



INDUSTRIAL CARBON MANAGEMENT: CROSSCUTTING SCIENTIFIC, TECHNICAL AND POLICY IMPLICATIONS

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The technologies for using fossil fuels with minimal emissions of CO₂ are little understood beyond the group of technologists who are developing them.

Chairs' Essay:

Industrial Carbon Management: A Review Of The Technology And Its Implications For Climate Policy

By David W. Keith and M. Granger Morgan

Prologue

In July 2000 we convened a workshop on industrial carbon management (ICM) under the auspices of the Aspen Global Change Institute. We were motivated by concern that despite growing understanding of the technologies for using fossil fuels with minimal emissions of CO₂, and despite the central role that these technologies might well play in the reduction of CO₂ emissions over the next half-century, they are little understood beyond the group of technologists who are developing them. We were worried that growing public concern about climate change, continued inaction on CO₂ mitigation, and growing technical knowledge of ICM pose serious risks in the absence of adequate assessment of the implications of ICM for energy systems, regulation, and climate policy. Among these concerns, is the risk that ICM will be seriously assessed only in an atmosphere of crisis, as it is suddenly raised as an alternative to better-known means of CO₂ abatement. Such a situation might well result in a policy "train wreck" involving costly choices, cumbersome regulations, and inadequate public participation.

Our principal goal was therefore to forge links between the diverse interest groups who must come to share a common basic understanding of the technology if assessment of ICM is to avoid the pitfalls described above. There is an obvious need for shared understanding between technologists, industry, and environmental NGOs (we hope for shared understanding, not necessarily agreement about outcomes). Equally important is the need for shared understanding between the technologists who understand ICM and the broader community that will be needed to successfully manage it, including environmental regulators, experts on climate policy and politics, and energy economists.

The workshop ran for one week, in Aspen, Colorado. The 32 invited participants included representatives from the fossil energy industries, the U.S. government, U.S. national laboratories, and environmental NGOs, along with academics whose research focuses on climate policy, energy technology and policy, risk assessment, and others whose focus is on the technology of ICM itself. This document and the reports of individual participants are the formal product of the workshop. Some additional material, such as planning documents and working group reports, is available from us (the conference convenors) on request. The most important products were, we hope, new insights carried away by the participants, dialog begun, and new collaborative projects initiated. We thank all participants, sponsors, and the Aspen Global Change Institute.



1. Introduction

It is possible to use fossil fuels with minimal atmospheric emissions of carbon dioxide. We call the required technologies Industrial Carbon Management (ICM) — defined as the linked processes of capturing the carbon content of fossil fuels while generating carbon-free energy products, such as electricity and hydrogen, and sequestering the resulting carbon dioxide away from the atmosphere. Although many of the component technologies currently exist at large scale, the idea that ICM could play a central role in our energy future is a radical break with recent thinking about energy system responses to the climate problem.

While ICM is best viewed as just one element in a broad portfolio of greenhouse gas mitigation technologies, it may nevertheless transform the politics of the CO₂-climate problem. By lowering the cost of emissions mitigation, ICM may enable stabilization of atmospheric concentrations at acceptable cost. By weakening the link between fossil fuel energy and atmospheric CO₂ emissions, ICM makes it feasible to consider a fossil fuel-based global economy through the next century. By reducing the severity of the threat that emission reduction poses to fossil fuel industries and fossil-fuel-rich nations, ICM may ease current deadlocks in both domestic and international abatement policy.

There are, however, no magic bullets with which to slay the CO₂-climate problem. All current energy supply options — ICM included — are either impractically expensive or pose significant environmental challenges. Moreover, global energy systems are highly heterogeneous, making it implausible that any single technology will triumph everywhere. Finally, the history of energy policy is replete with technologies their advocates argued would be too-cheap-to-meter, yet which are now irrelevant. Thus, while we paint an optimistic story about the potential role of ICM in mitigating CO₂ emissions, skepticism is wise. The very fact that ICM was not on the energy policy agenda even a decade ago should make one cautious about any predictions for the next century.

In this essay we first survey the scientific and technological basis for ICM (Section 2), then examine how the economics of ICM might shape its adoption in a CO₂-constrained world (Section 3), and finally discuss the challenges for assessment, regulation, and public policy (Section 4).

Use of fossil fuels with minimal emissions of CO₂ requires two steps. The energy content of the fuels must first be separated from their carbon content in a process that takes a fuel with high carbon-to-energy ratio as input and produces a low- or zero-carbon output along with a carbonaceous stream with low free energy to be sequestered from the atmosphere. In practice, this generally means a system that uses coal or gas to produce electricity or hydrogen with sequestration of the resulting CO₂, but other options may well prove important. More fossil energy is required to supply a unit of final energy using these processes than would be required without CO₂ sequestration; this energy penalty is of order 10 to 25%. Separation and sequestration together comprise industrial carbon management (Figure 1).

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We chose industrial carbon management to describe the management of emissions that arise directly from the energy system.

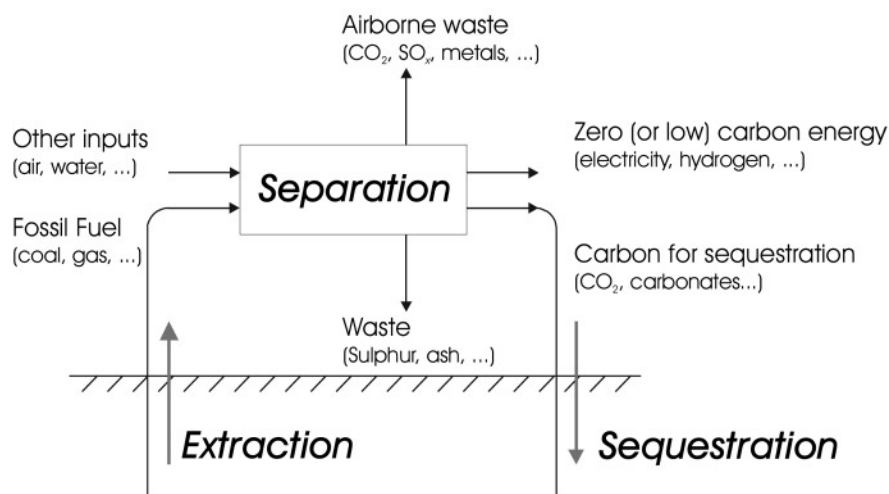


Figure 1: Industrial carbon management (ICM)

A schematic illustrating the definitions of sequestration and separation adopted here. We chose industrial carbon management to describe the management of emissions that arise directly from the energy system as opposed to emissions that arise from land use. The output may be a low- but not zero-carbon stream, as when synthetic natural gas is made from coal with CO₂ sequestration. All methods of ICM involve an energy penalty so that the output stream contains less energy than was present in the inputs.

Many alternative names are used to describe these processes. Most authors refer to “capture” rather than “separation” of CO₂, and “storage” or “disposal” are frequently interchanged with “sequestration”. Some definitions are very broad; the U.S. Department of Energy, for example, has defined carbon management to include (i) demand-side regulation through improved energy efficiency, (ii) decarbonization via use of low-carbon and carbon-free fuels or non-fossil energy, and (iii) carbon sequestration by any means including sequestration of industrial CO₂ in geological formations or in the ocean, and the enhancement of biological sinks including ocean fertilization. We chose industrial carbon management to describe the management of emissions that arise directly from the energy system as opposed to emissions that arise from land use.

While there is obviously no single correct formulation, we judge that the following underlying distinctions will matter for implementation and will shape public opinion:

- Regulating CO₂ concentration is different from regulating climate, for example, by manipulating planetary albedo to compensate for increased CO₂ (Keith 2001).
- Regulation of the CO₂ concentration by minimizing sources is different from regulation achieved by counterbalancing sources with sinks.
- Mitigation of climate impacts by reduction of consumption is different from mitigation achieved by technological improvements that reduce net environmental impact per unit of final product.

