



GHGT-12

Improving oil recovery and enabling CCS: a comparison of offshore gas-recycling in Europe to CCUS in North America

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Abstract

This paper presents a comparison of European offshore gas-recycling in the North Sea to an exemplar onshore carbon capture-utilization-and-storage project (CCUS) in North America. Natural gas recycling has a long and successful history in the North Sea; while North America has pioneered the utilization of CO₂ for enhanced oil recovery. With renewed interest in CO₂ EOR as a means of stimulating carbon capture and storage (CCS), a simple comparison of these two gas injection cultures illuminates the potential of CCUS to change the velocity of, and cost-of-entry for, large CCS projects in Europe. The comparison of Weyburn, a large CO₂ EOR operation in Canada, with Åsgard, offshore Norway, a large natural gas recycling operation, is based on a comparative CO₂ price of 70 USD per tonne and conservative oil price for the last decade of 70 USD per barrel. A hypothetical offshore CO₂ EOR scenario is described to illustrate how the revenue-expenditure ratios are similar for offshore and onshore projects – around 5:1 for the additional oil produced from acquired CO₂. A nominal carbon tax of 35 USD per tonne increases this to 10:1, demonstrating the potential for CO₂ EOR to stimulate CCS. However, large upfront capital investments and a regional shortage of captured CO₂ are significant hurdles to offshore European CCUS. The comparison also suggests a CO₂ emissions-storage ratio of 2:1. While this is a low carbon footprint for oil, in order for these projects to have a zero carbon footprint, they would require a transition to significant associated storage. It follows that the role of CO₂ EOR in a European CCUS context is primarily to stimulate the role-out of capture and transport infrastructure, and to access to large offshore CO₂ storage hubs in the North Sea.

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1. Introduction

Europe expects to store much of its waste CO₂ in the North Sea, a mature petroleum province with many oil fields in tertiary recovery since the mid-1990s. The main options for industrial-scale CO₂ storage are to utilize saline aquifer formations, depleted oil and gas fields, and active oil fields as part of CO₂ EOR projects. Taking the case of Statoil-operated fields, offshore Norway, we observe that natural gas recycling for improved oil recovery peaked at 40 Gsm³/yr (1.4 Tcf/yr) a decade ago, indicating the abundance of offshore natural gas available for recycling; the current rate is around 35 Gsm³/yr, reflecting a strong European market for natural gas products and a limit on field capacity for recycling (Fig. 1). These fields have utilized natural gas recycling to optimize oil production since the early 1980s, which along with other improved oil recovery methods have resulted in recovery rates exceeding 50%, with an average recovery rate of 45% for the Norwegian Continental Shelf as a whole¹. The scale of injection is extraordinary: 35 Gsm³/yr of natural gas would be equivalent to 64 Mtpa of CO₂, assuming a simple volumetric substitution based on the density of CO₂, 1.85 kg/m³ at standard surface conditions (reservoir conditions vary but will likely increase this conservative estimate to around 100 Mtpa). Two of the larger injection projects, Oseberg and Åsgard (pronounced ‘Aasgard’), would correspond to 18 and 8 Mtpa CO₂ equivalent, respectively (Fig. 1).

