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The acceptability of CO_2 capture and storage (CCS) in Europe: An assessment of the key determining factors Part 1. Scientific, technical and economic dimensions

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ABSTRACT

The ACCSEPT project, which ran from January 2006 to December 2007, identified and analysed the main factors which have been influencing the emergence of CO_2 capture and geological storage (CCS) within the European Union (EU). The key clusters of factors concern science and technology, law and regulation, economics, and social acceptance. These factors have been analysed through interviews, a large-scale questionnaire conducted in 2006, and discussions in two stakeholder workshops (2006 and 2007). In Part I of this paper, we aim to distil the key messages and findings with regards to scientific, technical, legal and economic issues. There are no compelling scientific, technical, legal, or economic reasons why CCS could not be widely deployed in the forthcoming decades as part of a package of climate change mitigation options. In order to facilitate this deployment, governments at both the EU and Member State levels have an important role to play, in particular in establishing a robust and transparent legal framework (e.g. governing long-term environmental liability) and a strong policy framework providing sufficient and long-term incentives for CCS and CO_2 transportation networks.

1. Introduction

CO_2 capture and geological storage (CCS) is now recognised as an important technological option for carbon abatement within Europe. Whilst our focus in the European Commission-funded Acceptance of CO_2 Capture, Storage, Economics, Policy and Technology (ACCSEPT) project was primarily on the acceptability of CCS within the EU27 nations, non-EU countries such as Norway and Switzerland are important players in CCS research, development and demonstration (RD&D), hence our interest extended somewhat beyond the EU countries. The ACCSEPT project framed the challenges surrounding adoption of CCS in Europe via a number of critical questions which need to be addressed before CCS could be reliably, effectively, efficiently, equitably and safely implemented within the EU. The questions are as follows:

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1. Is CCS geologically feasible within the EU and what storage capacities are available?
2. Can the risks of CCS be appropriately assessed and managed?
3. Can CCS be undertaken under existing international and European law?
4. Is there sufficient fossil fuel to make investment in CCS worthwhile in the long term?
5. How large are the externalities arising from CCS and how important are they?
6. Is the information on the costs of CCS good enough to make robust decisions?
7. What policies can help to make CCS more economically feasible?
8. Is CCS acceptable to European stakeholders?
9. Is CCS acceptable to the European public?
10. How should CCS be communicated to the European public?
11. Can CCS be incorporated into the clean development mechanism (CDM) and what might be the impacts of this upon carbon markets and other CDM projects?
12. Will investment in CCS detract from the development and deployment of other zero- and low-carbon energy sources?

In Part I of this paper we address the technical and economic questions 1 through 7, whilst in Part II we tackle the remaining questions 8–12. The more detailed background analyses are available on the ACCSEPT project website (www.accsept.org), along with detailed recommendations to Europe's energy policy makers (ACCSEPT, 2007). We first set the scene with a discussion of recent EU energy policy and the possible future role of CCS.

2. The potential role of CCS within the European Union

At its spring meeting in 2007, the European Council adopted a European Energy Action Plan with the three goals of security of supply, efficiency and environmental compatibility. Ensuring the competitiveness of European industry and technology is a further important ambition of European energy policy making, in pursuit of the Lisbon Agenda. The Council gave clear commitments to promoting renewable energies, supplemented by introducing efficiency and energy savings measures. In addition, consent was given to the need for sustainable use of fossil fuels, and to work towards strengthening RD&D and developing the necessary technical, economic and regulatory frameworks to bring environmentally safe carbon dioxide capture, transport and storage solutions to markets, if possible by 2020.

In January 2007, the European Commission published a Communication to the Council and European Parliament on *Sustainable Power Generation from Fossil Fuels: Aiming for Near-Zero Emissions from Coal after 2020* (European Commission, 2007a). This document establishes the need for CCS and for policy development to assist in its wide deployment. The Communication notes that: "...coal can continue to make its valuable contribution to the security of energy supply and the economy of both the EU and the world as a whole only with technologies allowing for drastic reduction of the carbon footprint of its combustion" (European Commission, 2007a, p. 4). The Commission has declared that it will: "substantially increase the funding for R&D in the energy area, making the demonstration of Sustainable Fossil Fuels technologies one of the priorities for 2007–2013. ... the Commission will determine the most suitable way to support the design, construction and operation by 2015 of up to 12 large-scale demonstrations of Sustainable Fossil Fuel technologies in commercial power generation" (European Commission, 2007a, pp. 6–7).

With respect to its climate policy, the EU has an agreed objective to limit global temperature increase to a maximum of 2 °C above the pre-industrial level, implying global greenhouse gas reductions of 15–50% by 2050 compared to the emissions in 1990, and 60–80% reductions for developed countries (European Commission, 2007b). The Commission notes that: "it is clear that large-scale coal-based generation with current technology and associated CO_2 emissions is not compatible with this scenario" (European Commission, 2007b, p. 12). 50% of the EU's electricity is generated from fossil fuels (coal c. 30%, gas c. 20%). The combustion of coal in EU power plants produced 950 Mt of CO_2 in 2005, which is 24% of the EU's total carbon emissions and 70% of emissions from electricity generation (European Commission, 2007a). The Commission's TRENDS baseline scenario considers that electricity demand in the EU25 will increase from 3177 TWh in 2005 to 4367 TWh in 2030 (37% increase), extrapolated to 4631 TWh in 2050 (46% increase) (European Commission, 2007a).

