THE ROLE OF CARBON MANAGEMENT TECHNOLOGIES IN ADDRESSING ATMOSPHERIC STABILIZATION OF GREENHOUSE GASES

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ABSTRACT

Recent progress in decarbonization processes and engineered storage systems for CO_2, together with preliminary cost estimates for these technologies, indicate that capture and storage of CO_2 will have a major role to play in achieving deep reductions in emissions. These technologies hold the potential to reduce the cost of stabilizing the concentration of greenhouse gases, the ultimate objective of the UN Framework Convention on Climate Change (FCCC). Their value rises as the allowable level of cumulative carbon emissions declines. The value of these technologies is robust regardless of whether the world's economically recoverable oil and gas resources are eventually found to be large or small. This paper considers the economic implication of those advances in the context of long-term, global climate change mitigation strategies. This indicates the need for a broad, robust research and development strategy to reduce the cost of separating CO_2 and to make accessible the widest range of storage reservoirs. It is also important to demonstrate excellent security of storage, in order to win public acceptance of the use of capture and storage techniques.

INTRODUCTION - CARBON CYCLE AND CARBON EMISSIONS

The issue of global climate change differs from other atmospheric environmental issues in that the relationship between emissions and concentrations is complex. The goal of the UNFCCC is to stabilize the concentration of greenhouse gases at a level that would avoid dangerous interference with the climate. This implies that global emissions, from all nations of the world, will eventually have to be limited. In the long run, annual global emissions must peak and then begin to decline indefinitely (IPCC, 1996).

The most significant greenhouse gas is carbon dioxide (CO_2) and the most significant source of CO_2 is the combustion of fossil fuels, so most attention is paid to this but the deep reductions implied by IPCC will require reductions in emissions of all greenhouse gases from most sources. The long-term reductions in carbon emissions necessary to limit the concentration of atmospheric CO_2 have often been taken to mean stopping the use of fossil fuels - however, this does not necessarily follow. The availability of cost-effective technologies to capture and sequester carbon holds the potential for continued use of fossil fuels, even as CO_2 emissions are reduced.

Carbon capture and sequestration technologies (CC&S) provide a means of delivering deep reductions in CO_2 emissions whilst the world develops and deploys radically different energy supply technologies, which are necessarily more expensive than fossil fuel technologies. This realization is not new. For example, Marchetti (1977) and Steinberg et al. (1984) recognised the opportunity for CC&S and examined some of the issues that might arise in the deployment of such technologies. But, at that time, climate change was not seen as a significant threat and CC&S technologies were not considered necessary except for particular purposes (for example, early applications were in enhanced oil recovery operations). Both of these conditions have changed. The prospect of greenhouse gas emissions control is now taken very seriously and CC&S are now being considered as a serious technical response. For example, papers elsewhere in this conference describe the performance of the Sleipner aquifer storage facility, established by Statoil and its partners, national research programs sponsored by the governments of Canada, Japan, the Netherlands, Norway and the USA, and international research under the International Energy

Agency's Greenhouse Gas R&D Programme (IEA GHG), as well as at least one nascent private-sector-led consortium looking at capture and geological sequestration.

TECHNOLOGY OPTIONS

No one knows what ceiling is necessary to avoid dangerous interference with climate. To meet various possible ceilings on concentration, cumulative emissions of carbon over the course of the next century would have to be limited to the levels indicated in Table 1.

Table 1: Cumulative emissions of carbon for various concentration ceilings

CO_2 concentration ceiling	Cumulative emission limit
450 ppmv	714 PgC
550 ppmv	1043 PgC
650 ppmv	1239 PgC
750 ppmv	1348 PgC

Source Wigley et al., 1996. N.B. 1PgC=1 GtC=3.66GtCO_2

These limits imply significant reductions in emissions relative to such reference circumstances as the IPCC IS92a scenario (Leggett et al., 1992). The reduction in cumulative emissions range from 175 PgC (750 ppm case) to 809 PgC (450ppm case) (Wigley et al. 1996). To achieve these changes implies major alterations in the world's energy system–for example widespread use of renewable energy supplies or nuclear power, in addition to substantial improvements in energy efficiency and fuel switching. Using CC&S as part of the technology mix would significantly reduce the complexity of the change required but CO_2 is currently captured and stored on a very limited scale.

CARBON CAPTURE AND SEQUESTRATION FOR ENERGY SYSTEMS

CO_2 can be captured in various ways - after combustion, or before combustion during a transformation of the fuel, or directly from the atmosphere by for example enhancing natural sinks for carbon. These processes have been mainly explored for use with power generation plant, but could also find application in other energy-intensive industries such as oil refining and processing. A variety of technology options are potentially available in each category. The main ones are listed in Table 2.

