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Can geological carbon storage be competitive?

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Sammendrag:.
I dette arbeidsnotatet går vi igjennom litteraturen på kostnader og nytte av geologisk karbonlagring samt kvoteprisar under Kyotoprotokollen i perioden 2008-2012, og for perioden etter 2012. Ved å kombinere resultata for eit sett av ulike situasjonar finn vi at oppsamling og lagring av karbondioksid på kort sikt berre er økonomisk interessant i spesielle tilfelle, fyrst og fremst dersom gassen kan brukast til trykkstøtte og dermed gje opphav til større oljeproduksjon. På mellomlang og lang sikt, når betre teknologi er utvikla og kvoteprisen sannsynlegvis er høgare enn under Kyotoprotokollen, kan geologisk lagring av karbondioksid bli økonomisk interessant i fleire tilfelle.

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Abstract:
In this paper we review the literature on the costs and benefits of geological carbon storage and the estimates of greenhouse gas permit prices under the Kyoto Protocol commitment period and beyond. Combining these results for a set of circumstances, we find that in the near-term Carbon Capture and Storage (CCS) is likely to be an economically viable option only in a small set of circumstances, particularly enhanced oil recovery. In the medium and longer term, with improvements in CCS technology and the likelihood of increased greenhouse gas permit prices, CCS is likely to become an economically viable option under a wider range of circumstances.

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1 Introduction

When in 1995 the Intergovernmental Panel on Climate Change (IPCC) concluded that "The balance of evidence, from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate" (IPCC 1995), efforts to explore ways to mitigate climate change began in earnest. The UN Framework Convention on Climate Change, adopted in 1992, had already called for "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". When the Kyoto Protocol was negotiated in 1997, there was hope that it would represent a significant step in the right direction. However, the protocol has not yet entered into force. Moreover, the withdrawal of the world's largest emitter of CO_2, the United States, from the protocol, no emission caps on developing countries, and its relatively short time horizon (2008-2012), means that other, more ambitious measures will be necessary.

Indeed, the significant emission reductions required to achieve the aim of the UNFCCC would require a large-scale shift in energy systems from fossil fuels to new alternative energy sources and substantial improvements in energy efficiency. It is, however, not very likely that such large shifts will be technically and economically feasible in the near future. One reason for this is that the development of the required technologies depends on a large and sustained research and development effort, which is likely to require some decades. Furthermore, even if the technology should become available, and at competitive costs, it will take decades to replace the existing real capital stock of the global energy system, buildings and infrastructure because of its inertia and vastness.

On this background, other mitigation options such as "end-of-pipe" technologies are therefore increasingly being seriously considered by governments and businesses since they could play an important role in the transition from the present fossil fuel dependent economy to a future carbon-lean economy. A potentially very significant "end-of-pipe" technology is carbon (CO_2) storage (also referred to as carbon removal or sequestration). There are three major storage options: biological (forests and soils), geological, and deep ocean. This paper looks specifically at geological storage.

Geological carbon storage can be defined as *the systematic storage of carbon dioxide, captured from fossil fuel combustion or processing, in stable geological formations such as hydrocarbon fields and aquifers, thus preventing its build-up in the atmosphere* (Torvanger et al. 2004). We are concerned with three categories of geological storage: oil reservoirs, gas reservoirs, and aquifers.

Before CO_2 can be stored, it must be captured from flue gas. For geological storage this is feasible only for emissions from large stationary sources such as power plants with fossil fuel combustion, or industrial processes.[1] There are several technologies available for capturing. We will not discuss the technical details of these technologies. (For a description of three important CO_2 capture technologies, see Holt et al., 2000). After the CO_2 has been captured, it must be compressed and transported to a location (by ship or pipeline) where it can be stored. These technologies are collectively known as Carbon Capture and Storage (CCS) technologies.

[1] In the case of biological storage, CO_2 is captured directly from the atmosphere through photosynthesis.

Oil and technology companies have invested significant amounts in research and development of CCS technologies over many years. The main motivation for this interest, up till now, has been the potential for enhanced oil recovery (EOR) through injecting CO_2 in oil reservoirs. So far the only example of off-shore geological storage of CO_2 is found at the Sleipner field on the Norwegian Continental Shelf, where Statoil has injected 1 million tons of CO_2 in the Utsira aquifer formation since October 1996.

