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GSE briefing paper on CO_2 storage

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Executive Summary

The development of a European Union climate package and the European Energy Programme for Recovery triggered the need to investigate Carbon Capture and Storage (CCS), and what specifically will the storage of CO_2 offer opportunities to storage system operators. This has resulted in this GSE Briefing Paper on CO_2 storage.

The main issues regarding CCS can be summarised as:

- The operational framework differs from underground gas storage: after ending the storage activities, gas storage will be ‘empty’, while CO_2 storage will be ‘full’. The report lists the main differences between CO_2 storage and gas storage.
- A regulatory framework has been developed, and will be implemented in national law by 2011. It address among others the monitoring and liabilities after the storage activities have ended. The framework also addresses site selection and permitting.
- The European Commission considers CCS as a key element in its energy and climate policy. This may provide business opportunities.
- The longer term economic framework still has lots of uncertainties. However, once CO_2 prices will be at a sufficient level, the economics may become attractive. Much is to be learned from the demonstration projects that currently in early stages of development.

Content

1. Introduction

Late 2008 the European Parliament endorsed the Climate Package. This was finally approved by the Council in April 2009. Part of the package are directives on geological storage of CO_2 and emissions trading (ETS).

The European Energy Programme for Recovery calls for proposal for demonstration proeject, and will make available 1.05 billion € for support. Initial proposals for these demonstration projects need to be submitted by 15 July 2009. Although these demonstration projects are outside the scope of GSE, it is possible that they will lay a foundation for "CCS as a business".

Furthermore the 300 million ton emission allowances will be available to support projects that will make use of new technologies. Member States will have to submit proposals in 2010.

Both developments, the package and the programme, triggered the option to investigate what CCS is from a SSO perspective. Especially what could storage of CO_2 mean for SSO's so that each SSO can take a view whether there are business opportunities for them.

This paper addresses CCS from a process point of view. CCS will play, with several other technologies, an important role in achieving the CO_2 reduction targets. The paper gives a high level global overview, where CCS can be done. Attention is given to the economic and regulatory frameworks, and a high level comparison is made between CO_2 storage and natural gas storage. Lastly, a number of opportunities and threats will be presented.

2. Carbon Capture & Storage (CCS)

2.1. Introducing CCS

To tackle climate change effectively, global carbon dioxide (CO_2) emissions must be radically reduced. Fossil fuels like coal provide much of the world's electricity but won't be fully replaced by low-emission generating technologies for decades to come. That's why the utility industry is focusing its research and development on an innovative process called carbon capture and storage (CCS), which would make it possible to generate electricity from coal with nearly zero emissions. Three carbon-capture methods are currently being developed for coal-fired power plants: post-combustion capture, pre-combustion capture, and oxyfuel combustion. Carbon transport and storage are, along with carbon capture, essential components of the strategy for climate-friendly power production.

In post-combustion capture, CO_2 is chemically washed out of flue gas. In pre-combustion capture, coal is first transformed into a gas called syngas; CO_2 is then removed from the syngas prior to combustion. In oxyfuel combustion, coal is burned in pure oxygen instead of air, which results in a significantly higher concentration of CO_2 in the flue gas. The flue gas must then be scrubbed of its remaining components such as oxygen, sulfur dioxide, and nitrous oxides.

Power plants are rarely located near a suitable underground storage facility, so captured CO_2 must be transported to such a facility. Trucks or ships are suitable for transportation of small amounts or over long distances. But because power plants will continually capture large amounts of CO_2, it makes economic and environmental sense to use pipelines to transport CO_2.

Saline aquifers are suitable for permanent underground carbon storage. Typically more than 800 meters below the earth's surface, these rock formations consist of microscopic cavities filled with saltwater. CO_2 would be injected into an aquifer under high pressure, where it would displace and partially dissolve in the saltwater in a process similar to the carbonation of mineral water. This is an attractive solution because aquifers have the capacity to store the quantities of CO_2 that would be captured at power plants.

