Carbon dioxide capture and storage (CCS) – liability for non-permanence under the UNFCCC

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Abstract

Carbon Capture and Storage (CCS) has recently been gaining more and more attention as a climate change mitigation option. However, as CO_2 may re-enter the atmosphere after injection into geological reservoirs, the question of long-term liability has to be considered if an environmentally sound policy is desired. Apart from this aspect, additional complexities arise from the fact that CO_2 capture and storage can be carried out in two different countries. A classification of CCS cross-border activities shows that not all cases with non-Annex I participation fall under the Clean Development Mechanism. This classification is based on the assumption that according to Art. 1.8 of the Framework Convention on Climate Change, CCS would be considered an emission reduction at the source. Furthermore, we elaborate on the problem that seepage of CO_2 from reservoirs located in non-Annex I countries – under current rules – would not be subtracted from the emission budget of any country. We discuss options for creating liability in these cases.

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Abbreviations: CCS, CDM, CER, ECBM, Former S.U., GHG, HWP, IPCC, JI, LULUCF, RC, UNFCCC

CCS = Carbon Dioxide Capture and Storage
CDM = Clean Development Mechanism
CER = Certified Emission Reduction
ECBM = Enhanced Coal Bed Methane
EOR = Enhanced Oil Recovery
Former S.U. = Former Soviet Union
GHG = Greenhouse Gas
HWP = Harvested Wood Products
IPCC = Intergovernmental Panel on Climate Change
JI = Joint Implementation
LULUCF = Land-Use, Land-Use Change and Forestry
RC = Replacement Costs
UNFCCC = United Nations Framework Convention on Climate Change

1. Introduction

In order to reduce the adverse effects of human induced climate change, the international community agreed, inter alia, to work towards stabilising the greenhouse gas concentration in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system" (Art. 2, UNFCCC). There are two ways to achieve this: either reduce GHG emissions at their source, or increase the removal of GHG emissions from the atmosphere by sinks. Regarding emission reductions options, the focus of climate policy has been on improving energy efficiency on both the supply and demand sides, on fuel switching to less carbon intensive fuels, on the increase of renewable energy and on changes in industrial processes. Sinks enhancement options that have entered the climate regime thus far focus on activities enhancing the sequestration of carbon dioxide in the terrestrial biosphere.

Today, there are increasing problems regarding the reduction of greenhouse gas emissions, particularly in industrialised countries. In the late 1980s and the early 1990s, it was believed that deep cuts in emissions could be generated by energy efficient "no-regret" measures and an increased penetration of renewable energies. "No-regret" measures on the demand side have failed to materialise; on the contrary, efficiency improvements slowed during the 1990s while consumption levels of goods and services continue to increase (Michaelowa, 2005).

In this context, the capture of carbon dioxide at power plants and industrial facilities and its subsequent storage in reservoirs - carbon capture and storage (CCS) - recently entered the political discussion. If CCS is to be implemented in the international climate regime, two issues have to be addressed: the possible non-permanence of storage, and potential cross-border cases. These issues are dealt with in the present paper.

2. Carbon Dioxide Capture and Storage

The term "carbon dioxide capture and storage" refers to the capture of CO_2, and its subsequent storage in reservoirs. CCS can be separated into three elements:

1. Capture (including compression)
2. Transport
3. Storage

CO_2 can most efficiently be captured at large point sources[1] such as industrial facilities or power plants.[2] In some industrial processes, CO_2 is separated from gas flows (hydrogen production, natural gas sweetening) in order to be able to continue downstream operations. Most of the separated CO_2 is vented into the atmosphere and only a small fraction is used in, for example, the food industry.[3]

The bulk potential for CO_2 capture, however, can be found in the power sector. Three processes are available for the capture of CO_2 from such large point sources (Thambimuthu et al. 2002, VGB 2004):

a. *Post-combustion capture*, in which the CO_2 is scrubbed from the flue gas.

b. *Pre-combustion capture,* in which the CO_2 is removed prior to combustion by producing a hydrogen-rich fuel gas mixed with CO_2. The CO_2 is separated from the latter by physical absorption, while the hydrogen is used for combustion.

c. *Oxyfuel combustion* uses oxygen instead of air for combustion, resulting in a flue gas consisting mainly of water vapour and CO_2.