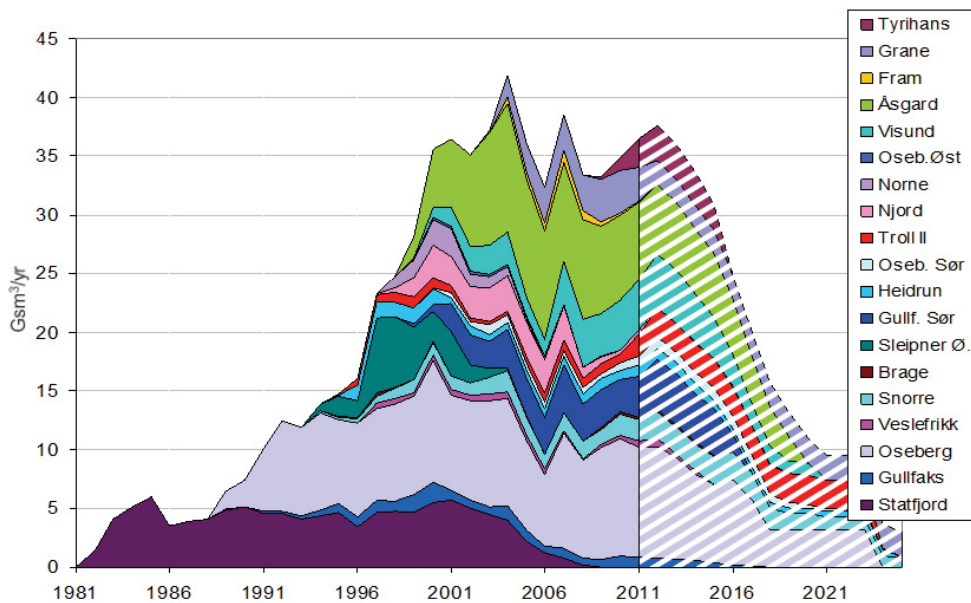


Fig. 1. An overview of gas injection rates for fields operated by Statoil in the Central and Northern North Sea as of 2011.

The scale of this gas injection activity, and the technical suitability of CO₂ as an alternative feedstock for improving oil recovery, suggests that carbon capture-utilization-and-storage (CCUS) could be feasible for the North Sea. Several technical studies on CO₂ EOR as an option for the North Sea basin have been published^{2,3,4,5}; however, a range of technical, political and economic factors leave this potential unrealized. In this study, two large North American and European gas injection projects of similar scale and duration (Weyburn and Åsgard) are compared to better understand the potential for CO₂ EOR to displace natural gas recycling and thereby help stimulate CCUS in the North Sea. The relative amounts of gas injected, oil recovered, and likely impact on emissions build a strong technical case for captured CO₂ as a preferred feedstock for tertiary recovery offshore. However, the large initial capital investment, scarce availability of captured CO₂, and the need to protect natural gas assets from CO₂ contamination, present significant hurdles to deployment.

2. A comparison with North America

In North America, CCUS is providing a low-cost pathway to industrial-scale CO₂ storage, underwriting the costs of capture technology and transport infrastructure⁶. Historically, North American utilization has been geographically localized to oil production areas with access to naturally abundant CO₂, such as the Permian Basin of West Texas and the Colorado Plateau, as noted in much of the recent literature on CO₂ EOR^{6,7}. However, the development of CCS capture technology allows for new CO₂ EOR projects to emerge in proximity to large industrial point sources (power stations and energy intensive industries such as steel and cement). Given that a typical CO₂ EOR operation requires several million tonnes of CO₂ per annum, capture clusters need to be significant in both size and longevity.

Pioneering projects such as Weyburn, Saskatchewan, Cranfield, Mississippi, and Bell Creek, Montana, demonstrate the economic sense of enhancing oil recovery while potentially providing the environmental benefits of greenhouse gas storage. These CCUS projects are self-funding and profitable, whereas many other CCS projects are currently uneconomic. Furthermore, there are a number of advantages to co-locating capture clusters, storage hubs and enhanced oil recovery. A “stacked storage” approach to CCS⁸ has become a popular conceptual model to explain the advantages of co-locating CO₂ storage and enhanced oil recovery (Fig. 2). Meanwhile in Europe, cost-effective storage management has long taken advantage of the co-location of CO₂ storage sites with operational gas fields. In the North Sea and Barents Sea, the cost profile of CO₂ storage and monitoring benefits from being co-located with large gas fields, as the CO₂ storage sites at Sleipner and Snøhvit fall within the gather of seismic surveys and other monitoring data used in gas field development and operation.

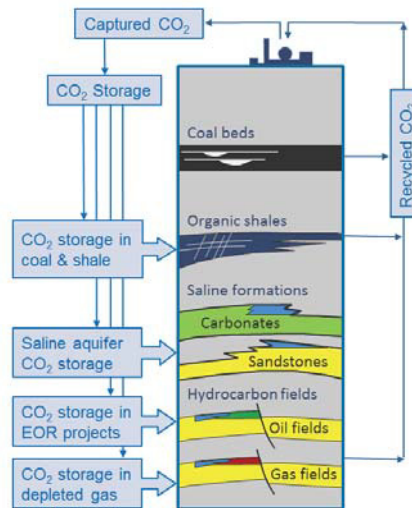


Fig. 2. Conceptual model for visualizing the advantages of co-locating CO₂ capture, utilization and storage.

