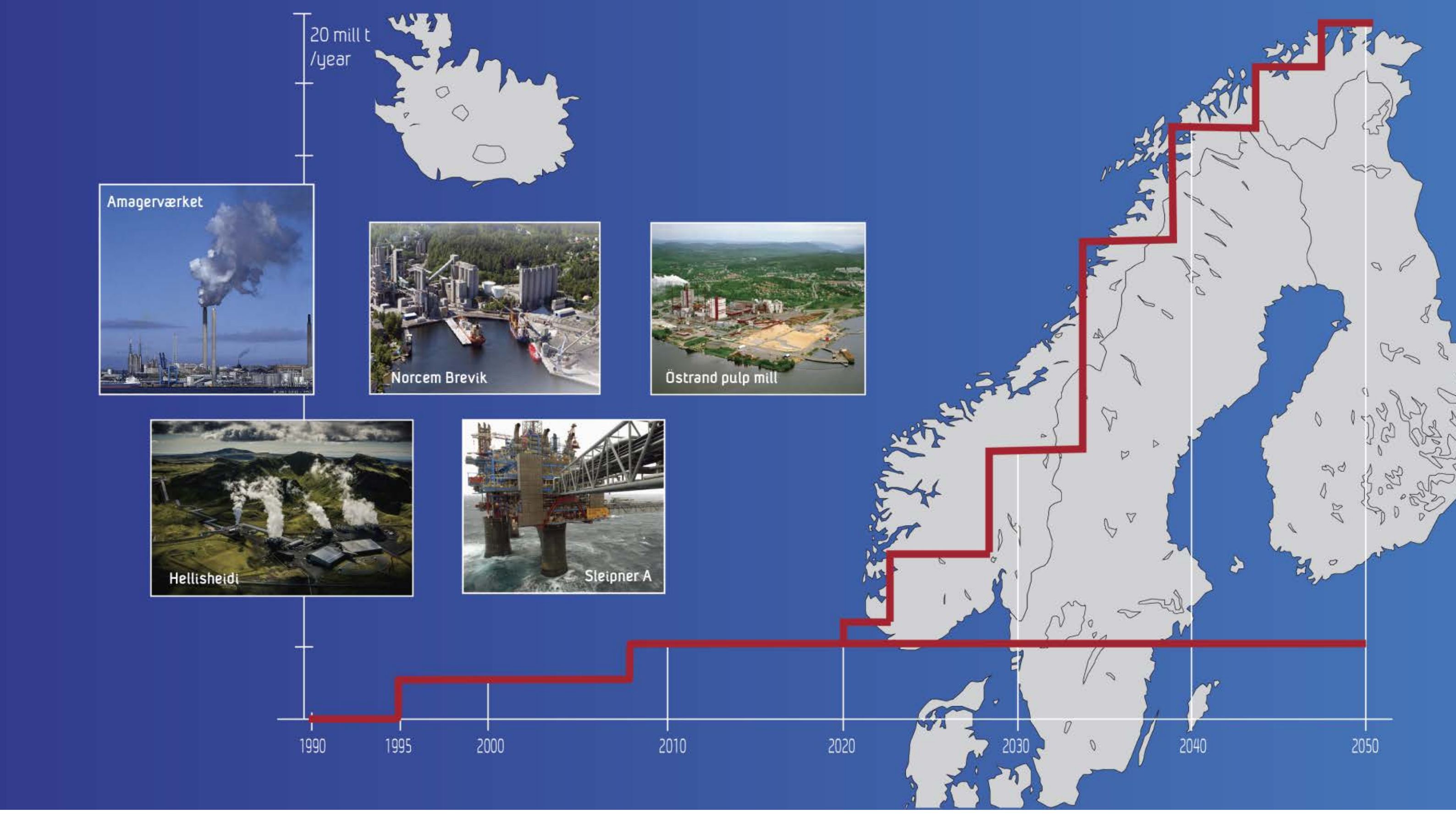


# $CO_2$ from Natural Gas Sweetening to Kick-Start EOR in the North Sea

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**NORDICCS Technical Report D1.1.1402**