Additional energy use caused by the capture processes is referred to as the energy penalty, which can range from 15 – 40 % of energy output (Haefeli et al. 2004). Prior to transportation, compression is generally required, resulting in additional energy use that is, however, much smaller than the penalty for capture.

Transport of CO_2 is a mature technology, as the technical requirements are similar to transporting other gases. Experience with CO_2 transport via pipelines has already been gained, especially in the USA, where around 2800 km of pipelines are currently in place (Gale and Davison 2004). The alternative is to transport carbon dioxide by ship[4], especially if transport distances are longer or if the capture and storage site are separated by water (Wildenborg and van Meer, 2002).

After transportation, the CO_2 is injected into the storage reservoir, which can be either a geological reservoir or the ocean. Presently, mainly storage in geological reservoirs is seriously considered as a climate mitigation option (OECD/IEA 2004), and as such will form the focus of this paper. Three main groups of geological reservoirs can be identified:

a. Oil and gas reservoirs (depleted, or in combination with Enhanced Oil Recovery, EOR or Enhanced Gas Recovery, EGR)[5]

b. Saline aquifers

c. Unminable coal seams (possibly in combination with Enhanced Coal Bed Methane Recovery, ECBM)

The size of the reservoirs available is a major determinant as regards to the relevance of CCS as a mitigation option. Various figures have been published (Grimston et al. 2001, IEA 2001). Data provided by Hendriks, Graus, and van Bergen (2004) are summarised in Table 1 below.

Table 1: Storage potential (Gt CO_2)

	Remaining Oil Fields	Depleted Oil Fields	Remaining Gas Fields	Depleted Gas Fields	ECBM
			Onshore		
Total Annex-1*)	2.6 – 186.2	8.4 – 16.8	91.2 - 382	2.5 – 156.7	0 – 401.7
Total non Annex-1*)	6.4 – 547.8	13.6 – 27.2	127.8 - 543	1.5 – 234.3	0 – 1078.3
Total	9 - 734	22 – 44	219 - 925	4 - 391	0 - 1480
			Offshore		
Total Annex-1 *)	0.6 – 67.2	6.1 – 32.6	38.3 – 412.3	13.6 – 20.5	10.4 – 374.1
Total non Annex-1 *)	2.4 – 240.8	13.9 – 74.4	110.7 – 365.7	6.4 – 11.5	19.6 – 706.9
Total	3 - 308	20 - 107	149 - 778	20 - 32	30 - 1081

*) Own calculation based on data from: Hendriks et al. (2004, p.28) (for example, Former Soviet Union may include both Annex I and non Annex I countries)

As can be seen in Table 1, there is great uncertainty regarding the storage capacity. Global potential in geological reservoirs is within the range of about 476 - 5880 Gt CO_2, with a best estimate of 1660 Gt. The geographical distribution of the possible storage capacity differs for different types of reservoirs. Saline aquifers seem to be distributed most evenly across the world, but also the distance to large amounts of point sources of CO_2 is of relevance. The larger part of the world-wide storage potential seems to be located in the non Annex I countries of the UNFCCC.

When analysing the costs of CCS as a climate mitigation option, the full chain, from capture to storage and monitoring has to be taken into account. The cost of CCS therefore, consists of:

$$C_{CCS} = C_{capture} + C_{transportation} + C_{storage} + C_{monitoring}$$

The costs for CO_2 capture per ton avoided vary according to the plant characteristics and capture system applied.[6] The largest part of CCS costs consists of capture costs, with values ranging from about 24 to 52 €/t CO_2-avoided (Hendriks et al. 2004, VGB 2004). Significantly lower costs are achieved in the capture of CO_2 from ammonia and hydrogen production.[7] Any statement on capture cost must, however, be treated carefully.