The economic and environmental benefits of CCUS are significant, with part of the initial capture and transport investment being offset by the income derived from enhanced oil recovery; while the emissions impact of the oil recovered is reduced, if not entirely offset (as discussed in more detail below). Monitoring, management and verification costs can also be shared with routine operational oil and gas field surveying; and pioneering projects often benefit from a reduced financial risk, given the “first-of-a-kind” potential for replication and roll-out. Typical costs for large-scale integrated European CCS projects have been estimated^{9,10} to be in the range of 60-90 EUR (80-120 USD) per tonne of CO₂ depending on the CO₂ source and technology deployed, though this cost is expected to come down as the market emerges. Meanwhile in North America, CO₂ EOR operators are paying approximately 30-60 USD per tonne¹¹, though this may increase slightly if supply fails to keep pace with the rapidly growing demand.

Using these ranges as a guide, we assume 70 USD (50 EUR) as the comparative cost of CO₂ feedstock for CCUS in North America and Europe, and then compare and contrast the Weyburn project to a hypothetical offshore CO₂ EOR project scenario where anthropogenic CO₂ has replaced recycled natural gas.

3. Weyburn and Åsgard

At Weyburn, over 20 Mt of CO₂ has been stored¹² during a commercial CO₂ EOR flood that has contributed over 120 million barrels of produced oil since the year 2000 (Fig. 3). The field was discovered in 1954, went into early production in 1955 and peaked at around 45,000 barrels of oil per day during the motor industry boom years of the late 1960s. Changes in regional tax regimes led to infill production-well drilling in the late 1980s, and secondary recovery using water injection. This was followed by the application of emerging horizontal production well technology in the 1990s. The operating company was also quick to seize on the opportunity presented by local carbon capture in the United States in the year 2000, importing industrial CO₂ from the Dakota Gasification Company, Beulah, North Dakota. The tertiary recovery plan supported the building of a 205 mile long pipeline, which delivered 94 mmscfd (1.8 Mtpa CO₂) to Weyburn until around 2005, increasing in 2006 to 150 mmscfd (2.9 Mtpa) for both Weyburn and a neighboring CO₂ EOR operation at Midale. The CCUS activity has also initiated local capture implementation at the Boundary Dam coal-fired power plant, which will bring the total capture rate around this hub to approximately 4 Mtpa by 2015. Not only does this demonstrate the potential for enhanced oil recovery to catalyze further capture and transport activity, it also provides a reasonable scenario for considering the broad economics of CCUS. Conservatively assuming an average oil price of 70 USD per barrel since the turn of the century¹³, Weyburn has generated approximately 5-6 dollars of oil revenue for every dollar spent on CO₂ by injecting 21.6 Mt to gain 120 million barrels of additional oil: a simple measure of the efficacy of CCUS.

