Feasibility of Danish CCS Scheme Comprised of Capture at Power Plants, Ship Transport and CO_2 EOR

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Feasibility of Danish CCS Scheme Comprised of Capture at Power Plants, Ship Transport and CO_2 EOR

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Sammendrag

Den såkaldte "Copenhagen Accord" har som målsætning at begrænse den gennemsnitlige stigning af den globale temperatur til 2 °C over de præindustrielle niveauer. Målsætningen indebærer et loft for den tilladte koncentration af drivhusgasser i atmosfæren, herunder CO_2.

Carbon Capture and Storage (CCS) er en teknologi der kan nedbringe bidraget af CO_2 til atmosfæren, ved at opsamle CO_2 fra store punktkilder og deponere den permanent dybt nede i undergrunden.

Fossile brændstoffer står i dag for omkring 80 % af den samlede energiforsyning i Danmark. Tidligere i år (februar 2011) fremlagde den danske regering sit energiudspil, den såkaldte "Energistrategi 2050" der beskriver de energipolitiske virkemidler der skal til for at gøre Danmark uafhængig af kul, olie og gas inden 2050. Kort fortalt, er de centrale elementer i strategien øget energieffektivisering, udbygning af vindenergi og øget brug af biomasse. CCS indgår ikke som et centralt element i strategien, men nævnes dog som en ikke uvæsentlig faktor, især på lang sigt. CCS kan være vigtig for fortsat drift af eksisterende kraftværker indtil bedre alternativer findes. Opsamlet CO_2 kan også kan bruges til såkaldt Enhanced Oil Recovery (EOR) der kan mindske konsekvenserne af den faldende olieproduktion i den danske sektor. Efterspørgslen på olie og gas forventes nemlig at overstige de danske ressourcer i 2018.

Nærværende undersøgelse sigter på at belyse gennemførligheden af en dansk CCS-plan omfattende CO_2-opsamling på kystnære fossilt fyrede kraftværker, borttransportering på små fartøjer, som ikke nødvendigvis er designet til CO_2-transport alene, samt injektion af CO_2 ved Enhanced Oil Recovery. Endemålet med undersøgelsen er at give en overordnet indsigt i hvorvidt den fremsatte CCS-plan ville kunne fungere og, som konsekvens heraf, hvorvidt en mere tilbundsgående undersøgelse bør overvejes.

En evaluering af den danske situation i relation til CCS viser at der er rigelige mængder af CO_2 til rådighed, primært produceret i større kystnære fossilt fyrede kraftværker. Samtidig kan det fastslås at der er et behov for EOR, potentielt CO_2 EOR, for at imødegå den stagnerende olieproduktion. Potentielle scenarier for opsamling, transport og injektion er i høj grad stærkt knyttet til den geografiske beliggenhed af CO_2-kilder og lagrings/injektions-faciliteter.

To potentielle scenarier er blevet undersøgt:

1. Opsamling på et mindre 378 MW kraftværk (Esbjerg) tæt ved oliefeltet.
2. Opsamling på et større 1,000 MW kraftværk (Asnæs) længere væk fra oliefeltet.

Kraftværket i første scenarie udleder omkring $1.7 \cdot 10^6$ tons CO_2 om året, mens det større kraftværk udleder omkring $4.5 \cdot 10^6$ tons CO_2 om året.

Baseret på en overordnet vurdering af de tekniske, juridiske samt finansielle aspekter af de undersøgte scenarier er der draget en række konklusioner.

Konklusioner	
1.	CCS planen er teknisk mulig at gennemføre, men der er behov for at afprøve og demonstrere teknologien på kommercielle vilkår.
2.	Opsamling af CO_2 på de danske kraftværker kan være med til udvikling af kulstoffattige samfund.
3.	Det er i denne tid at alle muligheder står åbne for EOR i den danske oliebranche.
4.	Kombinationen af teknisk usikkerhed og finansiel risiko kan stå i vejen for indføring af CO_2 EOR.
5.	Danske organisationer, virksomheder og universiteter har stor og dybtgående ekspertise, som kan være rigtig nyttig ved fremtidige CCS / CO_2 EOR projekter. Det forventes, at fremtidige projekter ville kunne leveres med overvejende danske ressourcer og kompetencer.
6.	Den danske shipping- og olie & gasindustri kan få en aktiv rolle i bestræbelserne på at opnå et kulstoffattigt samfund.
7.	CO_2-transport med skib er en fleksibel løsning med tilsvarende kort opstartstid.
8.	Analysen af de to forskellige scenarier viser, at transport-logistikken kan løses af to små (5.000 m^3 hver) CO_2 fartøjer i scenario 1 og med tre store (15.000 m^3 hver) CO_2 fartøjer i scenario 2.
9.	Ombygning af eksisterende, eventuelt danske, LPG-tankskibe kunne være en mulighed på kort sigt.
10.	De primære udfordringer er af økonomisk, lovgivningsmæssige og politisk art.
11.	CO_2 EOR kan udligne nogle af omkostningerne med traditionel CCS.
12.	Det vil være nødvendigt med betydelig offentlig støtte for at få søsat CCS plan.

Det skal bemærkes, at denne undersøgelse ikke har til hensigt at argumentere for eller i mod CCS, ligesom den heller ikke anbefaler eller fraråder at planen føres ud i livet. Undersøgelsen peger dog på, at CCS-planen i realiteten kunne fungere, og at den potentielt kunne udgøre en række fordele for det danske samfund og erhvervsliv.

Det er vores forslag at en bredere offentlig debat om fordele og ulemper ved CCS, fremmes af myndighederne, de berørte parter, og ikke-statslige organisationer. Dette bør ideelt set også omfatte en vurdering af effekten (i form af omkostninger, emissioner, forsyningssikkerhed osv.) af forskellige langsigtede strategier (vedvarende energi, biomasse, CCS osv.) for det danske samfund, med henblik på udvikling af et kulstoffattigt samfund.

Vi har med stor taknemmelighed modtaget økonomisk støtte fra Den Danske Maritime Fond til nærværende undersøgelse

Executive Summary

The Copenhagen Accord sets a goal of limiting the average increase in the global temperature to 2°C above pre-industrial levels. This translates into a maximum allowable concentration of greenhouse gases, including CO_2, in the atmosphere. Carbon Capture and Storage (CCS) is a means of mitigating the contribution of CO_2 to global warming, based on capturing CO_2 from large point sources and storing it permanently under ground.

Fossil fuels currently supply approximately 80% of the total energy supply in Denmark. Earlier this year in February 2011, the Danish Government presented its strategy "Energistrategi 2050" on how to make Denmark independent of fossil fuels by 2050. In short, the key elements are increased efficiency, expansion of wind energy and increased usage of biomass. CCS is not a key element in the strategy but is mentioned as it can potentially play an important role, especially in the long-term. It seems reasonable to assume that CCS could be important to allow continued operation of existing power plants until better alternatives become available. Captured CO_2 can also be used for Enhanced Oil Recovery (EOR) to reduce the impact of the declining oil production in the Danish sector. Denmark's demand for oil and gas is predicted to exceed the domestic supply by 2018.

The current study aims at investigating the feasibility of a Danish CCS-scheme comprised of capture of CO_2 from fossil-fuel fired power plants along the coast, transportation by small ships, not necessarily dedicated for CO_2 only, and injection of CO_2 for Enhanced Oil Recovery. The aim is to give a high-level insight into whether the proposed CCS scheme could potentially work and, consequently, if a more extensive study is worth considering.

A review of the Danish situation with regard to CCS shows that there is plenty of CO_2 available, primarily produced by large fossil-fuel fired power plants located along the coast. It is also concluded that there is an immediate need for Enhanced Oil Recovery, potentially CO_2 EOR, to address the declining oil production. Potential scenarios for capture, transportation and injection are strongly linked to the location of CO_2 sources and storage/injection sites. Two potential scenarios have been studied:

1. Capture at a small 378 MW_e power plant (Esbjerg) close to the oil field
2. Capture at a 1,000 MW_e power plant (Asnæs) at a large distance from the oil field

The power plant in Scenario #1 emits approximately $1.7 \cdot 10^6$ tonnes CO_2 per year while the larger power plant emits approximately $4.5 \cdot 10^6$ tonnes CO_2 per year.

Based on a high-level assessment of the technical, legal and financial aspects of the studied scenarios, a number of conclusions are drawn.

	Conclusions
1.	The studied CCS scheme is technically feasible but needs to be demonstrated at commercial scale.
2.	Capture of CO_2 at Danish power plants could provide a bridge to a low-carbon society.
3.	The window of opportunity for EOR in the Danish oil sector is now.
4.	The combination of significant technical uncertainty and financial risk may become a blocker for widespread implementation of CO_2 EOR.
5.	Danish organisations, corporations and universities have extensive and in-depth expertise that is relevant to a future CCS / CO_2 EOR project as discussed. It is foreseen that a future project could be delivered using primarily domestic resources and skills.
6.	The Danish shipping and oil & gas industry can play an active role in the pursuit of a low-carbon society.
7.	CO_2 transport by ship is a flexible option with comparably short start-up time.
8.	Analysis of two different scenarios demonstrates that the transportation logistics can be solved by two small (5,000 m^3 each) CO_2 carriers in Scenario #1 and by three larger (15,000 m^3 each) CO_2 carriers in Scenario #2.
9.	Conversion of existing, potentially Danish, LPG carriers could be option in the short term.
10.	The key challenges are financial, regulatory and the political will.
11.	CO_2 EOR can offset some of the costs with traditional CCS.
12.	Significant public funding is necessary to get the studied CCS project off the ground.

It should be noted that this study does not aim to make a case for or against CCS. Neither does it specifically propose or oppose that the studied CCS scheme including CO_2 EOR is developed further. However, it does indicate that the studied CCS scheme could work and, if implemented, would potentially bring a number of benefits to the Danish society and industry. It is suggested that more detailed studies are carried out to ensure that enough detailed information is at hand. In general, it is also suggested that a wider public discussion of the pros and cons of CCS is promoted by the authorities, stakeholders, non-governmental organisation etc. This should ideally include an assessment of the impact (in terms of cost, emissions, security of supply etc) to the Danish society of various long-term strategies (renewable, biomass, CCS etc) for a low-carbon society.

The current study has received financial support from the Danish Maritime Fund which is greatly appreciated.

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1 Background

The Copenhagen Accord, confirmed in Cancun, sets a goal of limiting the average increase in the global temperature to 2°C above pre-industrial levels. This translates into a maximum allowable concentration of greenhouse gases in the atmosphere of 450 ppm CO_2-eq – the "450 scenario" (IEA World Energy Outlook 2008 [1], 2009 [2], 2010 [3]). Carbon Capture and Storage (CCS) is a means of mitigating the contribution of CO_2 to global warming, based on capturing CO_2 from large point sources and storing it permanently under ground. Globally, CCS is predicted to deliver 10% of necessary CO_2 reduction by 2030 and 20% by 2050 with 3,500 projects foreseen by 2050 [4]. It is estimated that the costs to halve CO_2 emissions levels by 2050 would increase by 70% without CCS.

The Danish Government has, similar to a lot of other Governments, a clear ambition to reduce Denmark's contribution to global warming by reducing usage of fossil fuels that currently supply approximately 80% of the total energy supply. In February 2011, the Danish Government presented its strategy "Energistrategi 2050" [46] for how to make Denmark independent of fossil fuels by 2050. In short, the key elements are increased efficiency, expansion of wind energy and increased usage of biomass. CCS is not identified as a key strategy but it is mentioned that it can potentially play an important role, especially in the long-term. One option would be to keep some coal-based power production provided that it is fitted with CCS. Another option would be to apply CCS to biomass-fired power plants and thereby achieve a power production with net negative CO_2 emissions.

It seems reasonable to assume that CCS could potentially be important in Denmark for a number of reasons:

1. It could remove the CO_2 emissions from the currently installed fossil-fuel fired power plants and thereby allow continued operation until better alternatives become available.
2. It could create net negative CO_2 emissions if fitted on existing/future biomass-fired power plants that will be necessary as support to wind energy.
3. Captured CO_2 can be used for Enhanced Oil Recovery (EOR) as discussed below.

Captured CO_2 can be used for Enhanced Oil Recovery (EOR) where CO_2 is used to sweep additional oil and gas from an oil reservoir. The Danish offshore oil reservoirs continue to play an important role for Denmark in terms of domestic supply of oil and gas and provide very significant revenue streams to Denmark (in the order of €20 billion over the last five years according to Danish "Energistyrelsen"). However, the production is decreasing fast and several of the oil fields approach a time where it is not financially feasible to continue operation unless the oil production can be maintained above a certain production level.

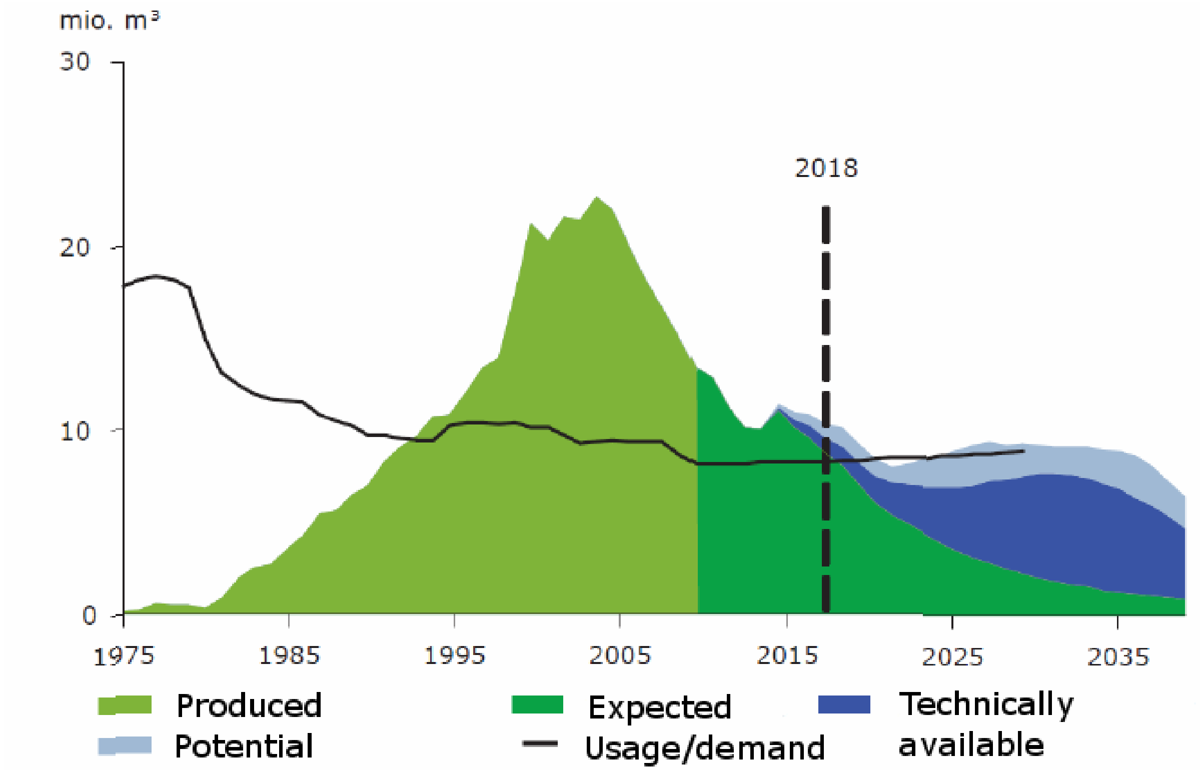


Figure 1. Oil production trend in Denmark. Source: DEA [24].

CO_2 EOR provides an opportunity to extract incremental oil that would otherwise be left in the reservoir. When the oil production becomes critically low, the operation will end and the production facilities decommissioned. Once the reservoir has been decommissioned it is unrealistic to open it again for use with CO_2 EOR due to mobilisation costs. Consequently, there is a real "window of opportunity" where CO_2 EOR has to be put in place soon, say within the coming five-year period, to allow continued operation.

CCS and use of CO_2 for offshore EOR is still in a development phase globally and more knowledge is needed to assess whether it is a feasible and attractive solution for Denmark. As with other new technical solutions of this scale, it is not only sufficient that it can be done technically and makes financial sense but will also have to be seen by the public as an acceptable method with regard to safety, intrusion in the environment etc. The feasibility of a Danish CCS scheme is probably best demonstrated by small-scale demo projects prior to a potential larger deployment. DONG and Vattenfall are currently testing capture technology in Denmark on fossil-fuel fired power stations (Esbjerg and Nordjyllandsvaerket) and for example

Maersk is looking into transportation as well as CO_2 EOR but there is no demonstration project covering the entire CCS chain yet.

The current study aims at investigating the feasibility of a Danish CCS-scheme comprised of:

1. **Capture of CO_2 from, potentially multiple, fossil-fuel fired power plants**. Approximately 80% of Denmark's total energy supply comes from fossil fuels such as coal, gas and oil and the energy production accounts for approximately ¼ of all CO_2 emissions[1]. Fossil-fuel fired power plants are large CO_2 emitters that are suitable for CO_2 capture (large point sources).
2. **Transport of CO_2 by small ships, not necessary dedicated for CO_2 only**. The majority of the power plants in Denmark are located along the coast and can be accessed by ship. Most international projects assume pipeline or large dedicated vessels as transport means. Pipelines cannot be moved once installed and large dedicated vessels require large, constant supplies of CO_2. If it can be shown that the proposed Danish supply chain CCS scheme is feasible, it will enable a domestic CCS supply chain with a much lower threshold of initial investment than other schemes currently being considered. Using smaller vessels and investigating the possibilities of alternate use of the vessels for other liquid, refrigerated cargoes will potentially allow CCS in smaller fields and rapid relocation of both collection and injection parts.
3. **Injection of CO_2 for Enhanced Oil Recovery within the Danish North Sea**. There is a window of opportunity where CO_2 EOR has to be put in place soon to allow continued operation and it is thus reasonable to assume that it is favourable to start with CO_2 EOR and then move on to full-scale CCS. CO_2 EOR will give valuable insight and the incremental oil production will help offsetting some of the costs with demonstrating CCS.

A new market for small scale distributed CCS based on Danish technology and suppliers will not only be beneficial to Danish industry, but also to Denmark in general: the injection of CO_2 will increase oil & gas production, secure a domestic supply of oil & gas and reduce emissions of greenhouse gases, which will help Denmark meet its climate change commitments within the UN-sponsored Framework Convention on Climate Change (UNFCCC). It should also be noted that there is need for CO_2 EOR also in other regions, for example in the UK oil and gas sector. An early demonstration project in Denmark will give the Danish industry valuable experience that can be used later if similar business opportunities are pursued in other regions.

[1] Data for 2008 from "Statistics Denmark". www.dst.dk

1.1 Method

This report does not attempt to be comprehensive or cover the majority of CCS topics but is focused on the specific purpose outlined in the introduction – to investigate the feasibility of a Danish CCS-scheme comprised of capture CO_2 at power plant(s) – transport with ships not necessarily dedicated for CO_2 transport – enhanced oil recovery using captured CO_2.

The attempt of the feasibility study is to give a high-level insight into whether the proposed Danish CCS scheme could potentially work and, consequently, if it is worth considering moving forward with a more extensive study to determine the detailed approach. As a consequence, only those CCS topics that are most relevant for the proposed Danish CCS scheme are described.

The interested reader is referred to any of the many available studies of various aspects of CCS, for example IPCC's "Special Report on Carbon Dioxide Capture and Storage" (443 pages!) from 2005 or IEA's "CCS Technology Roadmap" from 2009. Additional reports, papers and presentations are listed in Appendix A – References.

The content of the study is as follows:

- Section 1 gives a brief introduction to the topic and explains the background to the study.
- Section 2 provides a more detailed description and introduction to the various elements of the CCS chain in terms of technology, financials and legal aspects.
- Section 3 reviews the Danish situation and illustrates potential scenarios for deploying a distributed CO_2 supply chain. A high-level review is made of logistics, financials and challenges.

2 Introduction to CCS

2.1 Reducing Greenhouse Gases in Atmosphere

The Copenhagen Accord sets a goal of limiting the average increase in the global temperature to 2°C above pre-industrial levels. This translates into a maximum allowable concentration of greenhouse gases in the atmosphere of 450 ppm CO_2-eq – the "450 scenario" (IEA World Energy Outlook 2008
[1], 2009 [2], 2010 [3]).