December 2014

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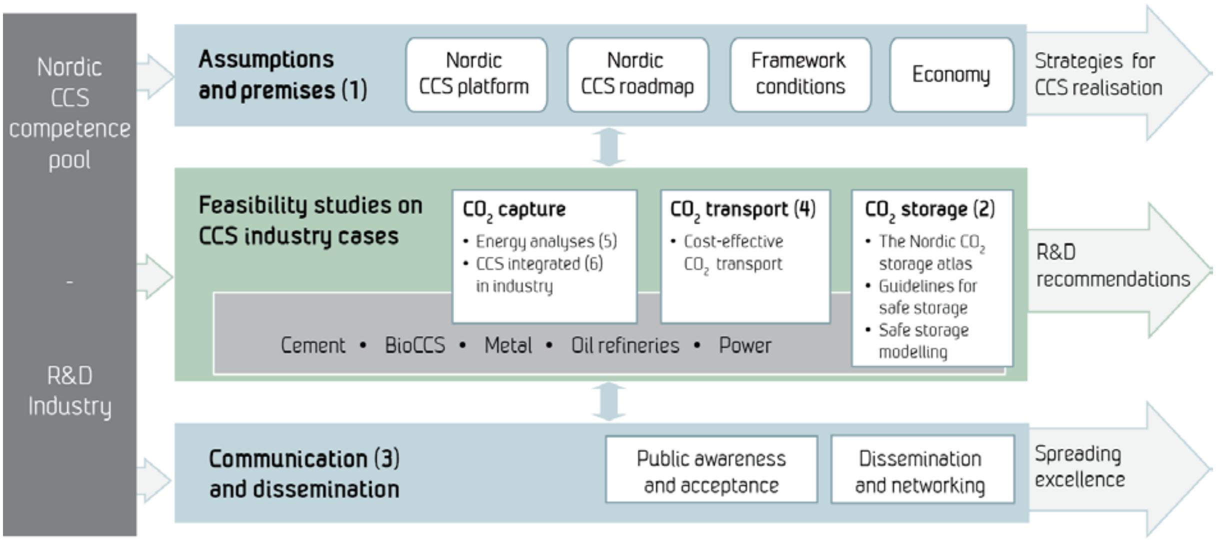


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# Summary

This is an extra deliverable in the NORDICCS Project. It was not part of the 2014 Implementation plan. It was an oral presentation at GHGT12 in Austin, Texas, USA.

**Keywords** Natural Gas Sweetening, $CO_2$ removal CCS, $CO_2$ EOR

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**Date** December 2014

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*Nordic CCS Competence Centre, NORDICCS, is a networking platform for increased CCS deployment in the Nordic countries. NORDICCS has 10 research partners and six industry partners, is led by SINTEF Energy Research, and is supported by Nordic Innovation through the Top-level Research Initiative.*

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Energy Procedia 00 (2013) 000–000

Energy Procedia

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GHGT-12

# $CO_2$ from Natural Gas Sweetening to Kick-Start EOR in the North Sea

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**Abstract**

The cost of $CO_2$ removal from natural gas with subsequent storage is estimated and the results show that it can be very close to an economically viable process. The cost of removing $CO_2$ from a natural gas stream(sweetening) using the MDEA process is 30% lower than cost of conventional amine MEA technology for $CO_2$ capture from flue gas, putting this project at a much lower cost than capture from most other industrial $CO_2$ sources. The cost of $CO_2$ removal is as low as 35€/tonne. In addition natural gas sweetening projects will capture potentially larger volumes of $CO_2$ than many industrial projects if new large gas fields are developed. The large scale could provide the necessary amount and steady supply of $CO_2$ needed to kick-start the deployment of CCS. This could happen either by allowing a large-scale offshore central $CO_2$ storage or offshore EOR projects. Large scale storage would reduce the storage cost for $CO_2$ improving the cost benefit situation for a CCS project. A large scale EOR project could create a market for $CO_2$ in the Nordic region that also land-based industry can sell to thereby reducing their costs for CCS sufficiently to allow industrial CCS projects to start.



*Keywords:* Natural Gas Sweetening;$CO_2$ removal; CCS; $CO_2$ EOR

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## 1. Introduction

In the US, commercial-scale CCS projects have been profitable for nearly 30 years due to the use of $CO_2$ for enhanced oil recovery ($CO_2$-EOR). Indeed, the combination of $CO_2$ -EOR with permanent $CO_2$ storage in oil reservoirs is a critical, near-term solution for creating economically viable CCS projects, facilitating early CCS infrastructure – and kick-starting deployment of CCS. It represents a win-win situation as it combines $CO_2$ capture from industries that need CCS with the use of $CO_2$ injection to increase oil production, thus financing a significant element of the project.

The reason earlier EOR projects in Denmark and Norway did not materialize when investigated about 10 years ago was mainly due to insufficient amounts of $CO_2$ available(at least 2-5 M tonnes per year is necessary to start an EOR project). One possible solution to this is to remove more $CO_2$ from natural gas that is exported from Norway to Europe. As natural gas sweetening projects will capture potentially larger volumes of $CO_2$ than many industrial projects – storing up to 3 Mt/year may be feasible, and they could hence kick-start an EOR project. They will also provide a continuous source of $CO_2$ which is necessary to start an EOR project.