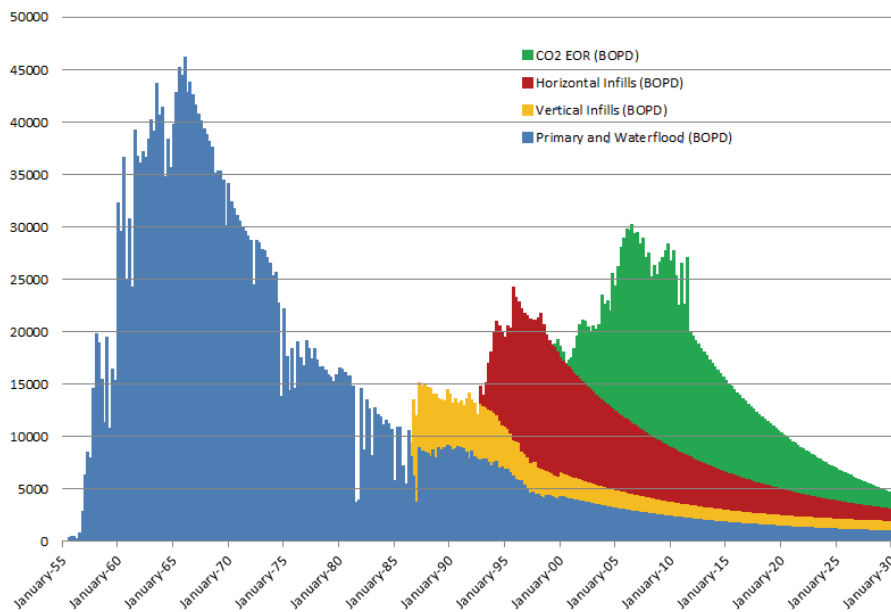


Fig. 3. The production profile, measured in barrels of oil per day (BOPD), for the Weyburn oil field, Saskatchewan, Canada¹².

Meanwhile, in Europe, a low trading price on CO₂ emissions, currently at around 6 EUR per tonne circa July 2014, has failed to drive large storage projects forward. An undervalued EU ETS price distorts the perception of what appears to be an actively emerging carbon price market (Fig. 4); globally, the median value may be closer to 35

USD¹⁴. By comparison, the Norwegian CO₂ emissions tax is high, currently at around 50 EUR per tonne (70 USD). This has enabled two industrial-scale CCS projects, Sleipner and Snøhvit, to progress. Norway has also implemented an offshore gas management policy, restricting flaring and promoting gas injection. An exemplar project under this gas management policy is the Åsgard development, 200 km offshore mid-Norway, which comprises three oil and gas fields, the Midgard, Smørbukk, and Smørbukk South discoveries. These were jointly developed as the largest subsea development on the Norwegian continental shelf at the end of the last century in water depths of around 250 to 300 meters. A further three satellite fields were subsequently tied in through the Åsgard production and transport system. To date, the Åsgard development comprises 56 wells and 17 seabed templates, connected by over 300 km of subsea pipelines. Natural gas is exported via regional transport pipelines to Germany; oil and condensate is shipped by shuttle tankers to Mongstad from the Åsgard A production ship, with natural gas management centered on the Åsgard B semi-submersible platform and Åsgard C storage ship.

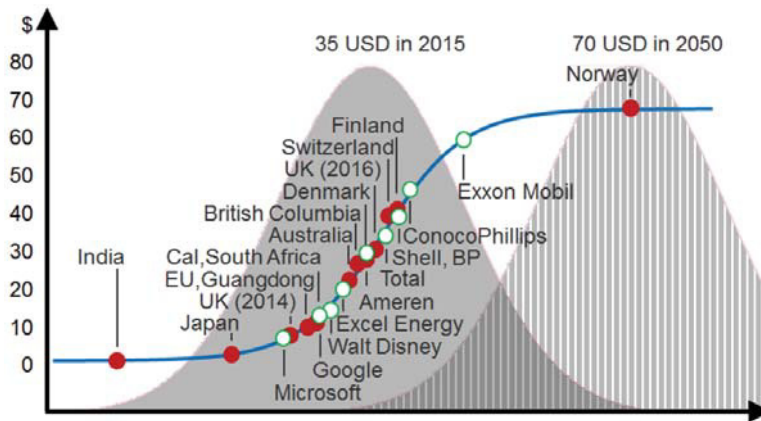


Fig. 4. Carbon price spread for regional and internal markets today, and the inflationary shift for 2050 (stipled) assuming 2% per annum.