Carbon Capture and Storage (CCS) is a means of mitigating the contribution of CO_2 to global warming, based on capturing CO_2 from large point sources and storing it permanently under ground. The heaviest CO_2 emitters are mainly fossil-fuel fired power plants. A 1,000 MW traditional coal power plant emit in the order of 5 Mt CO2 per year ([21]). CCS is considered a good idea for plants emitting more than 100,000 tonnes of CO_2 annually. Globally, there are around 8,000 plants emitting above this level and in total these sources emit approximately 50% of the global man-made CO_2 emissions.

The figure below shows the necessary CO_2 reduction to achieve IEA's "450 scenario" compared to the reference scenario (business as usual).

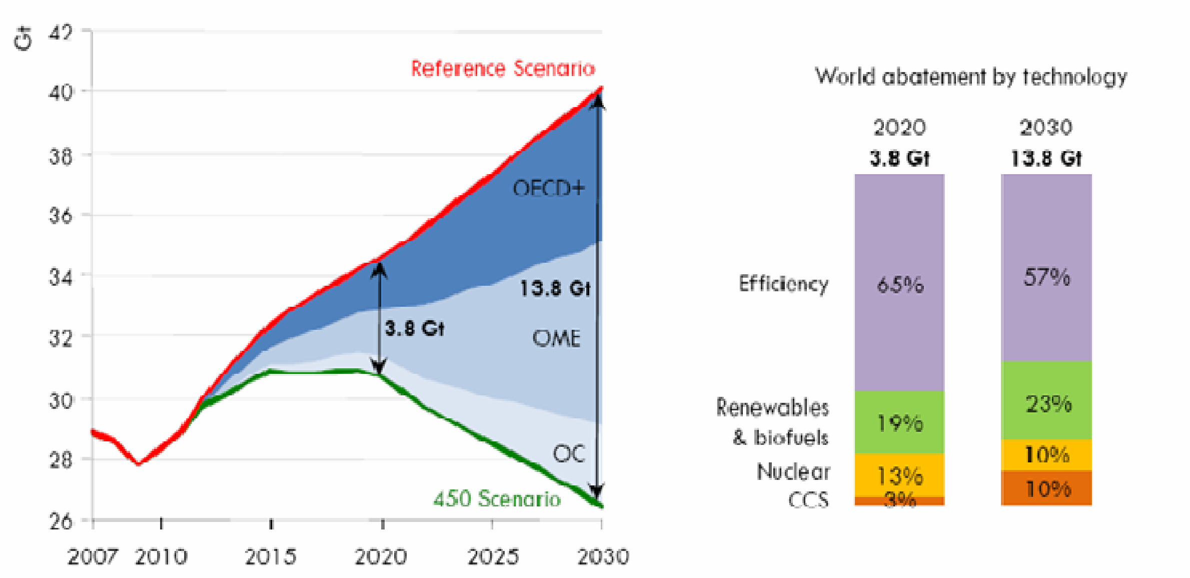


Figure 2. Foreseen abatement of CO_2 by technology by 2020 and 2030. Source: IEA World Energy Outlook 2009 [4].

The necessary reduction is estimated to 3.8 Gt (Giga tonnes) or 3,800 million tonnes by 2020 and a staggering 13.8 Gt by 2030.

Globally, CCS is predicted to deliver 10% of necessary CO_2 reduction by 2030 and 20% by 2050 with 3,500 projects foreseen by 2050 [4]. It is estimated that the costs to halve CO_2 emission levels by 2050 would increase by 70% without CCS.

2.2 Capture

2.2.1 Technology

The study focuses on CO_2 capture from power plants and does not look further into technologies from other sources of CO_2 such as cement factories, refineries and other energy intensive industry. CO_2 capture technology is usually categorized in "post-combustion", "pre-combustion" and "oxy-fuel combustion" as follows:

Post-combustion

Capture of CO_2 from the flue gas by chemical cleaning utilizing an absorbent as illustrated below.

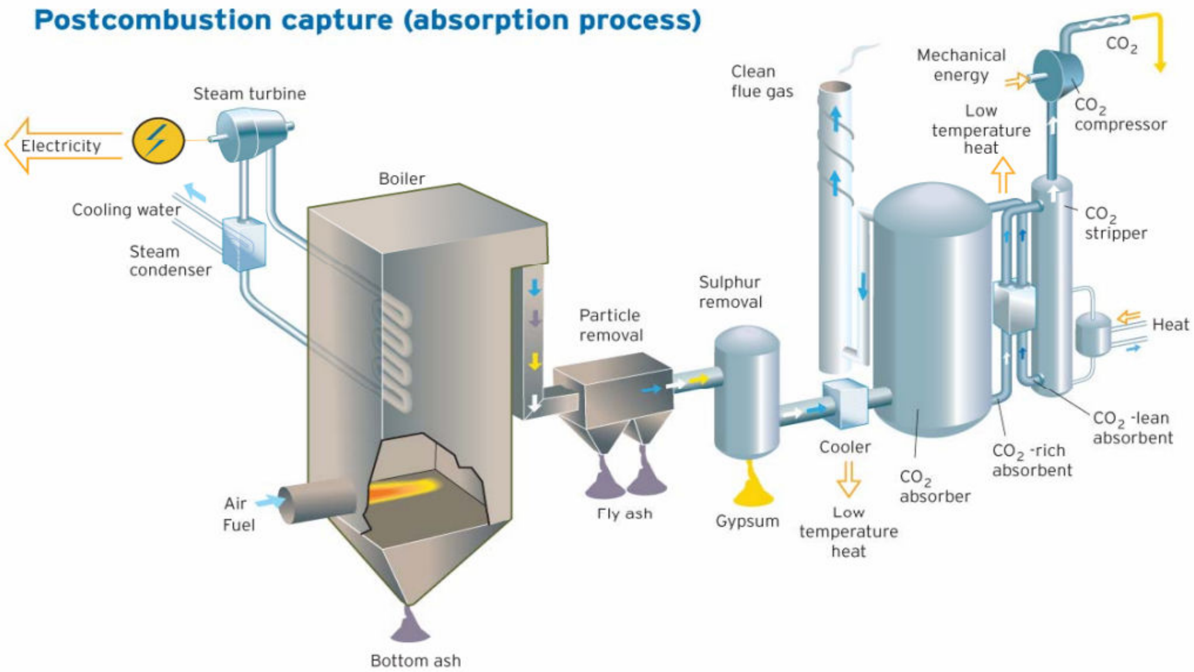


Figure 3. Schematic overview of postcombustion capture technology. Source: Presentation by Weeks D. [7] (Vattenfall / www.kjell-design.com).

Some examples on demonstration projects that utilize postcombustion technology are:

- "**Nordjyllandverket**" (Vattenfall) in Denmark. Nominal power is 400 MW and the plan is to capture 1.8 million tonnes CO_2 per year [21].
- **Porto-tolle project** (ENEL) in Italy. 1.5 million tonnes CO_2 per year.
- **Maasvlakte** project (ROAD consortium) in Rotterdam. 1.1 million tonnes CO_2 per year.

A drawback with postcombustion / chemical cleaning is the high energy consumption, primarily caused by the heat required for regeneration of the absorbent. Additional energy is also required to compress the CO_2 for transport.

The additional energy requirement results in a decrease of the net efficiency which has to be taken into account in the thermo-economic evaluation of a postcombustion system. The overall net efficiency reduction depends on many factors. Numbers in the range of 5-13 percentage points have been reported [11].

There are many examples of commercially available equipment for postcombustion:

- **Econamine FG PlusSM Technology by Flour**. The system is said to be (in 2003) the only commercial-scale CO_2 recovery unit in the world operating on gas turbine flue gas and produces CO_2 of a quality suitable for the food industry, i.e. better than necessary for CO_2 storage/injection.
- **Lummus** (owned by Alstom since 2009).
- **Mitshubishi Heavy Industries** (MHI). Kansai Mitsubishi Carbon Dioxide recovery (KM CDR) Process.

Approximately 80-90% of the CO_2 can be captured. As an example, approximately 4.5 Mt CO_2 per year could be captured from a 1,000 MW coal power plant.

Pre-combustion

The CO_2 is removed from the fuel prior to combustion using a steam reformer that converts the fuel to hydrogen (H2) and carbon monoxide (CO). The CO-gas and steam is then converted into H2 and CO2. Finally, the H2 and CO_2 gas is separated in the same way as in post combustion CO_2 capture as illustrated below.

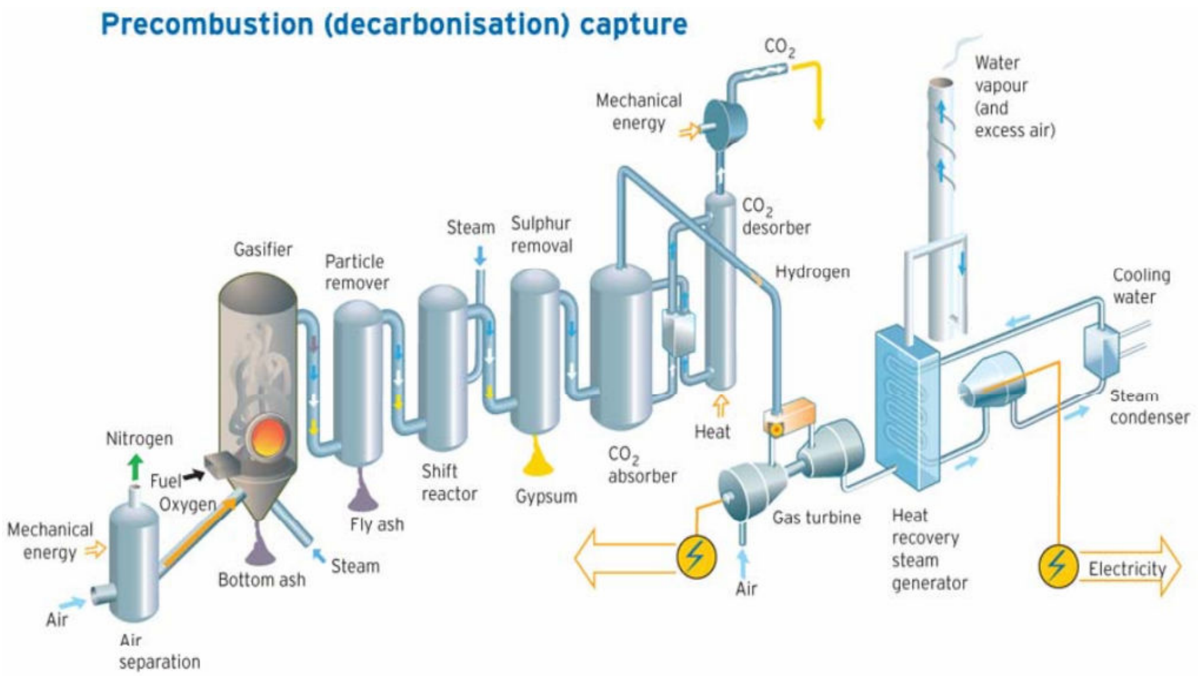


Figure 4. Schematic overview of precombustion capture technology. Source: Presentation by Weeks D. [7] (Vattenfall / www.kjell-design.com).

Precombustion technology is linked to "IGCC" technology (Integrated coal Gasification Combined Cycle), where coal is converted into CO_2 and H_2 before combustion. IGCC represents a large difference from traditional coal power plants since coal will not be combusted directly but rather hydrogen.

An advantage with precombustion compared to postcombustion is that CO_2 is captured on the fuel flow and not on the main exhaust flow. Pre-combustion is only applicable for new power plants because the capture process has to be an integrated part of the combustion process. Examples of challenges are high capital costs and operating gas turbines on hydrogen.

Examples on demonstration projects that plan to use precombustion technology are:

- **Hatfield** project (Powerfuel) in U.K. The project is planned to use IGCC technology.
- **ZeroGen** project in Australia (www.zerogen.com.au)
- **Puertollano** in Spain.
- **Wandoan** project in Australia (GE Energy and Stanwell). www.wandoanpower.com.au
- **Greengen** in China. www.greengen.com.cn

In general, precombustion is not considered to be as mature as postcombustion and can only be applied for new power plants. Net efficiency losses are of the same order of magnitude as for postcombustion.

A fairly recent study by the Kiel Institute for the World Economy [12] showed that IGCC plants with precombustion CO_2 capture is the most financially attractive option for plant operators. The profitability of various options for new coal fired power plants with CCS was assessed using an extensive life cycle analysis for various future scenarios for CO_2 prices, fuel prices etc.

Oxy-fuel combustion

A traditional fossil fuel power plant is operated by combusting fuel and air. Oxy-fuel combustion uses oxygen instead of air. This is very advantageous when it comes to CO_2 capture, as the flue gas is mainly composed of steam and CO_2, which can be very easily separated. 100% of the CO_2 can be captured. The main disadvantage is that the production of pure oxygen makes oxyfuel expensive.

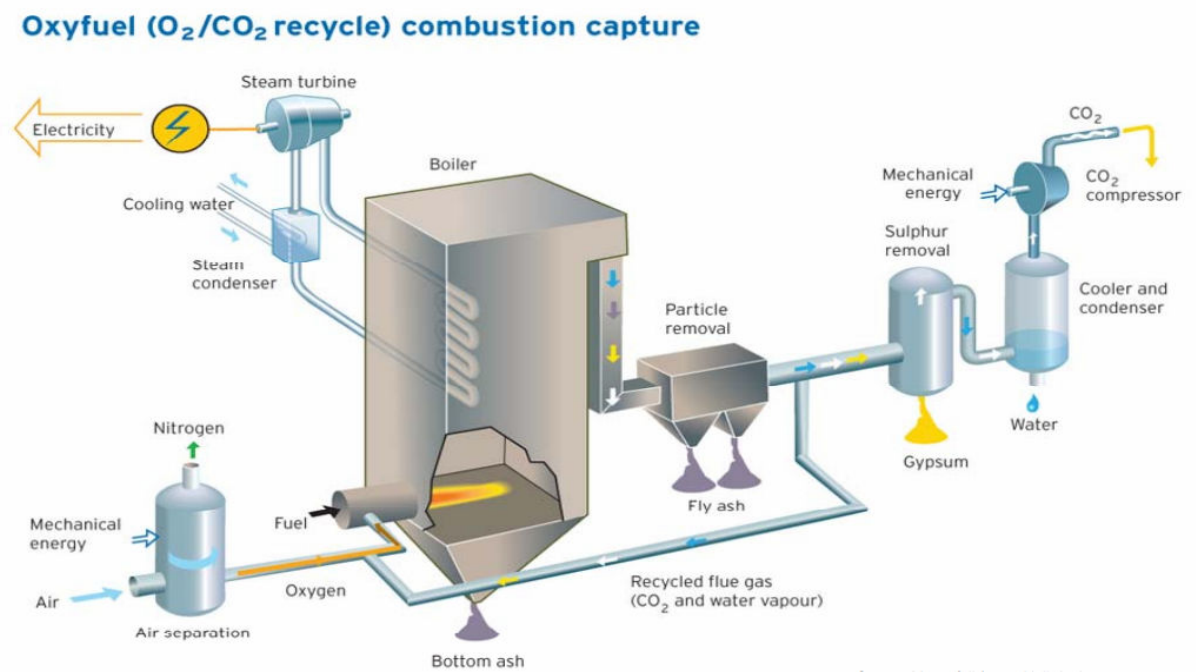


Figure 5. Schematic overview of oxyfuel capture technology. Source: Presentation by Weeks D. [7] (Vattenfall / www.kjell-design.com).

Examples on demonstration projects that plan to use oxy-fuel capture technology are:

- **Schwartze Pumpe** project (Vattenfall) in Germany.
- **FutureGen** project in the U.S.

Challenges

The three main technologies of CO_2 capture mentioned above are considered to be 'close to market' , meaning that they will soon be commercially available. Nevertheless, there is still work to be done to prove that the various concepts work at commercial full-scale.

Another challenge is related to impurities of the captured CO_2. In practice, it is not possible to obtain entirely pure CO_2 but the different capture technologies will produce CO_2 with various levels of impurities (see for example presentation by IEA Greenhouse Gas R&D Programme [13]) including N_2, O_2, Ar, NO_x, SO_x, Hg and other residues from the process. Low levels of impurities are normally not considered a problem but CO_2 is a quite complex substance with a phase diagram that is very sensitive to impurities as illustrated below.

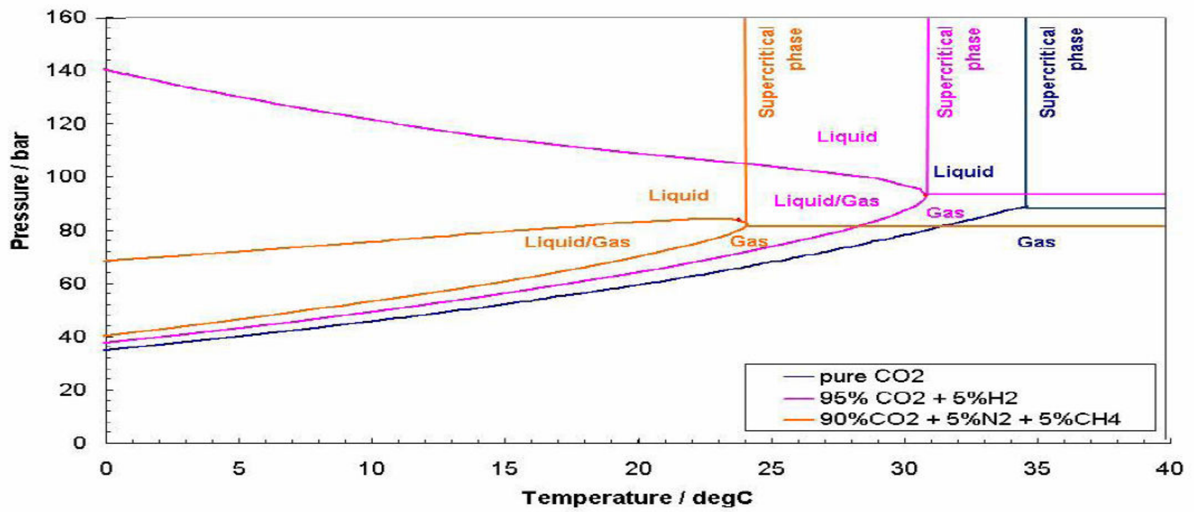


Figure 6. CO_2 phase diagram and influence of impurities. Source: [28]

As shown, even moderate impurity levels might alter the state of the CO_2 significantly. If for example the design pressure/temperature condition has been set to 100 bar / 30 degC this corresponds to supercritical phase for pure CO_2. Presence of 5% H_2 changes the phase diagram so that this pressure/temperature condition now corresponds to the liquid phase.

Examples of other problems with impurities include:

- It will (negatively) impact the integrity and fracture properties of equipment and pipelines where presence of liquid water can cause very severe corrosion.
- It will (negatively) impact the CO_2 hazard profile

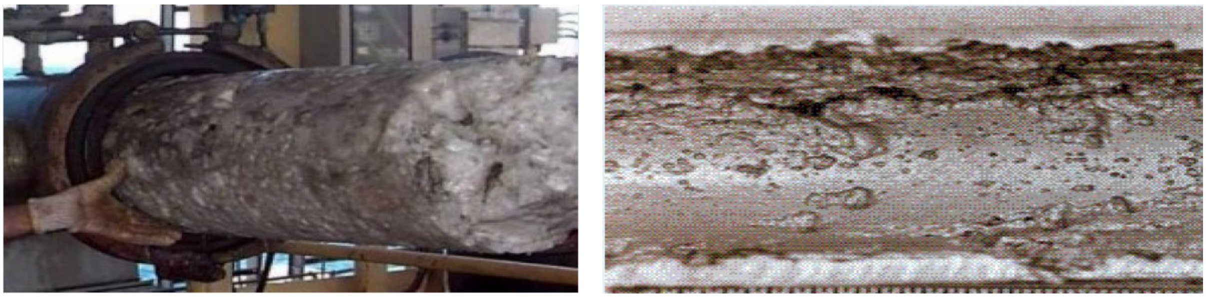


Figure 7. Examples of negative impact of CO_2 impurities. Left: hydrate formation. Right: corrosion on inside of pipe due to water. Source: [28]

It will not be technically and financially feasible to remove all impurities from captured CO_2 but the problem can still be handled. Examples of potential measures to manage risks with impurities are:

- Better understanding of the effect in order to determine allowable levels. Research is underway, see for example [13] and [28].
- Regulations of allowable impurities. This will be key to ensuring that CO_2 captured from various industry sources can be transported in a common transportation network, for example an international pipeline network as for natural gas.