The question we will explore in this paper is, whether, and under what circumstances, geological carbon storage can be a viable option for mitigating human-induced climate change. We examine cost estimates for the CCS technology and assessments of future carbon markets from previous studies. EOR is of particular interest in the case of oil reservoirs since this can lower the climate policy-related cost threshold for CCS significantly. We will combine this information to give an overall assessment of the economic viability of CCS as a climate mitigation option – today and in the near future.[2] The information available about CCS 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. We will estimate a total cost per ton of CO_2 captured. These estimates will not provide explicit information on what share is attributed to investment costs and to operating costs (for instance, if the CO_2 is transported by ship rather than pipeline, investment costs would be less, but operating costs higher). Furthermore, possible future costs associated with leakages will not be analyzed.

The paper adds to the literature on CCS by linking CCS costs per ton of CO_2 to estimated prices per ton of CO_2 equivalent in the Kyoto emissions trading markets. These costs are seen also in the light of sets of circumstances that reflect uncertainties regarding the development and cost of CCS technologies, and future permit prices at the international markets under the Kyoto Protocol. Beyond 2012 these uncertainties are even larger. Through this approach we can identify necessary, although not sufficient, requirements for CCS to be competitive with other mitigation options, such as energy efficiency measures, development of renewable energy sources, and biotic sinks.

We divide the economic analysis into three parts. First we will look at the costs of capturing and storing carbon. We then turn to the potential for generating income from the capture and storage, first through enhanced oil recovery, and second as part of a greenhouse gas mitigation strategy. Finally we assess the economic viability of geological carbon storage under a set of different circumstances.

2 The cost of carbon capture and storage

The process of CCS 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 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 processes and geological storage.

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[2] By near future we mean until 2020. However, in terms of relation to long-term climate policy and the temporary role of geological carbon storage, our time perspective is to the second half of this century.

A recent comprehensive review is Anderson and Newell (2003). They review the technical and economic feasibility of a range of carbon capture and storage options and estimate the current cost of carbon capture, for retrofitted or new power plants, to lie in the range of USD 45-58 per ton CO_2 captured.[3] With near-term (2010-2015) technical improvements, they predict that the cost of chemical absorption of carbon in new coal and gas plants can be reduced to USD 34-42. In the integrated gasification combined-cycle process, coal is gasified to form a mixture known as synthesis gas (CO and H_2), which is combusted directly in gas turbines. For this process, the authors estimated the current cost of carbon capture at USD 28. With near-term technical improvements they predict that this cost can be reduced to USD 17.

Anderson and Newell estimate the cost of carbon capture in hydrogen production (from natural gas) to be as low as USD 10. Total emissions from these industries are, however, in the short to medium term small compared to emissions from power plants.

Anderson and Newell quote transportation and storage costs of USD 5.50-15. They use a median value of USD 10 in their examples. In a breakdown of this combined cost they estimate transportation costs at around USD 1.40-2.70 per 100 km (pipeline), and geological storage costs at USD 1.40-8.20.

Hendriks et al. (2000) estimate costs for CO_2 removal projects in the Netherlands under various scenarios. They look at two specific cases that are of interest for our study: emissions from a natural gas-fired combined cycle power plant, and flue gases from a combination of an oil refinery furnace and a combined heat and power unit. They assume transport through an underground pipeline, and storage in aquifers and depleted gas and oil reservoirs. For a range of fuel prices and discount rates they estimate the following capture costs: Natural gas combined cycle USD 41-66 and furnace/combined heat and power USD 6-45. They estimate the cost of (compression and) transport per 100 km in a range from USD 3 for an annual flow of 4 Mt CO_2, to USD 7 for an annual flow of 1 Mt. The estimated storage costs for an aquifer or gas reservoir offshore is USD 7-16. The cost range is as low as USD 1-8 for onshore storage.

Hustad (2003) estimates the capture cost at Danish coal-fired power plants to be around USD 25, and for a Norwegian gas-fired power plant to be about USD 33-35. For ammonia production he estimates the cost to be USD 6-12. For all these cases, he estimates transportation costs to be USD 13 by ship or for an 18" pipeline (capacity 5 Mt/year), and USD 10 for a 24" pipeline (capacity 10 Mt/year).