The Commission notes that: "While increased use of energy efficiency measures and greater penetration of renewable energy sources are expected to contribute to meeting the increased demand, even ambitious scenarios foresee that most electricity will still be supplied by the traditional thermal power plants, both fossil fuel and nuclear" (European Commission, 2007a, p. 14). Whilst this view becomes less certain as we look further forward in time, it is estimated that the required installed thermal power plant capacity in 2030 is 800 GW producing 3700 TWh/year. The Commission's analysis assumes that the share of coal in the mix remains at around 30%. Therefore, it is assumed that there is an increase in the overall amount of coal-based electricity generation in the EU by 2030 compared to today. An important reason why coal remains important is energy security which comes from having a diverse energy supply. There are larger reserves of coal remaining than of oil and gas, as well as a more diverse set of suppliers than of oil and gas, including from politically stable parts of the world.

If we assume that the EU's CO_2 emissions need to be reduced by 80% by 2050, then overall annual emissions from all sources would be perhaps 760 Mt CO_2 compared to current coal-fired power plant emissions of 950 Mt CO_2. Coal-based emissions are anticipated to increase under current trends to 1300 Mt CO_2 by 2030. The combination of this increase in coal use and an assumed need for an 80% reduction in all CO_2 emissions by 2050 implies that all coal power plants must have CO_2 capture capabilities by 2050 and probably sooner. Whilst it may be technically feasible to meet the CO_2 reduction target by using other low-carbon energy technologies, the retention of coal for reasons of supply security and cost has been repeatedly expressed as a European priority. Approximately 75% of the coal-fired power plants in the EU27 are over 25 years old and 45% are over 30 years old (European Commission, 2007a). This suggests that several hundred units, representing 100 GWe, are facing retirement, or life extension through retrofitting, within the next 10–15 years (European Commission, 2007a). The Commission noted that: ''Replacement of these plants with coal-fired generating capacity to maintain a diverse energy mix will only be publicly acceptable, compatible with the EU's climate change objectives, and may only be economically viable if specific CO_2 emissions are reduced drastically'' (European Commission, 2007a, p. 14).

3. Creating a policy framework to facilitate the development of CCS

In January 2008 the European Commission produced a raft of proposed legislative measures called the ''climate action and renewable energy package'', aimed at delivering the EU's greenhouse gas reduction and renewable energy objectives for 2020. As part of the package the Commission proposed a Directive on the geological storage of carbon dioxide, along with a detailed Impact Assessment and a statement on supporting early demonstration of sustainable power generation from fossil fuels (European Commission, 2008a,b,c respectively). The proposed Directive will, if adopted, establish a bespoke legal framework to regulate the storage of captured CO_2 in the EU. It aims to cover the entire life-cycle of a geological storage site, from site selection and operation requirements, through to closure obligations and the transfer of post-closure responsibilities to competent authorities of Member States but only after there is near certainty that the possibility of leakage has been reduced to zero. Although the Directive's focus is on storage, it will also mesh with existing legislative instruments, which will be amended so that they explicitly cover the capture and transport components of CCS activities. In doing so, it is intended to clarify existing legislation and remove barriers that currently restrict the large-scale development of CCS facilities, particularly in relation to waste, water and industrial emissions legislation. The proposed Directive also includes a requirement that new power plants be built as 'capture-ready', hence capable of being equipped with CO_2 capture plant and with suitable geological storage sites and transport routes having been identified.

In 2007 the Commission had noted that it: ''believes that by 2020 all new coal-fired plants should be built with CCS'' (European Commission, 2007a, p. 10). It argued that ''a clear and predictable long-term framework is necessary to facilitate a smooth and rapid transition to a CCS-equipped power generation from coal'' (European Commission, 2007a) and explored three possible incentives.

- Establishing a more favourable long-term investment framework by ''ensuring the relative perpetuity of the emissions trading scheme and by facilitating commercial financing and risk-sharing instruments'' (European Commission, 2007a, p. 10).
- Developing EU CO_2 storage sites and pipelines for multi-user access or projects for CO_2 infrastructure development at Member State level.
- ''Adopting legally binding measures to regulate maximum allowed CO_2 emissions per kWh after 2020 and/or introduce a timed phase-out (for instance by 2050) of all high CO_2 emitting (i.e. non-CCS) electricity generation'' (European Commission, 2007a, p. 10).

The Commission undertook an assessment of different policy options with respect to sustainable power generation from fossil fuels against the EU's energy policy objectives (European Commission, 2007b). The three policy options considered were:

- Option 0: No policy change,
- Option 1: Removal of barriers to sustainable coal technologies,
- Option 2: Pro-active introduction of incentives for the penetration of sustainable coal technologies.

Under Option 0, there is a reduction in CO_2 emissions from coal-fired power plant due to efficiency gains but more significantly because of the replacement of coal by other energy sources, in particular natural gas. This increased use of gas raises considerable problems from an energy security perspective. The Commission concluded that: ''If the twin benefits of secure energy supplies and environmentally sustainable energy are to be secured in the EU, No Policy Change is not an option'' (European Commission, 2007b, p. 48).

Policy Option 1 leaves the penetration of sustainable coal technologies to the existing market framework and the Commission noted that: ''Its success is therefore entirely reliant upon the economics for clean coal and CCS being attractive to investors in the period after the technologies are demonstrated and are commercially available'' (European Commission, 2007b, p. 49). In other words, the uptake of CCS would require high gas prices relative to coal, a high value for CO_2 under the EU ETS and an RD&D strategy which successfully brings down the cost of CO_2 capture. Investors would only support CCS for coal-fired generation if sufficiently high CO_2 emission permit prices (€20–40 per tCO_2) were anticipated in the next several decades. Policy Option 1 is therefore a risky approach since it relies upon economic variables which are historically volatile and uncertain.