2.2.2 Financials

From the perspective of a power plant operator, the additional cost to capture CO_2 can be split into at least four categories:

1. Cost of capture equipment
2. Cost of power capture process
3. Cost of transporting CO_2 away from the site. Depending on the transportation type, additional cost may also occur for temporary buffer storage at site.
4. Cost of storing CO_2

Categories 3 and 4 are described in the following chapters and are not discussed further in this section.

The total cost related to the capture process itself (items 1 and 2 in the list above) is dependent on a large number of factors and changes as the technology is being developed. Some examples of estimations in publicly available studies are described in the table below. The cost does not include liquefaction necessary for ship transportation.

Table 1. Estimated cost for CO_2 capture.

Source of information	Type of plant	Cost (€/tCO_2)
McKinsey & Company. Report *Carbon Capture & Storage: Assessing the Economics*. 2008.	new 900 MW net output coal plant	25-32 (higher to retrofit)
Lako P. Report *Options for CO2 sequestration and enhanced fuel supply* . [31]	600 MW pulverised coal-fired	35-50
Pöyry. *Report Analysis of carbon capture and storage cost-supply curves for the UK*. 2007. [32]	Retrofit of coal power stations in UK	26
Report *Developing a CCS network in the Tees Valley Region* by Elementenergy and CarbonCounts [30]	Average cost for CO_2 capture on 5 new/existing coal power plants in Tees Valley	30
IPCC Special report on CCS. [42]	New pulverized coal plants	20-35

Informal discussions with people in the industry indicate that the cost may be considerably higher than in the table above, maybe up to 80 €/tCO_2, when using the technology available currently. The reason for the higher estimate is believed to be related to a more optimistic view by the available public feasibility studies about future improvements in performance and cost of capture technologies due to technical development and scale-up effects.

To put the number for the cost of CO_2 capture into a context, it is noted that the current "cost of CO_2" in the form of one EUA emission right (one European Union Allowance unit equals one tonne of CO_2) is approximately € 15 when traded in Europe. Consequently, the cost for a power operator to vent the CO_2 directly to the atmosphere is in the order of €15/tCO_2 which is less than half of the cost to capture the CO_2. This is a very simplified comparison but serves as an interesting illustration.

2.2.3 Safety Regulations

In addition to CO_2, the capture process will also bring large quantities of other hazardous substances onto power plant sites, for example ammonia, hydrogen and oxygen, depending on the chosen capture technology. All of these substances are harmful to humans at sufficiently high concentrations.

These toxic substances must be handled using appropriate safety routines. From this perspective, CO_2 capture is not different to an ordinary chemical plant where the same substances have been used safely for many decades following local regulations for handling of toxic substances.

The capture part of CCS should not pose any significant challenges as long as the equipment and operation comply with local regulations for health, safety, environment etc.

2.2.4 Summary

Summary: capture of CO_2 from power plants

- CO_2 capture technology has been demonstrated in small scale on several power plants around the world
- There are three major technologies – postcombustion, precombustion and oxyfuel.
- Work is underway to validate the technology for commercial scale operation
- The cost of the capture (capex for equipment and increased operational costs) depends on many factors but is in the order of €25-80 per tonne CO_2 for a traditional coal-fired power plant.
- The cost is believed to be the biggest challenge and is currently several orders of magnitude more expensive than letting out the CO_2 directly in the atmosphere.

2.3 Transport

2.3.1 Technology

There are two commercially realistic transport options: pipelines and ships.

The pipeline alternative

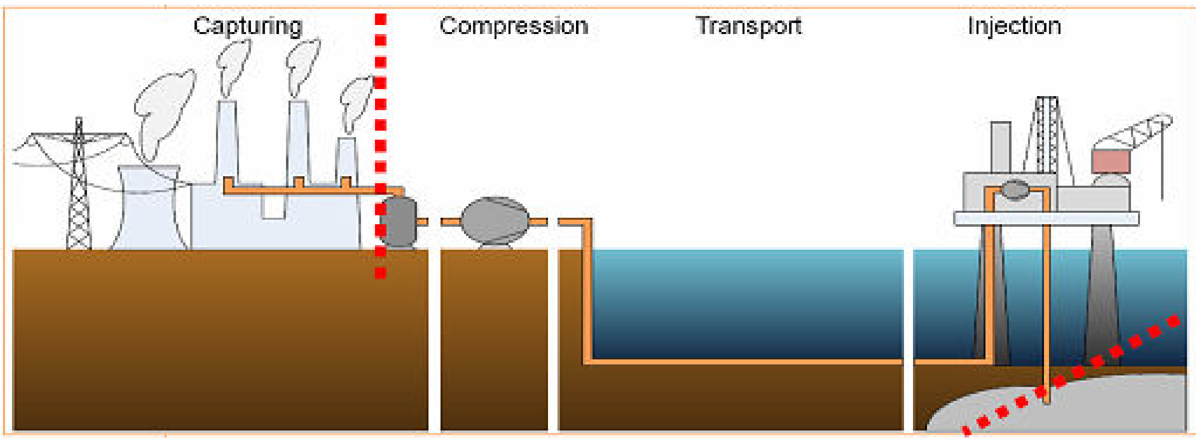


Figure 8. Transportation of CO_2 by pipeline from power plant to offshore reservoir. Illustration: Anthony Veder

Transporting CO_2 by pipelines is not a new idea. In fact, CO_2 has been transported by pipelines in the USA since the 1970s. There is a large network of pipelines for CO_2 transport where CO_2 is pumped up from naturally occurring CO_2 reservoirs and transported to oil fields where it used for CO_2 Enhanced Oil Recovery (EOR). CO_2 is basically transported in ordinary steel pipelines of the same type that are used for natural gas but there are additional technical challenges due to the complex properties of CO_2, especially when impurities are present, and the highly corrosive nature of CO_2 that is not completely free of water content. CO_2 is normally compressed to a high pressure (> 75 barg and 32°C) before pipeline transportation to reduce the volume that needs to be transported and also to ensure that the CO_2 is in a supercritical state to reduce friction and hence energy losses during transportation.

As mentioned in the introduction, the current feasibility study assumes transport by ship and transport of CO_2 by pipeline is therefore not explored or described further. The interested reader is recommended to read a suitable selection of the many papers and presentations on CO_2 pipelines, for example [9], [28], or [35].

The ship alternative

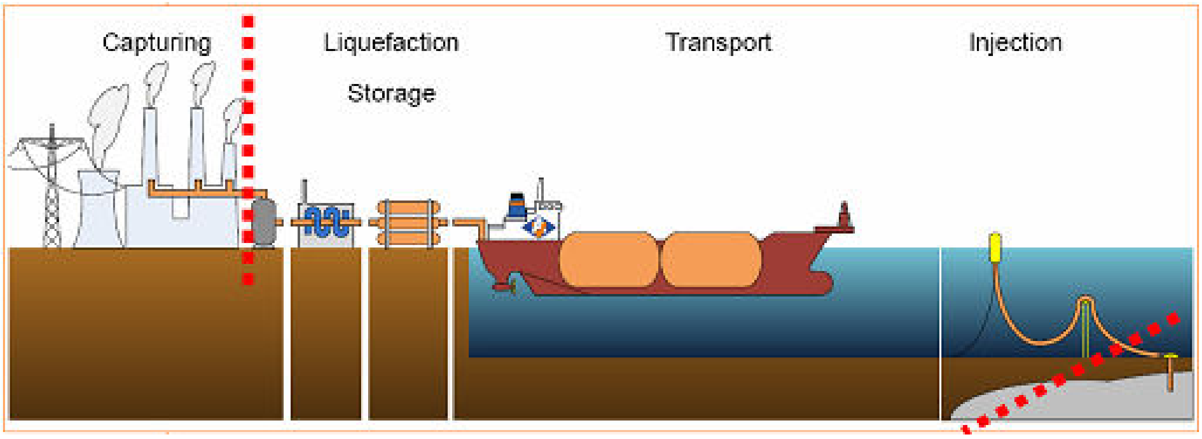


Figure 9. Transportation of CO_2 by ship from power plant to offshore reservoir. Illustration: Anthony Veder

The question whether CO_2 is best transported by pipeline or ship has no definite answer but is dependent on many factors. Some of the advantages of ship transport are:

- **Flexibility**. Ships can mobilize fast, operate between multiple sources, handle variations in capacity and can even change between markets, e.g. CO_2 and LPG, if designed for multiple cargo types.
- **Economy**. This depends heavily on the situation but ships can be cheaper than pipelines, especially for longer distances.
- **Facilitate early deployment of CO_2 transport**. There are available ships already and new larger CO_2 carriers have short lead times compared to new pipelines.

A transport system for CO_2 (for offshore EOR) based on ships would be comprised of at least the following components:

1. Liquefaction equipment
2. Loading facilities at port including buffer storage capacity onshore
3. Ships
4. Unloading facilities offshore, potentially with buffer storage included

It has been assumed that the capture process of the power plant does not include liquefaction.

Transporting CO_2 in liquid form

CO_2 is transported in ships as liquid corresponding to somewhere in the high-lighted area in the phase diagram below. Choosing the best combination of pressure and temperature is not obvious when taking into account technical as well as financial perspectives.

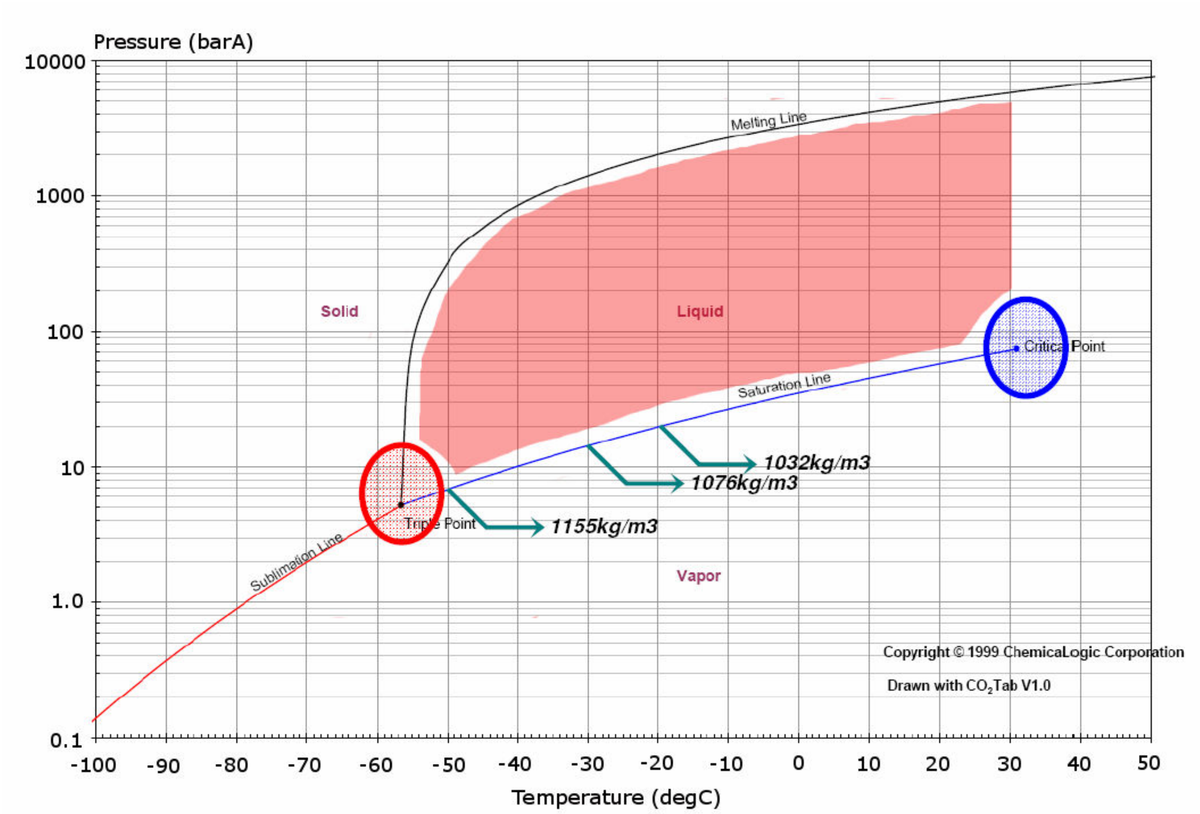


Figure 10. Phase diagram of CO_2.

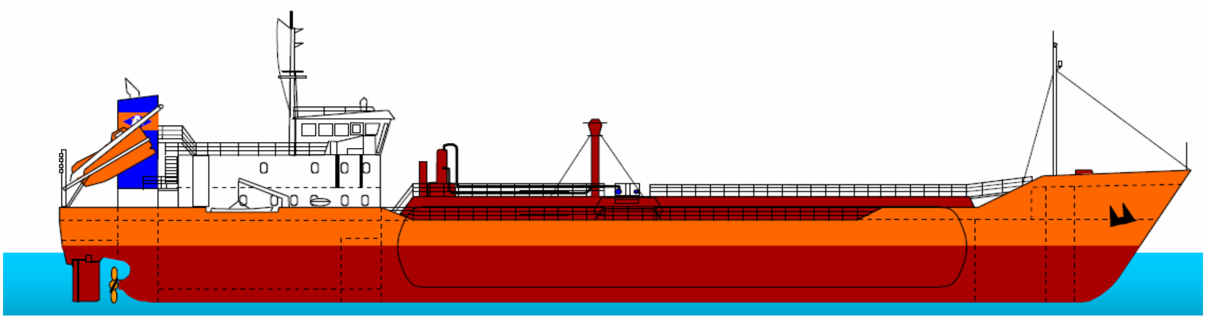
The "triple point" is at -56.5 degC, 5.2 barA. Close to this point, only a small change in pressure/temperature is needed to change the state between solid, liquid and vapour. The "critical point" is located at 31.1 degC, 73.8 barA. Above this condition there are no distinct liquid and gas phases.

In order to make CO_2 transport by ship feasible for larger volumes, the cargo volume must increase which in turn requires lower pressure to keep the tank wall thickness within reasonable limits. CO_2 can exist as liquid at pressure between 5 bar (triple point) and 74 bar (critical point). The density of liquefied saturated CO_2 changes from 1,200 kg/m^3 at the triple point to 600 kg/m^3 at the critical point which means that almost twice as much CO_2 can be stored close to the triple point as close to the critical point for the same storage tank volume. This suggests that storage close to the triple point would be best. Another benefit is the low pressure which is preferable since it keeps the production cost of the vessel down (lower tank wall thickness). On the other hand, the liquefaction process is more expensive for lower pressures. Aspelund et al [36] made an extensive study of the most optimal transport conditions and concluded that economic large-scale transport should be done in semi-pressurized vessels close to the triple point, for example at -50 degC / 6.5 bar. In addition to being a cost-effective combination of pressure/temperature it also enables the use of well-established design criteria for existing commercial LPG carriers.

Liquefaction of CO_2 is not complicated and is basically done by initial compression followed by cooling using an external refrigeration circuit. The CO_2 is then decompressed slightly to achieve a pressure equal to the storage pressure onboard. The initial compression is necessary if the gas is received directly from the capture equipment at the power plant which normally produce CO_2 at low pressure. If the capture plant is located far from the port, the CO_2 will most likely be transported to the port in a high-pressure pipeline and the initial compression would not have to be done as part of the liquefaction process.

Existing CO_2 carriers

Today smaller volumes of CO_2 used for cooling or in food production are shipped from producers to consumers in Europe. The size of these ships is typically up to 1,500 m^3 CO_2 with a pressure of 14-20 bar and a temperature in the range of -40 degC.



LOA	Speed	Tank capacity	Tank temperature	Tank pressure
79 m	12.5 kn	1,240 m^3 CO_2	-40 degC	18 barg

Figure 11. Example of CO_2 carrier "Coral Carbonic" – the world's first purpose built CO_2 carrier. Source: www.anthonyveder.com

The total number of existing CO_2 carriers in use is small, most likely fewer than 10 ships globally, but is expected to increase significantly as the CCS industry grows in the coming decade.

Use of existing larger gas carriers

CO_2 carriers are designed according to the same standard, the International Gas Carrier Code, as other liquid gas carriers, such as LNG (Liquefied Natural Gas) and LPG (Liquefied Petroleum Gas) carriers, and it is expected that future designs will draw heavily on experience from existing gas carriers and will be similar in design.

If existing gas carriers could be used for CO_2 transport it would allow faster mobilisation than if new CO_2 carriers need to be built and the capacity of each ship would be much larger compared to today's existing CO_2 carriers.

LNG tankers come in sizes up +250,000 m^3 but LNG is stored at very low temperature, typically in the range of -160 degC, at a pressure slightly higher than atmospheric pressure. This is quite different from the optimal storage conditions of CO_2 and it is therefore not believed to be feasible to convert LNG carriers for transport of CO_2 or design a new gas carrier capable of alternating between LNG and CO_2 [38].

The LPG market is well developed and there are more than 1,000 LPG tankers in traffic of various sizes:

- Pressure type: capacity < 5,000 m^3
- Semi-refrigerated ('semi-ref') type: capacity 5,000-20,000 m^3
- Low temperature type: capacity > 20,000 m^3

Semi-ref LPG carriers come in sizes larger than existing CO_2 carriers and have storage conditions similar to those required for CO_2 which leads one to believe that it may be possible to convert LPG tankers for CO_2 and/or alternating between LPG and CO_2.

Discussions with for example Lauritzen Kosan in Denmark have confirmed that existing LPG tankers of semi-ref type most likely can be utilized for CO_2 transport in the short-term by reasonable modifications.

LOA	Speed	Tank capacity	Tank temperature	Tank pressure
115 m	16 kn	6,500 m^3 CO_2	minimum -104 degC	max 6 barg

Figure 12. LPG carrier "Isabella Kosan" of Lauritzen Kosan A/S (www.lauritzenkosan.com).

Taking the LPG carrier "Isabella Kosan" as an example, the tank specification would allow transport of CO_2 near the triple point with a capacity of 6,500 m^3 - three times the largest existing CO_2 carriers.

With regard to the possibility of converting existing LPG Type C designs to carry carbon dioxide, the following points are advised:

i/ The relief valves and vent system would need to be given special consideration. The outlet pipework from the safety relief valves and vent mast may require to be redesigned to avoid the formation of solid carbon dioxide on operation of the valves. As carbon dioxide is neither flammable nor toxic the need to use a vent mast may be waived. The possibility of have a discharge outlet, local to the relief valve may be a way forward.

ii/ It is the reliquefaction plant which would need the most redesign or modification. However, if the carbon dioxide is only to be transported for sequestration then its purity would not be a problem and the oil-free compressors used for LPG cargoes would not be required. It is therefore considered that relatively cheap screw compressors could be used. This would then have the advantage to also deal with the high discharge temperatures produced when compressing carbon dioxide using reciprocating compressors. It is proposed that the reliquefaction plant be specially design for both carbon dioxide and LPG services. If a single design was used this would tend to be oversized for carbon dioxide and be relatively small for LPG service. As this would lead to operational difficulties it is proposed that for carbon dioxide an independent plant is fitted.

iii/ It is considered that filling limits would not require to be modified for the carriage of carbon dioxide.

iv/ The design pressure of the vapour system would be dependant on; the maximum design pressure of the cargo tank, the maximum ambient temperature used to determine the pressure of the superheated vapour entrapped in an isolated section due to heat ingress, and a safety margin of say 20%. For the liquid/condensate systems, due to the low critical temperature of carbon dioxide it is inappropriate to determine the design pressure by reference to saturation pressure at the upper ambient temperatures given in the IGC Code. It is up to the designer of the system to decide an appropriate design pressure depending on the anticipated operating and standstill conditions. The design pressure determined for the cargo pipework system would then be pressure limited by a relief valve arrangement.

v/ With regard to discharge manifolds and other off-loading arrangements, the actual required discharge conditions will determine the design. It is considered for sequestration some form of turret arrangement would be the ideal. However, for conversion of the existing Type C fleet, some other form of high pressure discharge arrangement would be required or the ship discharges to a specialist arrangement similar to a TORP buoy. The required discharge or field conditions will determine the design pressure of the system. Offshore unloading poses many challenges and will require additional equipment depending on the unloading and injection scheme, for example Dynamic Positioning (DP), compression equipment and heaters.

vi/ For LPG cargoes the reliquefaction plant is designed with an allowance to deal with vapour and flash gas generated during loading. It is considered that for carbon dioxide cargoes the loading terminal will have a dedicated vapour return facility thus the reliquefaction plant would be sized for pressure maintenance only.