Depleted natural gas reservoirs represent another option for permanent carbon storage. Gas accumulated and was conserved in such formations for millions of years, providing a naturally created storage facility for CO_2. Pressurized CO_2 is already injected into oil reservoirs around the world in order to boost their production and extend their operating lives.

2.2. Storage principles

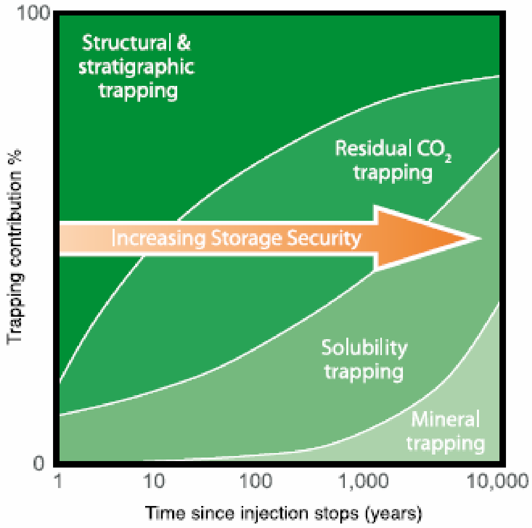
Four main storage mechanisms for CO_2 operate in reservoir rocks (Chadwick: 17). These are:

- Structural and stratigraphical trapping, where the migration of free (gas, liquid, fluid) CO_2 in response to its buoyancy and/or pressure gradients within the reservoir is prevented by low permeability barriers (caprocks) such as layers of mudstone or halite.

- Residual saturation trapping, in which capillary forces and adsorption onto the surfaces of mineral grains within the rock matrix immobilise a proportion of the injected CO_2 along its migration path.

- Dissolution trapping, where injected CO_2 dissolves and becomes trapped within the reservoir brine.

- Geochemical trapping, in which dissolved CO_2 reacts with the native pore fluid and the minerals making up the rock matrix of the reservoir. CO_2 is incorporated into the reaction products as solid carbonate minerals and aqueous complexes dissolved in the formation water (sometimes called “ionic trapping”, because of the often predominant bicarbonate anions).