Some natural gas fields on the Norwegian Continental Shelf (NCS) have $CO_2$ levels above the acceptable limit for export into the pipeline and sale. For commercial natural gas, the maximum allowable $CO_2$ level is 2.5%. The $CO_2$ must therefore either be removed from the gas before export or the level must be close enough to 2.5% that the gas can be mixed with gas from other fields with lower $CO_2$ levels and therefore reducing the average concentration in a blending process. There are at least 25 fields discovered off the coast of Norway which contain $CO_2$ levels above 5%, Fig. 1 [1]. Eight of these fields have $CO_2$ levels above 10%, one has a $CO_2$ level as high as 44 %. By going from left to right on this bar chart the location of the field is moving further to the north. Many of the newly discovered undeveloped fields with high CO2 concentrations shown towards the right of this figure are in the northernmost parts of Norway and the Barents Sea and Arctic (to the far right in yellow).

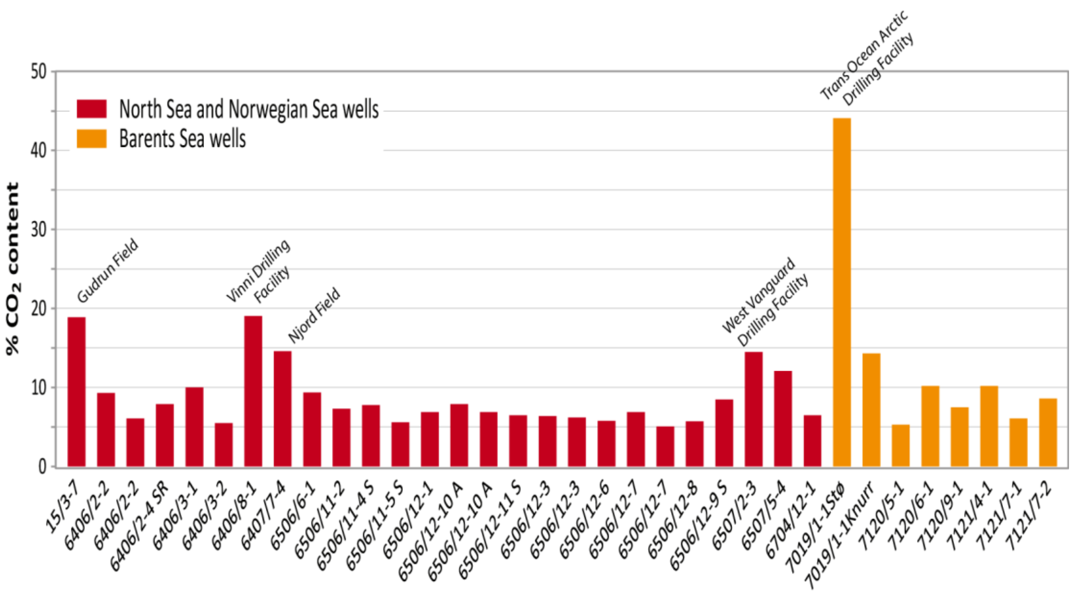


Fig. 1: A selection of wellbores with $CO_2$ ontent above 5%. Based on data from NPD fact pages, adapted from $CO_2$ Storage Atlas Norwegian North Sea[1]

(Vinni and Njord in Norskehavet outside Trondheim, West Vanguard off coast of Lofoten in Northern Norway)

During the NORDICCS project, the costs of several of the most economically viable Nordic CCS projects were analyzed. The results showed that for the Nordic region, natural gas sweetening (i.e. removing more $CO_2$ from natural gas before it is exported) is the most economically viable case for CCS [2], Fig. 2. The purpose of this study was to perform a detailed analysis of the natural gas sweetening case shown in Fig. 2 to confirm the earlier cost analysis data.