Policy Option 2 would make adoption of CCS for all new coal-fired plant a requirement after 2020 (not included in the proposed Directive) and would develop an 'enhanced' version of the EU ETS. The enhanced EU ETS would ''establish generally [a] more favourable framework for long term investment in low-emission technologies by introducing a concept of 'relative perpetuity''' (European Commission, 2007b, p. 31). Possible incentive mechanisms mentioned by the Commission include: privileged access to the electricity pool for zero-emissions power; high buy-back prices for 'sustainable electricity'; an obligation imposed upon suppliers to include a minimum share of 'sustainable electricity'; and/or timed phase-out of high CO_2-emitting installations. The Commission noted that: ''If there is too much uncertainty around Option 1 to ensure continued unhindered presence of coal in the mix, policy Option 2 offers a range of measures that could be adopted to secure the objectives'' (European Commission, 2007b, p. 51).

In its 2008 Impact Assessment, the European Commission (2008a) used a range of analytical tools to assess the costs and benefits (including potential positive externalities) of different policy options for CCS support. These options ranged from doing nothing, including CCS in the EU ETS, to various permutations of a CCS mandate (for new coal power plant from 2020; new coal and gas plant from 2020; new coal from 2020 and retrofit of coal built from 2015; new coal and gas from 2020 and retrofit of plant built from 2015) and, finally, inclusion of CCS in EU ETS with a subsidy. In this later document, the Commission came down in favour of the option of inclusion of CCS within the EU ETS, and argues against a CCS mandate or subsidy, an apparent change of position from the 2007 statement. The results of economic modelling are the main reason for this change, but the conclusion relies upon the ability of the EU ETS to provide a sufficiently strong economic incentive for CCS development; other commentators are less convinced that European politicians will be minded to stick with a tough carbon emission cap in Phase 3 of the scheme (Lockwood, 2008). Industry is, arguably, already discounting the price of CO_2 on the EU ETS, thus favouring new coal rather than gas power plant build, which could thereby enhance carbon lock-in and further increase the tendency for politicians to argue for a less demanding carbon cap (Lockwood, 2008).

In conclusion, it can be seen that CCS has become very firmly embedded in the energy and climate change policy making of the EU over the past 2–3 years. At the time of writing, the details of the proposed Directive are being negotiated within the European Parliament and with the Member States and the issue of a CCS mandate or Emission Performance Standard is still 'on the table'. The Commission (2008b) has proposed a separate mechanism by which financial support for the first tranche of CCS demonstration projects can be secured, though the details of how financing will occur are currently uncertain and somewhat controversial. However, all this assumes that CCS is technically feasible, credible and desirable within Europe and we now turn to address these questions.

4. Is CCS geologically feasible within the EU and what storage capacities are available?

There are numerous sedimentary basins and geological reservoirs within the EU that are judged suitable for CO_2 storage. The major, suitable off-shore sedimentary basins are located in: the North Sea, the Hebrides, the Norwegian Sea, the Baltic Sea, the Adriatic Sea, the Mediterranean Sea (four basins) and off the Iberian Peninsula. The major on-shore sedimentary basins are located in or below: Denmark, the North German Plain, Hungary, the Carpathians, Molasse, Paris, SE and parts of northern England, Belgium, the Appenines (Italy), Sicily, SW France, and Spain (three basins). The Zero Emission Power Plant Platform (ZEP) estimates that the Utsira formation in the Norwegian sector of the North Sea could be used for the storage of 2 billion tonnes of CO_2 each year (ZEP, 2006), which is probably enough storage capacity for the foreseeable CCS projects in the EU for at least the next 20–30 years. The EU Commission quotes IEA estimates that the Norwegian sector of the Utsira formation is capable of storing up to 600 billion tonnes of CO_2 and that this would allow storage of all of the EU's CO_2 emissions (at current levels) for over 300 years (European Commission, 2007a).

Questions have been raised regarding the accuracy of these estimates, however, the problem being that there is no agreed methodology for calculating the storage capacity of saline aquifers for CO_2 storage (Holloway et al., 2006a,b; Bachu et al., 2007; Bradshaw et al., 2007). One method is to assume that storage occurs only in the structural traps for buoyant fluids and that a proportion of this volume would be available for CO_2 storage. A second method is to assume that a fraction of the total pore volume of all potential reservoir formations would be available for CO_2 storage, a method which Holloway et al. (2006a) now consider to be inadequate and likely to give too high an estimate of the storage capacity. The aquifer storage capacity of the UK sector of the North Sea according to the first method is nearly 9 billion tonnes CO_2, whilst it is up to 240 billion tonnes according to the second method, i.e. 27 times larger than the lower estimate. It is this second method which is used to derive the figure of 600 billion tonnes CO_2 storage capacity for the Utsira formation; hence that figure is not reliable and more detailed work is required to derive a more realistic value.

Other EU 6th Framework Programme (FP) funded projects are examining the geological storage capacities of reservoirs within the European Union. Several projects in particular are worth mentioning: GeoCapacity, CO2GEONET, CCS-SCEN and CO2ReMoVe. It is anticipated that these projects will provide a more reliable basis for estimating CO_2 storage capacity within the EU and more widely. Some of the differences in capacity measurement are discussed in Bradshaw et al. (2007), Bachu et al. (2007) and in a report of the Technical Group of the Carbon Sequestration Leadership Forum (CSLF) (Technical Group, 2008). The latter report indicates that a confidence indicator can be given to measurements of capacity based upon two variables: the subsurface heterogeneity and the data density.