Hustad (2003) estimates that, overall, CO_2 can be transported to, and stored at the Gullfaks production field, at a cost of USD 38-42 if a total of 5Mt CO_2 is stored. If the total amount stored is 10Mt, the cost is reduced to USD 32.

Johnson and Keith (2004) look at under what assumptions, and with what carbon prices, carbon capture and storage can be competitive (with the assumed technology of around 2015). They find that CCS can contribute significantly to carbon reductions when carbon prices are below USD 27 per ton CO_2. This price can also be seen as the net cost of CCS. They find that new coal-fired power plants with carbon capture become competitive when carbon prices are around USD 20. Retrofitting existing power plants, is however, not competitive below prices of USD 82. Gas-fired power plants with carbon capture become competitive only at a much higher carbon price of USD 48. Johnson and Keith estimate the transport and storage cost to be USD 8.20.

Holt et al. (2000) do not provide a detailed breakdown of capture, transportation and injection (storage) costs. They estimate the total CCS cost to lie in the range USD 29-45.

[3] Throughout this paper prices and costs are given as USD per ton CO_2, unless otherwise stated.

Tables 1 and 2 summarise the capture costs and transportation and storage costs estimated in the cited studies.

Table 1 Capture costs in USD/ton 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/ton 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).

3 Enhanced Oil Recovery

Carbon storage has the potential of generating 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.

Anderson and Newell (2003) claim that opportunities for enhanced recovery would be insufficient for larger amounts of CO_2 storage. According to Torvanger et al. (2004), there is storage capacity for 33 000 Mt CO_2 in oil and gas reservoirs in Western Europe, versus 800 000 Mt CO_2 in aquifers. Comparing this to the 1990 EU emissions of around 3 000 Mt, oil and gas reservoirs can then theoretically store all EU emissions for 11 years, while aquifers can store more than 250 years worth of EU emissions.

The value of EOR depends on the amount of additional oil recovered per ton of CO_2 injected and the oil price. Typically the EOR response is around 0.6; that is, for every ton of CO_2 injected, 0.6 tons 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 ton 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 ton CO_2. Johnson and Keith (2004) claim that enhanced coal-bed methane operations might be able to pay up to USD 10 per ton of CO_2.

4 The carbon market

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, and more are planned before 2008. The EU will establish a trading scheme from 2005. Furthermore, it is likely that future international climate agreements will be negotiated. 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 therefore take a look at studies on both the Kyoto Protocol and future climate agreements. The emphasis will be on studies dealing with the Kyoto Protocol, because the emission reductions and the market structure have already been negotiated, and there is much less room for speculation regarding likely carbon prices.

Parties to the Kyoto Protocol have committed themselves to reducing their greenhouse gas emissions. The Protocol also 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.[4] The Protocol states that reductions should primarily be achieved through domestic action, and thus the use of these mechanisms should be "supplemental to domestic action".[5]

4.1 Permit prices under the Kyoto Protocol

The supply of emission permits depends on marginal abatement cost curves in each of the participating countries, the availability of competitive biotic sink projects, and the supply of

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

[5] There is, however, no definition of how "supplemental" should be understood, and this has been the subject of much debate.

"hot air".[6] The price, or prices, of the Kyoto Protocol permits will determine whether or not geological carbon storage will be a competitive option.

The literature on estimating permit prices is extensive.[7] Most of these studies assume that the permit market will be a relatively liquid market with an equilibrium permit price. The paper by Springer (2003) provides an overview of model studies. In the 16 models that assume CO_2 trading among Kyoto Protocol partners with emission caps (industrialized countries), permit prices range from USD 0.80 to USD 20.20 (with an average price estimate of USD 7.40). In general, when non-CO_2 greenhouse gases are included in the models, the permit price is lower; estimates range from USD 3.00 to USD 10.40.[8]

In the studies reviewed below, the price estimates, given in tons of CO_2 equivalent (CO_2e), range between zero and USD 15.[9] While this is a relatively large range, most studies seem to indicate a permit price in the region USD 5-10 per ton CO_2e as the most likely outcome. However, the different studies make widely differing assumptions, and therefore we check those assumptions in some more detail to be able to say something about the expected permit price.