Setting aside questions of terminology, ICM has been the subject of organized interest by a visible research community for at most a decade (the first International Conference on Carbon



Dioxide Removal called ICCDR-1 was held in Amsterdam in 1992), but it has only begun to attract significant organized research funding within the last half decade. One might expect that this short history would make it easy to summarize the field, as for example, it might be possible to summarize the first decade of work on amorphous solar cells. A summary of ICM, however, is far more challenging. While the cumulative research effort explicitly directed at ICM remains small, the amount of technical knowledge that underlies current understanding of ICM is very large because it grows directly out of the existing fossil energy infrastructure which has enormous heterogeneity and technical complexity.

2. A Brief Review of the Technologies

The technologies for using fossil fuels without significant emissions of CO_2 are far more than laboratory theory. Indeed, many of the required components exist at the largest industrial scales. Among the most important such technologies are the gasification of coal, the capture of CO_2 using aqueous amines, the steam reforming of methane and finally, the long-range transport of CO_2 by pipeline and its injection into deep geological formations. We have, in essence, a sizable basket of component parts out of which we might assemble a system for carbon management.

While the toolbox of existing fossil energy technologies would permit the assembly of some ICM systems today, such systems would be expensive and limited in application. There is widespread optimism that with careful integration of existing technologies, and with the commercial development of a limited suite of new technologies that now exist as laboratory demonstrations, it will be possible to substantially reduce costs, improve operating characteristics, and increase the diversity of systems for separating and sequestering carbon.

2.1. Separation

There are three broad paths to separation:¹

- Post-Combustion Capture (PCC): Burn the fuel in air, then capture CO_2 from the combustion products.
- Oxyfuel: Separate oxygen from air, burn the fuel in pure oxygen and then capture CO_2 from the combustion products.
- Pre-Combustion Decarbonization (PCDC): Reform the fuel to make hydrogen and CO_2 .

The first two, PCC and Oxyfuel, involve complete combustion to CO_2 and water and so are limited to producing electricity and heat, whereas PCDC produces hydrogen that may be used in an integrated system to produce electricity and heat, or may be distributed as a secondary fuel.

¹ As previously noted, the process is often called CO_2 "capture" rather than "separation". We prefer "separation" because not all processes end with CO_2 . It is also possible, for example, to produce stable carbonates as an end product.

The technologies for using fossil fuels without significant emissions of CO_2 are far more than laboratory theory.

Oxyfuel schemes offer the advantage that the most challenging chemical separation is performed on a clean gas mixture.

Most discussion of ICM has focused on large-scale electricity generation, where post-combustion capture is perhaps the most obvious route to separation because it is closely analogous to existing environmental control technologies, such as flue gas desulfurization, that remove pollutants from power plant exhaust streams. Amine solvents are now used to capture CO_2 from the exhaust streams of electric power plants for commercial uses such as the carbonation of beverages. Using current technology, amine systems are able to capture about 90% of the CO_2 but the energy cost of solvent regeneration reduces plant electrical output by about 15%. A host of other capture methods have been proposed, and there is evidence that amine technologies can be significantly improved. In comparison to the other routes to separation, PCC has the great advantage that it requires little modification to existing power plants and so could in principle be applied as a retrofit; its disadvantage is that the separation is performed at atmospheric pressure, on a dirty gas stream that contains dilute CO_2 . The exhaust gas from a coal-fired plant, example, contains at most ~15% CO_2 along with trace amounts of SO_x , NO_x , and various metals, thereby either forcing the CO_2 separation system to be tolerant of impurities or necessitating removal of impurities prior to separation. Significant opportunities exist for co-optimization of the multiple emissions control technologies that must be applied to coal-fired plants.

Instead of separating CO_2 from combustion gases, one can first separate the O_2 from air and then do the combustion in pure O_2 , producing an exhaust stream that contains only CO_2 and H_2O along with minor pollutants. The water may then be easily removed by condensation. Compared to PCC, oxyfuel schemes offer the advantage that the most challenging chemical separation is performed on a clean gas mixture (air) that is free from the many reactive impurities in combustion gases, while the disadvantage is the high energy requirement and capital cost associated with O_2 production. Oxyfuel systems also offer higher combustion temperatures, and thus in principle allow higher Carnot efficiencies. The flame temperature from pure oxyfuel combustion is too high to exploit directly, however, and so all oxyfuel schemes must use a diluent to reduce the temperature and increase the working fluid volume; the leading choices are direct injection of water or CO_2 recycle. In oxyfuel systems, pollutants such as SO_2 remain with the CO_2 following condensation of the water. If these pollutants can be sequestered along with the CO_2 , this would provide a further advantage for oxyfuel systems over PCC or PCDC. If pure CO_2 is required, however, the presence of contaminants counts against oxyfuel.

The direct use of methane in high-temperature fuel cells arguably counts as an oxyfuel route to separation because an oxygen-permeable membrane is used to transport O_2 to CH_4 for oxidation. This analogy is particularly apt because one of the promising advanced technologies for reducing the cost of oxygen separation in combustion-based oxyfuel schemes involves use of air separation membranes that are closely related to the membranes used in solid oxide fuel cells.

Pre-combustion decarbonization is most obviously accomplished by steam reforming of methane to make syngas ($\text{CO} + \text{H}_2$), followed by the water-gas shift reaction to produce a CO_2 and H_2 mixture. Separation of CO_2 from such gas streams is much easier than it is from combustion air in PCC systems because of the higher working pressures and higher



fraction of CO_2 . As described below, this method is now used to produce hydrogen at very large scales. Many other methods are possible. For methane one can, for example, produce syngas using partial oxidation instead of steam reforming. For coal, the best-understood process starts with O_2 -blown gasification to produce syngas, followed by cleanup of trace pollutants and finally the shift and separation. Many other coal gasification reactions are possible, including, for example, H_2 rather than O_2 -blown gasification. Even in an electric power plant, PCDC systems appear to be competitive with the other routes to CO_2 separation. In addition, PCDC has the important advantage that a power plant could sell zero CO_2 -emission hydrogen “over the fence,” providing a plausible path to development of a hydrogen energy infrastructure (Ogden 1999).

At present all three routes to separation appear broadly competitive. Their comparative advantages depend on choice of fuel, on the stringency of regulations for conventional pollutants and on the CO_2 purity and pressure requirements for sequestration.

2.2. Sequestration

The three most plausible means for sequestering large quantities of CO_2 are to inject it into geological formations, into the ocean, or to convert it to stable carbonates at the surface. Injection of CO_2 into geological formations is by far the best understood of the three, because it is currently practiced at large scale for enhanced oil recovery. When CO_2 is injected underground or in the ocean it first dissolves in water to form carbonic acid, and then may react with oceanic sediments or the formation rock to form buffered solutions or stable carbonates. In either case these geochemical reactions stabilize the CO_2 and increase the time before it returns to the atmosphere. The third alternative is to form stable carbonates by chemical processing at the surface, which we call geochemical sequestration.

The term “sequestration” has most often been used for the enhancement of terrestrial pools of organic carbon in forests and soils. The two forms of sequestration are sharply distinct. Carbon in terrestrial biota is in reduced form and is readily oxidized by biological action or by fire and returned to the atmosphere. An enlarged terrestrial carbon pool will require ongoing ecosystem management to avoid return of the carbon to the atmosphere. In this case, the goal is not to immobilize a specific body of carbon but rather to maintain an enlarged pool through which carbon cycles continuously. In contrast, when CO_2 is immobilized as carbonates or in geological formations the goal is to remove the carbon from biochemical cycling for thousands of years or longer.