Anderson and Newell (2003) show that these costs strongly depend on the reference scenario, for example on whether the alternative investment is assumed to be a gas-fired or a coal fired plant.

Transportation costs by pipeline vary with the transportation distance, the amount transported, pressure of CO_2, landscape characteristics, pipeline diameter, and country regulations. Per 100 km pipeline, the cost estimates range from 1-6 €/tCO_2, with decreasing costs for larger throughputs (Hendriks et al. 2004; Freund and Davison 2002). The transport of CO_2 by ship vessels will be cheaper over longer transportation distances (Freund and Davison 2002).

Storage costs reported in the literature are mainly based on the technical investment to be made, notably the drilling of wells and operation costs. Hendriks et al. (2004) estimated costs for storage in aquifers, natural gas and empty oil fields at 1 to 11 €/tCO_2, varying with the depth and permeability, as well as the type of the storage reservoir. For EOR, the cost range is from -10 to 30 €/tCO_2, taking into account the revenues resulting from the enhanced fossil fuel production.[8]

Theoretically, possible combinations of the different capture, transport and storage options based on the cost estimates mentioned above, may range from profitable values of minus 3 to values of plus 106 €/t CO_2-avoided.[9] Negative costs can mainly be expected in the case of enhanced oil recovery due to the revenue from additional fossil fuel production. Information on and experience with monitoring costs seems to be very limited.

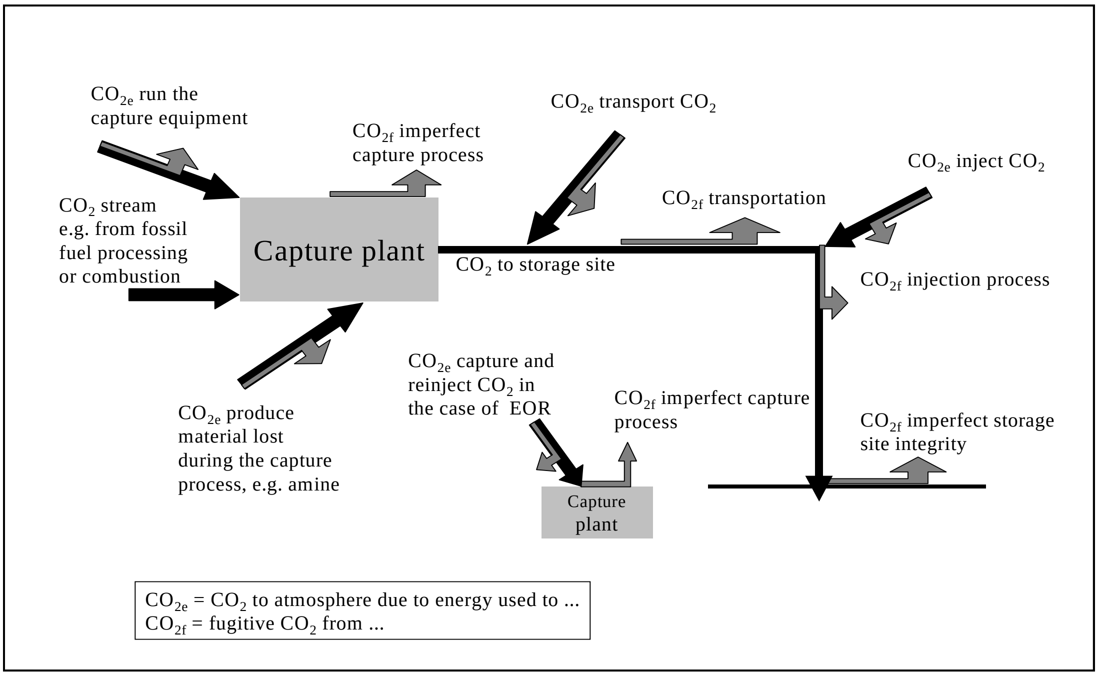
3. Performance of Storage

Apart from the technical and economic potential, the issue of the non-permanence of storage is also relevant for the implementation of CCS as a mitigation option.

