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Prerequisites for Geological Carbon Storage as a Climate Policy Option

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Sammendrag:. I den seinare tid har det blitt auka interesse for karbonlagring som klimatiltak. Denne rapporten vurderer grunnlaget for å satse på geologisk karbonlagring som ein del av klimapolitikken. Lagringskapasiteten på norsk kontinentalsokkel åleine er tilstrekkeleg for å large ein stor del av europeiske utslepp av karbondioksid i mange tiår. Dersom karbondioksid blir deponert i i oljereservoar blir det ein tilleggsgevinst i form av auka oljeutvinning. På den andre sida finst det store tekniske og økonomiske utfordringar, inkludert dei store investeringane i infrastruktur som er nødvendig, og som fører til stordriftsfordelar. Difor vil venteleg prosjekt for skilje ut, transportere og deponere karbon vere økonomisk sett mest attraktivt ved utbygging i stor skala. Dette kan stimulere samarbeid mellom to eller fleire land. I tillegg er risikoen for framtidige lekkasjar frå karbonlager ei utfordring. Regjeringa må ta på seg hovudansvaret for lekkasjar. I institusjonelle og politiske termer er viktige utfordringar den uavklarte statusen til geologisk karbonlagring i Kyotoprotokollen, manglande prosedyrer for rapportering og verifikasjon av lagring, og manglande avklaring på kobling til fleksibilitetsmekanismane under Kyotoprotokollen. Den relativt høge kostnaden per tonn karbondioksid lagra gjer at alternativet i dag primært er av interesse i oljereservoar der deponering av karbondioksid fører til meir oljeutvinning, sidan forventa karbonprisar ved handel med utsleppskvotar under Kyotoprotokollen er relativt lave. Uvisse og manglane avklaring på fleire område fører til at bedrifter og regjeringar i dag berre har svake incentiv for å satse på geologisk karbonlagring.

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Abstract: Carbon storage is increasingly being considered as an important climate change mitigation option. This paper explores provisions for including geological carbon storage in climate policy. The storage capacity of Norway's Continental Shelf is alone sufficient to store a large share of European CO2 emissions for many decades. If carbon dioxide is injected into oil reservoirs there is an additional benefit in terms of enhanced oil recovery. However, there are significant technical and economic challenges, including the large investment in infrastructure required, with related economics of scale properties. Thus carbon capture, transportation and storage projects are likely to be more economically attractive if developed on a large scale, which could mean involving two or more nations. An additional challenge is the risk of future leakages from storage sites, where the government must take on a major responsibility. In institutional and political terms, important challenges are the unsettled status of geological carbon storage as a policy measure in the Kyoto Protocol, lack of relevant reporting and verification procedures, and lack of decisions on how the option should be linked to the flexibility mechanisms under the Kyoto Protocol. In terms of competitiveness with expected prices for carbon permits under Kyoto Protocol trading, the relatively high costs per tonne of CO2 stored means that geological carbon storage is primarily of interest where enhanced oil recovery is possible. These shortcomings and uncertainties mean that companies and governments today only have weak incentives to venture into geological carbon storage.

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Abbreviations

CDM: Clean Development Mechanism

CH_4: methane

CO_2: carbon dioxide

EOR: Enhanced oil recovery

HFCs: hydrofluorocarbons

IPCC: Intergovernmental Panel on Climate Change

LULUCF: Land use, land use change and forestry

UNFCCC: United Nations Framework Convention on Climate Change

1 Introduction

Carbon dioxide sequestration or storage has become one of the major policy options to mitigate man-made climate change.[1] The three major carbon storage options are biological sinks (forests and soils), geological sinks, and sequestration in the deep ocean. Biological carbon sequestration has been included in the Kyoto Protocol framework, and extensive work has been invested in analyzing the scientific underpinnings of this mitigation option, and in negotiating rules for definitions, methodologies and verification. Much less effort has been put into developing geological carbon sequestration (or storage) as a policy option under the Kyoto Protocol. Thus the aim of this study is to explore the basis for including geological carbon storage in climate policy.

Geological carbon storage can be defined as *the systematic storage of carbon dioxide captured from fuel combustion or processing in stable geological formations such as hydrocarbon fields and aquifers, thus preventing its release to the atmosphere*.[2] The most interesting geological formations are hydrocarbon fields (oil and natural gas), sub-sea aquifers, coal seams, and salt cavers. Anderson and Newell (2003) provide a good overview of various geological carbon storage alternatives, as well as carbon capture possibilities from various emission sources. In this study we focus on offshore hydrocarbon fields (oil reservoirs) and aquifers, and not on onshore aquifers.

Despite the unclear status of geological carbon storage in the Kyoto Protocol, oil and technology companies have already invested significant amounts in research and development into carbon capture and storage technologies. The main motivation for their interest is *enhanced oil recovery* (EOR) achieved by injecting CO_2 in oil reservoirs. Other substances such as natural gas or water can also be injected for the same purpose. As an example, studies and experience show that around 13% more of the oil in oil reservoirs in the North Sea could be extracted through CO_2 injection (see Holt et al. 2000 and Nissen et al. 2002). Thus geological carbon storage in oil reservoirs could have an interesting dual potential in terms of greenhouse gas mitigation and enhanced oil recovery.

In spite of the significant investments made to develop carbon storage technology, there has been relatively little focus on the key political aspects. This article will therefore focus on both the *technological and economic* basis for using geological carbon storage as a climate mitigation option, as well as *institutional and political aspects.* The discussion of the technological and economic basis will consider issues such as storage capacities, danger of future leakages from storage sites, required infrastructure and related investments, carbon capture, transportation and storage costs per tonne of carbon, and economies of scale characteristics. The institutional and political analysis will consider the status of geological carbon storage as a policy measure in international climate policy agreements (foremost the Climate Convention and the Kyoto Protocol), relevant reporting and verification procedures, linking to the flexibility mechanisms under the Kyoto Protocol, and comparison of geological carbon storage costs per tonne with expected carbon prices under these mechanisms.[3] In a broader context we explore whether the institutional underpinnings of geological carbon

[1] Hereafter, “carbon” will also refer to carbon dioxide.