While manipulation of the terrestrial carbon cycle grants us considerable leverage over atmospheric CO_2 , that lever is puny in the face of our appetite for energy. Global energy use is now equivalent to more than 5% of terrestrial net primary productivity, and forecasts put this ratio as high as 10% by 2100 (Watson 2000). If our appetite for energy is to be supplied by fossil fuels, the 21st century’s consumption will exceed 1000 GtC, an amount comparable to the entire stock of terrestrial organic carbon, living and dead. Thus, while terrestrial sequestration in plants and soils can provide vital short-term mitigation, it cannot play a substantial role in the long-term stabilization of CO_2 concentrations absent a dramatic reduction in energy consumption.

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The CO₂ would be injected into geological formations similar to the formations from which we now extract oil and gas.

2.2.1. Geological formations

While much is uncertain about geological sequestration, the essence of current knowledge is easily stated: (i) It is possible to put very large volumes of CO₂ underground at comparatively low cost; (ii) it appears that a capacity of greater than 1,000 gigatonnes of carbon (GtC) exists in reasonably well-understood geological structures; and, (iii) while the fate of CO₂ is highly dependent on the specific geological character of the injection site, it seems highly likely that a large fraction of CO₂ could be confined underground for timescales in excess of a thousand years.²

As we now envision it, the CO₂ would be injected into geological formations similar or identical to the formations from which we now extract oil and gas, and the technologies employed would be readily derived from current systems used in the oil and gas industry. The most likely geological sequestration sites and their estimated capacities are shown in Figure 2.

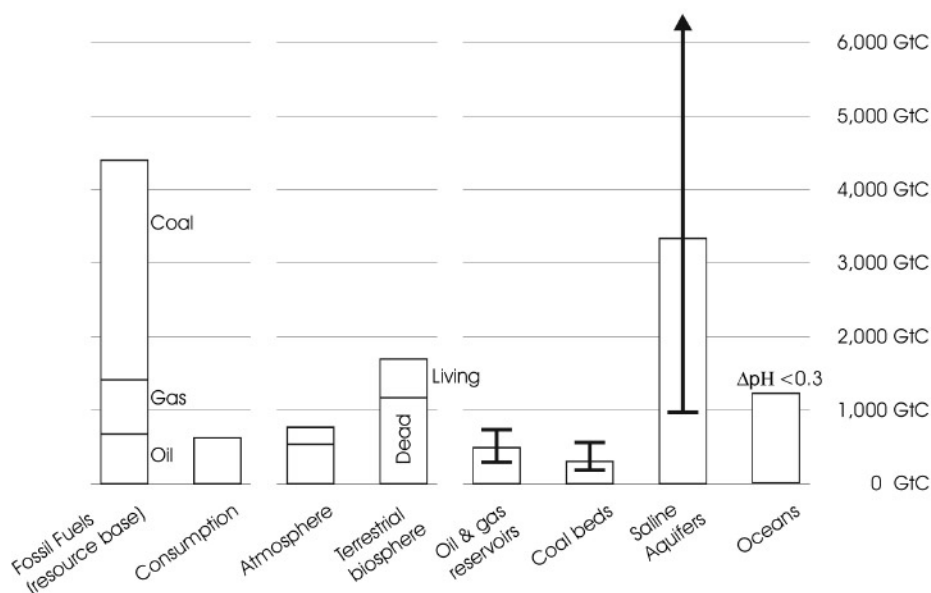


Figure 2: Carbon reservoirs and sinks

For fossil fuels we have used the resource base (i.e., the sum of reserves and resources (Rogner 1997) a measure that includes unconventional oil but not methane hydrates). The *consumption* box shows world-wide cumulative consumption of fossil fuels. The upper section of the *atmosphere* box shows the increase in CO₂ since pre-industrial times. The error bars for geological sequestration are a rough summary of current knowledge and do not reflect systematic analysis of uncertainty. The upper bound for storage in aquifers is on the order of 10,000 GtC. The oceanic capacity is based on an arbitrary upper limit to pH change of 0.3; note that surface ocean pH has already decreased by ~0.1 due to increased atmospheric CO₂ concentrations.

² These claims are conservative. Evidence from natural CO₂ reservoirs suggests that CO₂ can be confined in place for millions of years, and estimates of the capacity of deep saline aquifers extend to well over 10,000 GtC.



While geological sequestration will build on the totality of experience with fossil fuel extraction, it will build most directly on CO₂ injection for Enhanced Oil Recovery (EOR). Conventional extraction methods typically leave substantial oil in place, which may be extracted using enhanced recovery. Carbon dioxide injection (or “flooding” in industry jargon) is particularly effective because as an organic solvent the CO₂ acts to reduce the viscosity of the residual oil, and in addition causes the oil to expand thus helping to free it from the pores in which it is embedded. Finally, in EOR floods that operate at pressures above the critical point of CO₂, fluid flow is facilitated by the absence of a liquid/gas interface. Current CO₂-EOR projects typically yield a ratio of carbon in as CO₂ to carbon out as oil of approximately unity.³

The use of CO₂ for EOR will provide early sequestration opportunities at negative cost as EOR operations currently purchase CO₂ for around 50 \$/tC. In addition to EOR, CO₂ may also be used to Enhance the production of Coal Bed Methane (ECBM). Deep coal beds contain methane adsorbed on coal surfaces, in quantities on the same order as global conventional gas reserves. Injected CO₂ displaces adsorbed CH₄ in a molar ratio of ~2:1. The CO₂ is stably absorbed into the coal matrix, allowing the coal beds to serve as both a gas source and a highly stable CO₂ repository. While there is much less industry experience with ECBM than with CO₂-EOR, it appears that ECBM provides substantial potential for CO₂ sequestration at low cost.

Most assessments suggest that absent EOR or ECBM, the cost of geological sequestration will be of order 10-50 \$/tC. At this level the overall economics of ICM are dominated by the cost of separation. There are reasons, however, to expect that these estimates may be too optimistic, and that sequestration cost will consume a rising fraction of the total cost of ICM. Costs of CO₂ sequestration may be higher than are predicted from the EOR experience due to the additional costs involved in monitoring and verification. Depending on our experience with CO₂ injection and on the regulatory framework that is adopted (which will likely be different for current regulation of CO₂ EOR) the costs of monitoring could be very high. Moreover, sequestration cost estimates have tended to assume injection into previously characterized high-permeability structures, but in the long run these will be saturated and we will have to turn to lower-permeability structures and to include the full cost of subsurface characterization. Adopting these pessimistic assumptions, monitoring and exploration costs could drive the cost of sequestration closer to the cost of natural gas extraction (currently of order 100 \$/tC), but we judge that this is unlikely.

2.2.2. Oceanic Sequestration

One may view CO₂-induced climate change as a problem of mismatched timescales. The problem is due to the rate at which combustion of fossil fuels is transferring carbon from ancient terrestrial reservoirs into the comparatively small atmospheric reservoir. When CO₂ is added to the atmosphere, atmosphere-ocean equilibration transfers about 80% of it to

Enhanced production of coal bed methane provides substantial potential for CO₂ sequestration at low cost.

³ A ratio of 7,600 scf/bbl is equivalent to a 1:1 carbon ratio.

The injection of CO₂ into the ocean is very different from injection into geological reservoirs.

the oceans with a timescale of about 300 years⁴ (Archer et al. 1997). The remaining CO₂ is removed with much longer timescales. Injecting CO₂ into the deep ocean accelerates this equilibration, reducing peak atmospheric concentrations. Assuming, however, that the injected CO₂ is well mixed, then the same processes of equilibration act to return about 20% of the injected CO₂ to the atmosphere on the same 300-year timescale. Therefore on timescales longer than 300 years it makes little difference whether the CO₂ was injected into the atmosphere or the ocean.

The efficiency with which injected CO₂ equilibrates with oceanic carbon depends on the location and depth of injection. For example, injection at a depth of ~700 m into the Kuroshio current off Japan would result in much of the CO₂ being returned to the atmosphere in ~100 years, whereas injections that form “lakes” of CO₂ in ocean trenches might substantially decrease the rate at which CO₂ returns to the atmosphere.