The term non-permanence describes the likely releases of CO_2 after capture has taken place. Figure 1 illustrates possible emissions along the whole chain of CCS, which will have to be accounted for when integrating CCS into the international climate regime. In the following, however, we are focusing on emissions from the reservoir.

It is still difficult to predict seepage rates from long-term storage of very large volumes of CO_2 (OECD/IEA, 2004, p. 94 - 97). Experts consider these rates in well-selected geological reservoirs to be very low (DTI 2004). Storage site integrity depends on various factors, like the geological characteristics of the reservoir, the history of human usage, and the quality of well and sealing packages (e. g. Jimenez et al., 2003). The retention time of CO_2 is therefore site specific. Furthermore, unforeseeable events like earthquakes could lead to the rapid release of larger volumes of CO_2 from the reservoir. Strict criteria for site selection could be seen as one means of guaranteeing the high environmental integrity of geological storage (Haefeli et al. 2004). We consider such criteria a necessary, but not a sufficient condition for the integration of CCS into the international climate regime. They do not guarantee the complete accounting of emissions, which is one of the main principles of every greenhouse gas accounting framework (Haefeli et al. 2004). The fact that there is a possibility of non-permanence of storage makes it necessary to incorporate liability for future releases into the accounting scheme in order to guarantee that the burden relating to such potential releases cannot be shifted onto others.

Figure 1: Possible emissions occurring during CCS (source: Haefeli et al. 2004, p. 15)
Carbon Dioxide Capture and Storage Issues – Accounting and Baselines under the United Nations Framework Convention on Climate Change (UNFCCC
© OECD/IEA 2004, p. 15



4. Integration of CCS into the Climate Regime

4.1. CCS: removal or emission reduction

The special characteristic of CCS that results in the formation of CO_2 without its emission into the atmosphere gives rise to the important question of whether CCS is dealt with as:

1. Removal (sink enhancement) or
2. An emission reduction (at source) activity.

The answer to this question to a great extent determines how CCS and seepage will be accounted for in the emission inventories of Annex-I counties and how it will be treated under the project-based mechanism joint implementation (JI) and clean development mechanism (CDM). When treating CCS as a *removal activity*, the captured CO_2 would have to be considered as emitted - even though not vented in reality - into the atmosphere at the source, and would therefore appear as an emission in the national emission inventory. Any CO_2 stored would be accounted for as removal of CO_2 - similar to the accounting of sequestration in the land-use, land-use change and forestry (LULUCF) area (Haefeli et al. 2004). Regarding the removal approach, it should be noted that the term 'sink' is defined by the UNFCCC as "any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere" (Article 1.8 UNFCCC). This legal definition does probably not apply to the process of CCS, since this option mainly refers to the capture of CO_2 from point sources and not from the atmosphere.

Therefore, CCS could probably be considered an emission reduction in the framework of the UNFCCC.[10] Thus, a change in the emission factor will have to account for the captured CO_2. While in this paper, we assume that CCS will be treated as an emission reduction, this question is mainly a political one and still needs to be answered.

4.2. CCS Cross-border projects

The fact that CCS is considered an emission reduction has implications regarding the characterisation of this activity under the flexible mechanisms. An overview is given in Table 2.

All the cases where capture (the emissions reduction) takes place in a non-Annex I country (case 3, 5 and 6 in Table 2) fall under the CDM. In these cases, emission reduction credits would be generated.[11] Regardless of where the CO_2 is stored, projects with capture in an Annex I country (case 1, 2 and 4 in Table 2) can be considered Annex I mitigation, either conducted as domestic mitigation or as a JI project.[12] Those CCS activities in which CO_2 is stored in an Annex I country (cases 1-3) account for the possible non-permanence of storage. Seepage from the reservoir will appear in the national emissions inventory of the storing Annex I country. A new inventory category would have to be introduced for such purposes. However, as non-Annex I countries do not have emission targets, possible seepages from the reservoir located in non-Annex I countries – under current rules will not be subtracted from the emissions budget of whatever country.[13] Thus, the overall emissions budget of the Annex I countries might be inflated and environmental integrity of the climate regime endangered.