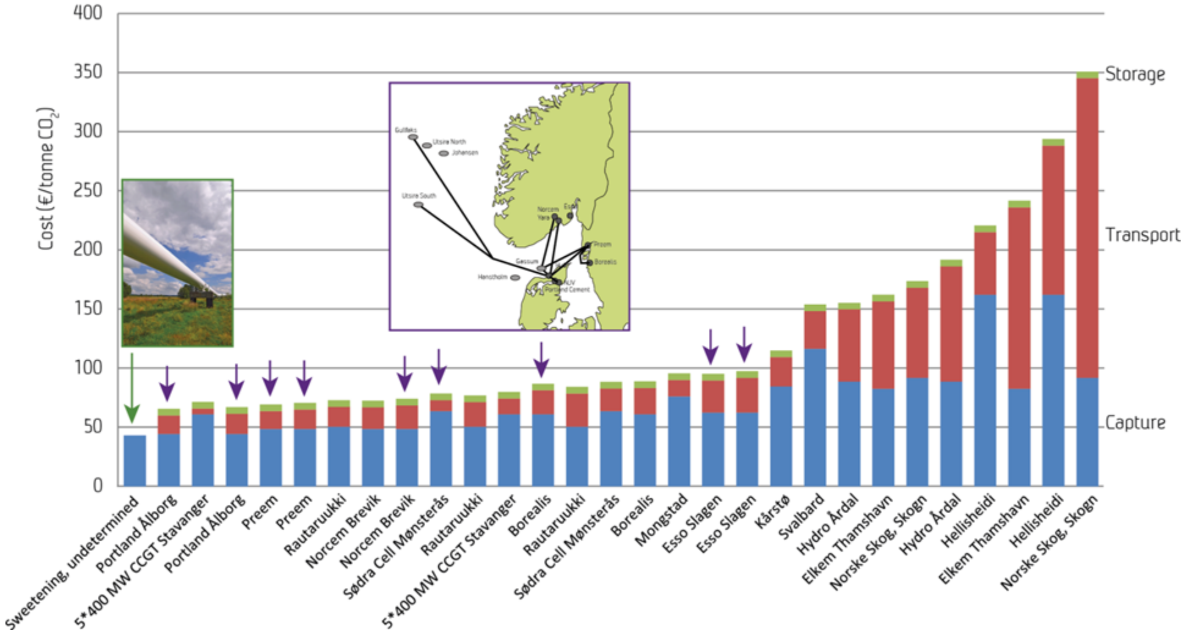


Fig.2: Cost for different Nordic CCS projects estimated by the NORDICCS Project [2]

This paper therefore describes a detailed cost analysis for a natural gas sweetening project with subsequent storage. For the purpose of these calculations a generic natural gas source is assumed with a high $CO_2$ content of 10%. The $CO_2$ level must be reduced according to the "natural gas sales specification". In this work a sweetening plant using MDEA is employed to reduce the $CO_2$ content of the natural gas to 2.5% and also compress the $CO_2$ removed back up to 70 bar. This process has the potential of becoming the least expensive way to obtain $CO_2$ for Enhanced Oil Recovery (EOR) and therefore perform CCS projects in Norway. The MDEA capture process is used to reduce the $CO_2$ levels. This process operates at significantly lower pressures than in the MEA process which results in reduced absorber size and higher input pressure to the $CO_2$ compressor, significantly reducing both energy consumption and investment costs. The availability of large volumes of natural gas also suggests that economy of scale can help reduce capture costs further[2]

The modeling of costs performed in this paper all assumes nth of a kind plant (NOAK). In order to assess the future cost effectiveness potential of a technology it is best to compare technologies on an $n^{th}$ of a kind cost basis. This is to allow a fair comparison between technologies and avoid taking into account the increased cost of prototyping which will be reduced as soon as more units are produced.

It will be difficult to modify the existing infrastructure of natural gas pipelines to accommodate $CO_2$ removal from the gas due to the high cost of construction in explosive areas and the safety of supply. The cases described here were therefore calculated based upon a yet to be determined source of $CO_2$ from any new oil and gas field – either at

Utsira, or at the new frontiers in Northern Norway and the Arctic which as shown in Fig.1 in many cases have higher $CO_2$ contents than fields already developed. Natural gas sweetening is a particularly interesting option in areas where the $CO_2$ concentration of the natural gas is high. Finally, an interesting aspect is that $CO_2$-EOR can be a reason to open up gas fields that were previously considered uneconomical due to the high $CO_2$ content. The use of the $CO_2$ for EOR could potentially make these projects profitable.

The costs of transport and storage have not been calculated for the sweetening plant as this is a new project, but it is reasonable to assume that it will be close to an offshore storage site, resulting in minimal transportation costs.

Another potential benefit from natural gas purification is that more $CO_2$ could be removed to go below the limit of 2.5% CO. This will result in a corresponding increase in the sales volume of the gas based on heating value and will therefore be more valuable per ton. Gas exports to Europe in 2012 were worth 242 billion NOK (€30 billion), which translates into an additional ~1.7 billion NOK (€210 million) per year if the $CO_2$ is removed totally and replaced with pure methane.