The model used by Babiker et al. (2002), a recursive dynamic computable general equilibrium model, is particularly interesting in that it includes all the six Kyoto Protocol greenhouse gases. The inclusion of non-CO_2 gases significantly reduces the cost of compliance in their model. This is because some of the non-CO_2 gases offer cheap abatement opportunities. The paper explores two main scenarios. In the first scenario all "hot air" is made available, and all sink credits are used. The permit price is then estimated at below USD 1.40 per ton CO_2e. In the second scenario, it is assumed that Russia and Ukraine form a cartel to maximise their revenue from permit sales. The permit price then increases to around USD 7 per ton CO_2e.

The study by Lucas et al. (2002) also includes all six Kyoto Protocol gases, but in a partial equilibrium model. With a competitive emissions trading market, they find that the estimated permit price drops from USD 1.65 per ton CO_2e to USD 0.55 when they introduce non-CO_2 gases into the model (as opposed to a model with only CO_2). If the former Soviet Union (FSU) countries act strategically and choose to bank permits, the permit price will increase to USD 3.

Nordhaus (2001) employs an integrated economic and geophysical model of the economics of climate change to estimated permit prices. He estimates the permit price to be USD 15.

Böhringer (2001) uses a static computable general equilibrium model to explore the effect of the US withdrawal under the Bonn accords (which include some sink provisions, but not as extensive as Marrakesh). Without the US, this model estimates a permit price of zero. However, with monopolistic permit supply by the countries in transition, the price will be positive. In the model it is optimal for Russia to restrict supplies to about 40% of their hot air, which will give a permit price around USD 15.50 per ton CO_2e.

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

[7] 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.

[8] The lower end of the price range is higher for models that include non-CO_2 gases because estimates are based on different groups of models.

[9] 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.

Den Elzen and de Moor (2001) use a policy-support model known as FAIR. They estimate the permit price at about USD 2.50 with the Marrakesh provisions for sinks. The study is based on the IPCC A1B SRES scenario. When they run some of the other SRES scenarios, they find business-as-usual emissions to be equal to or below the Kyoto commitments, such that the permit price will be zero. However, in the A1B scenario it is in the interest of the FSU to limit permit sales to about 60% of “hot air”, and in this case the authors estimate that the permit price will most likely be in the range of USD 4.00-5.50 per ton CO_2e. When they run the model for other SRES scenarios, they find permit prices in a range from USD 2.60 per ton CO_2e, to close to zero (without banking). Banking all the “hot air” would push the permit price above USD 8. Using higher cost curves in the model raises the permit price above USD 4.50.

Hagem and Holtsmark (2001) use a static partial-equilibrium model that includes CO_2 and non-CO_2 gases (as a group). Without US participation, the permit price is estimated to be USD 5 per ton CO_2e. The paper does not consider monopolistic behaviour.

Klepper and Peterson (2002) employ a recursive dynamic general equilibrium model to estimate permit prices under various scenarios. Their study focuses on FSU and Eastern European market power in the emissions trading market. They run the model for a set of scenarios with different assumptions regarding the structure of the permit market in this region, and regarding what objective is maximised when they exercise market power. They find that permit prices range from USD 2.10 to USD 8.50.

Jotzo and Michaelowa (2002) employ a partial equilibrium model in their study, which is one of only a very few that includes the CDM mechanism. They estimate an international permit price of USD 3.78.

Michael Grubb (2003), p. 3, argues that emission permits under the Kyoto system have economic value only to the extent that “supplying governments are willing to issue and transfer them, and the governments of receiving countries are willing to recognize and use those units for compliance assessment under Kyoto”. It will be possible to identify the source of all permits, and governments “will use this capacity to meet strategic concerns, and this will make the Kyoto “market” vary widely from least-cost “market” behaviour” (p. 3). On the supply side, the Economies In Transition (EIT) countries (which have significant amounts of hot air), have an interest in restraining supply to raise price, i.e. to exercise their market power. On the demand side, Grubb makes an argument that the buyer governments will “use the mechanisms selectively and strategically to support their interests and the political legitimacy of the Kyoto system overall, whilst protecting existing domestic legislation” (p. 3). This will result in significant price differentiation among the different types of permits. Grubb indicates likely price ranges from USD 15-40 (per ton CO_2e) for renewable energy CDM projects, to USD 3-12 for EIT transfers to other OECD countries (not EU). Within the EU trading system he indicates a price of USD 8-18. Grubb’s claim for buyer sovereignty seems compelling in light of the emerging evidence on the implementation of the Kyoto Protocol. Permits are being traded at widely differing prices; see for example Klaassen and Percl (2002) and Buen (2003).