Due to the energy penalty for separation, the injection of CO₂ into the ocean requires the use of more fossil fuels, and the production of more CO₂ than would be needed without ICM. While ocean injection of CO₂ could effectively reduce the atmospheric CO₂ concentration on hundred-year timescales, it may paradoxically increase the CO₂ atmospheric concentration on timescales greater than the ~300-year equilibration time (Herzog et al. 2000).

The injection of CO₂ into the ocean is thus very different from injection into geological reservoirs for which the goal is to remove the carbon from biogeochemical cycling in the atmosphere/ocean/terrestrial-biosphere system over timescales greater than 1000 years. The dynamic nature of the marine carbon cycle precludes defining a unique static capacity, as may be done for geological sequestration. Depending on the increase in mean ocean acidity that is presumed acceptable, and on any artificial enhancement of geochemical sequestration, the capacity for well-mixed CO₂ is of order ~10³-10⁴ GtC⁵ — much larger than current anthropogenic emissions of ~ 6 GtC per year.

2.2.3. Geochemical Sequestration

On the longest timescales, atmospheric CO₂ concentrations are partially controlled by the weathering of continental rocks which release elements (such as magnesium) that react to form stable carbonate deposits on the ocean floor, removing the carbon from shorter timescale biogeochemical cycling. Less permanently, the dissolution of calcium carbonate (limestone) buffers the ocean’s pH, allowing larger quantities of dissolved CO₂ to be maintained in equilibrium with a given atmospheric CO₂ concentration. In principle, these oceanic carbon sinks could be accelerated, for example, by addition of minerals to increase

⁴ This is a simplification. In fact, (i) there are many processes acting with different timescales, and (ii) the equilibrium between atmosphere and ocean depends on the amount of anthropogenic carbon added to the atmosphere/ocean system.

⁵ This estimate ignores the additional potential for sequestration in the form of long-lived lakes of CO₂ in ocean trenches.



ocean alkalinity (Kheshgi 1995; Rau and Caldeira 1999). The same geochemistry applies to the immobilization of CO₂ in geologic formations, where the effectiveness of geochemical immobilization depends on the chemistry of the formation into which the CO₂ is injected.

Alternatively, CO₂ could be immobilized at the surface by means of an industrial process that dissolved suitable source minerals and reacted them with a CO₂ stream to produce stable carbonates. Carbonate formation is exothermic; thus, in principle, the reaction requires no input energy. Ample reserves of the required serpentine rocks exist at high purity. The size of the mining activities required to extract the serpentine rock and dispose of the carbonate are comparable to the size of mining activity needed to extract the corresponding quantity of coal. The principal challenge is posed by the extremely slow rates of reaction under ambient conditions, and the difficulty of devising an inexpensive and environmentally sound industrial process to accelerate the reaction. Nevertheless, integrated power plant designs have been proposed, in which a fossil fuel input would be converted to carbon-free power (electricity or hydrogen) with simultaneous reaction of the CO₂ with serpentine rock (magnesium silicate) to form carbonates (Lackner et al. 1995).

The importance of geochemical sequestration lies in the permanence with which it removes CO₂ from the biosphere. Unlike carbon that is sequestered in organic matter or as CO₂ in geological formations, once carbonate is formed the only important route for it to return to active biogeochemical cycling is by thermal dissociation following the subduction of the carbonate-laden oceanic crust beneath the continents, a process with a timescale of >10⁷ years.

2.3. The ICM Tool Box

Industrial carbon management will be built atop the existing fossil-fuel infrastructure. Creating a robust capacity for managing carbon will require the adaptation and improvement of existing technologies as well as the development of new technologies to fill the gaps. We have, in essence, a box of tools which have been proved by previous experience. We could assemble these tools today, with minimum modification, to build an ICM infrastructure for the production of electricity and hydrogen, but the cost of CO₂ mitigation would be relatively high, perhaps 100 to 250 U.S. dollars per tonne of carbon (\$/tC). It is widely assumed that careful optimization of existing components into integrated systems along with development of a limited suite of new technologies, could substantially decrease the overall cost of ICM, particularly as the systems are greatly scaled up to accommodate fossil CO₂ streams.

Many technologies promise to reduce CO₂ emissions, from solar photovoltaics to geothermal heat pumps, and one may argue that the cost for any of them could be reduced with a bit more R&D. We judge that ICM is different. The basis for this judgment lies in the close connection between ICM and the existing energy infrastructure and consequently in the scale at which the enabling technologies already exist. Consider four key examples:

- Coal gasification. Integrated gasification combined cycle (IGCC) electric generation, a point of departure for many coal based ICM designs, has not been adopted

Careful optimization of existing components along with development of a limited suite of new technologies could substantially decrease the overall cost of ICM.

Nuclear and biomass are both used at very large scale, accounting for 9% and 3% of U.S. primary energy respectively.

commercially despite decades of R&D. There is nevertheless a large and rapidly growing fleet of gasifiers with a worldwide syngas capacity that exceeds 50 GW thermal.

- Hydrogen production. Steam-methane reforming to produce hydrogen now consumes ~2% of U.S. primary energy. Leading uses for the hydrogen are the production of ammonia and the reformulation of gasoline. Some current applications involve the long range transport of hydrogen in pipelines.
- EOR. About 18 MtC/year of CO₂ is used for Enhanced Oil Recovery; most of it is supplied by pipeline from natural CO₂ formations. The longest pipeline runs over 800 km. If the CO₂ were derived from fossil fuels it would account for ~0.5 % of U.S. primary energy.
- CO₂ capture with MEA. Monoethanolamine (MEA) solvents are today used for CO₂ capture from exhaust gases at more than 10 facilities worldwide, and are also widely used for stripping CO₂ from natural gas.

In addition to these enabling technologies, several integrated systems provide important examples of nascent ICM. The first large project that sequesters CO₂ in order to avoid emissions is in Norway, where Statoil operates one of largest gas fields in Europe. The gas produced contains ~9% CO₂, which must be reduced to 2.5% for sale to customers. The CO₂ is separated on an offshore platform and injected into a high permeability aquifer ~1 km beneath the sea bed. The capture and sequestration project was developed in response to Norway's offshore carbon tax of \$170/tC. Statoil has sequestered about 0.3 MtC/year of CO₂ since 1996, and the transport of the sequestered CO₂ is now being monitored by an international research team (Herzog et al. 2000). A similar project planned in Indonesia at the Natuna field will, if it proceeds, inject 30 MtC/year, roughly 0.5% of present global emissions.

A project using CO₂ from the Dakota Gasification plant to enhance oil recovery at Pan Canadian's Weyburn field in Saskatchewan is perhaps the existing project that most resembles ICM. The Dakota plant has produced synthetic natural gas from coal since 1984; a project of the 1970s Synfuels program, it is the largest facility of its kind. Weyburn is a large oil field that is nearing the end of conventional production. With CO₂ EOR, the amount of recoverable oil will be increased by ~30%. A 325-km pipeline now transports 0.5 MtC/yr of CO₂ from the gasification plant to Weyburn (Hattenbach et al. 1999).

It is instructive to compare the scale of these technologies with current low-CO₂-emission alternatives. Nuclear and biomass are both used at very large scale, accounting for 9% and 3% of U.S. primary energy respectively, but solar and wind are much smaller, at 0.08% and 0.04% respectively (Energy Information Administration 1998). In comparison, the Dakota/Weyburn project alone sequesters 0.03% of U.S. CO₂ emissions, and all of the key enabling technologies listed above are in use at scales that far exceed the current scale of wind and solar.