The start of an EOR project could create a market for $CO_2$ in the Nordic region that the land-based industry can sell into thereby reducing their costs for CCS. Hence it could help start CCS projects in a range of industries that have no other means of reducing their $CO_2$ emissions, as the $CO_2$ is produced as part of the manufacturing process such as in the Cement and Steel industries.

**Nomenclature**

| | |
|---|---|
| MDEA | Methyl diethanolamine (*N*-methyl-diethanolamine), $CH_3N(C_2H_4OH)_2$ |
| MEA | Monoethanolamine or 2-aminoethanol (C2H7NO) |
| EOR | Enhanced Oil Recovery – process to inject CO2 to enhance oil extraction from fields |
| NOK | Norwegian krones, the currency of Norway |
| € | Euro |
| NCS | Norwegian Continental Shelf |
| $CH_4$ | Methane |
| $CO_2$ | Carbon Dioxide |
| $H_2O$ | Water |
| Bar | Pressure = 0.98692 standard atmosphere (atm) |
| Pa | SI unit for Pressure = one newton per square metre,= $9.8692\times10^{-6}$ atmosphere (atm) |
| kgmole/hr | Molar flow rate |
| CAPEX | Capital Expenditure |
| OPEX | Operational Expenditure |
| NOAK | N$^{th}$ of a Kind |
| Tonne | Metric tonne = 1000kg |

## 2. Methodology of Cost Estimations

### *2.1. Generic Natural Gas Field Parameters*

Some natural gas fields on the Norwegian Continental Shelf (NCS) have $CO_2$ levels above the acceptable limit for export into the pipeline and sale. For commercial natural gas, the maximum allowable $CO_2$ level is 2.5%. For the purpose of these calculations a generic natural gas source is assumed with a high $CO_2$ content of 10%. The $CO_2$ level must be reduced according to the "natural gas sales specification". A sweetening plant using MDEA is employed to reduce the $CO_2$ content of the natural gas to 2.5% and also compress the $CO_2$ removed back up to 70 bar. The purification plant may also be placed on an optimal site onshore with shortest possible distance for $CO_2$ transport to $CO_2$storage or EOR site. Fig. 3 shows an illustration of the streams entering and exiting the generic sweetening plant and their composition.

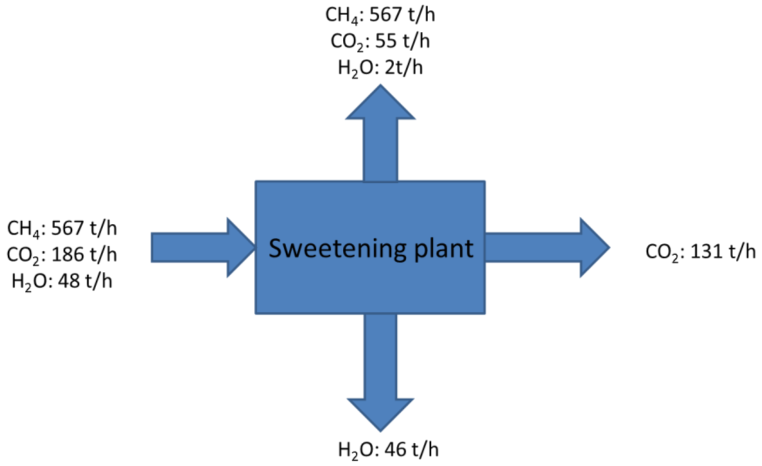


Fig. 3: Natural gas streams entering and exiting a generic sweetening plant

A representative natural gas composition from a generic field with gas containing 10% $CO_2$ is shown in Table 1. The natural gas contains $CH_4$, $H_2O$ and $CO_2$ among other compounds. The sweetening process reduces the $CO_2$ content significantly.

Table 1.Natural gas composition: (assumed generic site)

| Natural Gas Composition | Inlet values (mol %) | Mass flow in (tonne/h) | Mass flow out (tonne/h) |
|---|---|---|---|
| $CH_4$ | 83.6 | 567 | 567 |
| $CO_2$ | 9.9 | 186 | 55 |
| $H_2O$ | 6.3 | 48 | 2 |
| Pressure (bar) | 70 | | |
| Temperature (C) | 40 | | |

### *2.2. Scope of Analysis*

It is expected that the natural gas sweetening plant will be built on an existing site where it will be operated as an extension of the other plants (One person extra on shift (total 6 persons) and one engineer extra)
Included in scope:

- All capture units
  - Absorber
  - Circulation system
  - Desorber (stripper) system
  - Compression and drying system

Not included in scope:

- Purchase of land

- Preparation of land (roads etc)
- Utilities systems (treated as OPEX)
- Offices, workshops, storage etc.