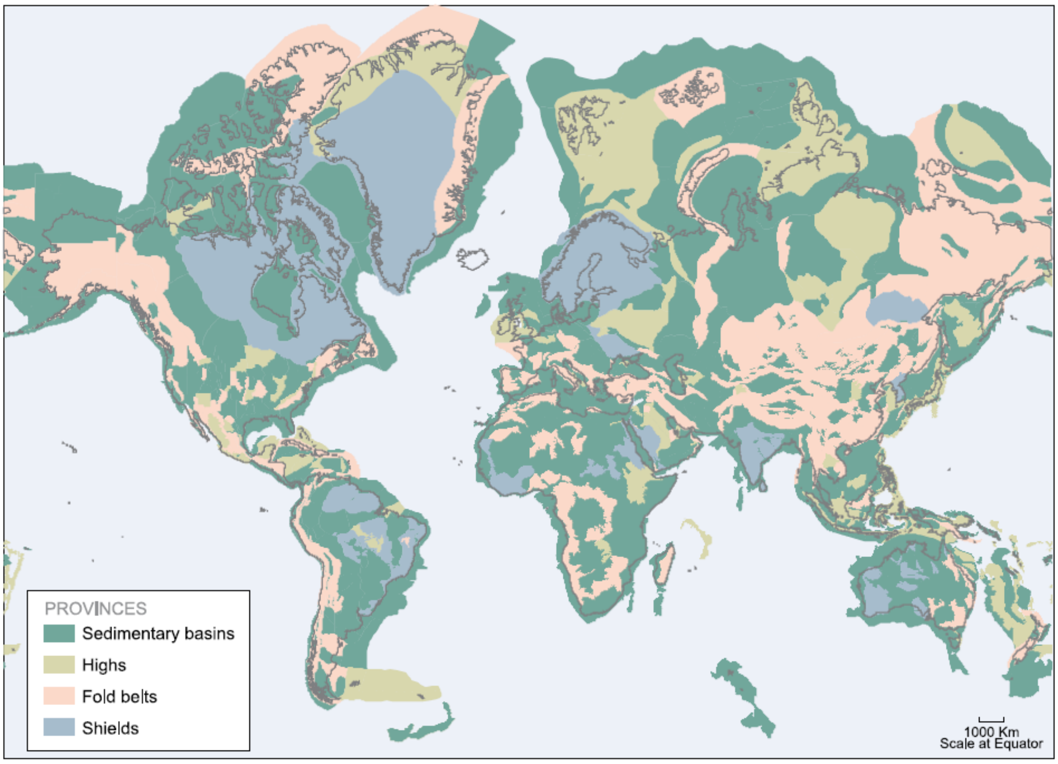


Storage security depends on a combination of physical and geochemical trapping. Over time, the physical process of residual CO_2 trapping and geochemical processes of solubility trapping and mineral trapping increase.

(SRCCS: 208)

2.3. Storage potential

The following map shows the distribution of sedimentary basins around the world (after Bradshaw and Dance, 2005; and USGS, 2001). In general, sedimentary basins are likely to be the most prospective areas for storage sites. However, storage sites may also be found in some areas of fold belts and in some of the highs. Shield areas constitute regions with low prospectivity for storage. The apparent dimensions of the sedimentary basins, particularly in the northern hemisphere, should not be taken as an indication of their likely storage capacity. (SRCCS: 214)



3. ECONOMIC FRAMEWORK

To assess the economic framework the cost of the CCS chain should be assessed against the expected CO_2 price in the Emissions Trading Scheme. The following overview of estimated CCS cost in € per tonne is taken from Clingendael International Energy Programme[1]. It should be noted that these estimates come from a variety of sources. However, the message is clear: as of now there is no consensus on the costs of CCS.

[1] Clingendael International Energy Programme, 2008, *Carbon Capture and Storage: A reality check for the Netherlands*.

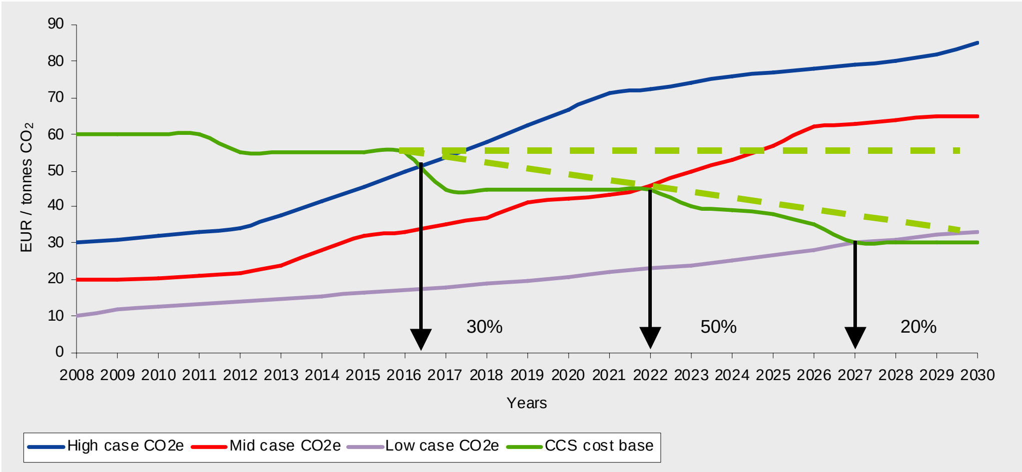
	Capture	*Transport*	*Storage*	**Total**
CERA (2008)	$60-75	$5 – 35		$65 - 110
Rotterdam Climate Initiative (2008)	€13 - 40	€7.5 - 10	€4.5 – 6.5	€25 - 57
Power industry estimate (2008)				€ 45 (+/- € 5)
Pöyry (2007)	€30 - 45			€45
European Commission (2008)				€35
EnergieNed		€8		
World Coal Institute (2007)	Coal/gas power plant: $15 – 75	$1-8	Injection: $0.5–8/t Monitoring: $0.1–0.3	$40-90
Ecofys (2007)				€30 - 40
IPCC (2005)			Injection: $0.5 – $8	€20
Rubin et al.	$23 - 63	Transport and storage cost: 4 – 10% of Cost of Electricity (COE)		$32 -72
MIT (2007)			$20	
E3G				€75 - 120