[2] The term aquifer is used in this connection to describe a deep underground reservoir formed of carbonate and sandstone filled with saline water. A suitable reservoir for CO_2 storage needs a cap rock of low permeability. Injected CO_2 will replace the water, but will also to some extent be soluble in the water. The CO_2 may also react with minerals to form carbonates.

[3] The formal name of the Climate Convention is United Nations Framework Convention for Climate Change (UNFCCC). The Kyoto Protocol is a protocol to the UNFCCC.

storage are sufficient to give companies and governments strong enough incentives to venture into such projects.

2 Technological and economic basis

2.1 *Storage experience and capacity – the example of Norway*

In this paper we use the Norwegian Continental Shelf as an example to illustrate the potential and challenges of geological carbon storage. There are two main reasons why the Norwegian Continental Shelf is of particular interest. First, Statoil has injected about 1 million tonnes (Mt) of carbon dioxide annually from the Sleipner field into the Utsira aquifer formation since October 1996 to save carbon tax on CO_2 emissions. We can draw on experiences from this experiment.[4] Second, the potential storage capacity for CO_2 on the Norwegian Continental Shelf is large, and sufficient to store a sizeable share of European emissions for decades. Holt et al. (2000) estimate a storage capacity of 33 000 Mt CO_2 in oil and gas reservoirs in Western Europe (the EU and Norway), where there is a potential for EOR, and 800 000 Mt CO_2 in aquifers.[5] Assuming that 50% of the storage capacity is in Norway means a potential for storing 16 000 Mt CO_2 in oil and gas reservoirs alone.[6] The Norwegian capacity can be compared to the EU's emissions in 1990 of about 3 000 Mt CO_2, and the 2001 emissions in Norway of 42 Mt CO_2. Thus the theoretical capacity for oil and gas reservoirs in Norway is in the region of for example 50% of the EU's emissions for 11 years. If half of the aquifer capacity is used and assuming that half again of this is situated in the Norwegian Continental Shelf, the storage capacity becomes 200 000 Mt CO_2, which would be enough to store all of the EU's emissions for 67 years (provided the emissions are at 1990 levels).

2.2 *The cost of carbon capture and storage*

Geological carbon storage can involve significant investment costs due to the requirements for large investment in infrastructure such as pipelines, compressors, pumps and other facilities, in particular if it is developed on a large scale involving multiple sites and a sizable infrastructure. We examine cost estimates for geological carbon storage technologies and assessments of future carbon markets from previous studies. Enhanced oil recovery (EOR) is of particular interest in the case of oil reservoirs since this can significantly lower the climate policy-related cost threshold for geological carbon storage. The process of geological carbon storage can be broken down into three main cost components: carbon capture, compression and transport, and storage. Cost estimates will vary significantly between different fuels and types of processes (from e.g. coal-fired power production to ammonia production from natural gas). Capture costs will for example vary between coal- and gas-fired power plants – as the concentration of CO_2 is much higher in the flue gases from coal combustion than from gas combustion. The transport costs vary between modes of transport (by ship or pipeline), and the storage costs vary between types of reservoirs (from oil and gas reservoirs to aquifers). In this paper we are concerned exclusively with carbon capture from fossil fuel combustion and a few industrial processes and geological storage. Tables 1 and 2 summarise capture costs and transportation and storage costs estimated in some recent studies.

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[4] Kaarstad (2002).

[5] Based on personal communication with T. Holt (SINTEF) 31.3.03 a realistic assumption is an equal share of oil and gas reservoirs. Thus both oil and gas reservoirs have a capacity at about 16 000 Mt CO_2. Aquifers are mostly off-shore.

[6] The assumption on the Norwegian share of the capacity is based on personal communication with T. Holt (SINTEF) 31.3.03.

Table 1 Capture costs in USD/tonne CO_2

Source	Current cost	Near-term cost
Anderson and Newell (2003)		
- coal/gas power plant	45-58	34-42
- integrated gasification combined-cycle	28	17
- hydrogen production from natural gas	10	
Hustad (2003)		
- coal power plant	25	
- gas power plant	33-35	
- ammonia from natural gas	6-12	
- integrated gasification combined-cycle		15-20
Johnson and Keith (2004)		
- coal power plant		20
- gas power plant		48
Hendriks et al. (2000)		
- Natural gas combined cycle	41-66	
- Furnace/combined heat and power	6-45	

Table 2 Transportation and storage costs in USD/tonne CO_2

Source	Transport	Storage	Total
Anderson and Newell (2003)	5.60-10.80*	1.40-8.20	7-19
Hustad (2003)	10-13		
Johnson and Keith (2004)			8.20
Hendriks et al. (2000)	12-28*	1-16	13-44

*Cost is given per 100 km pipeline. We assume an average transport of 400 km (Denmark or Northern Great Britain to North Sea oil reservoirs).