Building a plant within a high risk area (explosion) can increase the CAPEX with 50% but this has little influence on the final capture cost (€/tonne).

### *2.3. Process Model*

The process simulation was performed using Aspen Hysys Simulation Software. The process flow diagram (PFD) is shown in Fig. 4. The “sour” natural gas (70 bar) enters an absorber, and a MDEA mixture is added. After exiting the absorber the rich MDEA is reduced from 70 bar to 1.8 bar: Here some natural gas will be released into the flash tank, and this natural gas has to be recompressed to the original pressure level. The liquid part will be treated in a desorber and split in a $CO_2$ stream (EOR quality) and a lean MDEA solution. The $CO_2$ will then be compressed (and dried) up to 70 bar (dense phase).

The lean MDEA solution is then compressed to reach the absorber pressure of (70 bar). An economizer is installed in order to recover the heat. The process data used in the estimation is shown in Table 2.

Table 2. Process data used in the simulation

| Input Parameters for Simulation | Input Value |
|---|---|
| Vapour Phase ( Fraction) | 0.938 |
| Temperature (C) | 40 |
| Pressure (kPa) | 7000 |
| Molar Flow (kgmole/h) | 42373 |
| Mass Flow (kg/h) | 803561 |
| Std Ideal Liq Vol Flow ($m^3$/h) | 2174 |
| Molar Enthalphy | 10016 |
| Molar Entrophy | 183 |
| Heat Flow | 424414151 |
| Act. Volume Flow($m^3$/h) | 12924 |
| $CO_2$ Molar flow (kgmole/h) | 4237 |
| MDEA Amine Molar Flow(kgmole/h) | - |
| $H_2O$ Molar Flow(kgmole/h) | 2675 |
| Methane Molar Flow(kgmole/h) | 35461 |

### *2.4 Cost Estimates of CAPEX*

For the calculation of CAPEX the following assumptions were made and used in the ASPEN Calculations:

- $N^{th}$ of a kind -the first plant will be more expensive
- New plant
- Generic cost level (Rotterdam)
- Brown site (existing industrial area)
- Extension of the existing plant
    - No new operating organisation

    - Using the existing control system
    - Using existing office and welfare buildings
    - Using existing infrastructure, power, steam, cooling water, process water, demineralised water etc.
- No extra pre-treatment of the flue gas
- $CO_2$ to be delivered at 70 bar, 20 °C
- Natural gas to be delivered at 70 bar, 20 degree °C
- Flue gases are brought to the capture plant
- All utilities are brought to the capture plant
- Owners cost is not included
- 2013 Cost level
- Detailed factor estimate as used in $CO_2$ Capture Project (CCP) (CCP1-2006 & CCP2-2009)[**3,4**]

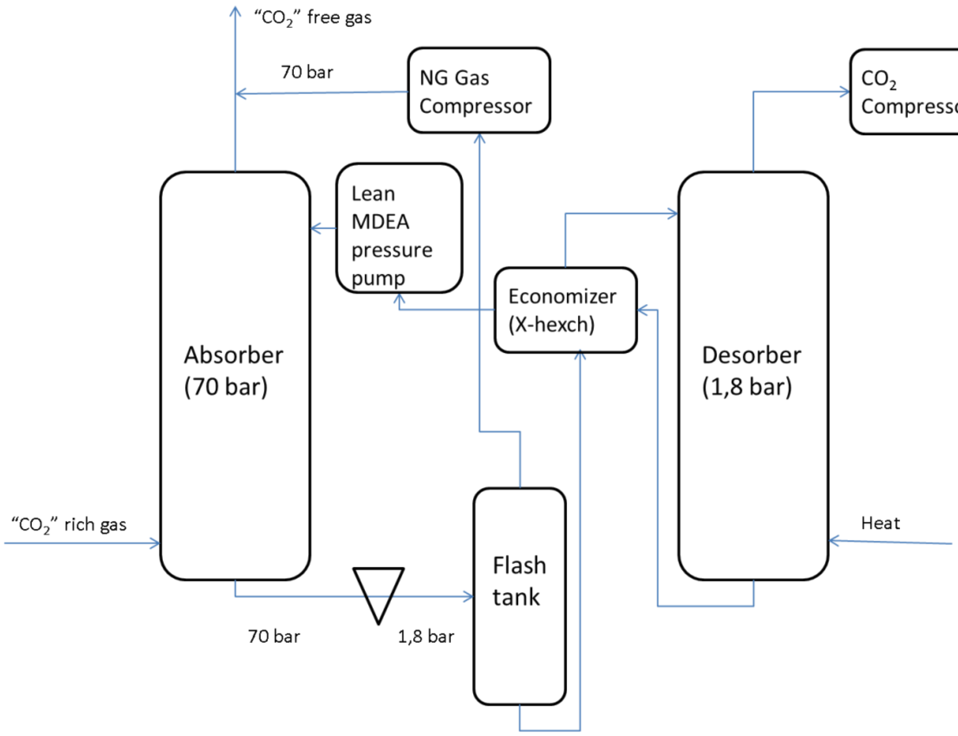


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Fig.4. PFD for the MDEA sweetening process