In general, the possibility for conversion depends on many factors and it is likely that only a small portion of all existing LPG carriers are suitable.

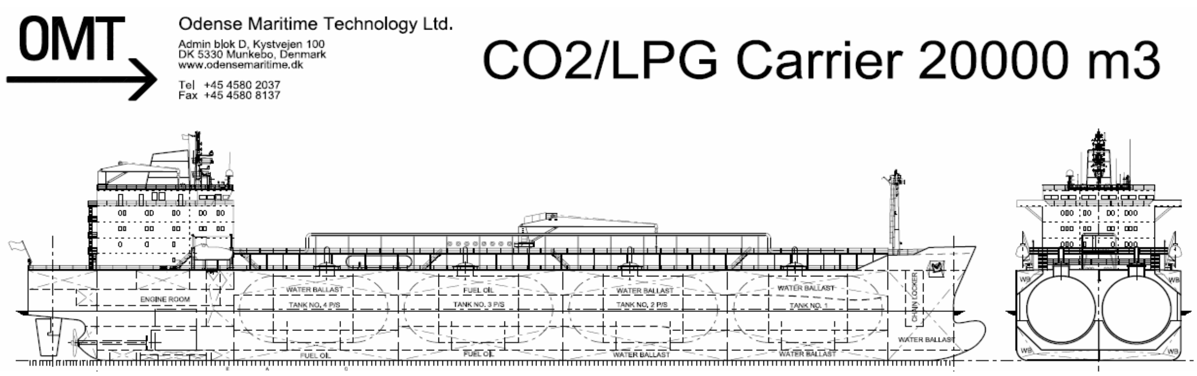
New designs concepts

Many companies have presented new proposed concepts for various size CO_2 carriers in the last few years. Many are based on designs similar to existing LPG carriers with cylindrical or bi-lobe type tanks.

Figure 13. CO_2 carrier concept design by TGE [22].

The concept by TGE shown above is based on a combined CO_2/LPG carrier with storage volumes in the range of 10,000-40,000 m^3 [22].

Odense Maritime Technology in Denmark has a similar concept with details as illustrated below.



LOA	Speed	Tank capacity	Tank temperature	Tank pressure
173 m	16 kn	20,000 m^3 CO_2	-50 degC	max 6.9 barg

Figure 14. CO_2 carrier concept design by OMT (www.odensemaritime.dk).

Maersk Tankers [23] has developed a concept design together with Hyundai Heavy Industries for a multifunctional CO_2/LPG/Ammonia carried for up to 38,000 m^3 at -55°C / 6.5 bar.

There are examples on even larger CO_2 carriers. DSME has published concept designs for CO_2 tankers with up to 100,000 m3 transport volume based on a concept where the CO_2 is stored in liquid form (-50 degC, 6.8 barA) in a large number of vertical tube-shaped tanks.

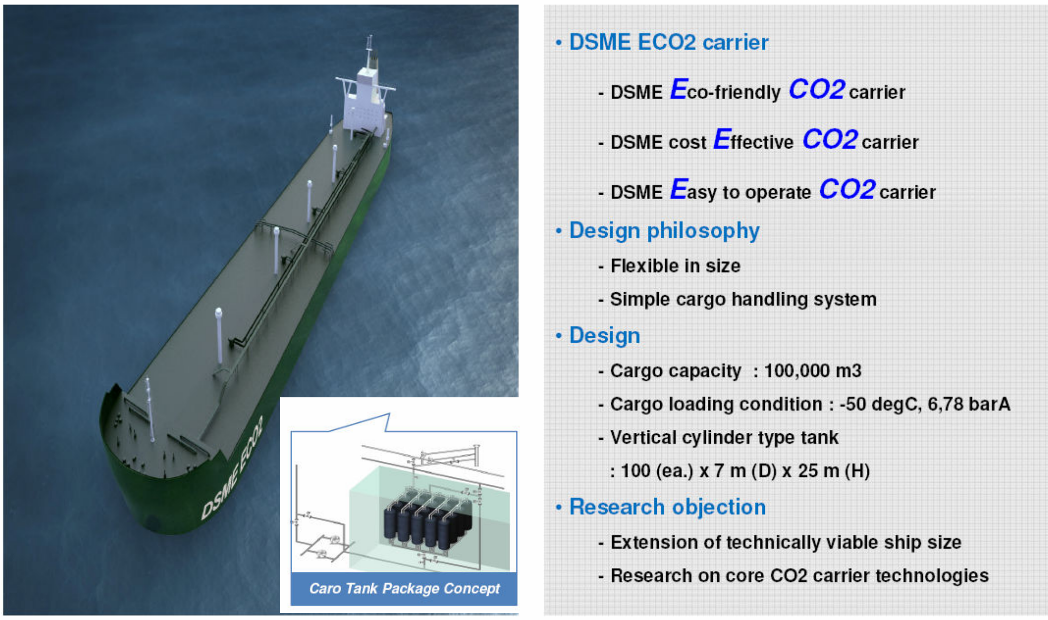


Figure 15. Concept design for large CO_2 carrier by DSME [37].

There are also examples of designs that are significantly different compared to traditional gas carriers, for example the barge container concept by TGE as shown below.

Figure 16. CO_2 barge concept design by TGE [22].

The lead time for a new CO_2 carrier is in the order of 2-3 years.

Loading facilities at port

Loading of CO_2 at port is not technically challenging.

Loading times are dependent on the used equipment at port. Based on available studies by for example MHI [38] it seem reasonable to assume a loading time of 8 hours.

Buffer storage capacity in form of onshore tanks will be required given that the capture process is continuous while the ship loading/transport is not. The necessary storage capacity is entirely dependent on the transport logistics and needs to be determined for each individual case but is not regarded to be a technical challenge. An example of 0.8-1.5 × ship cargo capacity is mentioned in a study by Panaware [40].

Unloading facilities offshore

Unloading CO_2 offshore has not been performed at commercial scale and involves several new challenges related to:

- Operating in harsh weather conditions
- Maintaining required pressure/temperature to avoid phase changes of CO_2
- Compatibility with required/allowable flow rates and temperature of offshore platform / buoy/reservoir

Several different systems designs have been suggested:

- **Discharge at a buoy**. The ship connects to a buoy which is connected to the discharge pipe. There are different options available as illustrated below in Figure 17 and Figure 18. See references [22], [23] and [41].
- **Discharge at another floating unit**. This could for example be a dedicated CO_2 Floating Storage and Injection Unit (FSIU) as proposed by Maersk (Figure 19) or a Floating Liquefaction Storage and Offloading (FLSO) as proposed by TGE (Figure 20).

An important technical aspect of the discharge is the discharge rate (CO_2 volume per time interval) since it influences the transportation logistics. Publicly available information suggests possible discharge rates in the range of 2,200 tonne CO_2/hour (Maersk [23]). MHI [38] assume an 8 hour offloading time for a 50,000 m^3 CO_2 tanker which corresponds to almost 7,000 tonne CO_2/hour. However, the study also concludes that the injectivity of the well will determine the maximum flow rate of the entire system. This is of course dependent on whether the ship discharges directly to the well, to a buoy or to an intermediate FSIU/FLSO with buffer capacity.

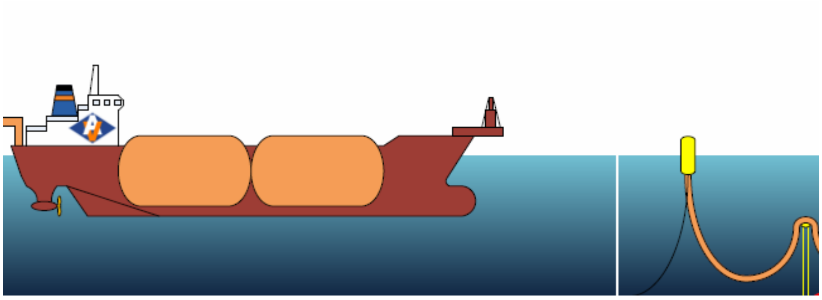


Figure 17. Discharge at socket buoy. Left: overview of system [39]. Right: close-up of bow discharge equipment [22].

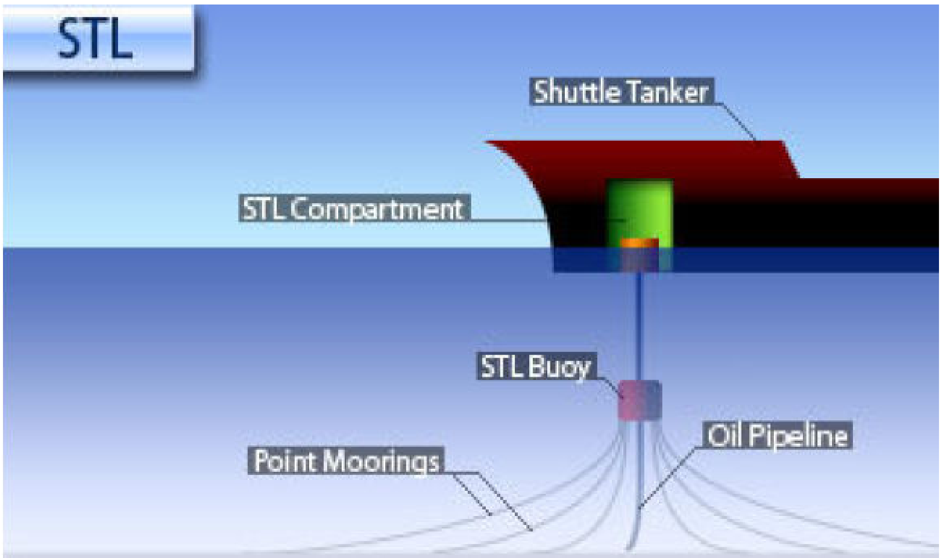


Figure 18. Discharge system with submerged turret off-loading system (STL) [23].

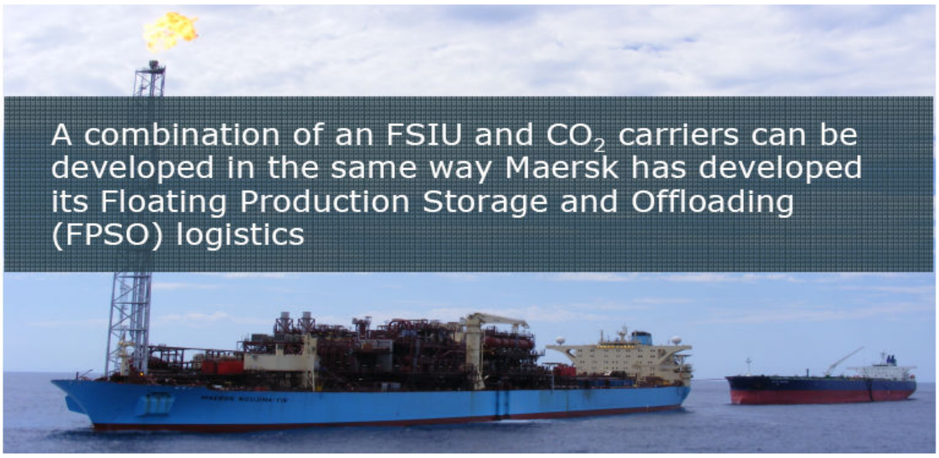


Figure 19. Floating Storage and Injection Unit (FSIU) concept by Maersk [23].

Figure 20. Floating Liquefaction Storage and Offloading (FLSO) concept by TGE [22]

2.3.2 Financials

Traditionally, transportation by ship is cheaper than transportation by pipeline for greater distances and this is likely also true for CO_2 as illustrated below.

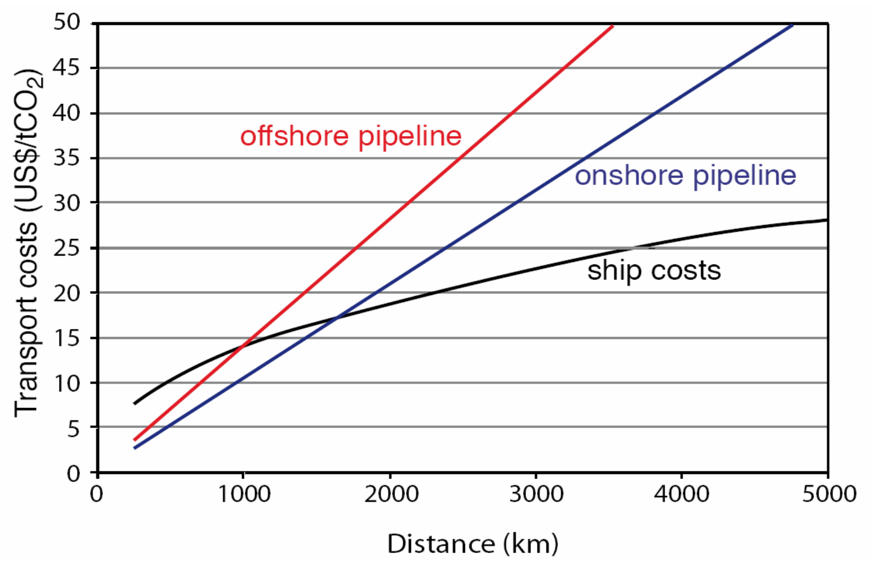


Figure 21. Comparison of transportation costs of pipeline versus ship. Source: IPCC special report on CCS [42].

An overview of the estimated cost in three different studies is shown below.

Table 2. Estimated cost for CO_2 transport by ship.

Source of information	Comment	Cost (€/tCO_2)
MHI report "Ship transport of CO_2" [38] from 2004	- Distance <1,000 km - Ship size 30,000-50,000 tonnes - Liquefaction from atmospheric pressure	13-15
Study by Panaware [40] from 2010	- Distances 180 km, 750 km - Ship size 20,000-30,000 m^3 - "all in" scenario, including liquefaction	13-14
IPCC special report on CCS [42] from 2005. See Figure 21.	- US$13/tCO2 for 1,000 km distance read from Figure 21 - 6 Mt CO^2 per year - Cost include storage facilities, harbour fees, fuel costs, loading, unloading activities and liquefaction	10
Study by Bario et al "Ship-based transport of CO_2" [43], 2006	- 150-200 NOK/tonne for volumes larger than 2 million tonnes/year and distances limited to the North Sea	20

The cost of *liquefaction* is included in the cost estimates given above. If separated out as individual cost, several studies ([36], [38], [40]) indicate a cost in the region of €5-7 /t CO_2.

A significant cost that is *not* included in the estimates above is the cost for compression from the pressure used during transportation, say 6-7 bar, to the pressure required for injection of CO_2 in the reservoir which is in the order of 100-300 bar depending on reservoir. It can be discussed whether this cost should be attributed to the transport or to the injection/storage but it is nevertheless a cost that needs to be taken into account for.

The cost for *new build* of a CO_2 carrier varies considerably. Estimates for a 20,000 m^3 CO_2 carrier are in the order of €40-50 million ([42], stating Statoil and IEAGHG as references). As a comparison, the new build price for a 20,000 m^3 LPG carrier is currently approximately €35 million.

As mentioned earlier, the *cost to modify* an existing LPG carrier to also carry CO_2 is difficult to estimate. The necessary modifications would, most likely, as a minimum include modifications to pumps and adding a bow discharge arrangement. The cost is expected to be at least in the order of €75,000 (US$ 100,000) for a 6,500 m^3 LPG carrier.

It should be noted that the uncertainty in the estimated cost is considerable given that a ship-large-scale based CO_2 transportation system has yet not been implemented so there is no experience to build on when estimating the cost.

2.3.3 Legal

Transport of CO_2 by ship is already happening, albeit at small scale. The safety requirements of the ships are governed by classification rules of the various classification companies such as Lloyd's Register, Bureau Veritas etc.

The "London Convention" (IMO) was one of the first global conventions to protect the marine environment from human activities and has been in force since 1975 [57]. It was later followed by the "London Protocol" that entered into force in March 2006 and currently has 38 Parties. Under the Protocol all dumping is prohibited, but Parties may issue permits to allow the dumping of certain materials including carbon dioxide streams from carbon dioxide capture processes for sequestration (CCS).

Unless the cargo tanks are capable of withstanding the saturated vapour pressure of the cargo at ambient temperatures of 45°C air and 32°C seawater, then some form of cargo temperature/pressure control is to be provided. The International Gas Carrier (IGC) Code stipulates that carbon dioxide can be carried in a type 3G ship which only requires moderate preventive measures to preclude the escape of the cargo. As carbon dioxide is one of the six greenhouse gases legislated against by the Kyoto Protocol venting it to the atmosphere is restricted. However, in accordance with the Chapter 7, paragraph 7.1.1.5 of the IGC Code, the final acceptance of allowing cargo to be vented lies with both the ship's Administration and the relevant Port Authorities.

Studies by for example IPCC [42] and IEAGHG do not identify significant legal challenges that would hinder a future expansion of CO_2 shipping.

2.3.4 Summary

Summary: transport of CO_2 by ship

- Some of the benefits with transport by ship include flexibility with fast mobilization, operation between multiple sources and even between markets, e.g. CO_2 and LPG, if the ship is designed for multiple cargo types.
- CO_2 is already transported by ship, albeit at small scale.
- Scaling up of the transported CO_2 volume requires substantially larger ships.
- Several concept designs have been presented by DSME, TGE, OMT and others
- The lead time for a new CO_2 carrier is approximately 2-3 years.
- Existing LPG carriers of semi-ref type can be modified to be able to also transport CO_2. This would give "immediate" additional capacity but requires investments in modifications and increased operational costs.
- The cost of transport (including cost of liquefaction) dependens on many factors but is in the order of €10-20 per tonne CO_2 for modest distances using a new-build CO_2 carrier of approximately 20,000 m^3 size

2.4 CO_2 Enhanced Oil Recovery

2.4.1 Technology

History

Large-scale onshore injection of CO_2 for EOR has been carried out for more than 30 years in the U.S and Canada where more than 3.5 million metric tonnes of CO2 has been injected so far [14] in the IEA Weyburn project to give one example. Another example is the onshore In Salah Gas CO_2 Storage Project in Algeria. Gozalpour [16] report about more than 80 CO_2 EOR projects worldwide.

Potential to grow the CCS industry

CO_2 for EOR is increasingly seen as a potentially favourable option to help growing the CCS industry. Some of the reasons for this are:

1. Injection of CO_2 can potentially mobilize more oil, thereby offsetting some of the costs with demonstrating CCS.

2. Several of the oil fields in the North Sea are thought to be approaching cessation (end) of production. CO_2 EOR could potentially increase the oil production to the point where it is financially viable to continue production for a number of years if the EOR can start before it is too late ([9], [24]).
3. At the end of an EOR project the reservoir is considered depleted: at this point, the reservoir can be considered as a potential CO_2 storage site – i.e. storage in a depleted oil/gas reservoir.

Overview

In short, EOR is a term for a range of methods to increase oil production by a combination of reducing the viscosity, maintain/increase pressure and improve the flow of oil. There are three main methods:

- **Gas injection**. Injection of a gas, for example CO_2, can reduce the viscosity of the oil considerably.
- **Chemical injection**. By injection of water and chemicals, for example polymers, the viscosity of the water is *increased*, leading to a more efficient displacement of moderately viscous oils. In certain circumstances, the addition of chemical can also reduce the oil-water interfacial tension which helps displacing trapped residual oil.
- **Thermal recovery**. The crude oil is heated up to reduce the viscosity. Steam injection has been widely applied and reduces the viscosity of viscous oils, making it flow more readily. Another thermal recovery method, in situ combustion, involves injection of air or oxygen, causing oxidation of the oil which in turn generates heat that reduces the viscosity of the oil.

EOR is used in the third "tertiary" phase of a typical oil field production life-span:

1. **Primary phase**. Oil is produced using the initial "natural" reservoir pressure.
2. **Secondary phase**. Water and/or gas is injected in so called Water-Alternating-Gas methods (WAG) to maintain production pressure and avoid too much reduced oil production.
3. **Tertiary phase**. Further refined methods, for example injection of CO_2, are used to facilitate oil production by increasing pressure and making the oil less viscous and thereby easier to move out of the reservoir.