Table 2: Possible combinations of capture and storage countries and resulting type of mechanism under the Kyoto-Protocol

Case	Capture	Storage	Type of mechanism
1	Annex I (same as storing country)	Annex I country	Annex I mitigation*
2	Annex I (other than storing country)		Annex I mitigation*
3	non- Annex I country		CDM
4	Annex I	non- Annex I country	Annex I mitigation*
5	non- Annex I ((same as storing country)		CDM
6	non- Annex I(other than storing country)		CDM

*Annex I mitigation can either be domestic mitigation or JI.

4.3. Dealing with liability for non-permanence in non-Annex I countries

In order to account for the non-permanence in the case of storage in non-Annex I countries, two different solutions are possible.

1. Ban on CCS with storage in non-Annex I countries
2. No ban but
   a. Consideration of seepages by discounting
   b. Creation of rules that account for actually occurring releases

The first option of restricting CCS to projects with storage in Annex I countries[14] would, however, decrease the storage potential significantly. Another option (2a) is the discounting of emission reductions based on an assumed standard rate of seepage (see Haefeli et al. 2004). However, discount factors for seepages would have to be estimated ex ante for the whole time frame of storage.[15] At present, credible values for discounting are not available.[16] Another reason why discounting is problematic is that it is difficult to account for unforeseeable events or wilful releases.[17] If the discount factor acknowledges the possibility of these events or releases it is very conservative and thus provides little incentives to invest in CCS.

Option 2b mentioned above relies on a determination of releases from the reservoir by monitoring. Thus, the ability of monitoring technologies to quantify possible seepage events is an essential condition for creating such a liability framework. In the following section we will analyse in further detail, which rules in the framework of the international climate regime might be able to guarantee liability for releases from storage reservoirs located in non-Annex I countries. In outlining how liability for these releases could be established in the Kyoto Protocol, one has to distinguish between the CCS projects falling under Annex I mitigation (case 4) and those falling under the CDM (case 5 and 6). In case 4, as mentioned above, the emission reduction due to capture of CO_2 is accounted for by subtracting the captured CO_2 from the total CO_2 emissions formed at the source. Thus, the capturing Annex I country would have to be liable for possible emissions from the storage reservoir if it is exporting CO_2 into a non-Annex I country. Creating liability for emissions in the non-Annex I country could thus be seen simply as an inventory question.[18] Similar inventory issues have been discussed regarding the treatment of harvested wood products (HWP). Emissions from the reservoir in the non-Annex I country could, for example, be included in the national emissions inventory of the capturing Annex I country.[19]

In the two CDM cases with storage in a non-Annex I country (case 5 and 6), liability has to be dealt with differently.[20] The buyer of the CERs resulting from a CCS project should remain liable for possible emissions. Therefore, expiring CERs[21] similar to those issued for CDM forestry projects could be one option for guaranteeing liability for the stored CO_2 in the framework of the international climate regime.

The respective mechanisms guaranteeing liability in each of the described cases are summarised in Table 3.

Table 3: Different CCS cases and respective mechanisms to guarantee liability for non-permanence of storage

Case*)	**Capture - Storage**	**Mechanism**	**Rule guaranteeing liability**
1 & 2	Annex I – Annex I	Annex I mitigation	Possible emissions appear in inventory of country storing CO_2
4	Annex I – non-Annex I	Annex I mitigation	Possible emissions appear in inventory of country capturing CO_2
3	non-Annex I – Annex I	CDM	CER issued, possible emissions appear in inventory of country storing CO_2
5 & 6	non- Annex I – non-Annex I	CDM	Temporary credits issued (buyer liability)

*) see Table 2

The above analysis shows that the way in which CCS is accounted for in the international climate regime would probably depend largely on where capture and storage take place. This suggests that the elaboration of rules and modalities for integrating CCS into the international climate regime is likely to be a complex task.