Viable business opportunities should appear if the CCS cost is lower than the carbon prices in the Emission Trading Scheme (ETS). The table below is from the same Clingendael report and shows the estimated prices in the ETS.

Price estimate €/t	**ETS 2 2008 – 2012**	**ETS 3 2013 - 2020**	**2020**
Deutsche Bank*	€40	n.a.	€65 – 70
Ecofys (2007)	€5 - € 25	€15 – €35	€20 - €50
Fortis (March 2008)**	€48/t (a) €27/t (b)	Max. €100	
IDEAcarbon/ECON Global Carbon Report	€15 – 20	n.a.	n.a.
New Carbon Finance (2008)	€38	€35-55	n.a.
Point Carbon	€30	€30 - 70	n.a.
Societe Generale	€27 – 39	n.a.	n.a.
UBS	€30-35	€ 30-40	n.a.
* Up from €35 in 2007 ** (a) Without a post-Kyoto agreement; (b) with 430m offset emission allowances			

Currently CO_2 prices are too low for economic CCS, but in these prices may become sufficiently attractive, as shown in the graph below. The reason for this is that in the third phase no longer free emission allowances will be given to the power sector. Furthermore, the total number of allowances is expected to reduce.

Development of CO_2 Value Versus CCS Costs



Investment in CO_2 storage facilities may be different than underground gas storage. First of all, there is no need to withdraw CO_2 from the storage, and secondly CO_2 has different properties, e.g. it is corrosive, than natural gas, and this may lead to differences in design. An element to consider as well is the cost of the monitoring after operations have ended, and determine who should be responsible for these costs.

It is likely that the governments will keep a close eye on the development of the CO_2 business. The reason for this is that the first demonstration projects will need subsidies, and for future CO_2 storage projects transport infrastructures will be needed. Governments may take the lead to develop these infrastructures.

4. REGULATORY FRAMEWORK

4.1. Introduction to EU Directive

The regulatory framework in the EU is set by the Directive 2009/31/EC of 23 April 2009 *On the geological storage of carbon dioxide*.

Whether to use carbon capture and storage or not is still a matter for independent decision by each EU member state. For EU countries that wish to do so, the directive sets out the conditions for the assessment of storage sites, for authorisation procedures and for the closure of such sites. In order to ensure harmonized application throughout the European Union, the Commission will review draft storage permits and draft decisions on closure prepared by national authorities before their final approval.

Operators are obliged to monitor storage sites and report to the Member State's authorities, both while storing carbon dioxide and after the closure of sites and the cessation of storage activities. Responsibility for a site reverts to a public authority when sufficient proof is obtained that the carbon dioxide will be completely and permanently contained.

Member States are required to transpose the Directive into national law within two years.

The main elements of the Directive are given in the following paragraphs.

4.2. Objective

The Directive establishes a legal framework for the environmentally safe geological storage of carbon dioxide to contribute to the fight against climate change. The purpose of environmentally safe geological storage of CO_2 is permanent containment of CO_2 in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health.

4.3. Scope and prohibition

The Directive shall not apply to geological storage of CO_2 undertaken for research, development or testing of new products and processes with a total intended storage below 100 kilo tonnes.

- Enhanced Hydrocarbon Recovery (EHR) is not itself included in the scope of the Directive;
- the storage of CO_2 in a storage site with a storage complex extending beyond the frontiers of the EU will not be permitted;
- the storage of CO_2 in the water column will not be permitted.