In conclusion, whilst there are certainly abundant potential reservoirs for CO_2 storage, at this stage it is difficult to provide reliable estimates of CO_2 storage capacities in European reservoirs. The European Commission's Impact Assessment (2008b) included an analysis of CO_2 sources and geological reservoirs and concluded that there was sufficient storage capacity to 2030, and at a reasonable cost, under the deployment scenarios examined; furthermore, there was sufficient storage capacity in nearly all countries for domestically-produced power plant CO_2 to be stored in the country of origin, though this required the use of deep aquifers in addition to depleted oil and gas fields. More work on producing valid methodologies for storage capacity estimation and applying these methods to produce more robust capacity estimates, is underway within 6th FP funded projects and through other initiatives in the CSLF and the Regional Carbon Sequestration Partnerships Program in North America. Existing estimates based upon controversial methodologies, including the 600 billion tonne storage capacity claim for the Utsira formation, should not be used in policy making because the attendant uncertainties surrounding the validity of such estimates are too large. Furthermore, only large point source emissions of CO_2 are amenable to capture with existing technologies, and these sources are not necessarily located close to potential sinks. Claims that all of the European Union's CO_2 emissions for the next several hundred years could be stored in saline aquifers cannot, at the current time, be justified and could give a misleading impression to policy makers.

5. Can the risks of CCS be appropriately assessed and managed?

The risks of CCS are difficult to define and identify, not just technically, but in terms of the way different people and organisations understand and interpret risks. It is noted, for example, that in looking at the risks of CCS, one has to consider the risks both of implementing it and of *not* implementing it. The precautionary principle applies as much to employing CCS to avoid global warming as it does to avoiding leakage from CCS. The basic conclusion of an examination of potential risks is that, because the risks from climate change due to fossil fuel emissions are larger and far more difficult to manage than the risks from CCS, the risk of leakage from storage should not impede CCS development overall. From this perspective, it is important to move quickly and to learn by doing.

The message is not that environmental risks need to be ignored however: rather, the already identified major risks incurred by CCS should be guiding the initial decisions about site location and exploitation, and ongoing monitoring and evaluation should be robust enough to draw further conclusions. Whilst risks from CCS are often presented as technical risks posed by introducing CO_2 into a new environmental context, and the unintended consequences thereof, it may well be that management decisions about storage are as important as, if not more important than, physical risks. This is to say that because geological sites *can* be found and managed in such a way as to all but rule out leakage, does not mean they *will* be found and managed in that way if the proper guidelines, incentives and oversight are not in place. Many of these elements are already in place, but need reinforcement.

To ensure that proper procedures are agreed and followed, governments and institutions can have an important role in harmonizing approaches, but such harmonization has to take place at an appropriate level to guarantee enough detail is captured to make it useful. The higher the level of discussion, the more general is the regulation, which is appropriate for establishing some basic principles. Much of the difficulty in regulating CCS, however, lies in the site-specific nature of CO_2 storage and associated risks. Hence, diverse levels of analysis and action are needed, which will require further capacity building and coordination.

Finally, whatever the physical reality of risk, as perceived by scientists, industrialists or regulators, if stakeholders are not convinced of that reality, storage may face acceptance problems. Furthermore, stakeholders' overall perceptions of energy policy, and of the risks of competing low-carbon energy options, may also influence their readiness to accept the risks of CO_2 storage. For instance, if a stakeholder considers the risks of nuclear power to be unacceptable, yet also regards climate change as a major environmental risk, then this is likely to influence the way in which the risks of CO_2 storage are perceived. Some prominent environmental NGOs and Green Parliamentarians have even made their support for CCS contingent upon phase-out of nuclear power and/or of nuclear energy RD&D (Reiner, 2008).

Risk perceptions among stakeholders and project developers may well differ, and it may be hard to settle such differences by appeal to the 'facts' because of different interpretations of the salience of those facts, and what 'the' facts actually are, or whether particular risks exist in the first place. Defining risk authoritatively, in either qualitative or quantitative terms, is difficult for new and relatively untested technologies such as CCS. Going beyond defining risk to communicating conclusions about risk is an added layer of complication. It is imperative to find a common language for the characterisation and communication of risk both among professionals and between professionals and the public, a topic we return to in Part 2.

6. Can CCS be undertaken under existing international and European law?

At present, the construction and operation of a CCS project would fall within the scope of a diverse array of international and European law. That is not to say that a CCS project would necessarily contravene international or European norms. Indeed, a European company could, subject to domestic law and strict geographic and technical conditions, set up and operate a CCS project in accordance with existing supranational law. However, there are a number of unresolved legal concerns that, until addressed, render the widespread deployment of large-scale CCS projects impracticable. In order to understand these concerns, it is useful to draw a distinction between CO_2 capture and transport on one hand, and CO_2 storage on the other. The most problematic legal issues centre on CO_2 storage, and so warrant particular attention.

6.1. *The capture and transport of CO_2*

In principle, European law is sufficiently developed to regulate the capture and transport of captured CO_2 from emission sites to storage facilities. The capture of CO_2, for example, could fall within the scope of the IPPC Directive (96/61/EC, as amended), even though that Directive was adopted without specific reference to CCS activities. It imposes a permitting regime on certain industrial and agricultural activities, and provides that Member States are entitled to withhold permits from companies where certain environmental conditions are not met. Accordingly, Member States could, in theory, use the IPPC Directive and associated legal instruments to regulate the risks associated with CO_2 capture. In this context, it is notable that the Commission's proposed Directive on the geological storage of CO_2 explicitly acknowledges the role of the IPPC Directive without significant amendment, reinforcing the idea that the existing law is capable of regulating the capture of CO_2.

The regulation of transporting captured CO_2 similarly falls, in theory, within the scope of existing international and European law: liquefied CO_2 is already transported in significant quantities by road, ship and pipeline across the EU and is regulated in accordance with dangerous goods laws and regulations. However, there are two reasons why the existing framework on the transport of CO_2 may ultimately prove to be inadequate.