5. Economic Implications of Non-Permanence of CCS

With the exception of EOR, CCS does not produce any additional income except for that generated by the credits for the CO_2 storage. Kallbekken and Torvanger (2004) compare the net economic benefit of geological storage with different levels of permit prices. However, when comparing costs with the benefits of CCS, the term "cost" must also include the costs of the non-permanence of carbon dioxide storage.[22] Therefore, in the following economic analysis, we apply the approach of temporary credits in the CDM to CCS.

In case of releases of CO_2, temporary credits have to be replaced by the country which has used them for compliance. We call the costs incurred to compensate for future releases of CO_2 replacement costs (RC). The replacement costs are equal to the discounted costs incurred for buying (permanent) credits on the market to compensate for future CO_2 releases.[23] Therefore, the benefit of temporary storage in economic terms lies in the postponement of the purchase of a permanent permit. Consequently, the value of temporary storage (V^{temp}) is equal to the value of a permanent emissions reduction (V^{perm}) minus the RC:[24]

$$V^{temp} = V^{perm} - RC$$

With decreasing RC, the value of the temporary credit will increase. Due to these additional costs related to the future releases of CO_2, any (temporary) CCS activity must be cheaper than permanent mitigation options by an amount equivalent to the RC. Based on this concept, the value of temporary storage for different release and discount rates is calculated and expressed as a percentage of the value of a permanent emission reduction (see Table 4). In the calculation, we assumed a stable price for (permanent) emission reduction credits.[25] While at low release and high discount rates, the value of temporary storage is almost equal to the value of permanent emissions reductions, high release rates and low discount rates lead to substantial decreases in the value of temporary storage. With permanent storage, the value of a temporary credit would, of course, be equal to the value of a permanent one.

In spite of the fact that the temporary credits approach has only been proposed for cases 5 and 6, the results represented in Table 4 are, from an economic perspective, also valid for the other CCS cases.

Table 4: Value of temporary storage

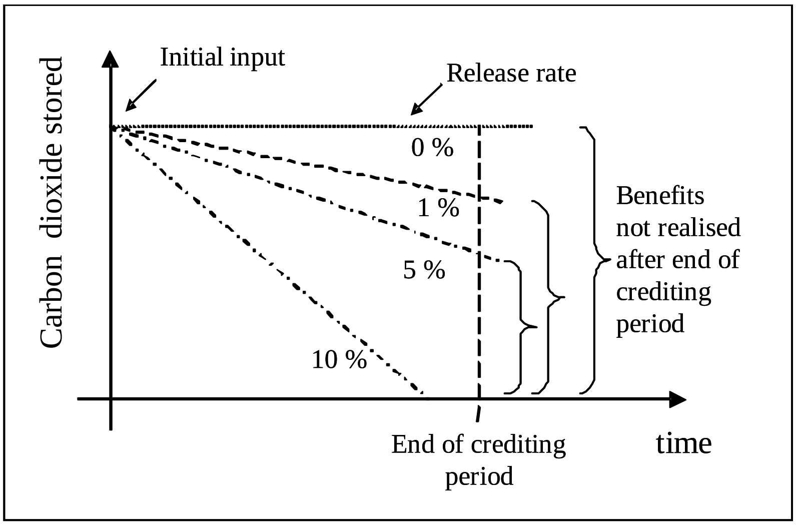
Value (in percent of permanent emission reduction) *)		**Release rate (%)**			
		0	**0.01**	**0.1**	**1**
Discount Rate (%)	**1**	100	98.8	90.6	48.5
	5	100	99.6	97.7	80.8
	10	100	99.7	98.7	88.0

*) Constant carbon price assumed

As long as liability for future releases is guaranteed, either the capture country (as in case 4), or the storing country (as in cases 1, 2 and 3), have to incur the cost related to future releases from the reservoir. As release rates are expected to be rather low in most cases, it can therefore be concluded that the decrease in the value of temporary storage due to non-permanence is almost negligible for CCS in general.