2.3 Enhanced Oil Recovery (EOR)

Carbon storage has the potential to generate substantial income streams from EOR. EOR involves injecting CO_2 to pressurize oil reservoirs in order to facilitate extraction of additional oil. EOR can potentially recover an additional 6-15% of the original oil in place, and thereby increase total production from an oil reservoir by 10-30% (Hustad and Austell 2003). This implies that the oil or gas extraction period for a reservoir is prolonged. Similarly, carbon storage can also be used for enhanced gas recovery, and enhanced coal-bed methane production. The value of EOR depends on the amount of additional oil recovered per tonne of CO_2 injected and the oil price. Typically the EOR response is around 0.6; that is, for every tonne of CO_2 injected, 0.6 tonnes of additional oil is recovered. With oil prices that range from around USD 15-25, we could expect an EOR income of USD 9-15 per tonne CO_2. The price paid by current EOR operations for CO_2 lies in the range USD 11-18 (Anderson and Newell 2003). According to Hustad and Austell (2003), given an oil price of USD 18 per barrel, the average price paid for delivered CO_2 in 2000 was USD 12 per tonne CO_2.

Anderson and Newell (2003), however, claim that opportunities for enhanced recovery would be insufficient for larger amounts of CO_2 storage. Therefore geological carbon storage has to be attractive also when EOR is not feasible, for instance in the case of carbon storage in aquifers, to become a major climate change mitigation option.

2.4 Leakage from storage sites

The issue of permanency of geological carbon storage could be an obstacle to political acceptance. Studies show that some leakage is likely, because the geological formations are not completely stable, or they could be disturbed by e.g. earthquakes, or because the injection points could become unstable over time. An example of the latter could be a depleted oil reservoir where the injection point (well) is sealed by a concrete plug, and where the concrete deteriorates over time.

For oil and gas reservoirs the current leakage rate of CO_2 to the atmosphere is likely to be relatively small due to the fact that these geological structures have contained the petroleum for a very long time period. However, we have limited experience with the injection of CO_2 under such sub-sea conditions. Leakage from sub-sea storage is not likely to differ much from on-shore leakage, where we have some experience indicating that leakage is close to zero. In any case there will be some uncertainty with regard to the extent of future leakage from geological carbon storage. Hawkins (2002) suggests that one cannot be confident that current systems have leakage rates of less than 0.1 % per year. Dooley and Wise (2002) assume a leakage rate of 1% per year, but this is an average over different types of geological reservoirs. Leakage rates may differ between saline aquifers and oil and gas reservoirs. The latter type has proven to be able to store gas for long periods of time. Lindeberg (2000) has employed models to estimate emissions over the reservoir life-time. His modelling study suggests very low leakage rates for current years, and that annual leakage rates are not constant, but have a peak in emission rate after about 2000 years, and a decrease in emission rate after that.

Even if a considerable share of the CO_2 should leak from a reservoir to the atmosphere over time, temporary storage has a value since climate change is delayed. But future leakages can cause problems if a threshold of atmospheric greenhouse gas concentrations is exceeded some time in the future, leading to a steep increase in marginal damages from climate change, and if there are insufficient inexpensive backstop technologies available to reduce emissions of greenhouse gases to keep concentrations below the threshold. Dooley and Wise (2002), Hawkins (2002), and Hepple and Benson (2002) find that the annual leakage rate must be lower than 0.1% if geological storage is to be an attractive mitigation option.[7] If the leakage rate is higher, targets for atmospheric greenhouse gas stabilization in the range of 450 to 550 ppmv could become unattainable. In another study Pacala (2002) finds that a 450 ppmv stabilization target is still attainable even if the leakage rate is 1%. The more optimistic scenario is due to an assumption of heterogeneity among reservoirs. The emissions from

[7] In the best cases the seepage rate must be lower than 1%, and in the worst cases the rate must be lower than 0.01%.

leaky reservoirs are re-injected into more average reservoirs with much lower seepage rates, thereby reducing the average seepage rate over time. Herzog et al. (2003) employ an economic modelling framework where all carbon mitigation options are seen as more or less temporary, and asks what the value of temporary storage is. They find that (temporary) carbon storage is attractive if carbon prices remain (nearly) constant or if there is a backstop technology that caps the costs in the not-too-distant future.

With the current carbon sequestration at Sleipner (so far 5 million tonnes of CO_2 injected), an annual leakage rate of 1% would be negligible with respect to total emissions in Norway. However, in a scenario when 100 million tonnes or more are sequestered at the Norwegian Continental Shelf, even an annual leakage rate of 0.1% would give significant emissions. Consequently, developing methods for cost-effective monitoring will be essential for getting public and political acceptance for this mitigation option. With present technologies there would be significant uncertainty in monitoring and verifying leakages from geological storage of carbon. The implications for climate agreements of the danger of leakages are discussed in sections 3.2 – 3.5.

Possible leakage from underground carbon storage is a challenge that raises a number of issues. The first issue is the responsibility for future leakages. If such leakages occur they should be accounted for in the national inventory of emissions (see section 3.4), and in case joint implementation credits are involved, these could be discounted over time, or be given a limited life-time.

The second issue relates to intergenerational ethics. If accumulated leakages over the next decades turn out to be large, this implies an implicit transfer of burden from our generation to future generations, either in the form of more emission mitigation required in the future, or in the form of increased climate change and related damages. To what extent are we willing to transfer this type of risk to our children and grandchildren?

The third issue is the potential additional costs incurred by geological carbon storage due to leakage. There is also a significant element of uncertainty involved since it will be impossible to know exactly how well a reservoir will perform over a time span for at least some decades, and possibly many hundred (or a thousand) years. The higher the expected leakage rate and the larger the uncertainty, the less attractive this mitigation alternative will be as compared to other mitigation alternatives such as biological carbon storage, renewable energy sources, and improved efficiency in production and consumption of energy.