First, the scale of future CCS projects may mean that new infrastructure is required to transport captured CO_2 through pipelines to storage sites. The construction of major project infrastructure such as pipelines and pumping stations is likely to be regulated by the Environmental Impact Assessment Directive (85/337/EEC, as amended). If the construction of CCS facilities develops at a rapid pace across national borders, it may place an unmanageable administrative burden on authorities charged with reviewing such assessments.

Second, the transport of CO_2 bears a strong analogy with natural gas transport. As such, it is worth bearing in mind the European experience of that sector, which has shown that the infrastructure required to transport large quantities of gas is significant, requires large economies of scale and involves long-lead times. These considerations mean that the owners of such infrastructure are reticent to allow third party access to the networks without adequate compensation. Competition concerns arising from such restrictions have led to laws and regulations dedicated to providing open and non-discriminatory access to pipeline networks. Unfortunately, existing European law on third party access does not lend itself naturally to CCS activities. Accordingly, a bespoke third party access regime is desirable, balancing the rights of ownership against the benefits of allowing wider participation in the technology or infrastructure. The Commission's proposal on the geological storage of CO_2 recognises the shortcomings of the existing third party access framework. It requires that Member States 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 issues outlined above are not insurmountable obstacles to the development of CCS projects. However, they do indicate legal 'gaps' where existing law and regulation may be found wanting. Similar gaps can be found in relation to: (1) property rights (including intellectual property rights over capture technology and the ownership of the CO_2 after capture); (2) the role of international incentives to develop CCS projects (such as the inclusion of such projects within the EU Emissions Trading Scheme and the Clean Development Mechanism); and (3) environmental liability for the release of captured CO_2 (including the role of insurance). Some of these gaps are of particular relevance to the capture and transport elements of CCS. Others apply in particular to the storage of CO_2, to which we now turn. In both cases, pre-emptive clarification of gaps in the relevant law (i.e. before the substantive development of a CCS market) is desirable. Here, it should be noted that whilst addressing many of the issues set out above, the European Commission's proposed Directive on CCS does not sufficiently deal with all legal uncertainties concerning the capture and transport of CO_2 derived from CCS facilities.

6.2. *The storage of CO_2*

The legal framework governing the long-term storage and monitoring of captured CO_2 presents the most challenging area for legislators. There are two facets to this: (1) the definition of captured CO_2 when it is put into long-term geological storage; and (2) liability for any escape of CO_2 from geological storage formations.

Under current European law, it is uncertain whether CO_2 that is captured and then stored would be classified as 'waste'. If, for example, captured CO_2 was used in Enhanced Oil Recovery (EOR), then an argument could be made that it is an industrial product. The importance of this determination is that if captured CO_2 is deemed to be waste, then its storage would be subject to the permitting regime under European waste law. In certain circumstances, this could result in potential storage sites being off-limits.

Against this background, it should be noted that the international community has started to address these issues. For example, the London Protocol (an international agreement that prohibits dumping waste in the sea) has been amended so as to allow the sub-seabed disposal of "CO_2 streams from CO_2 capture processes" in certain circumstances. This is a significant step; the London Protocol had previously been a notable international impediment to the widespread development of CCS projects.

Putting to one side the definition of captured CO_2, the storage of CO_2 raises the fundamental concern of long-term risk allocation under international and EU law. Again, international law has taken a lead. The OSPAR Convention (a convention for the protection of the marine environment of the North-East Atlantic against pollution) was amended in June 2007 to allow the storage of CO_2 in geological formations under the seabed. In doing so, the OSPAR Commission also announced guidelines for risk assessment and management of CCS activities.

Like the amendments to the London Protocol, the changes to the OSPAR Convention are an important development in international law, and the European Commission's draft Directive on the geological storage of CO_2 is a welcome development. A failure to contain stored CO_2 undermines the environmental rationale for CO_2 capture, and a comprehensive framework is not yet in place: the current European legal framework does not clearly define who will be responsible for environmental harm in the event that a failure occurs once captured CO_2 has been stored.

For example, the Environmental Liability Directive (Directive 2004/35/EC) is fast becoming the overarching framework for environmental liability within Europe. In theory, much of the potential damage attributable to the escape of CO_2 post-injection would fall within its scope. However, it suffers three shortcomings: (1) it does not address climate liability (damage to the climate system caused by the escape of CO_2 from storage sites); (2) it does not extend to potential sub-seabed geological formations; and (3) it does not impose liability if more than 30 years have passed since the emission, event or incident resulting in the damage occurred (given the long time frames of CO_2 storage a 30-year longstop date may prove to be inadequate).

These issues are addressed in the Commission's proposed Directive on the geological storage of CO_2 in a three-pronged approach (European Commission, 2008a). First, Member States will retain the right to determine the areas within their competence that are suitable for storage sites. As a result, the opportunity for exploiting speculative storage sites can be limited by Member States taking a cautious approach to site selection. Second, the draft Directive provides for detailed 'storage permit' applications (including requiring that applicants put up adequate financial security to cover any liabilities incurred whilst they are responsible for the site). Finally (and perhaps most significantly), responsibility for the long-term management of storage sites post-closure will transfer to the competent authorities of Member States.

It is vital to strike the right balance in the liability regime between government and private entities. If, for example, a company can be held liable for leakage or migration of CO_2 from a storage site several decades (or more) into the future then it is very unlikely that that company will be prepared to invest in CCS activities. Weighed against this consideration are the high procedural standards that are required to ensure the integrity of storage sites. The Commission's proposed Directive clearly endeavours to strike such a balance. However, in light of the discretion afforded to Member States in relation to the selection of storage sites, it is a balance that will need to be monitored, reviewed and (if necessary), adjusted.