The price estimates from the cited studies are summarised in table 3.

Table 3 Literature estimates of greenhouse gas permit prices

Source	price (USD /tCO_2)	Comments
Babiker et al. (2002)	1.40 7.00	- all six Kyoto gases with unrestricted emissions trading, with and without market power
Lucas et al. (2002)	0.55 3.00	- all six Kyoto gases with unrestricted emissions trading, with and without strategic behaviour
Nordhaus (2001)	15	
Böhringer (2001)	0 15.50	With and without strategic behaviour in the permit market.
Den Elzen and de Moor (2001)	0-2.60 4-8	With and without strategic behaviour in permit market.
Hagem and Holtsmark (2001)	5	CO_2 non-CO_2 (grouped), no strategic behaviour
Klepper and Peterson (2002)	2.10-8.50	Varying assumptions regarding Russian permit market power
Jotzo and Michaelowa (2002)	3.80	Includes CDM-mechanism, fixed sales of “hot air”
Grubb (2003)	3-40	Disaggregated permit market

4.2 Permit prices beyond 2012

The Kyoto Protocol contains provisions for negotiating future mitigation agreements. Whether or not the Kyoto Protocol should enter into force, it is likely that other global climate agreements will be implemented after 2012. If the objective of the UNFCCC is to be met, then significant emission reductions will have to be undertaken through these agreements. If larger emission reductions are required than under the Kyoto Protocol, and without unexpectedly large and quick technological improvements, then carbon prices are likely to be higher in a future climate regime.

It is difficult to estimate carbon prices under such 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.

Baumert et al. (2002) explore three different scenarios for burden sharing under future climate agreements. The 2030 emission target is the same for all of these. The target is 66% above global 1990 emissions, but 22% below the business-as-usual emissions for the year 2030. With global emissions trading, the permit price is then estimated to be USD 26 per ton of CO_2 equivalent.

Johnson and Keith (2004) provide estimates for permit prices in 2026-2030 for different emission targets. The motivations for choosing the specific targets are not explained. With a 50% reduction in CO_2 emissions, they find a permit price of USD 23, and with a 75% reduction the price is USD 37.

4.3 The demand for geological carbon storage

Having briefly discussed the future carbon market, we also need to explore the possible role of geological carbon storage in this market. Torvanger et al. (2004) discuss the relation of geological carbon storage to the Kyoto Protocol, and the need for clarification regarding reporting, estimation methodologies and accounting, as well as possible caps on its use. In this paper we will assume that geological carbon storage units can be fully used to achieve compliance. "Permits" or credits generated from carbon removal projects related to forest and agriculture in industrialized countries are denoted Removal Units (RMU) under the Kyoto Protocol.

Recently there has been much debate around the merits of technology agreements, as opposed to "cap and trade" agreements such as the Kyoto Protocol is. In a technology agreement, countries would, for example, commit themselves to investing a certain amount of money in alternative energy research, and to sharing this technology with the other parties. With such an agreement there would not necessarily exist a carbon market. Without a positive price for carbon removal, there is no incentive to undertake geological carbon storage – except where income from EOR is sufficient to merit the cost.

If the permit market behaves as a disaggregated market, with widely different prices for different types of permits, the question is what market niche geological carbon storage removal units will occupy. Environmentally speaking, sinks have less credibility than the other abatement options. There are two main reasons for this. First, by using sinks a country is putting off the long-term structural changes (shifting to a lower-carbon economy) that are necessary in the long run. Second, sinks carry with them an environmental uncertainty – in that there is a non-zero probability for some leakage of CO_2 into the atmosphere over time.

Countries that are major fossil fuel producers might see a strategic interest in supporting geological carbon storage: The use of sinks will reduce some of the downward pressure on fossil fuel prices that emission reductions would otherwise entail. Sinks therefore provide an opportunity for these countries to support climate change policies, while at the same time suffering smaller welfare losses from depressed fossil fuel prices (and sales). If governments do see such a strategic interest, then they might be willing to pay a premium price for removal units, or subsidize the development of CCS technologies.