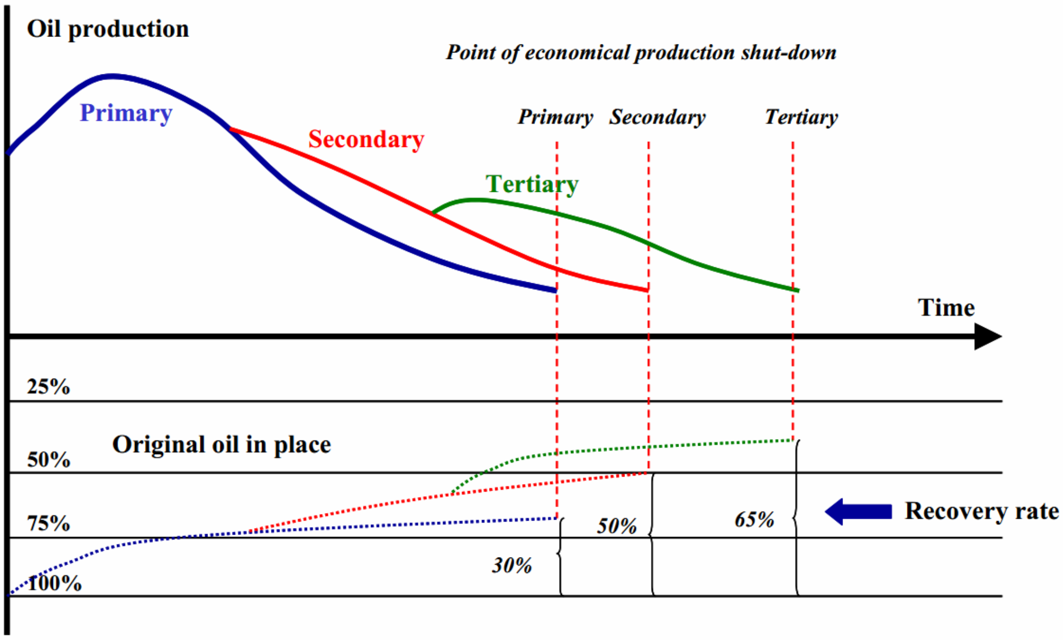


Figure 22. Example on phases in oil production. Source: [26]

Challenges with CO_2 EOR are related to the phase behaviour of the mixtures of the CO_2 and the crude, which are strongly dependent on reservoir temperature, pressure and crude oil composition. These mechanisms range from oil swelling and viscosity reduction for injection of immiscible fluids (at low pressures) to completely miscible displacement in high-pressure applications. In these applications, more than half and up to two-thirds of the injected CO_2 returns with the produced oil and is usually re-injected into the reservoir to minimize operating costs. The remainder is trapped in the oil reservoir by various mechanisms.

An example from an onshore CO_2 EOR project, the Denver project in Texas, is shown below.

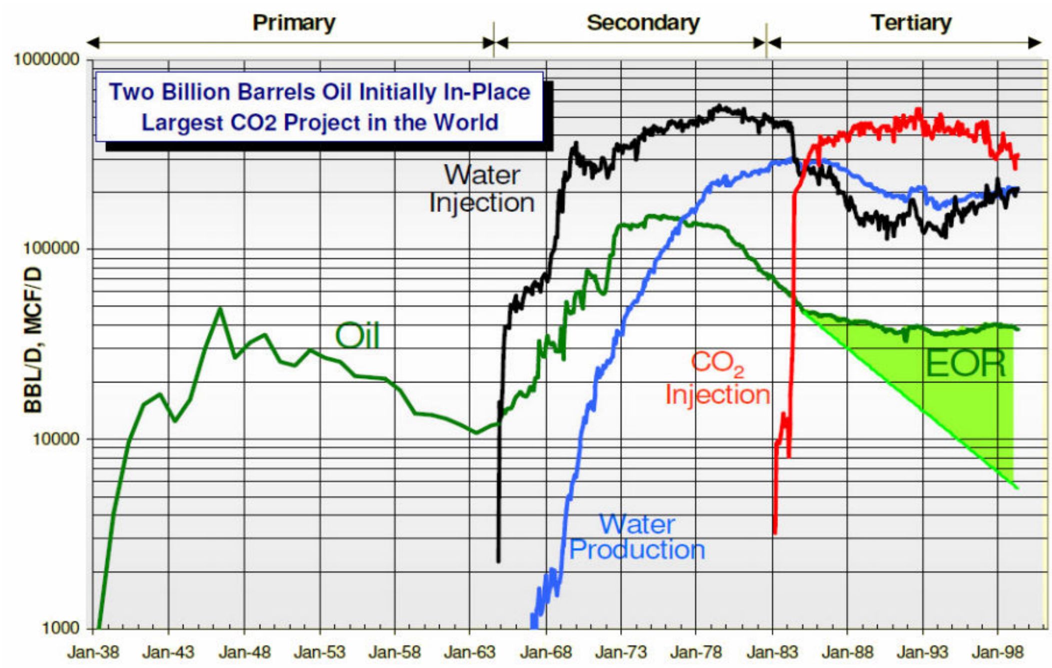


Figure 23. Example on phases in oil production for Denver onshore field in Texas. Source: [26]

The area marked with green colour corresponds to the incremental oil production due to CO_2 EOR and can be translated into a corresponding incremental revenue for a given oil price.

CO_2 injection volumes

The injection rates and amount of required CO_2 EOR are of key importance. As mentioned earlier, there is limited information available about the offshore CO_2 EOR but there is available information for onshore projects. An example from the IPCC special report on CCS is shown below where the injection rates are compared to the CO_2 produced by a typical 500 MW coal power plant.

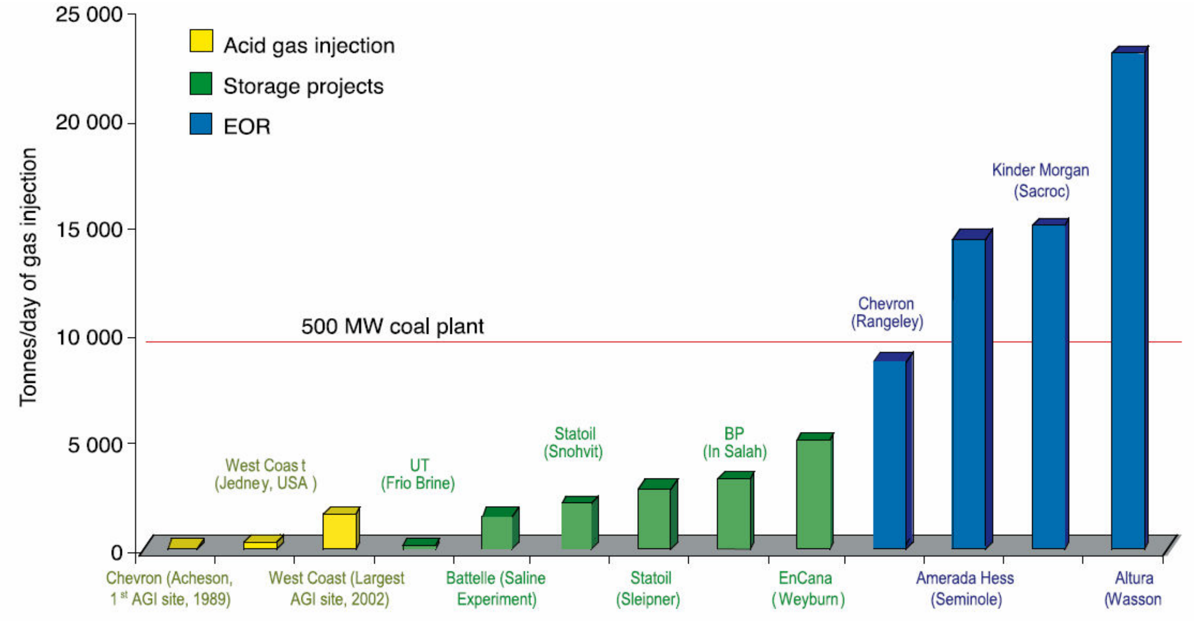


Figure 24. CO_2 produced by a 500 MW coal power plant compared to typical injection rates for acid gas, CO_2 storage and CO_2 EOR. Source: IPCC special report on CCS [42].

The (onshore) EOR projects shown require equal or more CO_2 per day than captured from a traditional 500 MW coal plant, say 10,000 tonnes CO_2 per day, which is a significant amount.

Matching demand and supply of CO_2

In general, the demand of CO_2 must be matched by the supply of CO_2. If ships are used to supply the CO_2, the supply will be discrete in time with, at least, short intervals with no supply unless there is significant buffer storage available offshore in the form of for example a Floating Storage and Injection Unit (FSIU) as proposed by Maersk (Figure 19) or a Floating Liquefaction Storage and Offloading (FLSO) as proposed by TGE (Figure 20).

Other aspects of matching demand and supply are related to how EOR will be deployed at the oil field(s), the fact that the CO_2 demand will decrease with time (due to recycling of injected CO_2) and the question whether CO_2 EOR will be combined with permanent storage of CO_2 in adjacent depleted oil fields. Figure 25 and Figure 26 illustrates two different possible scenarios as described by Maersk [24].

In the first scenario, full-field CO_2 EOR is deployed. The CO_2 import will be high in the beginning and then decrease over time due to recycling of injected CO_2. The incremental oil production due to injection of CO_2 will take some time to develop to a maximum rate after some time, say 5-7 years, and will then decrease as more and more oil is swept up by the CO_2 flood.

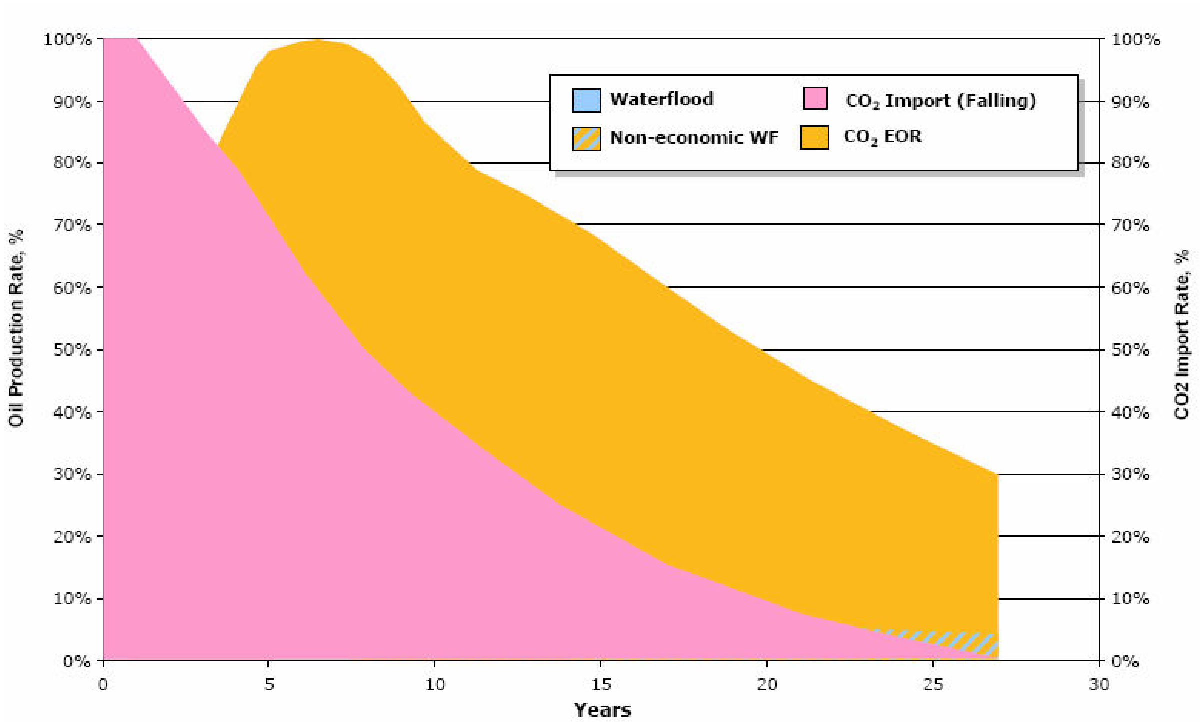


Figure 25. Illustration of full-field CO_2 EOR. Source: Maersk [24].

In the second scenario, a phased approach is deployed where CO_2 EOR is combined with waterflood and also with CO_2 storage in adjacent depleted oil fields. By alternating between EOR and storage, the flexibility is increased considerably. If the supply is bigger than the demand, for example by temporary shutdown of the EOR, all received CO_2 is directed to the storage site.

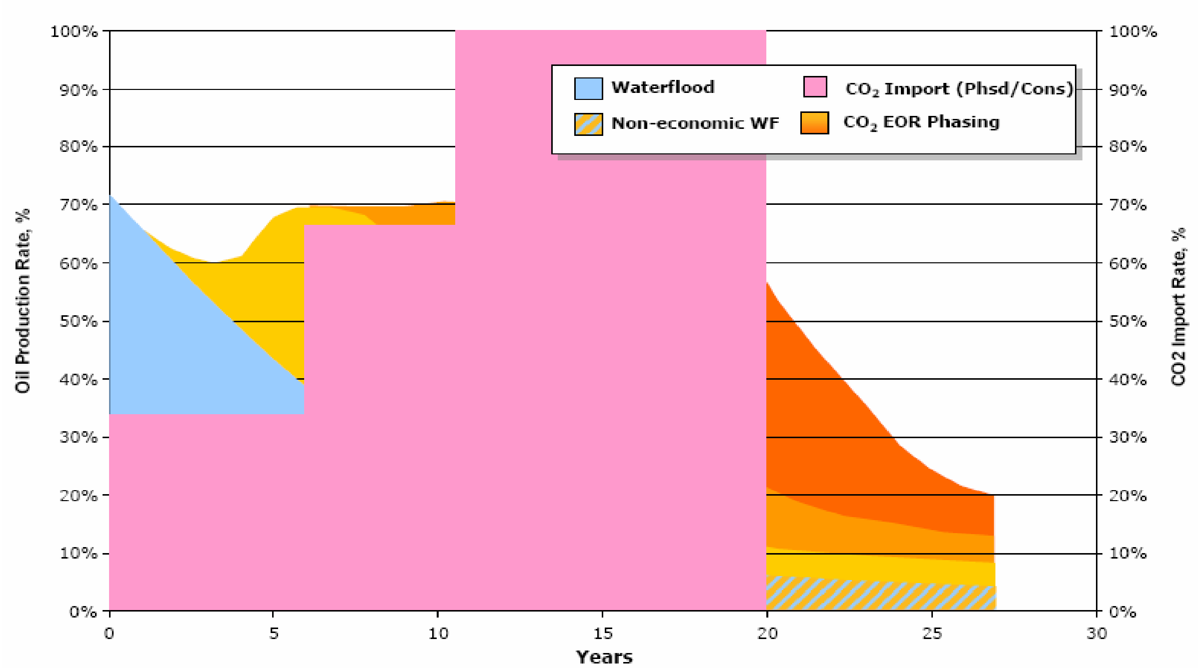


Figure 26. Illustration of phased CO_2 EOR. Source: Maersk [24].

Additional oil recovery

While CO_2 EOR has been successfully deployed onshore for several decades, there is limited experience of offshore CO_2 EOR at large scale.

A key challenge is related to recovery uncertainty, i.e. how much incremental oil that will be achieved for a given amount of injected CO_2 in a particular way. For CO_2 EOR this varies considerably depending on, among other things, the reservoir characteristics, but numbers in the range of 10% OOIP (Original Oil In Place) oil production has been reported. There are examples on much lower incremental oil achieved and it shall not be taken for granted that as much as 10% OOIP can be achieved.

A study [47] by GEUS/DTU in Denmark suggests that very high values of additional oil recovery factors could be achieved in the Danish sector which has a high degree of dense chalk. Laboratory tests using extracted bore cores from one of DONG's reservoirs in the Danish sectors indicate that up to 50% more oil could be achieved by injecting CO_2 increasing the oil recovery rate from 30% to 45%. The primary mechanism is reduced viscosity of the oil when mixed with CO_2. Increasing the oil recovery rate from 30% to 45% corresponds to approximately €100bn (DKK750bn) worth of additional oil. The results are surprisingly good and it has been questioned if they will also apply in-situ at a real offshore oil reservoir. In a recent article [48] in the Danish newspaper "Ingeniøren", Maersk commented that while they respect the results obtained by

GEUS/DTU the conditions in the laboratory are very different from the conditions offshore and it is likely that the increased oil production will be considerably less than achieved in the laboratory tests by GEUS/DTU.

Additional knowledge and experience is needed by for example demo projects, tests in laboratory and in field, improved simulation models to finally determine how much additional oil that can be recovered by CO_2 injection in the Danish sector.

Safety & risk

The safety aspects of CO_2 EOR can be split into two different categories:

1. Risks associated with the operation, i.e. the injection of CO_2
2. Risks associated with leakage of the stored CO_2

Risks of category 1 are similar to risks already faced in offshore oil & gas operations and can be mitigated using the same safety approach.

Risks of category 2 are similar to those of permanent storage of CO_2 given that some of the injected CO_2 will not be recycled and it thus needs to be ensured that it will stay underground permanently. A good overview of the various safety and risk aspects is given in a paper from 2009 by Stenhouse et al. [17].

A key aspect of CO_2 storage is the long time scale for which it needs to be verified that the CO_2 is stored "permanently" underground. This is linked to the various mechanisms that act to keep the CO_2 underground, including physical trapping, solubility/dissolution trapping and trapping by mineralization as described briefly below. The timeframes for these processes can be long and consequently this needs to be taken into account of the risk assessment of CO_2 leakage. As a result, the risk analysis needs to span several hundred years up to several thousands years.

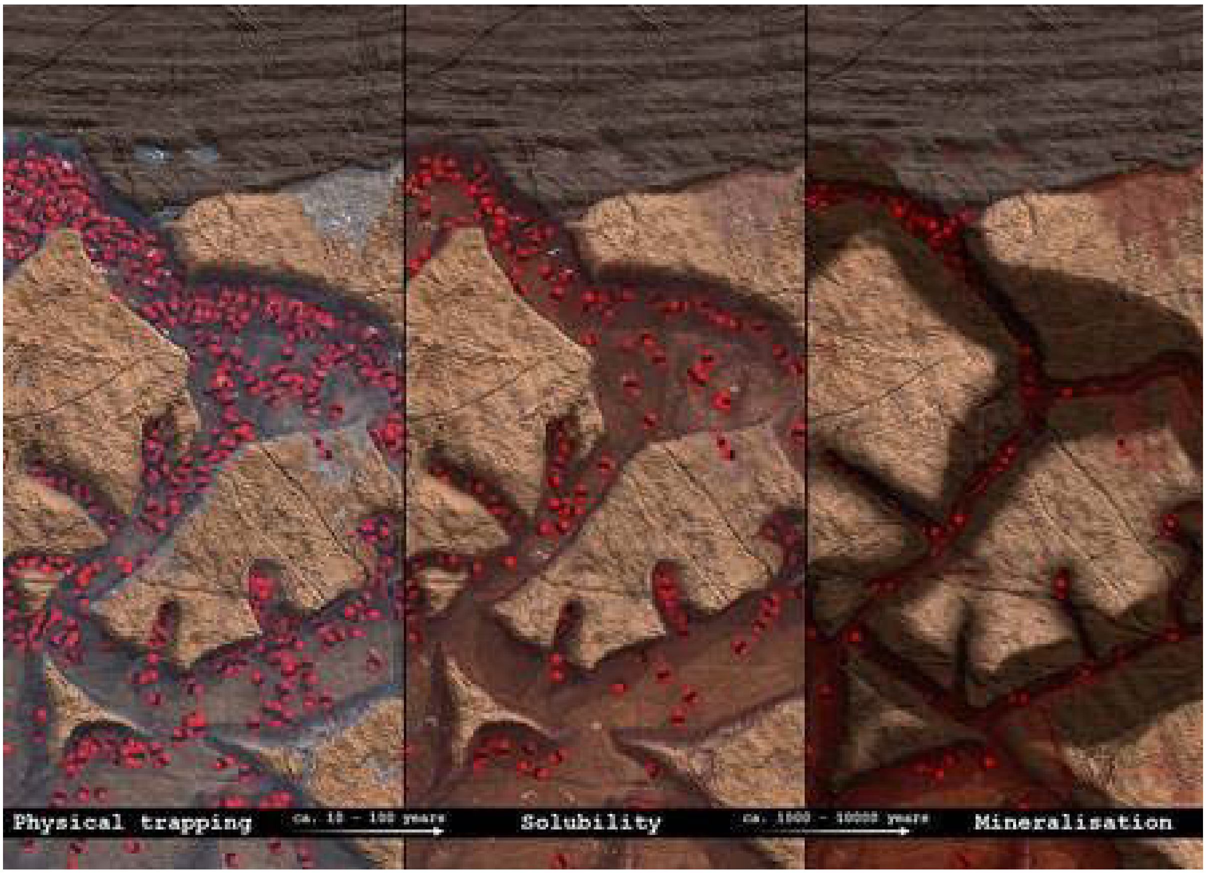


Figure 27. Illustration of various trapping mechanisms. Source: Bellona Foundation.