7. Is there sufficient fossil fuel to make investment in CCS worthwhile in the long-term?

It has been widely assumed that coal, unlike oil and gas, will be abundant for at least another century. A recent estimate by the US Department of Energy of coal resource life time is 164 years at the current production rate (USDOE, 2007a). Another estimate is that coal has a resource life of 133 years at current production rates, i.e. a resource life of 133 years (BP, 2007). This compares to estimated reserves of oil and gas which are expected to last for 42–60 years respectively at current rates of consumption (BP, 2007). There are compelling reasons for concern regarding the reliability of such estimates. An example is Germany where the official estimated recoverable coal resources were reduced by 92% in 2004 because of the use of more restrictive criteria for the depth and thickness parameters associated with underground and surface mining. In the USA, the National Research Council has admitted that the often quoted estimates of resource lifetime of coal have a very shaky foundation (NRC, 2007). In China, only 115–192 Mt of reported coal resources are 'proven' (IEA, 2007). All of China's 'unproven' coal is relatively deep, which precludes surface mining and implies relatively low recovery rates (IEA, 2007). Although India has large coal resources at shallow depths, the ash content of India's remaining coal resources is very high, which requires considerable washing and blending with low-ash coal which must be imported (IEA, 2007). If the potential increase in coal consumption is taken into account, then the coal resource life decreases. The USDOE considers that coal consumption might increase by 77% between 2005 and 2030, which would reduce the resource life globally to about 70 years (USDOE, 2007a). It would appear that the historical abundance of coal, which has typically been believed to last up to tens of generations of human lifespan, has prevented serious efforts in reliable accounting of its long-term availability.

A new coal-fired power plant has a design life of approximately 40–50 years. If CCS were not to be implemented in any serious way until 2020, however, then it may well be the case that only one generation of CCS power plants is constructed due to the depletion of coal supplies. Aggressive, early implementation of CCS could still be justified nonetheless, since it would find application in hundreds of power plants built in succession to 2050 and learning can take place with experience as it evolves from the earliest plants. Furthermore, much learning can be incorporated into design changes which take place through upgrading and retrofitting of plants once they have been in operation for a number of years. It is also worth noting that CCS could be applied to biomass-based combustion, either with coal or by itself, and, in this respect, the technology, and regulatory and legislative framework, could have greater longevity than that implied by the estimated coal resource life.

In summary, economically-accessible coal supplies are probably not as abundant as is commonly assumed, in part because of the rapid growth in its consumption. Even if supplies are not guaranteed to last for 'hundreds of years', as is often claimed, there are still sufficient supplies that the current generation of coal-fired power plants will probably be replaced before coal supplies dwindle away or become too expensive to use for electricity generation.

8. How large are the externalities arising from CCS and how important are they?

CCS has potential negative impacts arising from increased coal extraction, increased sludge production from this and from the capture process itself, increased water usage and completely new emissions from chemical scrubbers where post-combustion CO_2 removal takes place (Rubin et al., 2007). Because of the energy penalty of capture and compression, the overall energy generation capacity must be increased, and this implies that more coal is required in regions where CCS is installed and where coal use is prevalent in energy production. This means more intensive use of existing mining and transport infrastructure and/or development of new infrastructure. Clearly, coal resources would also be drawn down more rapidly with attendant impacts on landscapes, local environmental impacts, human healthy and safety, etc. Adoption of CCS will likely require greater use of water for cooling purposes in power plants and for operating the capture process itself. Estimates range from an increase in water requirement with CO_2 capture, relative to no CO_2 capture, of 10–20% for Integrated Gasification Combined Cycle (IGCC), 90–100% for pulverised coal post-combustion capture, and 55% for Natural Gas Combined Cycle post-combustion capture (USDOE, 2007b). Already, some thermal power plants in the EU face the problem of insufficient water for cooling purposes at times of water stress. If CCS were to make this situation worse, then it could pose a problem, though provisions might be made for temporarily reducing or stopping CO_2 capture altogether should water supplies come under stress. Therefore, there is a high probability that capture plants will have lower capture efficiency in hotter, drier regions where general scarcity of water and periodic water stress are common. Use of amine-based scrubbers could also pose problems in terms of local pollution that are not currently well understood.

A related externality regarding CCS is that some of the potential CO_2 storage sites might also find an application as a storage site for other substances, such as compressed air in association with renewable energy systems, or indeed of natural gas. This could complicate the economic assessment of CCS if regard has not been taken of these possible further applications. In summary, there are a range of potentially negative externalities associated with CCS which have not yet been thoroughly investigated but require detailed scrutiny to ensure that negative impacts can be averted or ameliorated.

9. Is the information on the costs of CCS good enough to make robust decisions?

Decision making by corporate entities and public bodies on CCS projects is influenced to a large extent by the perceived costs. Numerous studies on the costs of CCS exist in the peer-reviewed literature, including economic modelling using various models, the present state of affairs having been summarised in several recent reviews (IPCC, 2005; MIT, 2007; IPCC, 2007). Behind this wealth of information, however, many gaps and uncertainties still exist (de Coninck et al., 2007; MIT, 2007). Below we assess the main information gaps and problems.