3. The role of ICM in mitigating CO₂ emissions

While industrial carbon management may be used to mitigate most CO₂ emissions arising



form the use of fossil fuels, the heterogeneity of energy distribution and use implies that the comparative advantage of ICM over other CO₂ mitigation technologies will vary widely. Most analysis of ICM has focused on electricity generation, where the technology could enable deep reductions in emissions with minimal reorganization of the energy distribution infrastructure, but ICM can also be used for hydrogen production where its comparative advantage is larger than it is in electric generation. The widespread use of hydrogen as an energy carrier could enable deep reductions in CO₂ emissions via the substitution of hydrogen for natural gas or petroleum, although achieving such reductions requires development of a large-scale hydrogen distribution infrastructure — a difficult and uncertain venture. Finally, ICM can be most readily applied in niche applications in the industrial sector where there are significant point-source emissions of waste gases with high CO₂ concentrations. Such applications are found in natural gas processing, petroleum refining, industrial chemicals, and cement manufacture.

3.1. Electricity

There are several good reasons to focus on electricity generation as an early application of ICM technologies:

- Electric power plants are among the largest point sources of CO₂.
- Deep reductions in emissions can be achieved without requiring system-wide changes in distribution and end-use equipment.
- Most coal is used for electric generation (93% in the U.S.), and coal has the highest carbon-to-energy ratio of the fossil fuels.

Given existing technologies, the cost of electricity with ICM is about 0.05 - 0.07 \$/kWh, about 0.02 - 0.04 \$/kWh more than the cost from new conventional fossil-fueled generation (Herzog 2000), and roughly comparable to the cost of electricity from wind, biomass or nuclear. Figure 3 illustrates the relationship between cost of electricity and intensity of CO₂ emissions for various technologies.

Published estimates of the cost of capturing CO₂ from electric generation (in \$/tC) vary by as much as an order of magnitude, but the variation in estimates overstates the real uncertainty. Part of this variance arises from unavoidable uncertainties in assessing the cost and performance of unproven technologies, but in addition, significant variance arises from inconsistencies in question formulation that exaggerate the actual uncertainty in cost estimates. Inconsistencies arise in four ways:

1. Most obviously, studies may use inconsistent economic assumptions for key parameters such as discount rates, fuel costs, capacity factors and the costs of CO₂ sequestration.
2. Inconsistency also arises from choice of reference cases when calculating mitigation cost. If the goal is to estimate the incremental cost of energy at the plant gate, then one can compute the cost of electricity given the estimates of factors specific to the plant alone (such as the cost of capital, thermal efficiency, and the cost of CO₂ sequestration). Mitigation costs, however, are often expressed in terms of dollars per ton carbon avoided. A reference case with a specific energy cost and CO₂ emissions per unit energy is therefore required. For example, while the cost of

Electric power plants are among the largest point sources of CO₂.

Published estimates of the cost of capturing CO₂ from electric generation vary by as much as an order of magnitude.

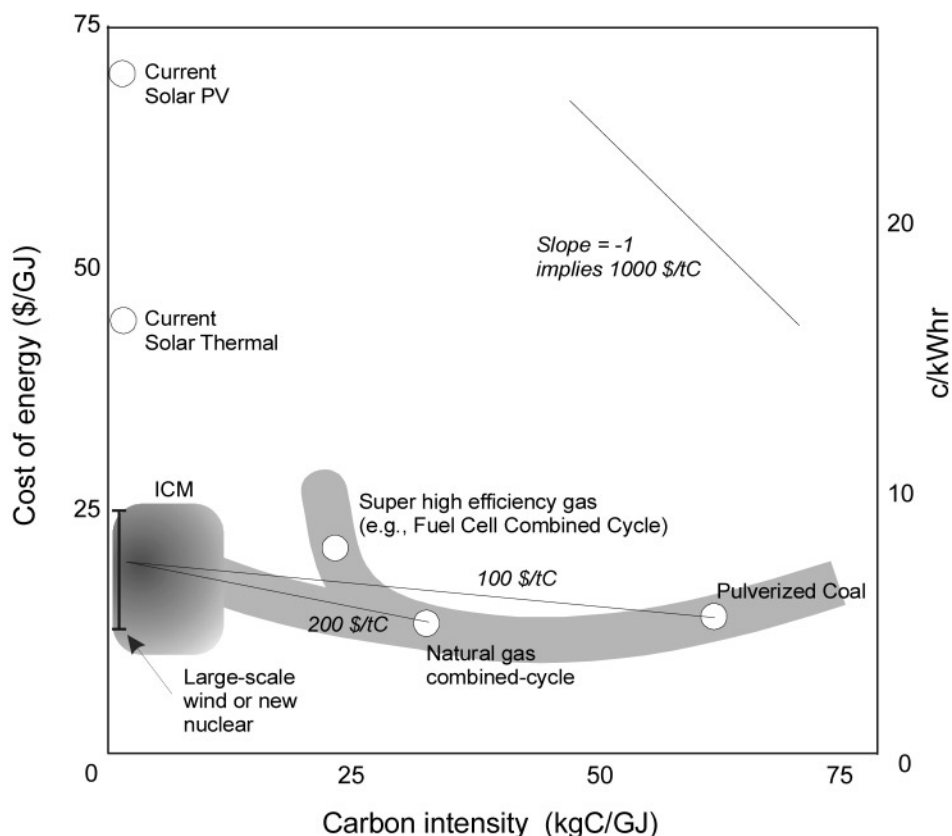


Figure 3: The cost of electricity vs. carbon intensity

The X axis shows CO₂ emissions (in kg carbon) per unit of electricity generation (in gigajoules). The Y axis shows the approximate cost of electricity from new generating units including costs for capital, fuel and operations. These figures represent our judgment of costs given current technologies. The likely cost of ICM technologies is on par with the estimated costs for large scale wind or new nuclear. Currently coal dominates fossil electricity supply, so replacement of coal with natural-gas-fired electrical generation achieves substantial CO₂ mitigation at minimal cost, although this effect depends strongly on natural gas prices. Costs shown here are for baseload generation with gas at 3.5 \$/GJ. The cost of intermittent renewables does not reflect the additional expenses, such as storage, resulting from their intermittency.

electricity from natural gas- or coal-fired plants with CO₂ capture are similar, the mitigation cost is about twice as high for gas as it is for coal because of the lower carbon emissions from conventional gas-fired generation.

3. Most engineering studies have focused on evaluating the cost of a particular plant configuration, but the variance of the resulting cost estimates does not reflect the uncertainty in the cost of a plant that would actually be commissioned, since the design of such a plant would be chosen to minimize cost (along with other factors such as risk). Some of the variance in cost estimates therefore reflects emerging knowledge about which plant configurations are best rather than technical uncertainty about the cost of a plant optimized for a given application.
4. Finally, engineering studies have used widely differing assumptions about the



availability of new technologies, with some focusing on estimating the cost of a plant that could be ordered almost immediately with no development of new technology, and others studying designs that involve components that do not yet exist commercially.