Physical trapping

The most effective storage sites are those where CO_2 is injected into porous sediments below a thick solid rock, called caprock, that the CO_2 cannot penetrate. Sedimentary basins with such closed, physically bound traps are found all over the world, and they are occupied mainly by saline water, oil and gas.

When CO_2 is injected into a formation (left illustration in Figure 27) it displaces saline formation water and then migrates buoyantly upwards, because it is less dense than the water. When the CO_2 reaches the top of the formation and meets the caprock (shown as dark grey), which it cannot penetrate, further movement upwards is hindered.

The only way that CO_2 can escape and continue its upward movement is through fractures or faults in the caprock. Therefore, it is important to characterize the geology of storage sites and caprocks prior to CO_2 injection, and only inject CO_2 in sediments where there are no faults or fractures. The shape of the caprock is also important. In the figure above the caprock has the shape of a cup turned upside down which traps the CO_2 inside. If the caprock had been completely flat, the CO_2 could have escaped at the ends of the caprock. In addition to caprock, the CO_2 can also be physically trapped in the pores of the sediment where it is stored.

Dissolution

Over a long time scale, significant quantities of CO_2 dissolve in the formation water and then migrate with the water (illustration in middle of Figure 27).

The primary benefit of solubility trapping is that once CO_2 is dissolved, it no longer exists as a separate entity, thereby eliminating the buoyant forces that drive it upwards. CO_2 dissolved in water moves very slowly. It could take hundreds of years to move just a few meters.

Mineralization

CO_2 in the subsurface can react with the rocks in the sediment where it is stored. This is a trapping mechanism known as geochemical trapping, mineralization, or mineral trapping (right illustration in Figure 27). CO_2 dissolved in water will form solid and stable carbonate minerals that cannot move. This is the most permanent form of geological storage. Mineral trapping is believed to be comparatively slow, potentially taking thousands of years or even longer. Nevertheless, the permanence of mineral storage makes this a desirable feature of long-term storage.

As mentioned earlier, CO_2 has been injected for several decades at various locations around the world so there is real experience to be drawn upon. One of the most relevant examples for offshore storage is the CO_2 storage in the Utsira formation in the North Sea where about 1 million tonnes of CO_2 has been stored annually since 1996 without any indication of leakage. Other examples include the Weyburn project in North America, the In Salah project in Algeria and the Snøhvit projects in the Barents Sea where CO_2 is separated from natural gas and stored underground, just like the Utsira project. Based on these projects, it seems that CO_2 can be stored safely underground but further work is needed to further confirm this for the very long time-scale involved and for all of the planned locations, each with its own characteristic properties.

While the ideal situation of course is that all CO_2 is stored "permanently" underground, the long time scales and general technical uncertainties require that this is quantified in terms of allowable leakage rates, i.e. risks are regarded to be acceptable if the leaks are sufficiently small. Acceptable leakage rates are usually expressed as a percentage of the total volume. Officially available numbers are typically in the range 1% over 100 years – 1% over 1,000 years. To put this in context, it is interesting to note that the current operation with the majority of the world's energy being produced by fossil-fuel fired power plants without CCS corresponds to a 100% risk that 100% of the CO_2 "leaks" to the atmosphere immediately.

Concluding remarks

As mentioned earlier, injection of CO_2 for EOR has been carried out for more than 30 years onshore. Deploying it offshore is more challenging with several unique and new challenges. Nevertheless, the technology is reasonably well understood and a recent industry consultation study carried out by DTI [19] concluded that the industry regards CO_2 EOR to be proven technology that can be deployed in the North Sea without major difficulties. It seems likely that CO_2 can be stored safely underground but further work is needed to further confirm this for the very long time-scale involved and for all of the planned locations, each with its own characteristic properties.

2.4.2 Financials

Long-term experience from onshore CO_2 EOR has shown that the overall economics can be good, especially if low cost CO_2 sources can be used. Offshore is generally more challenging than onshore and the financials of offshore CO_2 EOR is challenging to estimate due to combination of complex technology, limited experience and dependence of incremental oil obtained with the volume as well as the future oil price being uncertain. In general the costs are comprised of:

1. Cost to adapt existing infrastructure to handle CO_2. Example include adaptation of existing platform, upgrade of well.
2. Cost for unloading facilities and intermediate storage capacity if needed (see section 2.3.1 for description of examples on floating units for storage and processing
3. Systems for monitoring, reporting and verification of injected CO_2.
4. Operational expenses (staff etc)

Department of Trade and Industry (DTI) in the UK launched a comprehensive campaign in 2004 to gather feedback from stakeholders in the industry about their view on what needs to be done to get a CO_2 EOR demonstration project off the ground. An overview of the findings is found in *Implementing a demonstration of enhanced oil recovery using carbon dioxide* [19]. There were two key findings:

1. The stakeholders regarded CO_2 based EOR as proven technology.
2. EOR using CO_2 was <u>not</u> seen to be economically feasible given the market conditions (in 2004).

The cost of CO_2 EOR was estimated to be in the order of £28-35 per tonne CO_2 when disregarding the income from the addition oil that is recovered. When this credit is included the cost fell to £4-10 per tonne CO_2. The latter figure is of course entirely dependent on the oil price at a given time.

The financial attractiveness of CO_2 EOR is critical if wide-scale deployment is wanted, especially by existing O & G operators that assess CO_2 EOR in comparison with conventional O&G developments that have much higher return on the investment. At the same time, the financial risks with CO_2 EOR are potentially much higher than with conventional O&G developments. In the study by DTI, some of the O&G operators commented that CO_2 would need to be supplied to the production platform at zero cost to make CO_2 EOR commercially attractive. This view has been confirmed again by several O & G operators in recent discussions with the author.

A recent study from 2009 by Senergy [9] looked at the economic feasibility of CO_2 EOR applied at the Claymore field in the UK North Sea. The key assumptions that were made are as follows;

- Around 1450 million barrels initially in place, around 46% recoverable so far
- Estimated incremental oil 120 -160 million barrels (8%-11% of oil initially in place)
- CO_2 imported 50 million tonnes. CO_2 recycled 150 million tonnes
- Begin 2017 end 2043
- Capital costs £1.1- 1.2 billion (new auxiliary CO_2 platform, adaptation, upgrades etc)
- Operating costs £90 million per annum
- Oil £50 ($70) per barrel
- CO_2 neither cost nor subsidy, i.e. supplied at no cost, no credits earned for storage

With these assumptions, the study estimated the rate of return to be 12-16% before tax using an unrisked discounted cash flow analysis.

Gozalpour et al [20] describe a study by Ren. et al[2] in which the unit cost to produce one(1) barrel by CO_2 EOR (using CO_2 captured from an onshore coal fired power plant and transported by pipeline) was estimated to $43. Consequently, CO_2 EOR would yield a positive financial return for oil prices higher than $43 per barrel. The current (April 2011) oil price is approximately $110 per barrel.

[2] Ren, S.R. and Tohidi, B. (2004) Gas Injection for Improved Oil Recovery: Reservoir Simulation and Economic Analysis. Presented at the 2nd IOR Europe 2004 Conference, UK.

2.4.3 Legal

There are many complex legal mechanisms related to CCS and CO_2 EOR that the potential investors in CCS / CO_2 EOR need to feel confident about in order to invest.

CO_2 EOR projects in Europe will be governed by European legislation. The "CCS Directive" (Directive 2009/31/EC) has been in place since 2009 and provides the necessary legal framework for long-term storage of CO_2 underground. The EU legislation now needs to be transposed into national laws in Member States. Guidance on how to implement the CCS directive is described in four (4) guidance documents "Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide"

1. CO_2 Storage Life Cycle Risk Management Framework.
2. Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures.
3. Criteria for Transfer of Responsibility to the Competent Authority
4. Article 19 Financial Security and Article 20 Financial Mechanism

The guidelines have been through a number of reviews by stakeholders by industry representatives. Serious concerns have been raised about various aspects of the guidelines, for example the criteria for how the responsibility/liability can be transferred from the operator (of the storage site) to the authorities, i.e. the member state in which the storage site is located. Another cause of concern is the financial security that the operator needs to set aside for the event of the operator not being able to fulfil its obligations.

The most recent versions of the guidelines were released in April 2011[3]. The final versions are supposed to be ratified by the member states by the summer of 2011, i.e. only a couple of months away.

Without going into details, it seems fair to conclude that there is still significant uncertainty in how the regulations will finally be implemented. The recently released updated versions of the guidelines are currently being reviewed by the industry and it is too early to confirm if the concerns raised earlier have been addressed and resolved. The uncertainty is likely to last at least

[3] http://ec.europa.eu/clima/policies/lowcarbon/ccs_implementation_en.htm

until the guidelines have been tested in practice in real CCS projects involving the entire CCS-chain.

2.4.4 Summary

Summary: CO_2 Enhanced Oil Recovery

- CO_2 EOR is increasingly seen as a potentially favourable option to help grow the CCS industry (offset of cost, security of supply, storage demo)
- There is lot of experience from onshore but not yet proven commercially feasible offshore.
- The cost is difficult to estimate. A large consultation from 2004 EOR using CO_2 was not seen to be economically feasible given the market conditions. It is likely that this may still be true. Discsussions indicate that CO_2 needs to be supplied at neutral cost (no cost to obtain, no storage credit)
- There is still considerable uncertainity related to EU's regulatory framework for CO_2 storage/EOR

2.5 Community Engagement

The CCS industry is still in its early development phase and CCS as a concept is not widely known yet among the public. However, this is likely to change due to increased focus on global warming and the fact that many large CCS demonstration project will be deployed in the coming years.

Experience so far shows that while CCS projects seem to be accepted in some regions/countries, strong opposition is seen in other regions/countries. An example of a project of the latter category is the Barendrecht project (Netherlands) which was stopped due to public perception. The Dutch government later decided to not support onshore CO_2 storage project and would rather focus on offshore CO_2 storage. The Beeskow project (Vattenfall) in Germany is another example of a project that has been met with a lot of scepticism from the local community.

Figure 28. News showing opposition to Beeskow CO_2 storage project in Germany [52]

In general, CCS is generally regarded as less favourable than other options concerns and "an excuse to continue with unsustainable fossil fuel technology" rather than transition to renewable energy sources. Examples on other concerns are related to the risk of leakage and negative impact on tourism.

In recent years, the public's view on CCS has been studied more extensively and methodically using various methods including public opinion surveys. To give an example, the European Union recently launched the NEARCO2 project (http://www.communicationnearco2.eu) to look at effective strategies for objective communication to the public about risks and advantages of CO2 capture and storage.

Figure 29 and Figure 30 shows two examples from a study [55] carried out by researchers in the United States, United Kingdom, Sweden and Japan where public attitudes towards energy and the environment were investigated, focusing on attitudes towards CCS.

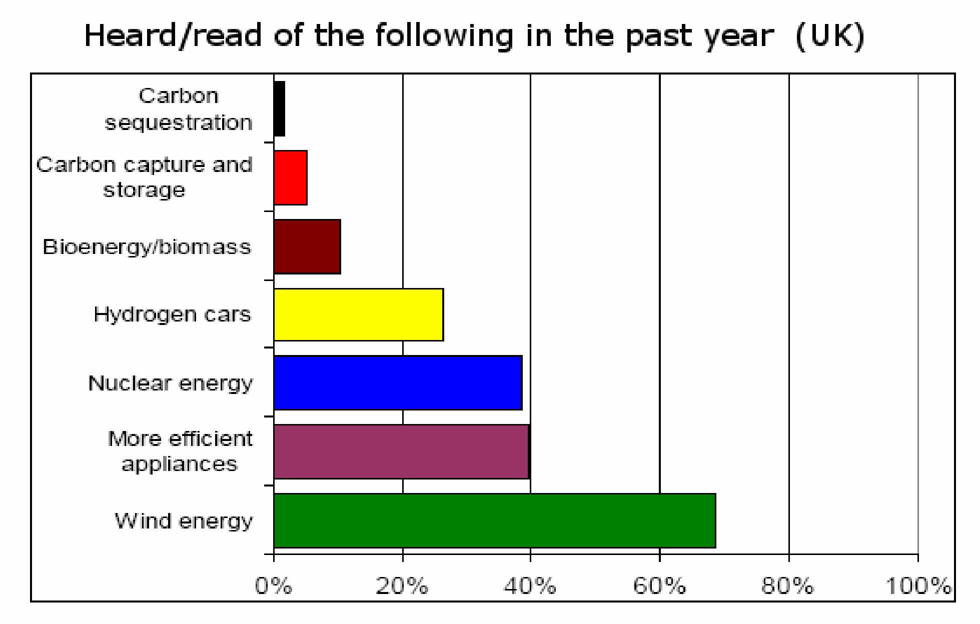


Figure 29. Example on results from public opinion survey. [55]

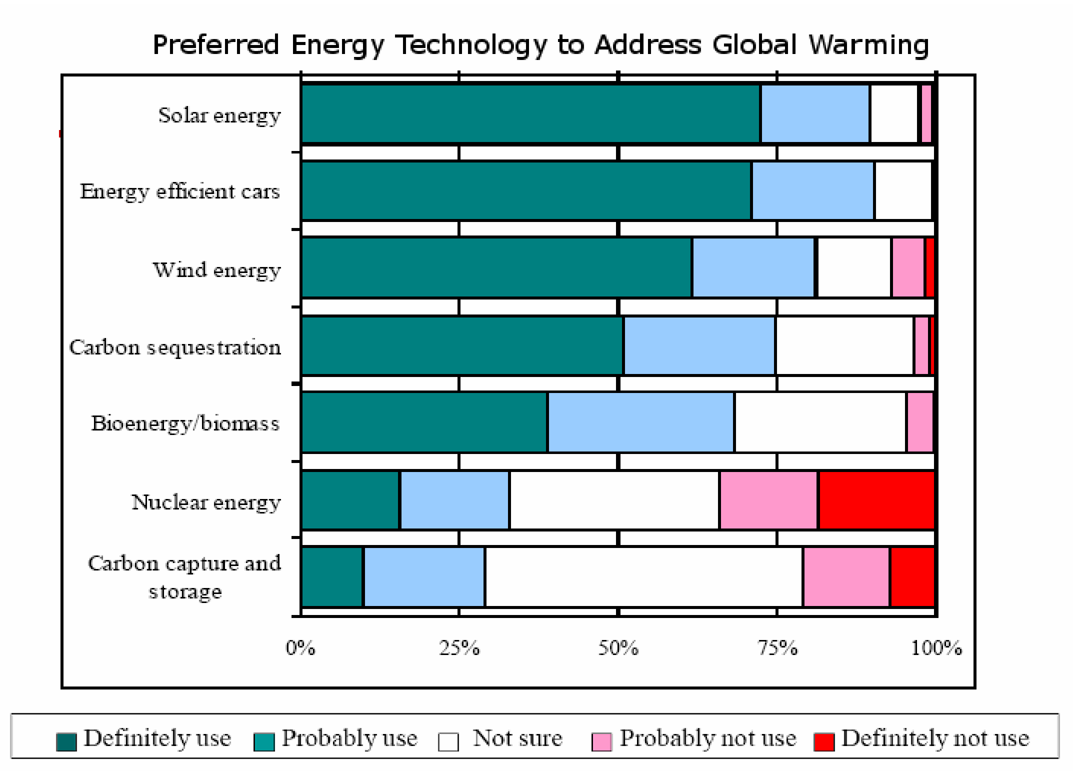


Figure 30. Example on results from public opinion survey. [55]

Clearly, CCS is not very well-known and is not seen in general to be a preferred solution to address global warming. Further, it is clear from experiences with planned demonstration projects, that the local opposition can be detrimental to a projects implementation. Local community support is believed to be best achieved through meaningful public participation, trust building and compensation.

Guidelines for how to involve the local community during the planning of CCS projects have been published by for example the World Resources Institute[4] [50]. The guidelines have been comprised by authors at WRI in consultation with a large number of international stakeholders and experts. An overview of the key principles for regulators, load decision makers and project developers is shown below.

Key Principles in CCS Community Engagement and Roles for Each Party in the Process

	Understand Local Community Context	Exchange Information about the Project	Identify Appropriate Level of Engagement	Discuss Risks and Benefits of Project	Continue Engagement through Time
REGULATORS	Learn community concerns. Determine, meet, and possibly improve public participation requirements.	Educate, respond to, and provide information to the public.	Establish a multistakeholder engagement process.	Require communication and contingency measures and regular updates during life cycle. Evaluate environmental and other impacts.	Require public participation at key stages and increase engagement in the process.
LOCAL DECISIONMAKERS	Understand community interests, identify leaders, and establish a dialogue early.	Contact developers early. Ask questions. Identify, seek, and publicize pertinent information about the project.	Determine engagement level and establish a transparent process.	Ask questions. Identify and communicate concerns and clarify follow-up process. Insist on full disclosure.	Establish institutional memory, possibly a taskforce. Consider participating in monitoring and reporting. Regularly update the community.
PROJECT DEVELOPERS	Assess community dynamics and your historical presence. Weigh participatory engagement.	Engage early and develop a relationship with the community. Answer questions. Seek input, and provide information openly and transparently.	Foster two-way engagement; consult and negotiate with communities. Address concerns. Convey feasible level of engagement.	Answer questions. Discuss with community risks, benefits, uncertainties, and mitigation and contingency plans. Consider benefit sharing.	Engage community at each step of project schedule. Consider informal, long-term relationship to ease stewardship transition.

Figure 31. Key principles as suggested by World Resources Institute [50].

[4] WRI is a U.S. based environmental think tank funded by private partners in form of corporations, individuals, foundations etc.

The National Energy Technology Laboratory [51] in the United States has drawn upon the experiences from the seven Regional Carbon Sequestration Partnerships (RCSP[5]) in the United States / Canada where it has been recognized that it is important to conduct public outreach programs early in the process, preferably together with pilot-scale field tests. Table 3 gives an overview of the 10 recommended practices by the National Energy Technology Laboratory.

Table 3. Best practices in Public Outreach Programs and Activities. [51].

Best practices in Public Outreach Programs and Activities	
1.	Integrate Public Outreach with Project Management
2.	Establish a Strong Outreach Team
3.	Identify Key Stakeholders
4.	Conduct and Apply Social Characterization
5.	Develop an Outreach Strategy and Communication Plan
6.	Develop Key Messages
7.	Develop Outreach Materials Tailored to the Audiences
8.	Actively Oversee and Manage the Outreach Program throughout the Life of the CO_2 Storage Project
9.	Monitor the Performance of the Outreach Program and Changes in Public Perceptions and Concerns
10.	Be Flexible – Refine the Outreach Program As Warranted

The recommended best practices are self-explanatory and are not described further in detail. More information can be found in the report [51] that also contains a sample communication plan, a sample press release and other useful information.

[5] RCSP is a U.S. led government/ industry effort tasked with determining the most suitable approach to CCS in different areas of U.S. and Canada. See www.netl.doe.gov for more information.

3 Feasibility of Danish CCS scheme including ship-based CO_2 transport

3.1 Overview of Danish situation

Political ambitions

Approximately 80% of Denmark's total energy supply comes from fossil fuels such as coal, gas and oil [5].