- Referencing same work: despite the large number of engineering-cost studies, most of those studies use data from just a few base studies. The considerable body of literature creates the impression that many independent sources converge on cost estimates, but, in reality, those many sources share a few common origins. The IPCC (2005) typically reviewed between three and six separate engineering-cost studies for a range of technology design options, whilst MIT (2007) reviewed seven design and cost studies. The MIT study noted that: ‘‘Several studies that were on a substantially different basis or fell well outside the range expected were not included in the analysis because there was no adequate way to effectively evaluate them’’ (MIT, 2007, p. 127).
- Changes in fuel and material costs: most studies assume pre-2005 oil and gas prices and do not take account of the rising costs of materials, particularly steel prices. This mostly affects steel-intensive options with already high investment costs, in particular integrated gasification combined cycle systems with CO_2 capture, often hailed as a low-cost CCS option based on outdated fuel and steel costs. MIT (2007) estimates that the rise in construction costs increases the capital costs of power plants by 25–35% relative to the situation in 2004.
- Confidentiality: CCS technologies have evolved largely from existing, commercial technologies rather than from public sector R&D. Corporate entities are motivated to protect their intellectual property through patents, confidentiality agreements and keeping information secret, because it is through exploitation of such proprietary knowledge that they add value to their enterprises. Detailed information on CCS technologies and their costs is, therefore, not fully available in the public domain and it is difficult for independent researchers to assess the validity of assumptions in their cost models without access to such data.
- Technology advocacy and optimism: There are approximately one to two thousand experts working on CCS worldwide, this number having grown from a couple of hundred individuals only 2 or 3 years ago. We know from the experience of other energy technologies, in particular nuclear, that there is a tendency for those working on a particular technology to over promote the virtues of their own option and to under promote the case of competitor technologies. Those closely involved in developing a particular technological option frequently need to attract policy attention and resources, and this may lead them to underestimate the costs, leading to information bias.
- Risks: Before new technologies such as CCS can be implemented, corporate decision-makers need to find a way of incorporating technological and policy risks in their investment decisions. Whilst confidence in CCS has been growing rapidly, the risks of seepage (also known as leakage) are still uncertain, as are the scale-up costs for CO_2 capture from a fully-fledged power plant.
- Policy interactions: the future development of CCS depends to a considerable extent upon policy frameworks and the implementation of economic incentives. The uncertainty surrounding the course of future policy development therefore generates large uncertainties regarding the costs of CCS development.

Unless these different sources of uncertainty are taken into account by all decision-makers, modellers, policymakers and the private sector alike, poor decisions on CCS may be taken, resulting in disappointment and harming the reputation of CCS.

10. What policies can help to make CCS more economically feasible?

With the exception of some niche CO_2-based Enhanced Oil Recovery projects, the only reason why CCS is implemented is to reduce CO_2 emissions. Hence, the economic feasibility of CCS depends upon the readiness of governments to internalise the external costs of CO_2 emissions. Public bodies may also have a role in encouraging infrastructure development, e.g. should the costs of establishing a CO_2 transport infrastructure be coordinated on the EU level rather than on the national level? To further investigate the technical and economic feasibility of CCS, we consulted experts from the private sector, especially those companies that are active in the field of CCS. The view of such companies matters because if they perceive the technical or economic risks to be too high, CCS will not be deployed.

10.1. What policies can be considered for incentivising CCS?

The core instrument of EU policymaking to address climate change in large industrial sectors is the EU Emissions Trading Scheme (ETS). CCS would have to be supported by this scheme, and legislation for that to be possible is in the making. However, even if the ETS could be guaranteed over a longer time horizon than at present, and the price signal were high enough for structural deployment of CCS, it may not fully address the barriers (economic and otherwise) that exist for new technologies such as CCS. In order to promote and accelerate technological advance, it may be justified to consider additional policies to complement the ETS. Such policy measures are currently being considered both at the EU and Member State levels.

Member State policies that could enhance the economic feasibility of CCS include investment support for demonstration projects, guaranteed CO_2 prices to enable domestic implementation, and feed-in subsidies for CCS-based electricity supply. EU-level policies under consideration to complement the ETS include a portfolio standard (a requirement to source a minimum percentage of electricity from a specific kind of sustainable energy source or fuel, probably combined with tradable certificates), an emission standard for power production, or an obligation to capture and store CO_2 from the power sector and other large point sources. Incentive mechanisms for CCS need to recognise the maturity of the technology, which differs per application. CCS in the power sector, for instance, is not yet fully demonstrated on the scale that will probably be required. An argument can be made for the use of fixed-price tariffs as incentives in such instances, as opposed to market-based schemes, which are more appropriate for well-proven technologies (UKERC, 2007; de Coninck and Groenenberg, 2007).

10.2. Is an EU-wide CO_2 transport infrastructure economical?

Based on the specific characteristics of the CO_2-source/reservoir distribution in Europe, a coordinated CO_2 infrastructure that serves a number of capture and storage operations, as well as a number of countries, may be more efficient than leaving the transport logistics to each individual project or country. It is therefore recommended that the institutional design of such a network is considered, especially if analysis indicates that CCS could be deployed at a large number of facilities. Since the eventual deployment of CCS may be contingent upon the success of such a pan-European network, the role of the EU in coordinating such a CO_2 pipeline network may be important. The actual arrangement and ownership, including the formation of a public–private sector partnership for the trans-boundary CO_2 network, could be organised amongst the Member States. The way that the distribution of natural gas is governed could serve as a useful precedent, although the problems encountered in the management of that system in the recent past, and subsequent lessons learned, will need to be taken into account.

10.3. How does the private sector perceive the risks of CCS?

Interviews with companies that are faced with making an investment decision on a CCS project have shown that these firms are quite optimistic about the future economic feasibility of CCS. The discussions about climate change policies in the EU, and the ambitious emission targets set by the European Council and the EU Member States, are interpreted by firms as clear signals that policies will be developed in the short term, possibly even before the investment decisions for their projects. As yet, however, there have been no positive investment decisions regarding potential large-scale demonstration projects; in fact, several proposals have already been cancelled because of increasing costs and disappointing projected revenues (the Magnum project of Nuon in the Netherlands; the Miller-Peterhead project of BP in Scotland; and the Tjellbergodden project in Norway).