5 Discussion

Based on the reviews of CCS 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 CCS cost intervals – based on the reviewed studies. Together these estimates produce nine sets of circumstances for the economic viability of CCS. These are presented in table 4.

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.[10] These assumptions will, systematically, produce low permit prices in economic models of the Kyoto Protocol carbon markets. In this case, we estimate a price range of USD 0-5 per ton CO_2. This estimate

[10] Russia was responsible for 17.4% of CO_2 emissions from industrialized countries in 1990, and is allowed the 1990 emission level under the Kyoto Protocol. Due to the fall in output during the process of transition to a market economy Russia is likely to have a vast surplus of permits to sell. Therefore Russia could be able to exercise market power to try to increase the permit price and thus its earnings.

and the underlying assumptions are in line with for example Babiker et al. (2002), Lucas et al. (2002) and Jotzo and Michaelowa (2002).

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. These assumptions are in line with the results from Klepper and Peterson (2002) and Böhringer (2001). Our “medium” estimate is a price range of USD 10-15.

For the “high” estimate we look beyond the Kyoto Protocol, and at a possible future climate agreement with more severe emission reduction commitments. Based on the studies cited above, we estimate a price range of USD 25-35.

When it comes to CCS 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 CCS technology, such as the integrated gasification combined-cycle process with near-term technological improvements (Hustad 2003 and Anderson and Newell, 2003). We further assume that the CO_2 is used for enhanced oil recovery. We then estimate a cost range of USD 7-21 (EOR income is USD 9-15 per ton of CO_2).

The “medium” cost estimate is based on the best existing technology for a gas- or coal-fired power plant (Hustad 2003), with medium transportation costs, and no income from EOR. Our estimated cost range is USD 40-50.

For the “high” cost estimate we make less optimistic assumptions regarding the best available CCS technology for a gas-fired power plant (Hendriks et al. 2000, and Anderson and Newell 2003), and we assume high transportation costs and no EOR. Our estimated cost range is USD 75-95.

Table 4 Net economic benefit of CCS under various assumptions (USD per ton of CO_2)

		CCS 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 4 shows that CCS very likely to be economically viable only in the case where costs are low and permit prices are high. The combination of a low CCS 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 CCS.

These cost estimates confirm that CCS for enhanced oil recovery can be profitable. Such activities already take place at some oil reservoirs. CCS for the purpose of mitigating climate change is not competitive, and to our knowledge it is only being carried out at the Sleipner oil field in Norway, where the incentive is to save on a relatively high carbon tax.

There are also reasons to expect that governments might see a strategic interest in developing CCS technologies, and therefore make investments or create economic incentives that lower the cost of CCS. One reason they would be interested in exploring the potential of geological storage is the fact that the major global fossil fuel reserve is coal. In addition, major coal reserves are found in the USA and in key developing countries like China and India. These developing countries are likely to achieve prolonged economic growth and related growth in energy use based on coal, since it is not probable that they will face (stringent) carbon emission caps during the next decades. The cost of coal can be competitive with oil and gas, given that most of the associated air pollution that leads to health problems, increased corrosion of materials, and crop damages can be removed through inexpensive measures. These countries may also be willing to subsidize coal extraction and use to some degree in order to save spending on imports of oil and gas and shield local communities dependent on coal mining. For such reasons, both the USA and many developing countries would welcome the development of technologies for geological carbon storage that could make this a viable option for combining a realistic energy policy with a climate policy.

While the permit price and CCS 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 CCS. 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 CCS less competitive.

In our study we have said nothing about the potential for CCS and different permit prices. While we provide only rough estimates for the total cost of CCS per ton of CO_2 stored, it is obvious that different combinations of sources and storage options will be competitive at different permit prices. We have not attempted to estimate the potential for geological carbon storage at different permit prices. However, it is clear that the theoretical potential of CCS is very large, and if CCS was to be used as a climate mitigation option on a large scale, it could significantly affect the prices in the market.

We conclude that CCS is competitive today only under particular circumstances, primarily where CO_2 injection can be used for EOR. 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 CCS. 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). Given the potential importance of CCS in a transitory phase where a carbon-lean energy system is being developed, we expect that both governments and industry will be willing to spend resources on research and development of promising technologies, and also on the development of institutional foundations for this climate policy option.