A key element of this cluster-field development was the decision in 1999 to use natural gas recycling to maximize hydrocarbon production¹⁵. Gas from the Midgard field is partially used to achieve higher liquid recoveries for the oil and condensate fields, Smørbukk South and Smørbukk. The gas recycling strategy has multiple benefits: improved oil recovery, postponed pressure depletion, and avoidance of gas flaring. The cumulative gas injection rate is 160 Bcf/yr, equivalent to around 8 Mtpa of CO₂. Gas recycling has contributed approximately 430 million barrels of oil equivalent (mmboe) to production from Åsgard over the last decade. Looking to the future, Åsgard is currently constructing the world's first seabed gas compression facility, due to come on stream in 2015; this is expected to further boost increased oil and gas recovery by 280 mmboe, considerably extending the lifetime and value of the project. If we assume the same 70 USD barrel-and-tonne price model, as applied to Weyburn, a hypothetical offshore CCUS project on a similar scale to Åsgard (injecting 80 Mt of CO₂ to gain 430 mmboe), would also generate 5-6 euros of oil revenue for every euro spent on CO₂. Of course, prospective offshore CO₂ EOR projects require a more comprehensive technical and economic evaluation, including capital and operational expenditure analysis, such as performed in 2005 for the Gullfaks field⁴. The point of this simple revenue-expenditure ratio is that CO₂ EOR, both onshore and offshore, is likely to substantially support the cost of CCUS infrastructure installation, enabling capture clusters to access CO₂ storage hubs.

4. CCUS greenhouse gas emissions estimate

With respect to the relative impact on greenhouse gas emissions, a simple measure is the amount of produced fossil fuel as a result of CO₂ EOR, expressed as tonnes of CO₂, offset against the amount of CO₂ stored. To a first

approximation, this carbon footprint for a barrel of crude oil, from oil field to exhaust pipe, is straightforward: the extra oil produced is burnt for energy, resulting in greenhouse gas emissions; these emissions are offset to a greater or lesser degree by the sequestering of anthropogenic CO₂, which is injected into an oil field to enhance oil recovery, or a neighboring storage site. The precise offset depends on a number of factors and assumptions, which are much discussed in the existing literature¹⁶, but in general it can be argued that the net outcome is a smaller carbon footprint for the oil barrel. For the examples presented here, more CO₂ is emitted than sequestered. However, if storage were to be optimized in the post-production period, by continuing to inject CO₂ into saline aquifers or depleted oil and gas fields, the carbon footprint would be further reduced (Fig. 5) leading to significant large-scale CO₂ storage.

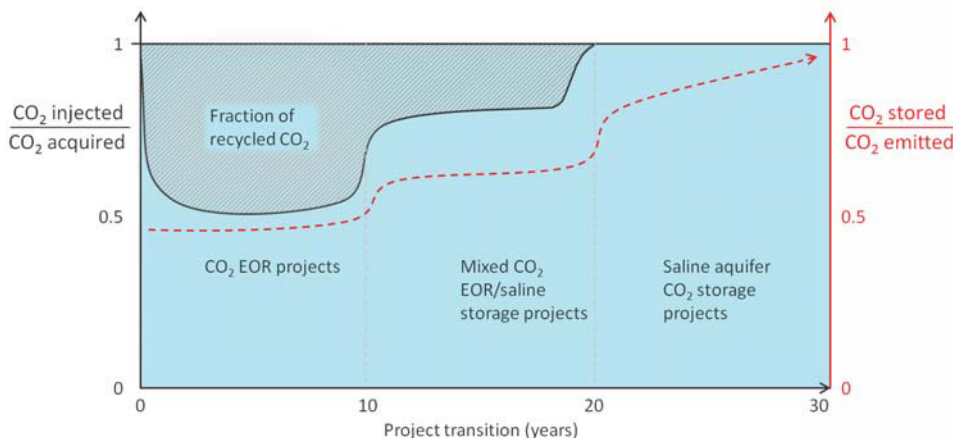


Fig. 5. A conceptual lifecycle for CO₂ emissions and sequestration during CCUS projects.

The following carbon footprint estimate assumes a moderate gravity crude (874 kg/m³), similar to that currently exported from Weyburn^{17,18}. We also assume that only 80% of the barrel (42 US gallons) is burnt for fuel¹⁹; the rest being used for plastics, lubricants, asphalt and the like. The fuel fraction is then equivalent to 100 kg per barrel.

Table 1. The fuel fractions for an average barrel of crude oil, equivalent to approximately 159 liters.