The companies are not worried that CO_2 capture and storage will fail for technical reasons. One of the concerns, however, is potential public resistance to CCS, and some companies indicate that governments should step in to provide neutral information to the lay public. A paradox emerged during discussions with firms on the risk of seepage and liability transfer. On the one hand, most companies express a high degree of confidence regarding the permanence of CO_2 storage in geological reservoirs. On the other hand, they are unwilling to remain liable for those reservoirs for a long time after site abandonment. A common explanation for this apparent discrepancy is that the lifetime of private site operators is generally shorter than the lifetime of the State, which would make the State the more appropriate organisation for assuming long-term liability. Suggestions are to limit the responsibility of the firm to several years (e.g. 10 years) after site closure, and/or to create a fund that could be used in situations where unexpected risks became evident only after the liability period of the private sector.

11. Conclusions

In order to limit climate change it has been estimated that CO_2 reductions of between 60% and 80% in 2050, compared to 1990, are required for industrialised countries such as those of the EU. Current trends and projections show an increased use of coal in the EU over the coming decades. If climate change policy objectives are to be met concurrently with coal and gas remaining an important part of the fuel mix for European electricity generation, then the implementation of CCS will be necessary in the EU.

There are numerous potential geological storage sites for CO_2 in Europe, though as yet there is no robust methodology for calculating CO_2 storage volumes, particularly in saline aquifers. Current estimates of storage volumes can differ by a factor of 30. Nevertheless, even using more conservative assumptions, storage volumes for different reservoirs range from millions to billions of tonnes of CO_2. Hence, there is sufficient storage volume for CCS to be regarded as a major option even if the larger estimates of storage volumes prove to be over-optimistic. Some of the reservoirs are within reasonable transport distance of major sources of CO_2, but other sources of CO_2 are not in close proximity of suitable storage formations. Until more reliable methodologies are available, it is prudent for the geological community to err on the side of caution when presenting estimated storage volumes (see, e.g., Bachu et al., 2007).

The growing body of knowledge on the risks of CCS should be guiding our initial decisions about site location and exploitation, and ongoing monitoring and evaluation should be robust enough to draw further conclusions. Management decisions about storage are as important as, if not more important than, physical risks. Because geological sites *can* be found and managed safely in such a way as to all but rule out leakage, does not mean they *will* be found and managed in that way if the proper guidelines, incentives and oversight are not in place.

There are no insurmountable legal barriers to CCS deployment in the EU. However, a number of issues or 'gaps' in the present international and European framework need to be addressed. In particular, although each stage of the CCS process raises potential legal concerns, the long-term storage of CO_2, and the need to implement a robust liability regime for that storage, presents the most significant challenge for legislators. Appropriate risk allocation between government and private entities, together with the need to incentivise CCS projects, means that a bespoke legal instrument is likely to be required. In this context, it is vital to strike the right balance between encouraging investment and maintaining the high procedural standards necessary to ensure the integrity of the environmental rationale for developing CCS technologies.

It is commonly stated that coal supplies are sufficient to last for 'hundreds of years', but recent re-evaluations of supplies in several countries indicate that there is more uncertainty over the longevity of supplies than has been generally acknowledged. Given a likely increase in the demand for coal, furthermore, supplies might diminish even more rapidly. The uncertainty surrounding coal supplies does not imply that CCS should not be implemented, however, because many hundreds of coal-fired power plants will likely be constructed worldwide over the next several decades, and CCS can be deployed progressively and more efficiently with the build-up of know-how.

CCS has potential negative externalities, e.g. greater utilisation of coal with associated impacts, greater demand for water for cooling and running the capture process, an extensive CO_2 pipeline infrastructure with space claims and risks, potential conflicts with other users of geological storage reservoirs, etc. The nature and cost of these externalities are not currently well understood and more research is therefore needed.

Existing information on the costs of implementing CCS is poor and potentially misleading. Much of the detailed information is held by the private sector and is confidential. Analyses in the academic literature tend to be based on just a few sources, and have not been updated to take account of rising fuel and material costs. Before a decision on appropriate policy for CCS is made, a thorough and updated assessment of the costs of CCS should be undertaken. There is, otherwise, a risk of underestimating the costs due to a range of factors. Budgets will be exceeded if decisions are taken on incorrect information, which would harm the overall acceptance of CCS and disappoint those expecting a cost-effective solution. An effort should be made to ensure that energy modellers are employing realistic cost levels (especially those analysts who are doing studies directly used for policymaking, e.g. Impact Assessments).

The European Commission's own analysis of 2007 suggests that there is a risk that CCS will not be deployed at a sufficient scale sufficiently rapidly to meet climate change objectives without the implementation of economic incentives and/or regulation (in addition to the Emissions Trading Scheme). EU-level policies that have been under consideration to complement the ETS include a portfolio standard (a requirement to source a minimum percentage of electricity from a specific kind of sustainable energy source or fuel, probably combined with tradable certificates), an emission standard for power production, or an obligation to capture and store CO_2 from all fossil-fuel-fired power production and other large point sources. The Commission (2008a) has more recently argued against incentives beyond inclusion of CCS in the EU ETS and financial help for the early demonstration plants (2008b), but its assessment is founded on uncertain and contestable assumptions, e.g. regarding the future performance of the EU ETS. Member State policies that could enhance the economic feasibility of CCS include investment support for demonstration projects, guaranteed CO_2 prices to enable domestic implementation, or feed-in subsidies for CCS-based electricity supply.

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