4.4. Selection of storage sites

Member States retain the right to determine the areas from which storage sites may be selected pursuant to the requirements of this Directive. This includes the right of Member States not to allow for any storage in parts or in the whole of their territory. Member States who intend to allow geological storage of CO_2 in their territory shall undertake an assessment of the storage capacity available in parts or in the whole of their territory, including by allowing exploration pursuant to the Directive. The Commission may organise an exchange of information and best practices between those Member States. A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist.

4.5. Storage permits

No storage site may be operated without a storage permit, and there shall be only one operator for each storage site, and no conflicting uses must be permitted on such site. Priority for the granting of a storage permit for a given site shall be given to the holder of the exploration permit for that site, provided that the relevant conditions are met (Articles 6-11 of the Directive).

- ***Applications for storage permits*** : applications to the competent authority for storage permits shall include at least the prescribed information, inter alia:
    - the total quantity of CO_2 to be injected and stored;
    - the prospective sources of CO_2 and transport methods;
    - the composition of CO_2 streams;

- the injection rates and pressures;
- the location of injection facilities;
- description of measures to prevent significant irregularities;
- proof that the financial security or other equivalent provision as required will be valid and effective before commencement of injection.

- ***Conditions for storage permits***: the competent authority shall only issue a storage permit if certain conditions are met (i.e. the financial soundness of the operator). The conditions and contents of the storage permits are listed in articles 8 & 9 of the Directive.
- ***Commission review of draft storage permits***: Member States shall make the permit applications available to the Commission within one month after receipt. They shall also make available other related material that shall be taken into account by the competent authority when it seeks to make a decision on the award of a storage permit.

4.6. Monitoring

Member States shall ensure that the operator carries out monitoring of the injection facilities, the storage complex, and where appropriate the surrounding environment for the purpose of, inter alia, detecting significant irregularities and updating the assessment of the safety and integrity of the storage complex in the short- and long-term including the assessment of whether the stored CO_2 will be completely and permanently contained.

4.7. Transfer of responsibility

Where a storage site has been closed, all legal obligations relating to monitoring and corrective measures, the surrender of allowances in cases of leakage and preventive and remedial action, shall be transferred from the operator to the competent authority on its own initiative or upon request from the operator, if certain conditions are met. These include whether a minimum period, to be determined by the competent authority has elapsed. This minimum period shall be no shorter than 20 years, unless the competent authority is convinced that all available evidence indicates that the stored CO_2 will be completely and permanently contained. (Articles 17 & 18 of the Directive)

4.8. Financial mechanism

The operator, on the basis of modalities to be decided by Member States, must make a financial contribution available to the competent authority before the transfer of responsibility has taken place. The contribution from the operator shall take into account specific criteria, and cover at least the anticipated cost of monitoring for a period of 30 years. (Articles 19, 20 & Annex I of the Directive)

4.9. Third-party access

Member States shall take the necessary measures to ensure that potential users are able to obtain access to CO_2 transport networks and to storage sites for the purposes of geological storage of the produced and captured CO_2. The access shall be provided in a transparent and non-discriminatory manner determined by the Member State. The

Member State shall apply the objectives of fair and open access, taking into account conditions listed in article 21 of the Directive.

5. OPERATIONAL FRAMEWORK

5.1. Storage operation: overview of similarities/differences CO_2 vs. natural gas

In contrast to natural gas Carbon Dioxide (CO_2) is non-flammable. It has no liquid state at pressures below 5.1 atm. At 1 atm the gas deposits directly to a solid at temperatures below −78 °C and the solid sublimes directly to a gas above −78 °C. In its solid state, carbon dioxide is commonly called dry ice. CO_2 is toxic only in higher concentrations:

The following table lists a rough workflow of natural gas storage (left column) and focuses on specific differences to CO_2 storage in the right column.