Crude fuel product	Fuel density (kg/m ³)	Volume per barrel (L)	Fraction of barrel
Gasoline	0.730	70	45%
Diesel	0.880	33	21%
Jet fuel	0.820	15	9%
Residual fuel	0.920	8	5%

There are a number of different ways to calculate the CO₂ emissions for a barrel, but perhaps the simplest is to assume that the fuel is comprised of a given mass of simple hydrocarbon chains, approximately equivalent to C_nH_{2n}. It follows that, for the atomic masses of carbon (12), and oxygen (16), a barrel of crude, consisting of 100 kg of fuel, emits about 314 kg of CO₂ on combustion:



100 kg x 12/14 = 85.7 kg (Carbon contribution to fuel mass)
 85.7 kg x 32/12 = 228.5 kg (Oxygen contribution to combusted fuel mass)
 228.5 + 85.7 kg = 314 kg (Carbon dioxide mass of combusted fuel)

The above calculation addresses the most obvious contribution to emissions, namely combustion. This analysis does not consider secondary additional emissions associated with production, transport and refining. However, a conservative estimate for these associated emissions is that they would increase the total footprint for a million barrels of oil to around 0.35 Mt of combusted CO₂.

This implies that the ratio for Weyburn is approximately 2 tonnes of combusted CO₂ emissions from exported CO₂ EOR fuel for every tonne of CO₂ stored (120 million barrels recovered for 21.6 Mt injected). The same conversion for the hypothetical offshore case gives approximately the same CCUS emissions-storage ratio of 2:1 (430 mboe for 80 Mt). This neglects the additional displaced natural gas, which has a relatively small footprint. It is clear from this comparison that neither onshore nor offshore CCUS projects provide an absolute reduction in CO₂ emissions; however, both would produce low-carbon footprint oil.

5. Conclusion

At present, no CO₂ EOR project has a negative carbon footprint; however, the next generation of CCUS may approach that goal. Implementation of CCUS in Europe would clearly increase the number and rate of large capture projects completions and also accelerate the deployment of a CO₂ transport network. This would significantly increase the velocity of European CCS, proving the technology, reducing costs and opening up offshore hubs that access saline aquifer storage.

With respect to the considered scenarios, Weyburn and the hypothetical offshore CCUS project have remarkably similar revenue-expenditure ratios: to a first approximation, for every dollar or euro spent on captured CO₂, five times that amount is generated in gross revenue. This ratio will diminish for significant CAPEX expenditures such as offshore well installations, and platform modifications. Nor does the analysis take into account a host of related OPEX costs such as CO₂ compression and recycling, compliance monitoring, well remediation and site closure. Furthermore, neither estimate includes a carbon tax. If the analysis had assumed a carbon price of 35 USD per tonne, the revenue-expenditure ratio would be closer to 10:1.

In reality, Åsgard will never be a CCUS project, as the natural gas in place is a valuable asset that is protected for future production. In this comparison, a conceptual offshore CCUS project would likely generate slightly less revenue than Weyburn and emit slightly more CO₂; this reflects the nature of offshore projects: higher CAPEX and OPEX, and increased operational energy intensity for deep water, marine environments. However, offshore well densities are much lower, lowering possible well intervention and remediation costs; Åsgard has only 56 wells compared to almost 1000 wells within Weyburn's operational area²⁰. With respect to Europe, the Åsgard integrated asset is reasonably representative of other large gas recycling operations and illustrates what a large offshore CCUS project might look like. However, natural gas has provided an effective alternative to CO₂ given its similar displacement efficiency under typical reservoir conditions for the North Sea. Additionally, for the many large gas-free oil fields in the North Sea, potentially viable offshore CO₂ EOR projects have not progressed due to the high initial investment cost and a lack of available CO₂; capture clusters in excess of 20 Mtpa are expected to emerge around the North Sea in the coming decade. From an engineering perspective, Europe has successfully implemented a number of large-scale gas injection and recycling projects similar to Åsgard. By rethinking policy drivers, this gas recycling story may yet be turned into a CO₂ management success story that provides Europe with an accelerated path to low-carbon energy.

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