3 Institutional and political aspects

The requirement for large investments in infrastructure, relatively high costs and danger of future leakages have implications for the possibility to include carbon storage in climate policies. With respect to climate policy institutions one key question is whether a Party to the Kyoto Protocol can get credits for geological carbon storage under the first and subsequent commitment periods. A related question is to what extent carbon capture and storage as a mitigation option will be able to compete with other mitigation options as reflected in the expected prices of greenhouse gas emission permits under the Kyoto Protocol.[8]

The legitimacy of geological carbon storage is also an issue in terms of international environmental agreements beyond the climate agreements. There could be a conflict between geological carbon storage and international environmental agreements. Hegna (2003) discusses whether geological carbon storage is legitimate under the worldwide London

[8] Unless further specification is called for we refer to the trading units (quotas and credits) under all the Kyoto mechanisms as ‘permits’.

Convention and Protocol, and the North-East Atlantic OSPAR (Oslo-Paris) Convention.[9] He finds that the disposal of CO_2 in underground reservoirs and aquifers is considered waste dumping and therefore prohibited, with the exception of injection related to offshore petroleum production, and then also for the purpose of EOR. These obstacles are not addressed further here.

3.1 Status in climate policy agreements

The references to carbon storage in the climate agreements are of a general nature and thus in terms of sinks and reservoirs of greenhouse gases. Neither carbon dioxide nor geological storage are specifically mentioned in the UNFCCC or the Kyoto Protocol.[10] The only exception to this is the Marrakech accord, where fossil fuels technologies storing greenhouse gases are mentioned, but only in the context of potential adverse effects on developing countries from mitigation measures. It seems that formal recognition of geological carbon storage is lacking in the climate agreements, which is line with the view of IEA (2001, p.26). Thus the incentives for countries and companies to engage in geological carbon storage are to a large extent so far missing in the climate policy context.

3.2 What can we learn from the rules for biological carbon storage?

Under the Kyoto Protocol, carbon storage can be accounted for under the categories Land Use, Land Use Change and Forestry (LULUCF), waste, and to some extent industrial processes. However, storage is not accounted for consistently within these categories. As described in more detail below, in the LULUCF sector there have been long political discussions that were concluded in the Marrakesh accords.[11]

The waste sector is normally not considered a sink category. Nevertheless, using state-of-the-art estimation methodologies (second-order decay method), it is taken into account that fossil carbon is accumulated in landfills as the emissions of CH_4 and CO_2 do not outweigh the disposal.[12] Storage can also be accounted for in long-lived industrial products, such as plastic. On the other hand, storage of carbon in long-lived wood products (other than landfills), such as buildings, cannot be credited during the first commitment period as the issue of accounting for import and export has not been decided at the political level. Emissions are attributed to the country of wood harvest at the time of harvest.

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[9] So far the issue has not been settled. Using CO_2 for EOR is legal according to OSPAR. On the other hand the London Protocol states that all dumping from man-made structures at sea is illegal. The Protocol has yet not entered into force.

10 The main general references to geological carbon storage in the Climate Convention are Articles 4.1.b and 4.2.a, where "removals by sinks of all greenhouse gases" and "protecting and enhancing its greenhouse gas sinks and reservoirs" are mentioned. In addition Articles 1.7 and 1.8 provide definitions of "Reservoir" and "Sink", and Article 4.2.c gives guidance on calculations of emissions by sources and removals by sinks. The Kyoto Protocol in Article 2.1.a.ii also mentions "protection and enhancement of sinks and reservoirs of greenhouse gases", and Article 5.1 states that the Parties should have in place "a national system for the estimation of anthropogenic emissions by sources and removals by sinks of all greenhouse gases". Article 5.2 states that "Methodologies for estimating anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol shall be those accepted by the Intergovernmental Panel on Climate Change". The most specific reference is Article 2.1.a.iv, which states "Research on, and promotion, development and increased use of, new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies". The Marrakech accord from the 7th Conference of the Parties to the Climate Convention in October to November 2001 in paragraph H.8.d has a more specific reference to geological carbon storage, stating that industrialized countries should be "cooperating in the development, diffusion and transfer of less greenhouse gas-emitting and advanced fossil-fuel technologies, and/or technologies relating to fossil fuels that capture and store greenhouse gases, and encouraging their wider use". Paragraph H relates to Article 3.14 of the Kyoto Protocol, which is on minimizing adverse effects on developing country Parties from emission mitigation measures in industrialized country Parties.

[11] UNFCCC document FCCC/CP/2001/13/, Add.1, Add.2, and Add.3.

[12] IPCC (2000).

Since biological storage within LULUCF was included in the UNFCCC and the Kyoto Protocol a substantial amount of work has been spent on the scientific underpinnings and on negotiating operational rules for this mitigation option.[13]. Many technical difficulties and delimitation challenges have created a rather complicated set of rules. In addition, political considerations, e.g. the need to strike a compromise between countries with different interests, have contributed another layer of complexity. This is the background for a number of constraints on the use of biological carbon storage under the Kyoto Protocol commitment period 2008 until 2012. The most important constraints are as follows:[14]

- Emissions and removal from afforestation, reforestation and deforestation are limited to human induced changes since 1990 (within the commitment period) (Article 3.3).
- There is a specific ceiling on forest management activities for each industrialized country, and for re-vegetation, grassland management and cropland management the credits are relative to the base year; (Article 3.4).
- LULUCF activities under the Clean Development Mechanism (CDM) must be based on afforestation or reforestation and are limited to 1% of 1990 emissions times five (due to the five year commitment period).[15]
- Biological sequestration credits generated within industrialized countries (‘removal units’) cannot be banked (to the commitment period after 2012).
- Banking of credits from joint implementation and CDM projects – including credits from LULUCF projects – is limited to 2.5% of each industrialized country’s annual emission permits for 2008–2012 as defined by the Kyoto Protocol.

This implies that for example for a country like Norway, only a fraction of the total biological carbon sink will be credited. Furthermore, the Kyoto Protocol stresses that removals in order to be credited need to be *verifiable*. This can be interpreted to mean that there are stricter requirements on reporting of removals than emissions, even if emissions are reduced relative to the base year.