Workflow natural gas storage	**CO_2 storage** **(Differences to the workflow natural gas storage)**
1. Screening / Data Room	Storage location (most favourable: close to CO_2 source(s)) Rough estimation of costs for capture, transport, storage
2.1 Exploration of potential storage site	Reservoir rock and cap rock properties, pressure influence, capacity estimate
2.2 Feasibility study / estimate of costs	Additional software for modelling and simulation, geochemistry, geomechanics Aim: sufficient injection rate, immobilization of CO_2 in storage, long-term safety Legal/regulatory framework in progress
3. Construction	Choice of material for borehole, pipeline and surface facilities depends on CO_2-composition, corrosion aspect
4. Operation	Continuous injection, no withdrawal More detailed monitoring (4D seismic), monitoring of CO_2 and water migration
5. End of storage operation / Closure	Dismantling infrastructure / abandon and seal-off wells Framework undetermined (e.g. transfer of responsibility to the federal state, liabilities) Monitoring after closure

5.2. Monitoring issues

Regarding monitoring issues the following questions are important to answer:

- How can we monitor CO_2 once it is injected? What techniques are available for monitoring whether CO_2 is leaking out of the storage formation and how sensitive are they?

  A Summary of direct and indirect techniques that can be used to monitor CO_2 storage projects is listed below. (SRCCS: 236) The methods "subface pressure", "well logs" and "time-lapse 3D seismic imaging are state of the art and usually applied in storage projects. All other methods need to be evaluated individually for each site whether they can give significant further insight into the subface process.

Measurement technique	**Measurement parameters**	**Example applications**
Introduced and natural tracers	Travel time Partitioning of CO_2 into brine or oil Identification sources of CO_2	Tracing movement of CO_2 in the storage formation Quantifying solubility trapping Tracing leakage
Water composition	CO_2, HCO_3^-, CO_3^{2-} Major ions Trace elements Salinity	Quantifying solubility and mineral trapping Quantifying CO_2- water-rock interactions Detecting leakage into shallow groundwater aquifers
Subsurface pressure	Formation pressure Annulus pressure Groundwater aquifer pressure	Control of formation pressure below fracture gradient Wellbore and injection tubing condition Leakage out of the storage formation
Well logs	Brine salinity Sonic velocity CO_2 saturation	Tracking CO_2 movement in and above storage formation Tracking migration of brine into shallow aquifers Calibrating seismic velocities for 3D seismic surveys
Time-lapse 3D seismic imaging	P and S wave velocity Reflection horizons Seismic amplitude attenuation	Tracking CO_2 movement in and above storage formation
Vertical seismic profiling and crosswell seismic imaging	P and S wave velocity Reflection horizons Seismic amplitude attenuation	Detecting detailed distribution of CO_2in the storage formation Detection leakage through faults and fractures
Passive seismic monitoring	Location, magnitude and source characteristics of seismic events	Development of microfractures in formation or caprock CO_2 migration pathways
Electrical and electromagnetic techniques	Formation conductivity Electromagnetic induction	Tracking movement of CO_2 in and above the storage formation Detecting migration of brine into shallow aquifers
Time-lapse gravity Measurements	Density changes caused by fluid displacement	Detect CO_2 movement in or above storage formation CO_2 mass balance in the subsurface
Land surface deformation	Tilt Vertical and horizontal displacement using interferometry and GPS	Detect geomechanical effects on storage formation and caprock Locate CO_2 migration pathways
Visible and infrared imaging From satellite or planes	Hyperspectral imaging of land surface	Detect vegetative stress
CO_2 land surface flux monitoring using flux chambers or eddycovariance	CO_2 fluxes between the land surface and atmosphere	Detect, locate and quantify CO_2 releases
Soil gas sampling	Soil gas composition Isotopic analysis of CO_2	Detect elevated levels of CO_2 Identify source of elevated soil gas CO_2 Evaluate ecosystem impacts

6. TREATS & OPPORTUNITIES IN CO2 FOR SSOS

6.1. Opportunities

CO_2 Capture and Storage is one option within the portfolio of measures to reduce greenhouses gases. CCS, in parallel with energy efficiency improvements or development of renewable energies contributes to CO_2 reduction, and then to meeting internationally agreed climate targets. The European Commission considers CCS as a key element of its energy strategy and « believes that after 2020 all new power plants using coal, and most likely gas as well, should be built and operate with CCS, whereas capture-ready plants built in the previous period (before 2020) should be "retrofitted". This vision is possibly too ambitious but provides the advantage of a very strong support to European CCS projects in the years to come.