During the workshop we attempted to address some of these uncertainties by eliciting judgments about the cost of electric power from coal under specific conditions aimed to eliminate the uncertainties described above. Figure 4 displays some of the results of this exercise. The importance of regulation of conventional pollutants in determining the additional cost for CO₂ mitigation emerged as a key issue in the ensuing discussion. Under more stringent controls on pollutants such as SO_x, NO_x, particulates and toxics, the additional

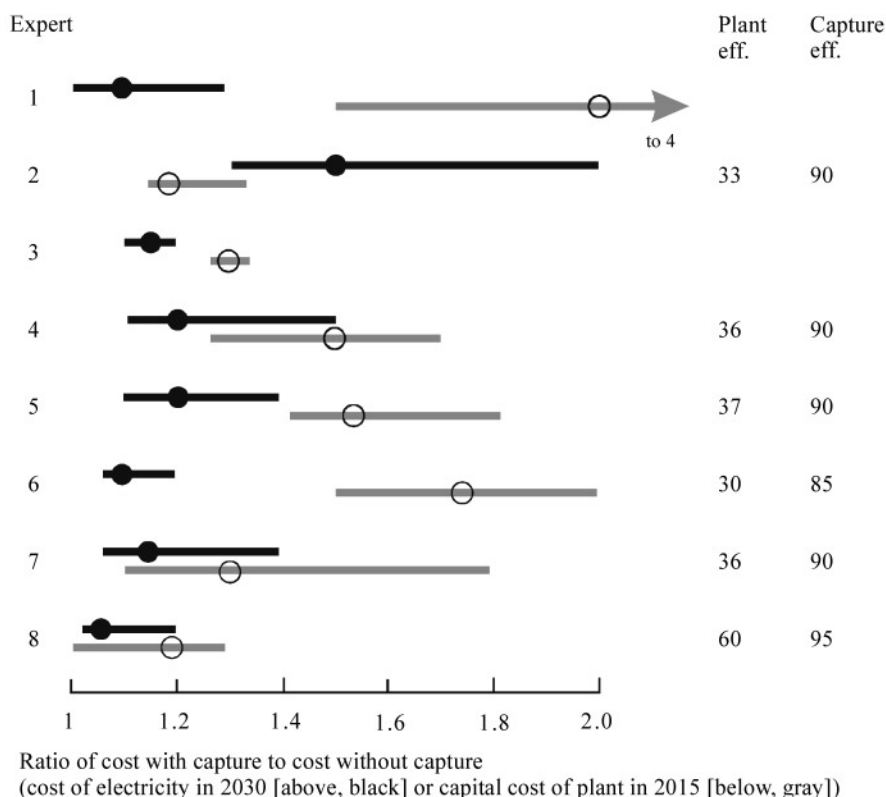


Figure 4: Estimates of the cost of producing electricity from coal

with and without CO₂ capture, made by participants at the AGCI workshop in July 2000. In each case the ratio of the cost with vs. without capture is plotted along with a 5-to-95% confidence interval provided by the participants. Two sets of results are shown. The black bars show estimated cost of electricity in 2030 while the gray bars show estimated “overnight” capital costs for plants to be brought on line by 2015. The elicitation protocol aimed to minimize uncertainty due to inconsistent question formulation. Participants were to choose the technologies of the capture and non-capture plant so as to minimize the cost of electricity under constraints that included specified costs for fuel, conventional pollutant emissions, plant unitization, and interest rate. For the 2015 case, the participants were invited to state their assumed plant thermal and CO₂ capture efficiencies; their answers are shown in the columns on the left. The full elicitation protocol is available from the authors; participants are listed at the end of this paper.

The importance of regulation of conventional pollutants in determining the additional cost for CO₂ mitigation emerged as a key issue.

It seems likely that utilities will find ICM less risky and less expensive than nuclear power.

cost of capturing CO₂ is less.

Given open competition between electricity technologies under a carbon tax (or economically equivalent regulatory mechanism), and assuming that carbon sequestration can meet environmental permitting requirements, there are significant structural reasons to expect sequestration to be adopted in preference to non-fossil alternatives even if the cost of electricity were similar. Unlike wind or solar power, for example, ICM plants would match the existing distribution system with respect to sizing and ease of dispatch. Moreover, ICM plants would likely be constructed using existing suppliers, and established upstream fossil energy companies could provide both fuel and CO₂ sequestration. While nuclear power could, in principle, play a central role in reducing CO₂ emissions, absent sweeping changes in the industry, its regulation, and its public perception, it seems likely that utilities will find ICM less risky and less expensive than nuclear power.

3.2. Hydrogen

In sharp contrast to the introduction of new electric generating technologies, the introduction of hydrogen into dispersed stationary uses requires development of an infrastructure for hydrogen generation, distribution, and use. The introduction of hydrogen into transportation requires development of effective hydrogen-fueled vehicles (with compact on-board storage) and a refueling infrastructure — an even greater challenge. Yet as a means to mitigate CO₂ emissions, the potential advantage of hydrogen from fossil sources with ICM over non-fossil energy sources (other than biomass) lies in the intrinsic advantages of thermochemical over electrochemical production of hydrogen. A crude comparison of energy costs serves to illustrate the point. At current prices, coal and natural gas — likely the most important fuels for ICM systems — have energy costs of roughly 1 and 4 \$/GJ, respectively. Either feedstock can be used to generate electricity with ICM at a producer cost of 15 to 25 \$/GJ (0.05-0.07 \$/kWh). As noted above, the cost of electricity produced from wind (absent all subsidies) arguably lies in the same range. In contrast, the price of H₂ produced from wind via electrolysis would be 20-30 \$/GJ while the price of H₂ produced from fossil fuels via ICM would be about 7-10 \$/GJ, a relative cost advantage of roughly 1:3 for ICM-hydrogen over wind-hydrogen despite the assumed equality of electricity costs. Similar disadvantages apply to the production of hydrogen from nuclear or solar though not from biomass. Moreover, large-scale production of hydrogen from fossil fuel, and its long-range transport, are already mature technologies in the petrochemical industry.

The relative ease of producing hydrogen via ICM implies that wherever hydrogen could replace oil or natural gas the potential exists for comparatively inexpensive mitigation of CO₂ emissions. Realizing this potential, however, will not be easy. Substantial technical and economic barriers will hinder the diffusion of hydrogen-fuel technologies across the energy system. Technical barriers range from the comparatively straightforward problems of constructing hydrogen-capable gas distribution systems to the serious engineering challenges that stand in the way of hydrogen-powered transportation systems. The economic barriers — including both economies of scale and network effects — are no less daunting. Consider the introduction of hydrogen-capable distribution systems: even if costs were low for both the distribution system and the end-user technology, the introduction of a new infrastructure will



likely be slow because distribution and end-user equipment must evolve together against the economy-of-scale advantages of existing systems. Nevertheless, ICM hydrogen likely offers the most direct route to a hydrogen economy.

3.3. Global models

While we have a limited understanding of the role of ICM technologies in bringing down the cost of CO₂ mitigation in the electric sector, very little is known about the influence of ICM on the overall cost of mitigating climate change. The uncertainty arises from the need to combine global economic models with models of technological change that consider timescales on the order of a century. Looking back 30 years at previous attempts to model the evolution of energy systems does not inspire confidence. Forecasting technological change would be difficult enough if one wanted to predict the evolution of a single technology, such as large-scale electric power generation. Predicting technological change over century timescales is still harder, however, because clusters of technologies evolve as tightly coupled systems, and the evolution of the full system is highly path-dependent.

Two extreme scenarios for the future of centralized electric generation serve to illustrate this path dependence. First suppose that electric power generation is rapidly decentralized, driven by the diffusion of small natural-gas-fired combined-heat-and-power generators — perhaps the technology that offers the most cost-effective near-term CO₂ mitigation. This would initially prevent diffusion of ICM because CO₂ cannot be effectively collected from distributed sources. But it would enable a later wave of decarbonization as ICM hydrogen (produced from cheap coal) competed against expensive natural gas. Alternatively, the economies of scale in large ICM electric generation might lower the relative cost of electricity — under a system-wide carbon tax — and cause acceleration of the fraction of primary energy converted to electricity at centralized facilities.

Despite the daunting challenges, several groups have used integrated assessment models to study the effect of ICM on the overall costs of stabilizing CO₂ concentrations (see Parson and FisherVanden 1997 and Rotmans and Dowlatabadi 1998, for reviews). These models allow one to compute the reduction in CO₂ that results from imposing a price on emissions that approximates the effect of a carbon tax or similar regulatory mechanism. The models may be used to find the trajectory of carbon price over time that most efficiently stabilizes CO₂ concentrations at a given level. Conventional economic models suggest that peak marginal carbon prices of order 500-1,000 \$/tC will be necessary to stabilize CO₂ concentrations at ~450 ppm.⁶ As we have seen above, simple technology cost estimates suggest that ICM could be used to mitigate a substantial fraction of total CO₂ emissions at much lower costs. Mitigation costs in the global models whose results are shown in Figure 5 decrease by roughly a factor of two when ICM is included.