There are some important similarities between biological and geological carbon storage, but one significant difference is that the former is dependent on biological processes that take time, whereas the latter is more of a physical process where injection is much less time-consuming. Another difference is that biologically stored carbon will eventually “leak” to the atmosphere unless the biological stock (e.g. forest biomass) is maintained forever, whereas carbon stored in stable underground geological structures in principle could stay there for thousands of years and longer without any specific human actions as long as the rate of leakage is zero (or very close to zero).

There may, however, be some of the same critical arguments in the case of geological carbon storage. First, both types of carbon storage can lead to other environmental consequences. Second, there are uncertainties about the permanence of the storage and actual leakage rates. The argument on permanence is not very strong in other situations than CDM projects (in non-Annex I countries without commitments to reduce emissions), as long as possible leakages (emissions) are accounted for, either initially or when the Party reports under future commitment periods. Finally, many environmentalists argue that measures

[13] IPCC (2000) op.cit. The decisions at COP 7 (Marrakesh accords): FCCC/CP/2001/13/add.1, FCCC/CP/2001/13/add.2, FCCC/CP/2001/13/add.3.

[14] See Torvanger (2001), pp. 7-8.

[15] CDM projects are undertaken in developing countries to reduce greenhouse gas emissions, for example through investments in enhanced fuel efficiency, fuel switching, or increased carbon sequestration in forests. Industrialized countries can buy credits from such projects and employ these as part of meeting their emission reduction under the Kyoto Protocol.

should focus on reducing fossil fuel consumption in stead of “end of pipe” solutions such as carbon storage.[16]

Due to technical complexities and the possibility of similar political considerations as in the case of biological carbon storage, constraints on the use of geological carbon storage may become embodied in operational rules for this mitigation option, provided that more specific rules are to be negotiated (see section 3.4). With a view to the constraints on LULUCF credits, a possible outcome is that only storage in some types of geological formations are eligible, that there is a ceiling on the volume stored for each country, that there is a constraint on the share of such projects under the joint implementation mechanism, and, finally, that there is a limit to banking of such credits.

It can, however, be argued that in spite of the uncertainties with respect to future leakages (as discussed in section 2), geological sequestration is less complex than biological sequestration so the arguments for using a cap or other restrictions for such reasons are not very strong. It is also important to bear in mind that by using restrictions on credits the incentives for using geological carbon sequestration as a climate measure will be reduced. If some type of ceiling should arise, this could both reduce storage and increase the cost per tonne, either due to an associated increase in administrative costs, or related to scale economies of geological carbon storage.[17] Thereby the attractiveness of the option can be reduced compared to for example domestic emission mitigation alternatives and to permits from the Kyoto mechanisms. When large-scale investments in infrastructure are required, a “political” ceiling could mean that the realizable scale is reduced, which raises the cost per tonne of CO_2, and could lead to sub-optimal infrastructure investments.

3.3 Relation to flexibility mechanisms under the Kyoto Protocol

The Kyoto Protocol encourages the use of (biological) carbon sequestration technologies in general terms, but with no specific reference to geological carbon storage. A major unresolved issue if such projects should be undertaken relates to the allocation of credits when sequestration of CO_2 takes place in a country other than where they were generated.

As mentioned in section 2.1, the huge storage capacity offshore in Norway implies that it might be feasible to sequester CO_2 gas from power plants and industrial plants also from other countries than Norway. Consequently, it will be necessary to clarify whether the exporting or receiving country will get the credits.

There are three options:

1. Carbon storage could be handled through the *flexibility mechanisms* of the Kyoto Protocol, for example as joint implementation projects.
2. It could be seen as an *end of pipe technology* for each emission sources. In the case where the gas is transported over borders, the credits are given to the country whose emissions were avoided.
3. It could be reported as a *separate sink category*. In the case where the gas is transported over borders, credits are given to the receiving country.

In the case of option 1, one country could export carbon dioxide to a neighbour country for storage in its geological formations. In this case, the carbon dioxide volume could be framed as a transfer of permits under emissions trading, or transfer of credits under joint implementation or CDM. Thus a country could sell “storage” permits on the international

[16] See for example Muttitt and Diss (2001).

[17] Due to the large investments required in carbon capture facilities and infrastructure (such as pipelines), the cost per tonne of carbon captured and stored in geological formations is likely to fall with the scale (i.e. with the volume of carbon processed).

market. The purpose of the flexibility mechanisms is to enhance international cost effectiveness. As an example, geological carbon storage in an oil reservoir can be defined as a joint implementation project. The joint implementation mechanism implies that two industrialized countries can cooperate to carry out a project that lowers emissions of greenhouse gases in one of the countries. By partially financing the costs of carbon storage, the carbon-exporting country can receive credit for reduced emissions that can go toward meeting its commitments under the Kyoto Protocol. The host country with the oil reservoir could be accredited part of the emission credit. The two countries must settle on a credit price that reflects the sharing of the credit and the costs.

Geological carbon storage within one country can be handled according to options 2 or 3. In the case of transfer between countries given options 2 or 3, geological carbon storage need not be based on the Kyoto mechanisms but on bilateral economic compensations. With option 2, a country with large carbon storage capacity does not have any direct incentives to handle emissions from other countries. Therefore an economic compensation must be given by the exporting country to the host country to cover transportation and storage costs.