For those CDM cases for which the temporary credits approach was proposed (cases 5 and 6), this conclusion is not generally valid. The assumption underlying such a calculation is that a CCS CDM project can generate temporary credits over an unrestricted period of time. However, the time for receiving CERs under the CDM, the so called crediting period, is currently limited. For energy projects, the maximum crediting period is 21 years, for forestry, 60 years.[26] While permanent CERs do not have to be replaced after the end of the crediting period, all temporary credits generated by forestry projects expire after the end of the crediting period. The latter is equivalent to the assumption that after 60 years, all the sequestered carbon is released into the atmosphere, even if it remains sequestered in the biomass thereafter. The special case of temporary credits with restricted crediting periods in the CDM will make temporary carbon storage less attractive since it reduces the value of temporary storage. The reason for such a pattern originates in the fact that crediting periods considerably shorter than retention times neglect a great part of the storage taking place beyond the crediting period. Therefore, the benefit from postponing the purchase of permanent credits can only be realised in part, as illustrated by Figure 2.

Figure 2: Effects of a limitation of a crediting period



Should CCS CDM projects using temporary credits (case 5 and 6) also be subject to a limited crediting period, the value of temporary storage would be significantly smaller than for the other CCS cases. In the case of short crediting periods (e.g. 20-60 years), the economic viability of such CDM projects is going to decrease significantly as compared to those generating permanent credits.

6. Conclusion

Carbon dioxide capture and storage does not avoid the formation, but the emission of CO_2 to the atmosphere. According to Art. 1.8 of the UNFCCC, CCS would probably be considered an emission reduction. While in this paper, we assume that CCS will be treated as an emission reduction, this question is mainly a political one and still needs to be answered. When integrating CCS into the climate regime, one has to take into account that there might be releases of the stored CO_2 back to the atmosphere and that CO_2 might be transported across country borders.

Based on the assumption that CCS is an emission reduction, we conclude that all CCS projects with capture in a non-Annex I country fall under the CDM, while the projects capturing CO_2 in an Annex I country could be considered Annex I mitigation (either domestic mitigation or JI), independently of where the CO_2 is stored.

When CO_2 is stored in an Annex I country that has ratified the Kyoto Protocol and complies with inventory quality standards, possible non-permanence of storage is accounted for as emissions from the reservoir. CO_2 releases will enter the national emission inventory of the Annex I country in which the reservoir is located. As non-Annex I countries do not have emission targets, possible seepage from the reservoir located in non-Annex I countries will, however, not be subtracted from the emission budget of whatever country. Thus, it could water down the overall emission target of the climate regime, which would require the implementation of special liability rules for those cases in which CO_2 is stored in non-Annex I countries. If an Annex I country is exporting CO_2 to a non-Annex I country, a possible solution may be to have the Annex I country report emissions from the reservoir and include them in its own national emissions inventory. In the case of capture and storage taking place in a non-Annex I country, liability for the stored CO_2 could be created by expiring credits, similar to those issued for forestry projects in the CDM.

If release rates from the storage reservoirs are as small as widely suggested (> 0.01), the cost incurred to compensate future releases can be expected to be almost negligible. It should be noted, however, that the economic viability of CDM projects that generate temporary credits and are subject to relatively short crediting periods, can decrease significantly as compared to those generating permanent credits.

The present paper focused on two of the most important issues: accounting for releases from the reservoir and cross-border cases. Nevertheless, there are further issues that must be dealt with before CCS can be accounted for appropriately as a climate mitigation option. Accounting might become much more complicated than discussed, if different CO_2 exporting (capture) countries use the same storage reservoir, and if release rates are a function of the quantity stored. Transboundary reservoirs, too, may be difficult to deal with due to the territory principle underlying the Kyoto Protocol. Finally, $CO_{2,}$ stored in non-Annex I countries may become a contentious issue when emission targets for these Parties are negotiated in the future.

Regarding the numerous complexities of integrating CCS into the international climate regime, it must be borne in mind that only accurate and complete accounting, which guarantees the long-term liability for future releases, will allow CCS to become a credible mitigation option.

End Notes

[1] Ha-Duong and Keith (2002) and Lackner et al. (no year) have also proposed to capture CO_2 directly from the air, showing that this might become a feasible option in the future.

