way to reduce the environmental effects from the CCS system is to reduce the efficiency penalty, the steam consumption for regenerating amines and the emissions of MEA, ammonia and acetaldehyde.

It is recommended that these results are presented to personnel in StatoilHydro that can participate in efforts to improve the design of the CCS system. This model can be used in an iterative process to provide information about the environmental improvements possible with suggested improvements in design. The model is also such that it is possible to model the life cycle environmental effects if alternative carbon capture processes are of interest. LCA is thus an important ecodesign tool for StatoilHydro's CCS system development, where technical expertise in StatoilHydro and their suppliers can be actively linked with the LCA model and the results can show where it is important for StatoilHydro to concentrate future efforts to fill gaps in knowledge and make design improvements.

## 6. References

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3. Carbon Capture and Storage (CCS) technologies. To prevent major climate change, CO<sub>2</sub> concentration in the atmosphere should be reduced by either CO<sub>2</sub> up-take from the atmosphere biologically or reducing the CO<sub>2</sub> emissions from the sources. In this study, only reducing/capturing CO<sub>2</sub> from flue gas will be considered among the three phases (capture, transport, storage) of CCS technology. The idea of separating and storing CO<sub>2</sub> for mitigation of its emissions to the atmosphere was first proposed in 1977 (Marchetti, 1977). Post-combustion CO<sub>2</sub> capture for power plants takes place after combustion of air and fuel to generate electricity, and immediately before the resulting exhaust gas enters the stack.