⁶ Including other radiative forcings, 450 ppm CO₂ is approximately equivalent to a doubling of CO₂ over pre-anthropogenic levels. The climate change resulting from a CO₂ doubling will likely have significant impacts on unmanaged ecosystems.

Very little is known about the influence of ICM on the overall cost of mitigating climate change.

ICM poses distinct challenges for carbon accounting: it complicates the imposition of a price on CO₂ emissions, and it complicates the design of policy instruments.

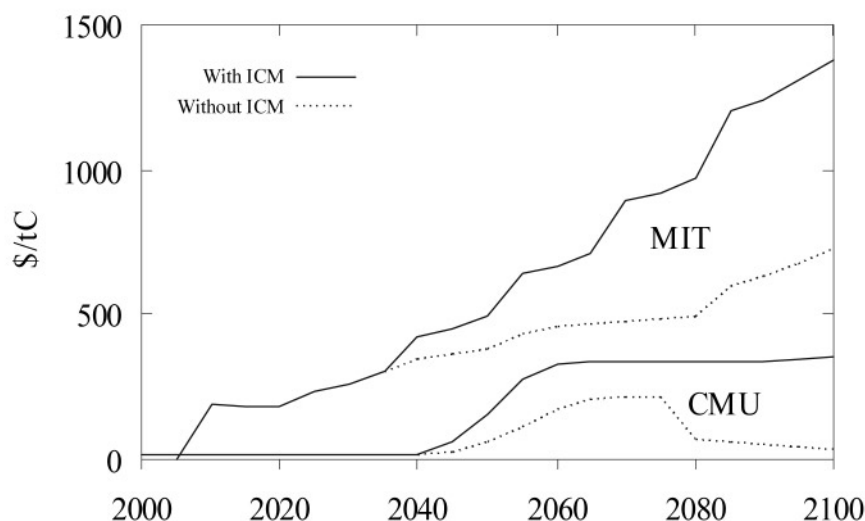


Figure 5: Estimates of the effect of ICM on the global cost of stabilizing CO₂ concentrations

The Y axis shows the carbon price (set by a tax or equivalent regulatory mechanism) required to keep atmospheric CO₂ concentrations below about 550 ppm (twice pre-anthropogenic). Results from two very different models are shown together. In each case the baseline simulation (solid line) does not include ICM, and the dotted line shows the carbon price if ICM technologies are included. The MIT model is a large general equilibrium economic model that reflects current technology and observed elasticities in demands for commodities (Biggs 2000). The CMU model is a simpler economic model that includes parameterizations for technological change in response to price signals. The models agree that ICM reduces the cost of stabilization by a factor of two or more. The large disagreement between the estimated control costs reflects differing assumptions about technological change, and illustrates the great uncertainty inherent in such predictions.

4. Challenges for Public Policy

4.1. Carbon Accounting

ICM poses two distinct challenges for carbon accounting: (1) By increasing the complexity of carbon flows within the energy system, it complicates the transparent and economically efficient imposition of a price on CO₂ emissions; and, (2) by introducing a new form of carbon reservoir — one that differs fundamentally from the biological sinks that are now salient in international climate policy negotiations and emerging carbon trading markets — it complicates the design of policy instruments intended to enable flexibility in the timing and location of emissions reductions (often called “where” and “when” flexibility).

Absent ICM, essentially all fossil hydrocarbons that are extracted are rapidly oxidized to CO₂, excepting only the small fraction (<2%) that are converted to long-lived products or are sequestered as waste in landfills. Ignoring the important carbon fluxes arising from land use and biomass energy, the flow of carbon through the energy system is conservative, allowing wide latitude in the way in which CO₂ emissions are measured and regulated. If,



for example, a carbon price was established at the point of extraction using either a tax or tradable permit scheme, the additional costs would propagate efficiently through the economic system with little need for further accounting. Without ICM a price might also be imposed at different points in the fuel cycle for different sectors, for example, CO₂ might be counted at the point of emission for electric generation, and at the refinery gate for transportation fuels.

By breaking the link between fossil-energy extraction and CO₂ emissions, widespread adoption of ICM would complicate the flows of carbon within the system, by increasing the linkages between end-use sectors and by requiring that CO₂ sent for sequestration be counted as non (or partial) emissions. A refinery poly-generation system might, for example, simultaneously produce hydrogen for local use, electricity for the grid, methanol as a transportation fuel, and CO₂ for EOR to be delivered by international pipeline.

The timescales over which CO₂ from ICM can be sequestered differ quantitatively from the timescales for maintaining terrestrial carbon pools, and this will likely demand qualitative differences in the way the different forms of carbon sequestration are counted in any future carbon trading regime. It seems likely that a carbon trading scheme will need three colors of poker chips, gold for measures such as energy efficiency and non-fossil sources that avoid the generation of CO₂, silver for the immobilization of CO₂ in long-duration reservoirs (perhaps defined as having lifetimes longer than 1,000 years and having sequestration quantities that can be readily measured), and finally bronze for the sequestration of carbon in terrestrial biota. All modes of reducing CO₂ emission are important, and there may be variable market prices for each, allowing exchange. It seems unlikely, though, that they can be incorporated into a single accounting system with uniform rules.

However, while ICM may complicate the design of market-based or other carbon management regimes, these complications will likely be minor compared with the measurement and certification problems posed by consideration of biomass sinks, and certainly minor compared with the problems posed by attempts to include other greenhouse gases in the same management regime as CO₂ (Victor 2001).

4.2. Multi-Pollutant Regulation

By allowing deep reductions in CO₂ emissions within the fossil-energy infrastructure, ICM complicates the link between CO₂ and the control of conventional air pollutants such as NO_x, SO_x, particulates and toxic metals, and so elevates the importance of efficient multi-pollutant management.

Without ICM, the emissions of conventional air pollutants and CO₂ are already coupled, most importantly by trade-offs between efficiency and emissions control. For example, reduction of sulfur in transportation fuels or electric generation decreases system efficiency by increasing energy consumption at refineries and power plants, thus increasing CO₂ emissions. While these efficiency versus emissions control trade-offs are real, they involve only small changes in CO₂ emissions (10% or less is typical) and do not involve complex interactions between controls of specific pollutants and CO₂. Without ICM, deep reductions in the CO₂

ICM elevates the importance of efficient multi-pollutant management.

The risks of large-scale underground sequestration of CO₂ may be divided into two kinds, the direct risks to humans and local environments, and the risk of slow leaks that return sequestered carbon to the atmosphere.

intensity of primary energy will be achieved by switching to non-fossil sources such as wind or nuclear. While these sources have significant environmental impacts, they emit virtually no conventional air pollutants, and thus simplify the coupling between CO₂ and conventional pollutants.

While CO₂ and conventional pollutants are coupled in the absence of ICM, the coupling is comparatively simple: increasingly stringent controls on conventional pollutants will simply add to the pressure exerted by CO₂ controls to drive the switch from fossil to non-fossil primary energy. ICM complicates the linkages, and makes it more important to consider the phasing of controls on CO₂ and conventional pollutants.

While this tighter coupling poses problems, the impact may prove beneficial. The history of power-plant environmental controls has seen an accumulation of one add-on or end-of-pipe fix piled on another. The changes required to include ICM may be large enough to force a systematic rethinking of power-plant emission control, which, in the long run, could bring significant improvements in cleanup efficiency and reductions in the overall cost of control.

4.3. Risk Assessment

The risks of large scale underground sequestration of CO₂ are poorly understood, and systematic efforts at risk assessment are only now beginning. The risks may be roughly divided into two kinds, first the direct risks to humans and local environments, and second the risk of slow leaks that return sequestered carbon to the atmosphere.