[2] OECD/IEA (2004) mentions the fuel extraction and transformation sector as an additional important emissions source where capture might be applied.

[3] Storage of CO_2 due to utilization in the food and fertilizer industry results in very low retention times, though, and is therefore, not a relevant option for CCS.

[4] Trucks and trains are also possible media of transport.

[5]While little experience exists with ECBM, EOR has already been applied for some decades to enhance oil production. Depending on the location, EOR is profitable today, especially when oil prices are high. Contrary to EOR, Enhanced Gas Recovery (EGR) is not yet technically mature or a commercially viable technology (OECD/IEA 2003).

[6] Costs per ton avoided include the costs of the energy penalty. They are, thus, greater than the costs per ton captured. The literature on costs is extensive. See for example OECD/IEA (2004), Audus 2000, Condorelli et al. (1991), Herzog (1999), David and Herzog (2001), Freund and Davison (2002), Göttlicher and Pruschek (1999), Reimer et al. (1999), Rubin and Rao (2003), Simbeck (1999), and Smelser (1991).

[7] However, whenever talking about costs in relation to the avoided emissions, the baseline plant used to calculate the emission reduction costs is of crucial importance. For detailed discussion of this issue see Anderson et al. (2003).

[8] Further storage cost estimates can be found in e.g. Gupta et al. (2002), Hendriks et al (2001), Reeves and Schoeling (2001), Smith et al. (2001), as well as Wildenborg and Van der Meer (2002). See also IPCC (2005).

[9] The IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC 2005) mentions a range of 0-70 US$/t CO_2 avoided for pulverized coal, and 20-270 $/t CO_2 with natural gas combined cycle as the reference plant, which are higher than costs stated in other sources.

[10] Biomass combustion will have to be dealt with differently.

[11] For further detail on this, see the analysis below.

[12] Regarding JI, a third Annex I country in which CO_2 is neither captured nor stored, could be part of the project buying the emission reduction units. The country in which the emission reduction takes place is

always the capture country, which is likely to be financially compensate the storing country for costs associated with storage (storage, monitoring, risks of later releases etc.).

[13] Similar problems occur if the country has not ratified the Kyoto Protocol or does not have sufficient inventory quality.

[14] Those Annex I countries which have ratified the Kyoto Protocol and comply with a minimum standard of inventory quality.

[15] For an overview of methods for the estimation of default factors and an outline of accounting rules, see Yoshigahara et al. (2004).

[16] DTI (2004) comes to the conclusion that "whilst a conservative approach to discounting could be adopted, based on estimates from some type of CO_2 seepage scenario modelling, current constraints in the understanding of specific CO_2 fluxes from potential storage reservoirs presents a barrier to setting credible rates". For monitoring technologies available, see for example Pearce et al. (2004)

[17] Depending on the rule for liability, there might be incentives for reservoir operators in non-Annex I countries to release CO_2 after "permanent" CERs have been issued and to subsequently refill the reservoir and to receive CERs again for the same reservoir.

[18] See also Haefeli et al. (2004), pp. 21-22

[19] This is similar to the 'Production approach' proposed for the consideration of HWPs which includes the emissions from the HWP pool in a non-Annex I country in the national inventory of the exporting Annex I country. For an overview of the HWP discussion, see UNFCCC (2003).

[20] Issuance of permanent CERs is unproblematic if CO_2 is stored in an Annex I country (case 3).

[21] For forestry projects, two types of expiring credits exist (temporary CERS, tCERs and long-term CERs, lCERs). For more information on temporary credits for LULUCF, see Dutschke et al. (2004).

[22] For a detailed analysis on the effectiveness of carbon storage with a focus on non-permanence, see Herzog et al. (2003)

[23] See also Ha-Duong and Keith (2003).

[24] The value of temporary storage consists of the price obtained for the chain of temporary credits generated during the crediting period.

[25] When assuming e.g. continuously increasing prices in the future, the general tendency remains the same.

[26] The rules and modalities offer a choice between a non-renewable crediting period of (10) 30 and a twice renewable crediting period of (7) 20 years.

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