In the case of option 3, the country where emissions are avoided does not have any direct incentive to capture CO_2 because another country receives the credits. Since carbon storage contributes to meeting the recipient's commitments under the Kyoto Protocol, even if some transportation and storage costs are involved, it should be willing to pay the country where emissions originate from to at least cover its capture and transportation costs. Two countries could agree on a contract specifying the amount of carbon to be injected where and when, and the price to be paid. The motivation for such a deal could be that a country wants at its own cost to undertake more carbon storage than legitimate under the Kyoto Protocol if there should be a ceiling on geological carbon storage. Another alternative is that countries that have not ratified the Kyoto Protocol nevertheless invest in geological carbon storage, for instance with a view to future participation in the climate policy regime. The transfer and storage of carbon in such a case is also likely to be in accordance with the rules for reporting greenhouse gas emissions and establishing a national emission inventory (see section 4).

3.4 Reporting and verification issues

Reporting and review of greenhouse gas emission and removal inventories is an important part of the implementation of the Kyoto Protocol (Article 5, 7 and 8). The emphasis on reporting and review in the Kyoto Protocol is to assure that the emissions and emission reductions that the Parties report are real, as far as can be judged. This implies that in order to be able to participate in emission trading and be in compliance the reported emissions and removals have to be estimated following the guidance provided by IPCC.

3.4.1 Reporting issues

Guidelines for reporting removals due to geological carbon sequestration have not yet been developed by IPCC and UNFCC. It is, however, likely that such guidelines will closely follow the principles adopted for other sources and sinks. The removals and emissions from leakages have to be accounted for in an appropriate source (sink) category. Because the gas can be transported over borders, capture from each source-category, transport and injection for storage all have to be reported in a transparent manner independent of how credits are given. This will ensure that the amount captured and stored can be cross-checked. The system for crediting discussed in Section 3.3 has to be designed to ensure that double-counting is avoided.

Irrespective of what method of crediting that is used, the only practical option is that the host country (e.g., Norway) would have to take the responsibility to monitor, verify and report possible emissions from leakages in their national emission inventory. If emissions from another country are sequestered within Norwegian territory, it would therefore be a Norwegian responsibility to verify and report leakages. This applies even if the reservoir has been abandoned. These future monitoring costs have to be reflected in the total costs of a project. This might, however, be difficult due to the very long expected retention time (thousands of years).

3.4.2 Methodology issues

Neither the IPCC guidelines nor the IPCC good practice guidance provide a method to estimate emissions and removals for geological carbon storage, or similar sink categories. However, the appropriate method can probably be deduced from the recommended estimation methodologies for other sources, such as HFCs stored in equipment that gradually leak out, or organic material stored in landfills which is gradually transformed to methane.

Annual net removals or emissions of carbon due to geological carbon capture can be calculated as follows:

> *Net emission/ removal of CO_2 for year t = -Amount captured + Emissions during transport/handling + Emissions during the injection process + Gradual leakages + "Accidental" leakages.*

The leakages will also be related to gas injected prior to the reporting year. End-of-pipe capture may not be 100% efficient, but the amount of carbon captured can probably be monitored with high accuracy, in particular if there are large-scale sequestering projects involving trade of CO_2. It is likely that the emissions from *transport and handling* will be small. Natural gas pipelines off-shore normally have low leakage rates (as opposed to land-based pipelines). Emissions may occur for reasons of maintenance when gas needs to be vented to the atmosphere.

Once the CO_2 has been stored, possible leakages must be accounted for as *emissions*. This can be done using annual leakage rates based on measurements or other data or by verifying that the leakage is practically zero.[18] To properly monitor this leakage rate is a major challenge when including geological sequestration under the Kyoto Protocol.

Storage of CO_2 at Sleipner at the Norwegian Continental Shelf has been monitored using 3D seismic surveys (Torp and Gale 2002). This type of monitoring is expensive and is useful for monitoring the behaviour of bulk gas, but will not give annual leakage rates that can be used for reporting and accounting. Monitoring probably has to be combined with model simulations in order to give numerical leakage rates (IEA 2002). In the end the required accuracy that is required for monitoring geological carbon sequestration is a key question.

Finally, *accidental leakages* would mean larger leakages due to structural damage in the reservoir, for example due to earthquakes and other natural geological changes. Although these types of accidents are not very likely, it is important to assess the risk for a long time interval and to monitor the emissions if such an accident were to occur.[19] Furthermore, it needs to be decided whether it is the commercial operator or the government that is responsible for the corresponding leakages (see section 3.5).

3.4.3 Documentation, Quality control quality assurance and verification

There are strict requirements for documentation of all emissions and removals reported in the national inventories. The documentation shall facilitate a review of the reported data. This implies that the expert review team should be able to track where data comes from, the methodologies used and the quality. It is a general concern that it can be difficult to obtain transparency when complex models are used (as is the case here). However, in the case of using complex models there should be a requirement that the methodologies have been peer reviewed.

[19] For onshore reservoirs such risk assessments would be essential also for health reasons.

3.5 The government and private entities

In accordance with the UNFCCC and the Kyoto Protocol, the responsibility of reporting emissions and limiting greenhouse gas emissions is placed on national states (and the EU). State governments must decide how companies and other private entities are to be involved in implementing these agreements at national level. One straightforward option is to distribute greenhouse gas emission allowances to companies and thereafter allow them to trade on the national and international market. Thus a company has a ceiling on its emissions for a certain time period (e.g. year) that can be met through increased efforts to reduce process-related emissions, using the Kyoto mechanisms, or through investing in or buying credits based on e.g. geological storage of carbon.