### *2.5 Cost Estimates of OPEX*

Table 1: Cost data used in economic calculations of OPEX (assumptions)

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| Price List | Unit Cost (*€/unit*) | Unit |
|---|---|---|
| Electric power | 0.10 | kW |
| Steam | 12.50 | tonne |
| Natural Gas | 0.25 | $Sm^3$ |

| | | |
|---|---|---|
| Town water | 0.1 | $m^3$ |
| Cooling water | 0.03 | $m^3$ |
| Amine replacement | 1.80 | kg |
| Na2CO3 | 0.58 | kg |
| Active coal | 5.50 | kg |
| Corrosion inhibitor | 1.88 | kg |
| Destruction of amine waste | 0.25 | kg |
| Operator | 55 | hours |
| Engineer | 70 | hours |
| Maintenance in % of CAPEX/year | 4 | % |

The economic parameters used in the simulations are shown in Table 4.

Table 4. Economic Parameters used in the simulations

| Economic parameter | Value | Unit |
|---|---|---|
| Rate of return | 7 | % |
| No of operating years | 23 | years |
| Construction time | 2 | Year |
| Capture cost | | Not avoided cost |

## 3. Results

### *3.1. Cost Estimate for $CO_2$ Capture from Natural Gas*

The results show that the cost of removing $CO_2$ from natural gas is 30% lower than the cost of the conventional amine MEA technology for $CO_2$ capture from flue gas. The capture cost for a generic location for a natural gas cleaning plant is 35€/tonne. In a remote location it can be up to 40 €/tonne. A similar cost estimate for post combustion capture of $CO_2$ from a Natural Gas Combined Cycle (NGCC) using MEA using the same amount captured and the same assumptions resulted in a cost of 50€/ton. The cost of natural gas purification is therefore significantly lower than for capture from power plant exhaust [5].

This puts this project at a much lower cost than capture from other industrial $CO_2$ sources. The significant reduction in cost is reasonable due to higher pressures in the MDEA process which results in reduced absorber size, therefore reduced energy consumption in the stripper, significantly reducing both energy consumption and investment costs. The amount of $CO_2$ captured is 131 ton/h which means the capture ratio of $CO_2$ is 70%.

Table 5. Results of the Cost Estimation.

| Location | CAPEX (*k€*) | OPEX (*k€/yr*) | Capture Cost (€/ton) |
|---|---|---|---|
| Generic location | 60000 | 33272 | 34.2 |
| Remote location | 90000 | 34470 | 37.8 |

The total cost of CCS for a project utilizing $CO_2$ from natural gas is compared with CCS using post combustion capture in Fig. 5. The costs of transport and storage have not been calculated for the sweetening plant as the exact location has not been determined, but it is reasonable to assume that it will be close to a storage site, resulting in low transportation costs. The only difference in cost is therefore the capture cost which is significantly lower from natural gas. A transport cost of 10€/tonne is assumed and the storage cost is assumed to 7€/tonne. The total cost for Capture, transport and storage for the natural gas project is therefore based on these assumptions of transport and storage costs only 50€/tonne.