Table 2: CC&S Technology Options

CO_2 Capture	CO_2 Storage	Carbon Sequestration
From the Energy System Central plant such as power plant, refineries, etc.	**Geological Storage** • Depleted oil or gas fields • Deep saline reservoirs • Unminable coal seams	**Terrestrial Carbon Capture and Sequestration** • Soils • Trees
In production of energy carriers for example, hydrogen	**Ocean storage** • Mid-depth dispersion • Deep lake • Hydrates	**Ocean Carbon Capture and Sequestration** • Fertilisation
	As a solid • Carbon • Solid CO_2 • As a mineral carbonate	**Direct Recovery from the Atmosphere**

The prospect of utilizing CC&S to capture large quantities of CO_2 raises other important issues such as the need for transport and temporary storage facilities. The nature of the temporary facilities will depend, at least in part on the technologies being employed to remove the CO_2 and the nature of the long-term storage technologies.

Some CC&S systems may produce desirable byproducts, thus offsetting some or all of the cost of capture and storage. For example, CO_2 can be used as a flush gas for coal bed methane recovery. Injection of CO_2 into the coal seam would drive out methane, whilst the CO_2 is stored in the coal. If the methane, itself an extremely potent greenhouse gas, were to escape into the atmosphere, it would potentially negate any climate change mitigation associated with the storage of CO_2. On the other hand, if the methane were captured, it could be utilized as an energy resource or sold as an energy product. Similarly, CO_2 is currently extracted and shipped via pipeline for use in enhanced oil recovery. It would then be a product with a positive economic value, but while the potential for positive externalities exists, this potential is limited.

The potential for CC&S technologies is not restricted to use in the traditional energy industries of power generation, oil refining, etc. It could also be used to enable the transition to hydrogen-based transport and distributed energy systems. For example, the decarbonisation of natural gas to produce hydrogen would be cheaper than large scale use of many of the renewable energy sources (Audus et al. 1996); storage of the CO_2 would avoid most of the greenhouse gas emissions.

COST AND PERFORMANCE OF CO_2 CAPTURE

System costs include the cost of capture (i.e. capital costs, efficiency loss, operation and maintenance), the cost of transport and temporary storage, the cost of sequestration, and the costs of monitoring and verification.

The cost of capturing CO_2 from power plant and other sources has recently been re-examined by IEA GHG. Typical cost of electricity and the cost of avoided CO_2 emissions with state of the art plant are illustrated in Table 3 (Audus, 2000) for natural gas costing \$2/GJ and coal at \$1.5/GJ, at 10% discount rate; these figures include compression of CO_2 to 110 bar for transmission.

Table 3: Costs and efficiency of CO_2 capture with natural gas and coal fired plant

Process	**Efficiency (% lhv)**	**Specific Investment (\$/kWe)**	**Cost of electricity (c/kWh)**	**CO_2 emission (g/kWh)**	**Cost of CO_2 avoided (\$/tCO_2)**
Gas combined cycle					
- no CO_2 capture	56	410	2.2	370	Reference
- post combustion capture	47	790	3.2	61	32
- pre combustion capture	48	910	3.4	65	39
Pulverised coal fuel					
- no CO_2 capture	46	1020	3.7	722	Reference
- post combustion capture	33	1860	6.4	148	47
IGCC					
- no CO_2 capture	46	1470	4.8	710	Reference
- pre combustion capture	38	2200	6.9	134	37

Edmonds et al. (1999) explored the implications of introducing CC&S options for power generation and hydrogen production within the context of a global regime to limit the concentration of carbon in the atmosphere. In 2020, CC&S technologies are projected to be cost-competitive with other modes of power generation under a scenario that greenhouse gas emissions are being strictly contained. Costs reported by the study for the United States in 2020 are shown in Table 4[1].

Table 4: Cost of power from various sources (projected 2020 values)

Technology	**Base case** (c/kWh)	**With C&CS** (c/kWh)
Hydro	3.2	Na
Natural gas	3.4	4.0
Coal	3.8	4.6
Conventional oil	4.8	5.4
Commercial biomass	5.2	Na
Nuclear	5.8	Na
Hydrogen fuel cell	na	8.1
Solar PV	12.3	Na

GEOLOGIC SEQUESTRATION

Geologic reservoirs capable of storing carbon in significant quantities appear to be available on a global scale. Estimates of available capacity are given in Table 5 (at various cost thresholds).

Table 5: Estimates of Global Capacity of Storage Reservoirs

Carbon Storage Reservoir	**Range (PgC)**
Deep Ocean	1,391 – 27,000
Deep Saline Reservoirs	87 – 2,727
Depleted Gas Reservoirs	136 – 300
Depleted Oil Reservoirs	41 –191
Unminable Coal Seams	> 20

Source: Herzog et al. (1997), Freund and Ormerod (1997).

Edmonds et al. (1999) report cumulative capture over the period 2000 to 2095 for efficient global regimes to limit atmospheric accumulation of carbon, Table 6, against two alternative reference energy system backgrounds, OGF[2] and CBF[3]. These values are well within the range of the available geological reservoirs.