In 2008, "Klimakommissionen" (Danish Commission On Climate Change Policy) was tasked to review how Denmark can, in the long-term, remove its dependency on fossil fuels. The final report [5] was published in September 2010 and presents a high-level roadmap to a carbon-free society. The energy supply is proposed to shift from fossil-fuel fired power generation to renewable energy primarily by expansion of offshore wind energy combined with increased energy efficiency. It is foreseen that it will be necessary to have a substantial energy supply from biomass-fired power stations as reserve power to ensure that the energy supply can be maintained even when there is little or no wind energy available. CCS is mentioned briefly in the report and is primarily thought to be applicable to coal and gas-fired power stations which are not part of the vision of a future fossil-free energy supply chain. "Klimakommissionen" does identify CCS as a possibility in combination with the foreseen biomass-fired power stations where the generated CO_2 would be captured and stored. In such a case, there would actually be a net removal of CO_2 since biomass plants (without CCS) are generally considered to be CO_2 neutral.

Risø DTU (National Laboratory for Sustainable Energy) recently published the report "Non-fossil energy technologies in 2050 and beyond" [6] that has a more positive view on CCS in a Danish perspective, at least in the coming decades when there is still sufficient supply of coal. It is concluded that Denmark has good potential to exploit CCS with a large domestic fossil-fuel fired power generation and plenty of geological storage available. Similar to "Klimakommissionen", it is assumed that an increase in wind energy will have to be supported by fossil-fuel fired power plants that can become carbon free if fitted with CCS and/or by biomass-fired power plants that can be fitted with CCS to create net negative CO_2 emissions.

Earlier this year in February 2011, the Danish Government presented its strategy "Energistrategi 2050" [46] for how to make Denmark independent of fossil fuels by 2050. In short, the key elements are increased efficiency, expansion of wind energy and increased usage of biomass.

CCS is not identified as a key strategy but it is mentioned that it can potentially play an important role, especially in the long-term. One option would be to keep some coal-based power production provided that it is fitted with CCS. Another option would be to apply CCS to biomass-fired power plants and thereby achieve a power production with net negative CO_2 emissions.

Available CO_2

Estimations of the availability of CO_2 in Denmark have been made by for example GESTCO that estimated that the potential supply from large industrial sources is approximately 29 Mt/CO_2 per year. An overview of the major point sources is shown below in Figure 32.

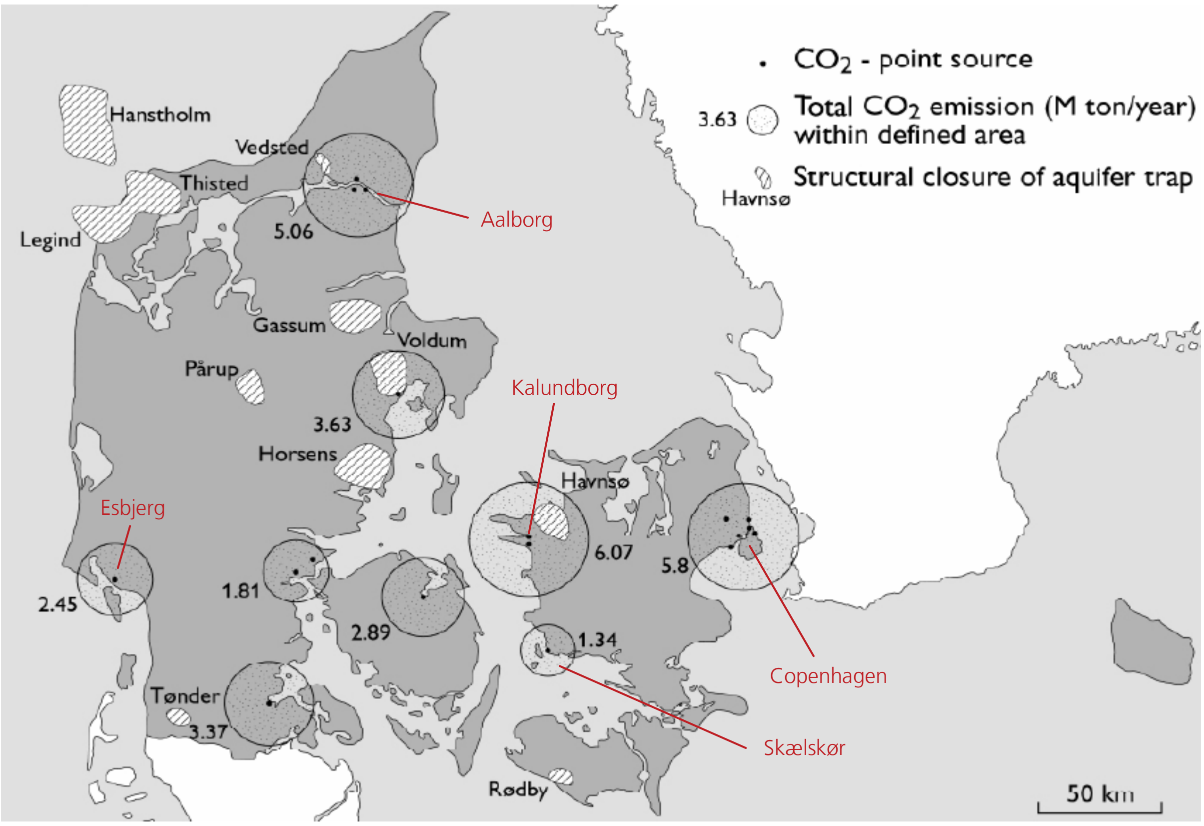


Figure 32. Location of major CO_2 sources in Denmark. Source: Gale J. [45].

The majority of the CO_2 emissions come from large power plants that are easily identified in the map above. A few examples are given below:

- **Esbjerg**. DONG's power station in Esbjerg harbour (379 MW, primary fuel is coal)
- **Aalborg**. The Nordjylland Power Station, operated by Vattenfall, is located on the outskirts of Aalborg. Total installed electric power is 660 MW using coal as energy source.
- **Skælskør**. The coal-fired "Stigsnaes" power plant (DONG) is located near Skælskør. Total power is 409 MW.

- **Kalundborg**. The Asnæs Power Station (DONG) near Kalundborg is Denmark's largest power station. Total 1,057 MW with coal as main fuel.
- **Copenhagen**. There are a number of fossil-fuel fired power stations around Denmark's capital including the Amager Power Station (410 Mwe, primarily fuel is coal) operated by Vattenfall and the Avedøre Power Station (810 Mwe, mix of fuels) operated by DONG.

CCS related activities

There is a wide variety of CCS related activities in Denmark, ranging from commercial research and development including pilot plants to academic research and political studies.

DONG has been investigating CCS for many years and has been capturing CO_2 since 2005 at their pilot plant "Castor" at Esbjerg Power Station. The project is a partnership between 30 research institutions and industry players. Approximately 1 tonne CO2/hour is captured and later vented into the atmosphere.

- Pilot plant operates on a slip stream taken directly after the FGD
- Flue gas conditions: ≈47℃ saturated, <10 ppm SO_2, <65 ppm NO_x, <10 mg/Nm^3 dust

Key design parameters

Parameter	*Design value*
Flue gas capacity	5000 Nm^3/h
CO_2 production (at 12% CO_2)	1000 kg/h
Absorption degree	90%
Max solvent flow	40 m^3/h
Max reboiler steam flow	2200 kg/h (3.5 bar)
Max stripper pressure	2 bar (g)

Figure 33. DONG Castor project [54].

DONG have recently announced a less pro-active approach to CCS and announced that they, while still believing in CCS long-term, will focus on renewable energy sources like biomass and wind, until CCS has been developed further.

Vattenfall have planned a CCS pilot-plant at Nordjyllandsværket (coal-fired, 660 MWe) for a number of years, including long-term onshore storage at Vedsted approximately 30 km north west of Aalborg. The initial start-up was planned to 2013 but has recently been postponed and it is not sure whether the project will go ahead.

CO_2 EOR is actively investigated by Maersk that entered into co-operation with Fortum with the ambition to capture CO_2 at the Meri-Pori coal-fired power plant in Finland, transport using CO_2 Carriers (Maersk Tankers') and use the CO_2 in depleted Danish oil and gas fields, either for storage or EOR. Fortum later decided to pull out from the project due to a combination of financial and technical risks and revised corporate strategy. It is believed that Maersk has the ambition to continue the project and has signed agreements with other suppliers of CO_2.

Research in CCS related technologies is carried out at Denmark Technical University (DTU). The Centre for Energy Resources Engineering (CERE) has CCS as a strategic research topic, covering the following topics:

- CO_2 Corrosion in Natural Gas Pipelines
- CO_2 for EOR - Knesebeck a field study
- Enhanced Oil Recovery through CO_2 Utilisation
- No CO_2 - Nordic Network for CO2 Capture and Storage
- Polymers in CO_2 Refrigeration Plants
- Post-Combustion Capture of CO_2 from Fossil Fueled Power Plants
- The Chilled Ammonia Process for CO_2 capture

CCS related research/studies are also carried out by organisations like GEUS (The Geological Survey of Denmark and Greenland).

Available storage capacity / need for CO_2

In 2004, the research project GESTCO (Geological Storage of CO_2) confirmed that Denmark has very good conditions for CO_2 storage. The total capacity in Denmark was estimated to 17 billion ton CO_2. As mentioned earlier, the total CO_2 production from the large point sources has been estimated to approximately 29 million tonnes CO_2 per year corresponding to approximately 600 years of available storage capacity. Risø also confirmed in a recent report
[1] that there is plenty of storage capacity available in Denmark.

The Danish offshore oil reservoirs continue to play an important role for Denmark in terms of domestic supply of oil and gas and provide very significant revenue streams to Denmark (in the order of €20 billion over the last five years according to Danish "Energistyrelsen"). However, the production is decreasing and several of the oil fields approach a time where it is not financially feasible to continue operation unless the oil production can be maintained above a certain production level.

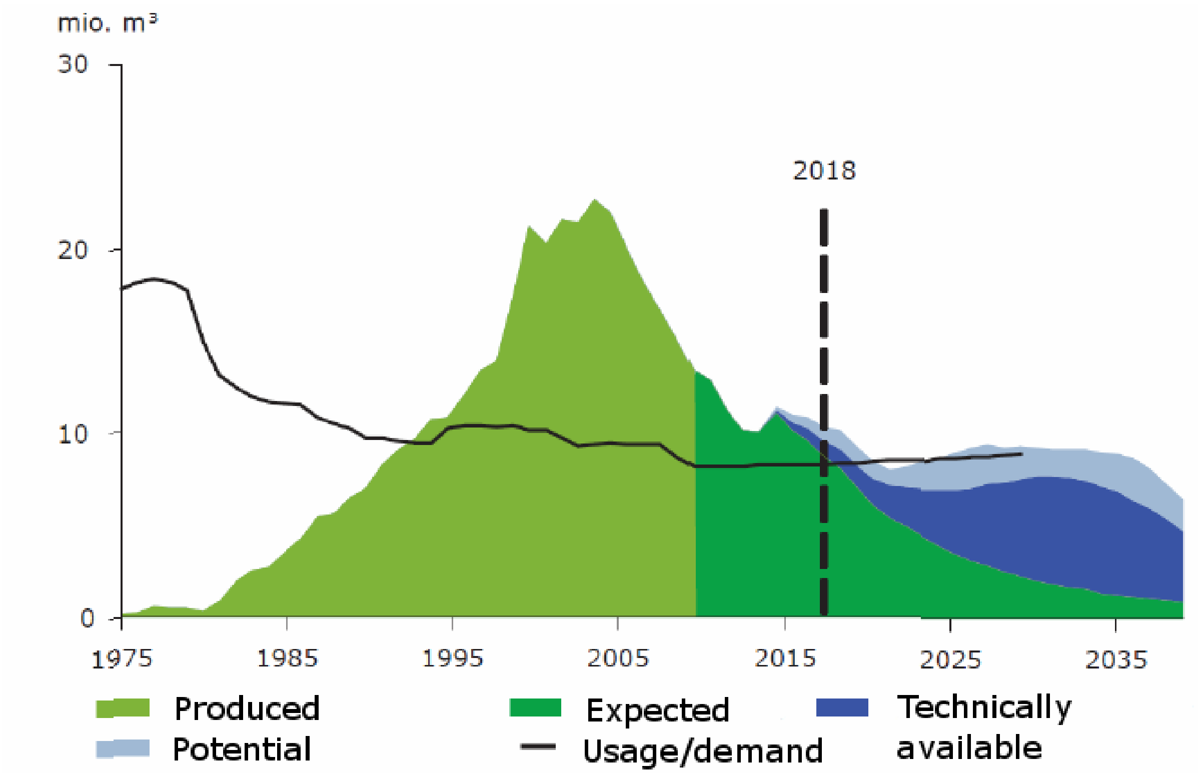


Figure 34. Oil production trend in Denmark. Source: DEA [24].

Note that Denmark's demand for oil and gas is predicted to exceed the domestic supply by 2018.

According to Maersk ([24], [56]), CO_2 EOR may become a viable technique to increase recovery and extend the field life of certain DUC fields and the company is pursuing a combination of EOR and storage to mature a commercial opportunity. Figure 35 shows the historical, current and foreseen oil production in the DAN field operated by Maersk.

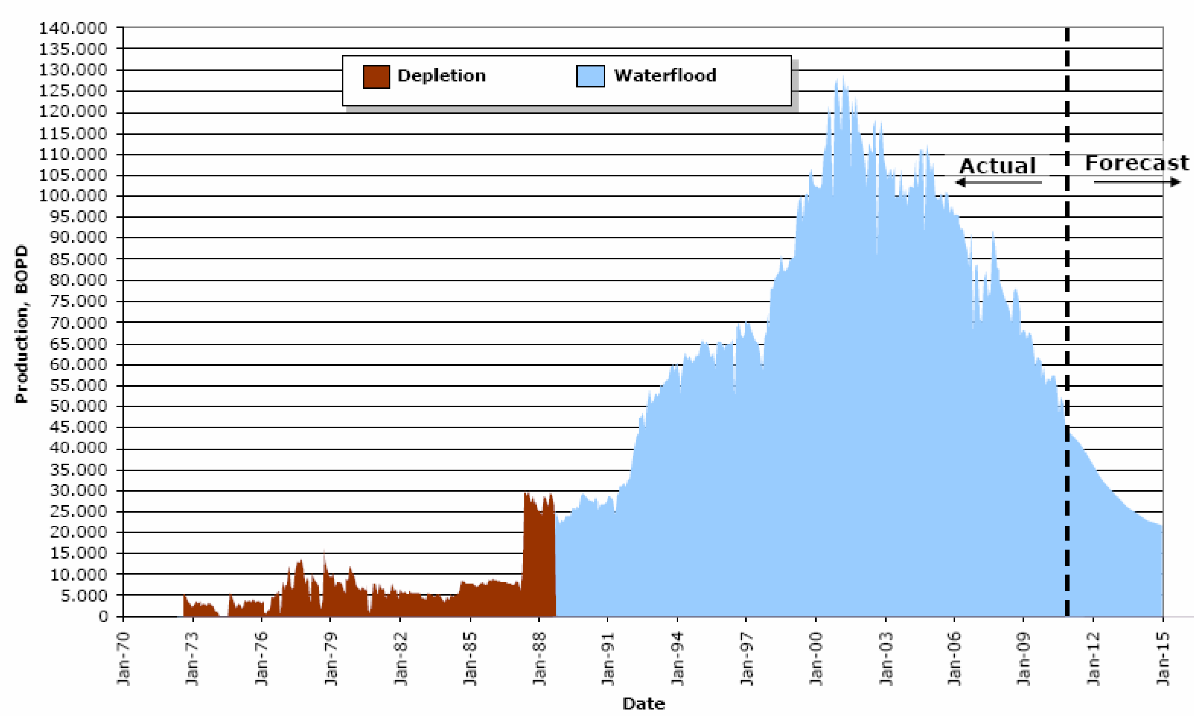


Figure 35. Dan field production. Source: Maersk [24].

Clearly, the production rate is decreasing fast and new methods are needed soon to slow down the decrease of the production rate to ensure that it is financially viable to maintain production. This again confirms that there is a real window of opportunity for EOR.

It is concluded that there is a need/potential for CO_2 EOR in Denmark and that the window of opportunity is "now". The required CO_2 volumes are anticipated to be quite large and is actually one of the most critical challenges for further development. In an analysis from 2003, it was estimated that the Danish oil sector will require approximately 28 million tonnes CO_2 per year over a period of 30 years [48].

3.2 Potential scenarios

Potential scenarios are strongly linked to the location of CO_2 sources and storage/injection sites. Starting with the CO_2 sources, the location of large point sources are well-known as discussed earlier and shown in Figure 32.

The Danish oil fields, operated by the Danish Underground Consortia DUC, are located west of Denmark, more or less halfway between Denmark and United Kingdom, at approximately 55.40°N, 4.5 °E as shown below.

Figure 36. Estimation of distance to DUC fields.

The most simple scenario for a capture-transport-EOR chain is a single source – single receiver combination using ships that navigate this route back and forth. The transportation distance should ideally be as short as possible.

With this in mind, it seems ideal to capture CO_2 at the power plant in Esbjerg which is closer to the DUC field than any other large CO_2 source (route "1" in Figure 36 above). This is chosen to be Scenario #1. The power plant in Esbjerg is fairly small CHP plant fuelled by coal. The nominal power is 378 MW_e.

Scenario #1 corresponds to a fairly small power plant at close proximity of the DUC field. In order to investigate the influence of the transportation distance and the size of the power plant (and thus the CO_2 volume), another scenario (#2) with capture at Denmark's largest power plant, the Asnæs plant in Kalundborg, at the other side of Denmark was also studied (route "B" in Figure 36 above). In this case the distance is much longer and the power plant is also much larger with a power production of approximately 1,000 MW_e. Note that a single source – single receiver scenario is still assumed with ships travelling back and forth between Kalundborg and the DUC field.

To summarize:

Scenario #1

- Route "1" as shown in Figure 36
- Capture of CO_2 at Esbjerg plant (378 MW_e)

Scenario #2

- Route "2" as shown in Figure 36
- Capture of CO_2 at Asnæs plant in Kalundborg (approximately 1,000 MW_e)

A third option that could be studied would be collection of CO_2 at multiple locations along the coast and transportation to the DUC field as illustrated by the blue dotted line in Figure 36 above. In this scenario, CO_2 is captured and collected at several locations, for example Skælskør – Kalundborg – Voldum - Aalborg, and then delivered at the DUC field. This could be done using many different combinations of ship movements. This would require a much more complex analysis compared to analysis of Scenarios #1 and #2 and it has therefore been decided to not include this third scenario in the analysis focus since it is believed that studying Scenarios #1 and #2 provides the level of insight that is sought.

3.3 Logistics

Table 4 shows the estimated CO_2 volumes for the two scenarios.

Table 4. Estimated CO_2 volumes.

	Scenario #1	Scenario #2
Power plant	Esbjerg	Asnæs
Nominal power	378 MW_e	1,000 MW_e
Captured CO_2 volume (at nominal power)	1.7 Mt CO_2 / year	4.5 Mt CO_2 / year
	4,660 t CO_2 / day	12,300 t CO_2 / day
	3,880 m^3 CO_2 / day	10,300 m^3 CO_2 / day

The captured CO_2 volume (in Mt CO_2 / year) has been calculated from the nominal power (in MW_e) using a factor of 0.45%. This factor is based on public information available for three future demonstration projects using postcombustion technology on coal power plants; Nordjyllandverket , Meri-Pori and Maasvlakte, with data as shown in Table 5.

Table 5. Data for three future demonstration projects. Source of information: [21], [58], [59].

	Nordjylland	Meri-Pori	Maasvlakte
Power (to which CO_2 capture is applied) in MW_e	411	283 (50% of 565)	250
Captured CO_2 volume (Mton CO_2 per year)	1.8	1.25	1.1
Factor	0.43	0.44	0.44

This is obviously an estimation dependent on many assumption but it is believed to be accurate enough for the purpose of the study.

The corresponding transportation volume has been estimated using a density of 1,200 kg/m^3 corresponding to transportation close to the triple point (-56.5 degC, 5.2 barA).

The smaller power plant in Scenario #1 is estimated to produce approximately 4,000 m^3 CO_2 per day while the bigger power plant in scenario #2 is estimated to produce approximately 10,000 m^3 CO_2 per day.

The estimated CO_2 volumes suggest that a smaller CO_2 carrier, say 5,000 m^3, could be sufficient for Scenario #1. One option would be to convert an existing LPG carrier, for example the 6,500 m^3 Isabella Kosan as shown in Figure 12.