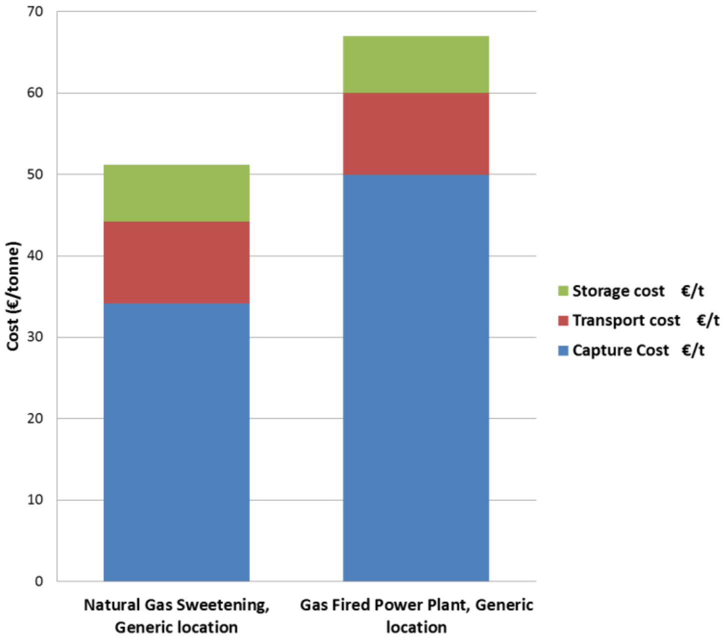


Fig. 5: CCS Project cost
Costs are N'th of a kind (NOAK) capture technology

In Norway the total offshore $CO_2$ tax and ETC fee is 450 NOK per tonne i.e.55€/tonne.[5], making these projects close to economically viable, particularly if the $CO_2$ can be used for EOR. It is also believed that the project will cost even less per tonne of $CO_2$ removed as the starting concentration of $CO_2$ is increased. This is an assumption and has not been cost estimated in this work.

Natural gas sweetening projects can capture potentially larger volumes of $CO_2$ than many industrial projects if the fields are large. Therefore storing up to 3 M tonnes/year may be feasible and such a project could therefore kick-start either of two scenarios:

- A central large scale $CO_2$ storage site in the North sea for example at the Johansen formation which is close to other oil and gas fields and industry. This would have reasonably low transportation costs for the $CO_2$ as well as lower storage costs due to large scale. There would be a land based hub for shipping the $CO_2$ out to the central storage site.
- An offshore EOR project where the $CO_2$ produced from this process and stored at a central hub close to several new oil fields could be utilized for $CO_2$ enhanced oil recovery ($CO_2$-EOR) at whichever nearby oil field that may need it. In addition to large volume it is critical for an EOR project to provide a continuous source of $CO_2$ for the duration of the project that is usually 5 years. Natural gas sweetening projects would meet this critical factor of steady supply of $CO_2$.

It is not realistic to retrofit existing offshore oil production fields to accommodate EOR as the shut-down period likely would be too long for such a project to be economically viable. EOR projects should be considered for new developments which must be set up to accommodate EOR projects during the initial field development and construction phase by making the correct materials choices among other things. This would prevent a long production stop after the field is in operation in order to start an EOR project. An EOR project represents a win-win situation as it combines $CO_2$ capture from industries that need CCS with the use of $CO_2$ injection to increase oil production, thus financing a significant element of the project.

The reason earlier EOR projects in Denmark and Norway did not materialise was mainly due to; insufficient amounts of $CO_2$ (at least 2-5 M tonnes per year); the high costs of retrofitting existing infrastructure with CCS, and most importantly the loss of creating revenues in the standstill period for retrofit. Urgent action is therefore needed to implement EOR while new oil and gas developments are still taking place.

## 4. Conclusions

The results show that the cost of removing $CO_2$ from natural gas is 30% lower than the cost of the conventional amine MEA technology for $CO_2$ capture from flue gas. At a cost of 35 €/tonne the total cost of a CCS project could be about 50€/ton making it close to economically viable  in Norway at least where the combined $CO_2$ taxes and certificate fees total 55€/tonne**.**

Natural gas is produced in large volumes, therefore the sweetening projects can capture potentially large volumes of $CO_2$.  The large scale would provide the necessary amount and steady supply of $CO_2$ needed to kick-start deployment of CCS. This could happen either by allowing large-scale offshore $CO_2$ storage or offshore EOR projects. In addition to large volume it is critical to provide a continuous source of $CO_2$ for the duration of an EOR project that is usually 5 years. A large scale EOR project would create a market for $CO_2$ in the Nordic region that also the land-based industry can sell to and thereby reducing their costs for CCS allowing start of industrial CCS projects.

Indeed, the combination of $CO_2$ -EOR with permanent $CO_2$ storage in oil reservoirs may be a critical, near-term solution for creating economically viable CCS projects, facilitating early CCS infrastructure – and kick-starting deployment of CCS. Urgent action is needed to implement EOR while new oil and gas developments are still taking place otherwise the cost will likely be prohibitive.

Finally, an interesting aspect is that $CO_2$-EOR can provide the necessary value creation to allow developing remote gas fields that were previously considered not viable due to the high $CO_2$ content.

## 5. Acknowledgements

This publication has been produced with support from the NORDICCS Centre, performed under the Top-level Research Initiative $CO_2$ Capture and Storage program, and Nordic Innovation. The authors acknowledge the following partners for their contributions: Statoil, Gassco, Norcem, Reykjavik Energy, $CO_2$ Technology Centre Mongstad, Vattenfall and the Top-level Research Initiative (Project number 11029).

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