Table 6: Cumulative Carbon Capture (PgC) from 2000 to 2095 for various CO_2 Concentration Ceilings

Reference Case	**450 ppmv**	**550 ppmv**	**650 ppmv**	**750 ppmv**
OGF	374	281	221	195
CBF	279	203	168	157

Sequestration requirements would be greater for technology regimes that focus on the deployment of carbon-neutral energy sources (Edmonds, et al., 1998) - CC&S capacity required could be up to twice the values presented in Table 6[4]. Hence it is important to know that the potential storage capacity will be available for use. Thus a research task for the future should be an assessment of the

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[1] Note that fuel costs are other assumptions may be different from those used in Table 3.

[2] OGF stands for "Oil and Gas Forever" a case in which oil and gas resources are sufficiently abundant to maintain present oil and gas prices indefinitely.

[3] CBF stands for "Coal Bridge to the Future," a case in which conventional oil and gas resources are limited and unconventional oil and gas resources are expensive. In contrast coal resources are abundant and inexpensive.

[4] For example, Edmonds, et al., 1997 estimate that in the OGF case a technology mandate to deploy carbon-neutral technology in new investments after the year 2020 would stabilize the concentration of carbon at about 550 ppmv in the OGF case, requiring the capture and sequestration of 342 PgC by the year 2095.

geographic distribution of CO_2 capture and storage sites. Local storage sites of appropriate quality may or may not be co-located with sources of captured CO_2.

VALUE OF CARBON CAPTURE AND SEQUESTRATION TECHNOLOGY

The presence of economically attractive CC&S technologies can significantly reduce the cost of achieving carbon concentration limitation goals. Edmonds et al. (1999) estimate that the minimum cost of limiting carbon concentrations could be dramatically reduced if CC&S technologies are available, as demonstrated in Table 7. They could account for something in the order of 50% of the global reductions in greenhouse gas emissions needed to achieve stabilization at a 550 ppmv level in the atmosphere. Cost reductions range from 68% to 81% relative to scenarios in which these technologies are not available for deployment.

Table 7: Reduction in Present Discounted Cost of Limiting Carbon Concentrations at various concentrations as a result of having CC&S technologies available in the MiniCAM model.

Reference Case	**450 ppmv**	**550 ppmv**	**650 ppmv**	**750 ppmv**
Global Reduction in Cost (10^9 US $)	4700	1100	400	200
Percentage Reduction in Cost	68%	73%	77%	81%

Source: Edmonds et al., (1999), CBF Case. Values discounted to present day at 5% per year.

OTHER IMPORTANT ASPECTS

Virtually all storage systems will require monitoring. If CO_2 storage is to be an important technology for emission mitigation, then significant quantities of carbon can be expected to accumulate. After 50 or more years, leakage rates of only 1% per year could amount to more than a billion tonnes of carbon released to the atmosphere annually. This in turn could be a significant share of the global annual emissions budget. While there is currently no reason to believe that any significant quantities of CO_2 would be released to the atmosphere, monitoring will be important if the technology is to be deployed. Although gases have been stored in similar reservoirs for geological timescales, any perception of a massive “accident waiting to happen” could undermine confidence in the technology. Unless the prospect of uncontrolled release of CO_2 can be demonstrated to be unrealistic, sequestration may prove unacceptable.

CONCLUSION

CC&S technologies appear to hold great promise for addressing the problem of climate change. From what is currently known, these technologies are potentially cost-competitive in a carbon-constrained world. Large-scale deployment, implying billions of tonnes of carbon capture per year, is indicated by energy-economy models. As these technologies have never been deployed on such scales, there is a clear need for further work to understand the implications of such systems. Monitoring and verification loom large on the research agenda. Further energy-economy analysis is also needed. For example, research is needed to begin to develop more realistic descriptions of the geographic distribution of potential source and sink sites and the implications of finite storage availability.

The development, demonstration, and deployment of CC&S technologies are potentially expensive. Such investment would be fruitless unless governments ultimately sanction it as part of a recognized national and international regime of emissions control. The independent development of these technologies is likely to be beyond the financial capacity of even the most resourceful individual institutions. Furthermore, even if an individual institution could develop these technologies, they are ultimately of interest only to the extent that nations and international institutions such as the FCCC recognize them. Joint development is therefore not only financially attractive, but also desirable from the perspective of deployment. Joint development also offers perhaps the only way to rapidly increase the rather small sums being devoted to the development of CC&S technologies. We estimate that in the major industrialized nations known to sponsor energy

R&D, CC&S technologies receive much less than 5% of all R&D funds. This modest investment does not seem commensurate with the likely promise of these technologies as outline above.

DISCLAIMER: The views expressed in this paper are solely those of the authors and were formed and expressed without reference to positions taken by their respective employers, sponsors of their research, or any government agency.

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