Due to the long time horizon relevant for geological carbon storage, it is problematic to leave the full responsibility for potential future leakage with the companies investing in this option. For instance a 50-year time horizon is difficult to handle for a company, and there is a substantial risk that the company will not exist so far into the future. This emphasises the government's responsibility both for the emissions and for monitoring. In addition there is uncertainty with regard to future leakages of CO_2 from geological storage sites and uncertainty with regard to monitoring since the exact amount of carbon stored cannot be determined. A cost-effective standard for monitoring leakage rates is needed. The costs of monitoring and verification for a long period have to be taken into account when assessing the costs of sequestration. One practical way of handling the risk of leakages is for the government to establish minimum requirements to be fulfilled by carbon storage projects, see Lindeberg (2002). When a company can document that the requirements are satisfied, the government accepts responsibility for any future leakages from the reservoir or aquifer. A second option is to transfer the responsibility for the permanence of the carbon storage to the government after a fixed time period, e.g. after 20 years. A third option is to credit the company for instance 80% of carbon sequestered, and leaving all future responsibility for leakages with the government. Obviously such responsibility could incur extra future costs on the government; in particular if future leakage rates are significantly higher than anticipated. Either the government could be willing to accept this risk, or it could require, as a fourth option, that involved companies finance an insurance fund that could cover future expenses, or the government puts a fee per tonne of geological carbon storage as a risk premium to cover potential future expenses for the state.

3.6 The carbon market and permit prices

With binding restrictions on emissions of greenhouse gases, the abatement or removal of emissions gains an economic value. To date, the most significant agreement that restricts emissions is the Kyoto Protocol. National greenhouse gas emission trading schemes already exist in Denmark and the UK. The EU will establish a trading scheme from 2005, and more are planned before 2008. If the Kyoto Protocol enters into force, negotiations on a second commitment period (after 2012) must at the latest commence by 2005. In assessing the market for carbon storage, we will consider studies on both the Kyoto Protocol and future climate agreements, as the price of emission permits will determine whether or not geological carbon storage will be a competitive option.

Parties to the Kyoto Protocol have committed themselves to reducing their greenhouse gas emissions. The Protocol establishes three so-called flexibility mechanisms that Parties to the Protocol may use to help them comply with their commitments: emissions trading, Joint Implementation and the Clean Development Mechanism (CDM), and each mechanism has its own type of permit. The supply of emission permits depends on marginal abatement costs in each of the participating countries, the availability of competitive biotic sink projects, and the supply of “hot air”.[20] Russian “hot air”, US non-participation, and inexpensive forest (CDM) credits from developing countries contribute to lowering the permit prices.

The literature on estimating permit prices is extensive.[21] Most of these studies assume that the permit market will be a relatively liquid market with an equilibrium permit price. In the studies reviewed, the price estimates, given in tonnes of CO_2 equivalent (CO_2e), range between zero and USD 15.[22] While this is a relatively large range, most studies seem to indicate a permit price in the region USD 5-10 per tonne CO_2e as the most likely outcome.

It is difficult to estimate carbon prices under a future climate regime. The estimated prices will depend heavily on the policy assumptions that are made: the size of the emission reductions to be undertaken, and the availability of mitigation options. Furthermore, the longer we look into the future, the more uncertain assumptions about economic parameters and technological change will be. Nevertheless, some such studies have been undertaken, and the price estimates they provide are the only ones that are available. Some recent studies give price estimates in the region USD 23 – 37 by 2030, depending on the emission targets.

3.7 Comparing carbon storage costs and permit prices

The key question is, whether, and under what circumstances, geological carbon storage can be a viable option for mitigating human-induced climate change. We assess this through comparing cost estimates for geological carbon storage technologies with estimates of future emission permit prices from previous studies. We combine this information to give an overall assessment of the economic viability of geological carbon storage as a climate mitigation option – today and in the near future (until 2020). The information available about geological carbon storage technologies is sufficient for making rough cost estimates, such as ours, but do not permit a more comprehensive cost analysis – such as constructing marginal abatement cost curves for carbon storage. These costs are seen also in the light of sets of circumstances that reflect uncertainties regarding the development and cost of geological carbon storage technologies, and future permit prices at the international markets under the Kyoto Protocol. Beyond 2012 these uncertainties are even larger.

Based on the reviews of geological carbon storage options and costs, the potential for EOR, and price estimates from the carbon market under international climate policy agreements, we have created sets of circumstances to evaluate the economic viability of carbon storage as an option for climate change mitigation. We provide low, medium and high estimates for permit price and geological carbon storage cost intervals – based on the reviewed studies. Together these estimates produce nine sets of circumstances for the economic viability of geological carbon storage. These are presented in table 3.

With respect to permit price, in the “low” estimate we assume a competitive international permit market under the Kyoto Protocol, where market power by Russia in particular is not fully exercised, but where all available CDM projects are carried out. For the “medium” estimate, we still assume that the Kyoto Protocol is implemented, but this time that market power is exercised fully, and that due to institutional barriers and high transaction costs, (no or) only a limited number of CDM projects are carried out. For the “high” estimate we look beyond the Kyoto Protocol, and at a possible future climate agreement with more severe emission reduction commitments.

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[20] “Hot air” is the term used to describe the excess permits allocated to Russia and certain Central and Eastern European states.

[21] We have limited our review to studies that consider international emissions trading, and where the United States is not a party to the Kyoto Protocol.

[22] In studies where the prices where not given in USD, prices were converted using the exchange rates as of April 10, 2003, which were USD 1 to EUR 0.927 and GBP 0.639.

When it comes to geological carbon storage technologies, we have again made three different sets of assumptions that give rise to three different cost estimates. For the "low" cost estimate, we assume a low cost geological carbon storage technology, such as the integrated gasification combined-cycle process with near-term technological improvements. We further assume that the CO_2 is used for enhanced oil recovery. The "medium" cost estimate is based on the best existing technology for a gas- or coal-fired power plant, with medium transportation costs, and no income from EOR. For the "high" cost estimate we make less optimistic assumptions regarding the best available geological carbon storage technology for a gas-fired power plant, and we assume high transportation costs and no EOR.