The most obvious of the direct risks is that posed by catastrophic release of substantial quantities of CO₂, which could asphyxiate exposed people or animals. However, there are also hazards from slow leaks, and possible risks such as induced seismicity or contamination of potable aquifers that stem from underground movement of displaced fluids. The bulk chemical industries routinely handle large volumes of far more hazardous materials with minimal (although not negligible) problems. Experts in the upstream oil and gas industry are generally confident that the risks from underground injection are small, and this confidence is strongly supported by the long history of CO₂ injection for EOR and of underground storage of other gases, including the very large scale storage of natural gas.

Nevertheless, the basis for concern is clear. Natural gas storage facilities have leaked to the surface causing dangerous buildup of gas in buildings, and natural emissions of CO₂ at relatively small rates can pose serious risks if the CO₂ concentrations build up, as they can if CO₂ is temporarily confined and then suddenly released. In 1986, for example, the water in Lake Nyos (Cameroon) turned over, suddenly releasing CO₂ accumulated from volcanic vents, creating a dense CO₂-rich cloud that killed over 1,700 people by suffocation. Recent efforts to reduce the risks from Lake Nyos by controlled degassing suggest that similar risks posed by leaks of anthropogenic CO₂ could also be controlled. Here in the U.S., widespread deaths of trees and one possible human fatality in the last decade have been linked to degassing of CO₂ from the Long Valley Caldera in the Mammoth Lakes area of California. A very recent death (July 2000) in a naturally occurring soda springs bath at Clear Lake,



California, underlines the constant danger posed by CO₂ emissions from the ground. While proper facility operation, site characterization and monitoring could presumably reduce such risks from ICM to a very low level, they cannot be ignored.

All separation technologies extract an energy penalty, typically 10-20%. Thus, more fuel must be consumed, and more CO₂ produced, per unit of delivered energy than would be the case if the CO₂ were not captured. In the worst case, therefore, in which CO₂ leaks to the atmosphere within centuries, ICM could increase future concentrations of CO₂. Simple modeling of underground transport suggests that lifetimes in excess of 1000 years can readily be achieved, and evidence from natural CO₂ formations suggest that retention times can be orders of magnitude longer. While there is ample reason to expect that sufficiently low leak rates can be achieved, it is not yet possible to specify with confidence the site characteristics and injection technology that are required to ensure (within a defined level of uncertainty) that a given leak rate will be attained. Such knowledge will be needed in order to devise a robust technical and institutional system for sequestering CO₂.

4.4. Public Perception and Acceptance

While managing the risks posed by ICM to levels at or below those that are widely accepted for other socio-technological systems is clearly a necessary condition for its acceptance, reducing the risks will not assure acceptance. The public acceptance of ICM will depend on at least three other interlinked factors: public perception of the technology, its risks, benefits and alternatives; the attitudes and behaviours of key interest groups, including environmental NGOs and the fossil energy industry; and the adequacy and public reputation of the risk management systems and institutions that oversee the operation of ICM.

Even a cursory look at the history of nuclear power, of genetically modified organisms, or of stem-cell research, is enough to demonstrate the controlling influence that public perception can play in shaping the adoption and diffusion of new technologies. While such perceptions are partially shaped by the objective characteristics of the technology and the social systems involved in its implementation, they can also be strongly influenced by broader social conditions and framing effects.

Thus for example, if ICM were advanced as part of a portfolio of strategies — along with conservation, renewables, and nuclear — for managing CO₂ emissions, public and environmental NGO responses would likely be very different than if it is framed as a way to avoid conservation and the adoption of renewables.

Different parts of an ICM system may involve significantly different public responses. For example, preliminary indications suggest that public response is likely to be far more supportive of sequestering CO₂ in deep geological structures than in the ocean, but that it will be important to demonstrate that there is not a significant risk of contamination of usable aquifers.

Legal definitions (e.g., is CO₂ an “industrial waste”, a “hazardous waste,” or a “pollutant”?) can also be important, as will be the form and evolution of existing and new regulatory regimes

A cursory look at the history of nuclear power is enough to demonstrate the controlling influence that public perception can play in shaping the adoption and diffusion of new technologies.

It is likely that carbon management will be a profoundly divisive issue for environmentalists. ICM is a technical fix on a grand scale.

for licensing, certification, monitoring, and insuring plants and sequestration sites.

While it is a bit too early to draw firm conclusions about any of these social and regulatory dimensions, it is critically important that the research and regulatory communities begin to address them, and that interested parties — including environmental NGOs and the fossil energy industries — become informed. How the social and regulatory issues play out could have impacts on the costs and social feasibility of ICM that are at least as great as the engineering and geophysical details.

5. Summary

The oil crisis of the early 1970s intensified concerns that the world would soon run short of fossil fuels, particularly oil and gas. Many energy experts theorized that a global transition to non-fossil energy would be necessary within decades. Three decades later, while new discoveries and new recovery technologies have increased estimated fossil reserves, putting to rest fears of their rapid exhaustion, concern about climate change has again led many experts to conclude that a rapid transition to non-fossil energy is required.

Part of the reason why fears of oil scarcity proved exaggerated was that analysts failed to anticipate the potential for technical and managerial innovation to drive down the cost of petroleum exploration and extraction. We may have made a similar error considering the link between fossil fuel use and climate. It has been assumed that the transfer of carbon from geologically isolated fossil reservoirs to the biosphere was a fundamental geophysical consequence of fossil energy use. Geological sequestration of CO₂ negates this assumption, and raises the prospect that the long history of technical success in controlling the environmental impacts of fossil fuels can be extended to the climate problem.

By weakening the link between fossil energy and CO₂ emissions, carbon management makes it feasible to consider a fossil-based global economy through the next century, even in a greenhouse-constrained world. By reducing the severity of the threat that emission reduction poses to fossil industries and fossil-rich nations, carbon management may ease current political deadlocks. Stated bluntly: if carbon management is widely adopted and if existing fossil energy industries can extend their dominance into the new markets for carbon sequestration, then the increase in total energy costs will benefit industries that would otherwise lose by actions to abate emissions.

It is likely that carbon management will be a profoundly divisive issue for environmentalists. It may be opposed for at least two reasons. First, industrial carbon management is only as good as the reservoirs in which the carbon is sequestered. If CO₂ leaks out much more quickly than we expect, then we leave our descendants with the double problem of uncontrollably rising CO₂ emissions and an economy still dependent on fossil energy. The history of toxic and nuclear waste disposal gives reason to be skeptical of expert claims about the longevity of underground disposal. Second, ICM is a technical fix on a grand scale. It was first proposed as “geoengineering,” a term now shared by proposals to cool the planet by injecting aerosols into the stratosphere to reflect solar radiation, and other schemes to engineer the global climate (Keith 2001). In addition to a reasonable distaste for technical



fixes, ICM collides with the deeply rooted assumption among many environmentalists that fossil fuels are the Problem and that renewable energy is the Solution. Yet, the rationale for support of carbon management is also strong. It may be that large-scale adoption of industrial carbon management will allow the world to make aggressive CO₂ emissions cuts at a politically acceptable cost.

Acknowledgments

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Further Reading

Several review articles cover much of the material presented here, including: Herzog et al. 1997; Socolow 1997; Parson and Keith 1998; Freund 2000; Herzog et al. 2000; Herzog 2001.

Elicitation Exercise Participants

The eight active participants in the elicitation exercise, listed here in alphabetical order but randomized in Figure 4, were Richard Doctor (ANL), Howard Herzog (MIT), Klaus Lackner (LANL), Richard Rhudy (EPRI), Edward Rubin (CMU), Dale Simbeck (SFA Pacific), Robert Socolow (Princeton), and Robert Williams (Princeton).

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SESSION 1

Industrial Carbon Management: Crosscutting Scientific, Technical and Policy Implications

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SESSION 1

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