References

Anderson S., R. Newell, 2003, Prospects for Carbon Capture and Storage Technologies, Resources for the Future, Discussion Paper 02-68, Washington, DC.

Babiker M.H., Jacoby H.D., Reilly J.M., Reiner D.M., 2002, *The Evolution of a Climate Regime: Kyoto to Marrakech*, Report 82, MIT Joint Program on Science and Policy of Global Change.

Baumert K.A., O. Blanchard, S. Llosa, J.F. Perkaus, 2002, Building on the Kyoto Protocol: Options for Protecting the Climate, World Resources Institute, Washington.

Böhringer C., 2001, *Climate Politics from Kyoto to Bonn: from Little to Nothing?!?*, Discussion paper no. 01-49, Zentrum für Europäische Wirtscaftsforschnung, Mannheim.

Buen J., 2003, *ViewPoint: Five is still the magic number*, Carbon Market Europe, March 21 2003, PointCarbon.

den Elzen M.G.J., de Moor A.P.G., 2002, Evaluating the Bonn-Marrakesh agreement, *Climate Policy* no.2 (2002), pp.111-7.

Grubb M., 2003, *On carbon prices and volumes in the evolving "Kyoto market"*, OECD Global Forum on Sustainable Development, 17-18 March 2003, Paris, document 12.

Hagem C., Holtsmark B., 2001, *From small to insignificant: Climate impact of the Kyoto Protocol with and without the US*, CICERO Policy Note 2001-01, Oslo.

Hendriks C.A., A.F.B. Wildenborg, K. Blok, F. Floris, J.D. van Wees, 2000, *Costs of Carbon Removal by Underground Storage*, Paper presented at the 5th International Conference on Greenhouse Gas Control Technologies (GHGT-5), Cairns, Australia, August 13-16, 2000.

Holt T., E.G.B. Lindeberg, J.J. Taber, 2000, *Technologies and Possibilities for Larger-Scale CO_2 Separation and Underground Storage*, paper presented at the 2000 Society of Petroleum Engineers Annual Technical Conference and Exhibition, Dallas, October 1-4, 2000.

Hustad C.W., 2003, personal communication.

Hustad C.W, J.M. Austell (2003), Mechanisms and incentives to promote the use and storage of CO_2 in the North Sea, Memo, CO2 Norway, Kongsberg.

IPCC, 1995, *IPCC Second Assessment: Climate Change 1995*, IPCC, Geneva, Switzerland.

Johnson T.L., Keith D.W., 2004, Fossil electricity and CO_2 sequestration: how natural gas prices, initial conditions and retrofits determine the cost of controlling CO_2 emissions, *Energy Policy* 32 (2004) pp. 367-382.

Jotzo F., Michaelowa A., 2002, Estimating the CDM market under the Marrakech Accords, *Climate Policy*, Vol. 2:2-3, pp. 179-196.

Klaasen G., Percl O., 2002, *Carbon trading: models, markets and modest supply*, CATEP workshop "global trading", Kiel Institute for World Economics, 30.09-01.10 2002.

Klepper G., Peterson S., 2002, *Trading Hot Air: The Influence of Permit Allocation Rules, Market Power and the US Withdrawal from the Kyoto Protocol*, Kiel Institute for World Economics, Kiel Working paper 1133.

Lucas P.L., den Elzen M.G.J., van Vuuren D.P., 2002, *Multi-gas abatement analysis of the Marrakesh Accords*, CATEP workshop "global trading", Kiel Institute for World Economics, 30.09-01.10 2002.

Ministry for Foreign Affairs Development Cooperation, 2003, *Finnish CDM/JI Pilot Programme*, http://global.finland.fi/english/projects/cdm/ [accessed April 8, 2003].

Niizawa H., Saijo T., Yasumoto A., 2003, *Proposal of upstream emissions trading in Japan*, OECD Global Forum on Sustainable Development, 17-18 March 2003, Paris, document 14.

Nordhaus W.D., 2001, Global Warming Economics, *Science*, 294:1283-1284.

Springer U, 2003, The marked for tradable GHG permits under the Kyoto Protocol: a survey of model studies, *Energy Economics*, 25:527-551.

Torvanger A., Kallbekken S., Rypdal K., 2004, *Prerequisites for Geological Carbon Storage as a Climate Policy Option*, CICERO Report 2004:04, Oslo.