Table 3 Net economic benefit of geological carbon storage under various assumptions (USD per tonne of CO_2)

		Geological carbon storage cost		
		Low* $7-21	Medium $40-50	High $75-95
Permit price	Low $0-5	-2 to -26	-35 to -50	-70 to -95
	Medium $10-15	-11 to +8	-25 to -40	-60 to -85
	High $25-35	+28 to +4	-5 to -25	-40 to -70

* Includes income from EOR.

Table 3 shows that geological carbon storage is very likely to be economically viable only in the case where costs are low and permit prices are high. The combination of a low geological carbon storage cost and a medium permit price can also be viable. These cases are marked with a grey shade in the table. For all other circumstances we find a negative net economic benefit of implementing geological carbon storage. These cost estimates confirm that geological carbon storage for enhanced oil recovery can be profitable. Such activities already take place at some oil reservoirs.

While the permit price and geological carbon storage cost estimates are independent of each other in other respects, there is a clear correlation over time. If we look beyond 2012 we expect carbon prices to rise, as long as more ambitious climate policy agreements are adopted, and we also expect technological advances to bring down the cost of geological carbon storage. Over time one might therefore expect to see a shift towards the lower left-hand corner of the table, where you find the economically viable circumstances.

Even though we expect that carbon capture and geological storage will improve its cost-benefit ratio over time, we also have to bear in mind that other carbon abatement options will develop over time. Cheaper abatement options might be developed, and this would lead to a downward pressure on the carbon price. Rapid improvement in renewable energy technologies could, for example, significantly reduce carbon prices, and make geological carbon storage less competitive.

4 Discussion and conclusions

Carbon storage in geological formations has considerable potential as a greenhouse gas mitigation option. While aquifers, gas fields, coal seams and salt cavers have a potential for storing carbon dioxide, oil reservoirs have an additional benefit in terms of enhanced oil recovery, making these formations particularly interesting candidates. In the case of Norway, there is a sizeable storage capacity within the Norwegian Continental Shelf that is sufficient to store a large share of European CO_2 emissions for many decades. There are a number of challenges to sort out to take advantage of geological carbon storage as part of an efficient climate policy. The challenges are both technical and economic on one hand, and political and institutional on the other.

In technical and economic terms, an important challenge is the large investment in infrastructure required, and related economies of scale properties. This means that the cost per tonne of CO_2 is relatively high. Therefore carbon capture, transportation and storage projects are more attractive if developed on a large scale, which, in many cases, would mean involving two or more nations.

The risk of future leakages from storage sites is another technical challenge, which has institutional implications in terms of the handling of responsibility for such leakages, and political implications in terms of public acceptance. There is both uncertainty with regard to future leakages of CO_2, and uncertainty in terms of the ability to monitor and verify the exact amount of carbon stored. If the amount stored is large, even small leakages may be significant. The government could be willing to accept a risk of leakages provided that a carbon storage project satisfies certain criteria. This alternative could be combined with the government taking the responsibility, but introducing a fee per tonne of geological carbon storage to be paid by the companies as a risk premium to cover potential future expenses. An alternative is to require that the responsible companies finance an insurance fund that could cover future expenses.

In institutional and political terms, important challenges include the unsettled status of geological carbon storage as a policy measure in the Kyoto Protocol. Only during the past five years has serious consideration been given to this mitigation option. Carbon sequestration is essentially a technology emanating from the oil companies, who at that time the Kyoto Protocol was negotiated opposed or ignored the climate policy process. Other issues are the possibility to monitor and verify leakages, and deciding how the option should be linked to the flexibility mechanisms under the Kyoto Protocol. Accounting and verification rules have not been well developed for geological carbon storage. Smaller projects can most likely be handled within the current reporting system under the Climate Convention and the Kyoto Protocol (seen as an end-of-pipe abatement), but in the case that e.g. Norway is handling large amounts of CO_2 from industrial plants, clarifications of reporting and crediting are needed. This includes the definition of appropriate reporting categories, estimation methodologies and requirements for accuracy and verification. Geological carbon "storage" units could be framed under emissions trading, as joint implementation or through bilateral agreements. The fact that the Kyoto Protocol has not yet entered into force adds to the uncertainty of carbon capture and storage as a mitigation option.

The capture and storage cost per tonne of carbon dioxide can become relatively high compared to alternative mitigation options. In terms of competitiveness with estimated CO_2 permit price under Kyoto Protocol trading (and thus other CO_2 abatement measures), geological carbon storage is today only of interest under particular circumstances, primarily where CO_2 injection can be used for enhanced oil recovery. Furthermore, due to the large investment requirements and economies of scale properties, the storage price can be competitive only if a carbon storage strategy is implemented so that the investments can be shared for a large storage volume and thus many carbon storage permits.[23] This may imply that there are gains from close collaboration between neighbouring countries. However, in the near future (one decade) it might become a competitive abatement option on a larger scale if carbon prices increase and technical improvements lower the cost of geological carbon storage. This conclusion depends crucially on the assumption that a future climate regime will have binding quantitative emission reduction targets – so that there is a market for CO_2 emission reductions or removal, and also that marginal abatement cost, and thus the permit price, is significantly higher than what is expected for the Kyoto period (2008-2012).

Due to the shortcomings and uncertainties we have mentioned, companies and governments today have only weak incentives to venture into geological carbon storage. Furthermore, uncertainties of the permanence may be an obstacle for public acceptance. If these obstacles can be sorted out, the potential of geological carbon storage to enhance the cost-effectiveness of carbon dioxide mitigation policies could be put to a real test.

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[23] Due to the dependency of investments in CO_2 capture technologies, transportation (pipelines), and carbon storage, contracting problems will arise as long as the owners of these facilities are different. One solution is intervention by the state.

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