For Scenario #2, the CO_2 volume is similar to the transportation volumes of new suggested CO_2 carriers, say 15,000 m^3 (see for example Figure 13 and Figure 14). Again, the design concept is similar to existing LPG carriers but the transportation volume is larger.

In order to assess the transportation logistics, the required time for loading, travelling and unloading are estimated. The travelling time has been estimated for an average speed of 12 knots which is common for these ship types.

Table 6. Estimated transportation logistics.

	Scenario #1	Scenario #2
Power plant	Esbjerg	Asnæs
CO_2 volume (per ship)	≈ 5,000 tonne	≈ 15,000 tonne
Route distance (one way)	≈ 150 nm (280 km)	≈ 450 nm (830 km)
Travelling time (12 knots)	≈ 13 hours	≈ 40 hours
Estimated time for travelling	12 hours	36 hours
Estimated time for loading	8 hours	8 hours
Estimated time for unloading (offshore)	12 hours	16 hours

The required time for loading is estimated to 8 hours which is not believed to be unrealistic based on other studies (reference 2.2.1).

The required time for unloading is complex to estimate since it is entirely dependent on the facilities available offshore. Publicly available information suggests possible discharge rates up to 2,200 t CO_2/hour (Maersk [23]) when only considering the ship itself. Unloading rates of 600-800 m^3/hr is the normal unloading capacity for LPG-carriers in the size of 4,000-8,000 m^3 (source: discussions with Lauritzen Kosan). The design criteria is normally that a vessel should be able to unload within 8 hrs. For CO_2 transport with unloading offshore, the unloading rate is most likely limited by the equipment available offshore, whether that is the well itself, a buoy or to an intermediate unit (FSIU/FLSO). For this reason, the unloading time has been assumed to be longer than 8 hours; 12 hours for the smaller ship and 16 hours for the larger ship. This assumption has to be verified when more information about a real scenario is available.

Figure 37 shows a potential transportation schedule for Scenario #1 using assumed time intervals for loading, transport and unloading as explained above.

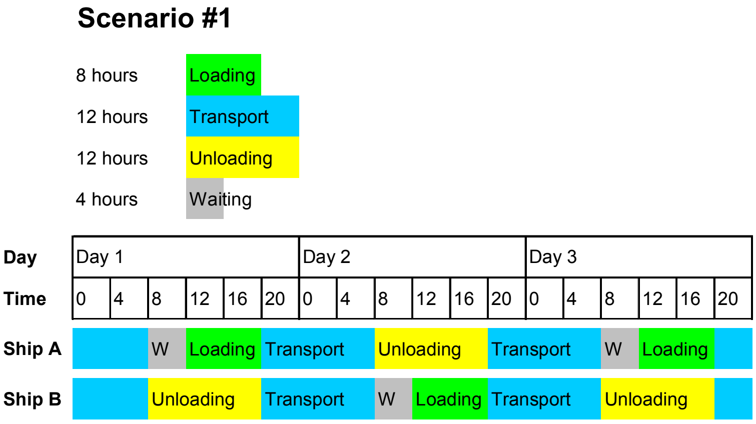


Figure 37. Transportation schedule for scenario #1 (route A).

Ship "A" would start loading CO_2 at noon day 1, sail to the oil field, unload in the morning at day 2, sail back and then start the same process again at noon day 3. At the same time as ship A starts loading at port at day 1, ship "B" starts unloading offshore. **It is concluded that the transportation logistics for Scenario #1 could be solved by two(2) CO_2 carriers of approximately 5,000 m^3 each using a two-day transportation cycle where one ship is loading at port while the other is unloading offshore**.

Continuing with Scenario #2, Figure 38 shows a potential transportation schedule for Scenario #2 using assumed time intervals for loading, transport and unloading as explained above.

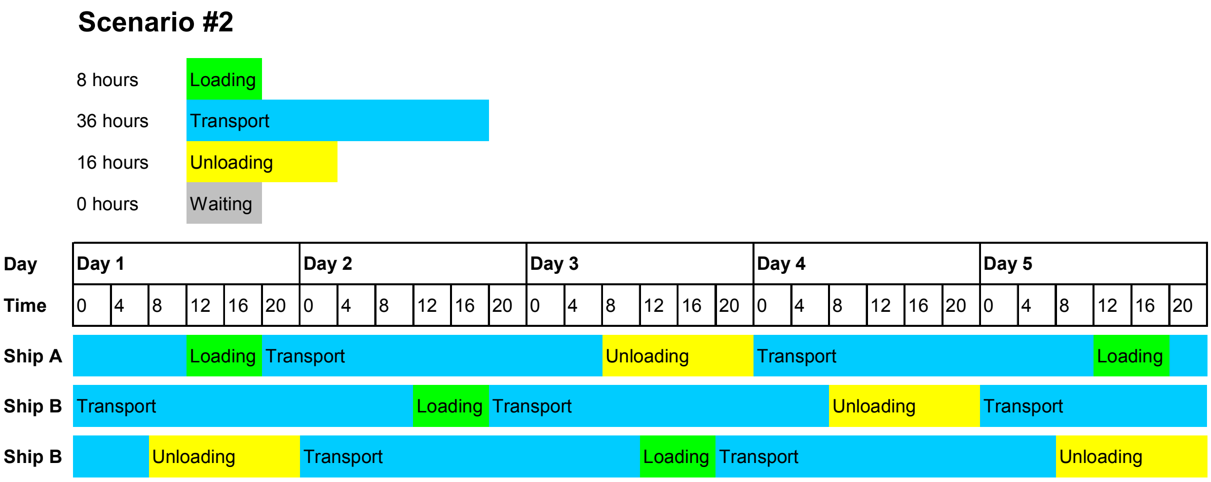


Figure 38. Transportation schedule for scenario #2 (route B).

For this case, a total of three(3) ships are required due to the long transportation distance. Similar to Scenario #1, ship "A" is assumed to start loading at part at noon day 1. The ship will reach the offshore location in the morning at day 3 after having spent 36 hours "en route".

After having unloaded (16 hours), the ship starts it voyage back and will return at port just before noon at day "5" when it is time to start loading again. Ships "B" and "C" have exactly the same cycles but start at noon day 2 and noon day 3 respectively. **It is concluded that the transportation logistics for Scenario #2 could be solved by three(3) CO_2 carriers of approximately 15,000 m^3 each using a four-day transportation cycle where (at the same time) one ship is loading at port, one ship is "en route" and the third ship is unloading offshore**.

The logistics demonstrated above are dependent on several assumptions about necessary time for loading and unloading, ship average speed etc that needs to be verified for potential specific cases in the future.

3.4 Financials

In the following, a high-level estimate of the financials of the two scenarios is made. Focus is put on the cost as seen from the CO_2 emitter, i.e. the operator of the power plant, since this is the entity that is faced with the choice of disposing of the CO_2 – either by continuing to vent it to the atmosphere or by capturing it and disposing it by storage and/or EOR. The cost is a major factor in this decision between these two options.

The analysis does not include capital expenses since these are entirely dependent on the details of the future projects. Never the less, it should be remembered that the capital expenses are very significant, especially for the capture plant and for offshore equipment (modification of current platform, intermediate buffer storage etc).

The cost of capture is the most critical since it accounts for the majority of the cost and it also the cost that is expected to be reduced considerably in the future due to improved capture technology. It is estimated to be in the range €25-70 per tonne CO_2 for a project as discussed and that is supposed to be delivered in the coming five-year period.

The cost for transportation is estimated to be in the range of €15-20 per tonne CO_2 given the fairly short distances and modest scale CO_2 carriers.

CO_2 EOR is assumed to be cost neutral with the revenue from the additional oil balancing the cost for the EOR operation. This can of course be discussed but it seems a sensible thing to do given that there is so much uncertainty in the cost estimations for offshore CO_2 EOR.

With the assumptions as above, the estimated operational cost as seen from the CO_2 emitter (power company) will be as follows.

Table 7. Estimated operational costs as seen from the CO_2 emitter (power company).

€ per tonne CO_2	Most favourable cost estimate	Least favourable cost estimate	Average
Capture	25	70	48
Transportation	15	20	18
CO_2 EOR	± 0	± 0	± 0
Total	**40**	**90**	**65**

The estimated operational cost is estimated to be in the range of € 40-90 per tonne CO_2.

In order to make a fair comparison with the current situation for a power plant operator, the cost above needs to be compared with the cost of the alternative, i.e. venting the CO_2 directly to the atmosphere which is done currently. Operators located in a country, like Denmark, that participates in the EU Emission Trading System (EU ETS) are given emission allowances that correspond to the allowed emission levels. The number of allowances is reduced over time so that total emissions fall. Emission allowances can be sold and bought. If a company reduces its emissions, it can keep the spare allowances to cover its future needs or sell them to another company that emits more than its allowances and thus needs to buy additional allowances. The idea behind the scheme is that this trading ensures that emissions are cut where it costs least to do so.

The price of one emission right (1 tonne of CO_2) is currently approximately €15 but is expected to increase significantly in the coming years. The long-term forecast for the carbon price is sensitive to many factors, not the least the outcome of political climate negotiations, and the available forecasts differ significantly. McKinsey [34] estimate a price of €30-48 per tonne CO_2 from approximately 2015 and onwards. Higher as well as lower estimates are made by others.

Given the fact that a CCS project in Denmark is likely to be at least 4-5 years away it has been decided to use a predicted carbon price for that time period rather than for the current time. **The carbon price is assumed to be €35 per tonne CO_2 (approximately twice the current price) at the time relevant for the studied potential Danish project(s)**.

The cost of venting CO_2 directly to the atmosphere in the future for a particular operator is dependent on the number of given emission allowances in relation to the actual emissions. The highest cost occurs if no allowances are given. The operator would then have to pay a cost (per tonne CO_2) equal to the cost of one emission right, i.e. the carbon price.

Comparing the estimated cost of the studied CCS scheme, €40-90 per tonne CO_2, with the cost of the alternative, i.e. venting directly to the atmosphere, taken as the carbon price of €35 per tonne CO_2, this leaves **a gap of €5-55 per tonne CO_2 for CCS to be cost comparable**. For a 1,000 MW_e plant that emits 4 Mt CO_2 per year, this corresponds to €20-220 million per year in increased costs if CCS is adopted compared to venting the CO_2 directly to the atmosphere.

In order for this gap to be reduced, two key changes need to take place:

- The cost of CO_2 capture needs to be reduced very significantly
- The price of carbon emission needs to increase significantly

The lower estimate of the gap is most likely not realistic in the near-term since it requires that capture and transportation can be achieved at the lowest cost estimates available today.

It is concluded that there will be a significant additional cost associated with CO_2 capture that needs to be funded.

3.5 Domestic expertise and resources

The feasibility and success of a potential future Danish CCS project is obviously related to technical and financial aspects of capture, transport and EOR but it is also dependent on whether there is relevant expertise and resources available in Denmark.

With respect to CO_2 **capture**, there is clearly a lot of expertise available among several power plant operators. DONG and Vattenfall have extensive experience from pilot capture plants and CCS related research in Denmark and other countries. The actual capture equipment would most likely have to be procured outside of Denmark from any of the major suppliers, for example Flour, Mitsubishi or Alstom.

CO_2 **transportation** is already investigated in detail by Maersk Tankers that are believed to have extensive expertise and progressed quite far with planning for real projects. Another example on a knowledgeable company is Lauritzen Kosan that has a lot of relevant experience from gas carriers and could operate CO_2 carriers in the future if required. There are also examples on ship designers that have demonstrated relevant expertise, for example Odense Maritime Technology (OMT) that has published a concept CO_2 carrier suitable for Danish conditions (Figure 14). Other Danish ship designer companies like Carl Bro and OSK-ShipTech could most likely also contribute in the development and procurement of future CO_2 carriers. New build of CO_2 carrier is note likely to happen in Denmark but conversions of existing LPG carriers to CO_2 carriers and other modifications could be carried out at Danish shipyards, for example Fayard (formerly Fredericia Shipyard A/S) and the Orskov yard.

Finally, with regard to CO_2 **EOR**, there is again considerable expertise and experience in Danish companies like Maersk and DONG. As mentioned earlier, Maersk is actively pursuing CO_2 EOR and is believed to have progressed quite far with the necessary preparations.

In addition to the expertise available at the companies mentioned above, there is relevant research carried out at Denmark Technical University (DTU) and also considerable expertise at various organisations as GEUS etc.

To sum up, it is concluded that there is considerable expertise and relevant experience across the entire capture-transport-EOR chain in Denmark today.

3.6 Conclusions

The most important conclusions are summarized below. It is emphasized that the carried out study is a high-level study of potential CCS scenarios and does not look into details of specific real power plants, ship transport solutions or EOR schemes. The conclusions are consequently of a fairly general character and further work is needed to validate the conclusions for the specific situation of potential projects in the future.

The studied CCS scheme is technically feasible but needs to be demonstrated at commercial scale

Even though there are still technical challenges, it is believed that the technology needed to establish a CCS scheme as studied is available today. Further refinement and scaling-up to commercial size is necessary but the technology is not among the key challenges to move forward with a real project.

Capture of CO_2 at Danish power plants could provide a bridge to a low-carbon society

This study does not aim to make a case for or against CCS. Nevertheless, it seems reasonable to conclude that capture of CO_2 at existing and potentially future Danish fossil-fuel fired power plants could provide a bridge to a low-carbon society, for a number of reasons:

1. It would allow continued operation of existing fossil-fuel fired power plants until enough renewable energy is available to replace some of the existing capacity
2. It would make the necessary back-up power (in form of fossil-fuel fired power plants) carbon neutral

The window of opportunity for EOR in the Danish oil sector is now

Clearly, there is a strong need to sustain the oil production from Danish oil fields. Even if the vision of a carbon free society will be fulfilled it will take quite some time before Denmark has no need of oil & gas. If the domestic supply is insufficient, Denmark may be forced to import large amounts of oil and gas which has a number of drawbacks in form of export/import balances, security of supply and volatile prices. EOR could help to sustain the oil production.

Based on the trends of the oil production that are showing a fast decline, it is quite clear that the need for EOR is now.

The combination of significant technical uncertainty and financial risk may become a blocker for widespread implementation of CO_2 EOR.

An extensive UK-based survey in 2004 revealed that the majority of the offshore CO_2 EOR stakeholders did not see CO_2 EOR to be economically feasible given the market conditions (in 2004). It is likely that the CO_2 would need to be supplied to the production platform at zero cost to make CO_2 EOR commercially attractive. This view has been confirmed again by several O & G operators in recent discussions with the author.

The financial risks, especially in terms of future liabilities, with CO_2 EOR are potentially much higher than with conventional O&G developments.

Danish organisations, corporations and universities have extensive and in-depth expertise that is relevant to a future CCS / CO_2 EOR project as discussed. It is foreseen that a future project could be delivered using primarily domestic resources and skills.

The study confirms what is already reasonably well known; there is extensive and in-depth expertise available in Denmark today that is directly relevant and necessary for the studied CCS scheme.

The Danish shipping and oil & gas industry can play an active role in the pursuit of a low-carbon society

If the studied CCS scheme is accepted as part of the transition to a low-carbon society, it is quite clear that the Danish shipping and oil & gas industry has a very important role to play since the CCS scheme could not be delivered without its involvement.

CO_2 transport by ship is a flexible option with comparably short start-up time

In terms of the transportation aspect of the studied CCS scheme, it is concluded that CO_2 transport by ship is an attractive option given that it is flexible and has short start-up time.

Analysis of two different scenarios – capture at a small power plant close to the oil field and capture at a large power plant at a greater distance from the oil field – demonstrates that the transportation logistics can be solved by two(2) small (5,000 m^3 each) CO_2 carriers in the first scenario and by three(3) larger (15,000 m^3 each) CO_2 carriers in the second scenario.

The logistics demonstrated above are dependent on several assumptions about necessary time for loading and unloading, ship average speed etc that needs to be verified for potential specific cases in the future.

Conversion of existing, potentially Danish, LPG carriers could be option in the short term

Conversion of existing LPG carriers could be an option in the short term for scenarios similar to Scenario #1 as studied, i.e. capture of CO_2 at a power plant of medium size. There is considerable experience of ship-based gas transport in Denmark and discussions with for example Lauritzen Kosan have confirmed that existing LPG tankers of semi-ref type most likely can be utilized for CO_2 transport in the short-term. Conversion is not straightforward and needs to be studied in details for each potential ship.

The key challenges are financial, regulatory and the political will

Overall, the three most critical challenges for the studied CCS scheme are regarded to be:

1. The financials. The cost of especially CO_2 capture is high and the proposed CCS scheme is not believed to be financially attractive enough without financial public support (see below)
2. Regulations related to storage of CO_2 are still being developed and the draft version published by the European Commission were challenging in many respects.
3. The political will. It is unclear if there is a political will in Denmark to investigate if the studied CCS scheme could play a part in the Danish energy strategy.

CO_2 EOR can offset some of the costs with traditional CCS where the CO_2 is disposed/stored

Even though the financials of the studied CCS scheme are challenging, it is clear that EOR can offset some of the costs that would have occurred for a traditional storage project.

Similar to other CCS projects, significant public funding is necessary to get the studied CCS project off the ground.

The brief financial analysis confirms what other CCS studies have also shown – early CCS projects will require significant funding (from the public) until the industry has developed further and the cost of especially CO_2 capture has been decreased significantly and/or the future price of carbon has increased orders of magnitudes compared to today.

3.7 Recommendations

Based on the findings in the study and the conclusions drawn, a number of recommendations are made below.

It should be noted that this study does not aim to make a case for or against CCS. Neither does it specifically propose or oppose that the studied CCS scheme including CO_2 EOR is progressed further. The recommendations made below are of general character and are believed to be applicable to the studied CCS scheme as well as to CCS in general.

Carry out a more detailed study of the studied CCS scheme to ensure that enough detailed information is at hand to be able to make a rational investment decision.

First of all, while it is concluded that the studied CCS scheme seems to be feasible it is clear that a much more detailed study is necessary to assess the details and ensure that enough information is made available to the potential stakeholders and the authorities.

Promote wider public discussion of CCS to ensure that the public is as well-informed as possible

The vast majority of CCS projects will require significant public funding in the initial phase. If this is to happen, the public, i.e. the "tax payers", should ideally be well informed about what they are supporting through the actions of their government. However, public opinion surveys confirm that the majority of people know very little about CCS. It is consequently suggested that a wider public discussion about the pros and cons of CCS is promoted by the authorities, stakeholders, non-governmental organisation etc. This should ideally include all aspects of CCS including environmental, financial, security of supply etc.

Carry out a detailed assessment of the impact (to the Danish society) of various long-term strategies for a low-carbon society

In order to make it easier to assess and compare various methods and strategies for a low-carbon society it is suggested that a detailed assessment is made of the impact (in terms of cost, emissions, security of supply etc) to the Danish society of various scenarios.

For example, the studied CCS schemes come with a quite substantial cost but it is difficult to assess whether it is “expensive”, “moderate” or even “cheap” without comparing the cost with the cost of alternative scenarios. Examples of three scenarios that are believed to be relevant and useful as basis for further discussion are given below:

1. **Fossil-fuel fired power generation replaced with wind energy as fast as possible without introducing CCS**. This would be in line with the recommendations by Klimakommissionen, i.e. extensive expansion of wind energy, increased efficiency of the energy system in general and phasing out and/or conversion of existing fossil-fuel fired power plant to biomass without introducing CCS.
2. **Fossil-fuel fired power generation allowed to continue provided that CCS is fitted to existing and future plants**. This would be the other extreme, i.e. minimal further expansion of renewable energy and instead continued operation of existing fossil-fuel fired power plants, CCS retro-fitted where possible on existing power plants and fitted for all new power plants.
3. **Renewable energy production is expanded as fast as possible but fossil-fuel fired power generation with CCS will play a significant role in the long-term energy supply**. This would basically be a mix of the two other scenarios.

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Appendix B – Abbreviations

barA	Absolute pressure relative vacuum
barg	Pressure relative atmospheric pressure
BOPD	Barrels of Oil Per Day
EOR	Enhanced Oil Recovery.
STB	Stock Tank Barrel. One barrel of stabilized oil at the surface after the gas has escaped
LPG	Liquefied petroleum gas
LNG	Liquefied natural gas
Mt	Mega tonnes or million tonnes
OOIP	Original Oil In Place