Indeed, availability of CCS at competitive cost would allow developing economically competitive «clean coal» and would provide advantages in terms of competitiveness when avoiding taxable CO_2 emissions. Coal which is an abundant resource would increase security of energy supply, when added to energy mix, including for electricity production. We have to consider that fossil fuels will remain necessary for a number of years and consequently that CCS has a strong transitional role to play.

Considering the storage part of this new business to come, saline aquifers and oil and gas fields are the main targets, offering in the latter case an additional period of operation when the fields are almost depleted. Not only E&P companies have a role to play: Storage Operators can take advantage of their existing competencies to build a new business line which is close to their current activity.

Finally, the number of companies of all kind currently participating to research projects, pilot or even pre-commercial demonstrators proves both the global interest in this new technology and the possibility to easily find partners to share risks and address the different industrial challenges involved.

However…it is worthwhile considering that many problems, difficulties, threats have to be resolved! These are listed in the next section.

6.2. Threats and weaknesses

First of all public acceptance is needed and communication actions are of fundamental importance. A sincere public debate will help develop the public's perception that a large scale deployment of CCS is vital. The main risk is to make people believe that this technology is only made to furthermore develop electricity production with a dirty source (coal) and not globally reduce CO_2 emissions, work on energy efficiency or put the main effort on developing renewable sources of energy.

Also, CCS is a capital intensive technology: funding of the first large demo projects is difficult. Because of heating, cooling and compression, large scale CCS will also require high operating costs. At the same time price of CO_2 is still at a low level on the market, so it may be for a long time more profitable to buy emission rights.

Technically, the choice of a capture technology for a new plant is not obvious at the moment and the three main possibilities (at least) have to be tested in parallel. In addition no emission performance standard is currently defined; CO_2 purity may be imposed arbitrarily. Additional efforts are then still needed to bring those technologies to maturity. These efforts include commitment of electricity producers and gas processing providers.

Definition of what is really capture readiness and when it will be imposed is unclear: it depends on storage feasibility criteria which are not defined: for example evaluation of leakage risks or propagation of minor components etc. which may lead to disproportionate monitoring requirements: in Europe it will be left to member states appreciation.

Currently it is uncertain whether CO_2 storage projects have any impact on the way the general public looks at gas storage projects.

Competition with protection of water resources may appear (which aquifer water cannot be said in the long term as economically transformable into drinkable water?). On the contrary, competition with geothermal activities should be limited to restricted geographical areas.

7. REFERENCES

Bradshaw, J.B. and T. Dance, 2005: Mapping geological storage prospectivity of CO2 for the world sedimentary basins and regional source to sink matching. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7), September 5–9, 2004, Vancouver, Canada, v.I, 583-592.

Chadwick, Andy, Arts, Rob, Bernstone, Christian, May, Franz, Thibeau, Sylvain and Zweigel, Peter: BEST PRACTICE FOR THE STORAGE OF CO2 IN SALINE AQUIFERS. Observations and guidelines from the SACS and CO2STORE projects.

Clingendael International Energy Programme, 2008: Carbon Capture and Storage: A reality check for the Netherlands.
http://www.clingendael.nl/publications/2008/20080930_ciep_energy_heuvel.pdf

E.On website, http://www.eon.com/ccs

SRCCS: IPCC Special Report on Carbon dioxide Capture and Storage. 2005.

U.S. Geological Survey, 2001: U.S. Geological Survey World Petroleum Assessment 2000 - Description and Results. U.S. Geological Survey Digital Data Series - DDS-60. http://greenwood.cr.usgs.gov/energy/WorldEnergy/DDS-60/.