POLICY FORUM: CLIMATE CHANGE

Fossil Fuels Without CO_2 Emissions

E. A. Parson and D. W. Keith

The climatic impact of fossil energy can be reduced by separating the resulting carbon and sequestering it away from the atmosphere (*1*). Recent work in carbon management (CM)—the linked processes of separating and collecting carbon and sequestering it in the ocean or ground—has shown substantial progress in developing the necessary technologies and in understanding the potential for sequestration (*2–4*). One large-scale project for sequestering CO_2 is operational; several others are planned. However, CM's technical progress is outpacing consideration of its limitations and potential risks. We sketch recent technical developments in CM and discuss its implications for the policy and politics of global climate change.

Technical Status and Prospects

A diverse and expanding array of technical options now exists for both separation and sequestration of carbon. Carbon can be separated from fossil fuels by separating CO_2 from products of combustion in air or in pre-separated oxygen, or by steam reforming of the fuel to yield a hydrogen-enriched fuel stream and a carbon-enriched stream for use or sequestration. In electrical generating stations, post-combustion amine solvent separation (a mature technology) imposes an energy penalty of ~20%, equivalent to a cost of \$70 to \$140 per metric ton (\$/tC) of carbon, depending on the base plant (*4*, *5*). Various approaches promise large cost improvements. Recent studies combining existing commercial components (for example, oxygen plants, gasifiers, and combined cycle systems) in integrated plant designs predict energy penalties under 15% and net plant efficiencies of ~50% (*6*). Advanced separation technologies such as new solvents, membranes, and low-pressure formation of CO_2 hydrates, promise energy penalties under 10%.

Because of economies of scale in CO_2 collection, CM in the transport sector would require shifting from petroleum to a nonfossil energy carrier, either electricity or hydrogen. Large-scale thermochemical production of hydrogen from fossil fuel, and its long-range transport, are mature technologies in the petrochemical industry (*3*). If hydrogen were the energy carrier, CM would benefit from the efficiency advantages of this thermochemical process over electrolysis (*5, 7*).

Carbon can be sequestered in the ocean or in geological reservoirs. Recent research has clarified the fate of the CO_2 injected into the ocean, its biological effects, and its legal status (*2–4*). The sequestration capacity of the deep oceans is $\sim 10^3$ to 10^4 gigatons of carbon (GtC), much larger than current anthropogenic emissions of 6 to 8 GtC per year. When carbon is emitted to the atmosphere, ~80% is transferred to the oceans on a time scale of ~300 years; the remainder is removed much more slowly (*8*). Injecting CO_2 into the deep ocean speeds this equilibration. Depending on the injection site, however, ~20% of the injected carbon returns to the atmosphere on the ~300-year time scale.

The most promising sites for geological sequestration are depleted oil and gas reservoirs (global capacity ~200 to 500 GtC), deep coal beds (~100 to 300 GtC), and deep saline aquifers ($\sim 10^2$ to 10^3 GtC) (*3*, *4*, *7*, *9*). Injection of supercritical CO_2 into oil and gas reservoirs, and its long-range pipeline transport, have long been practiced for enhanced oil recovery (EOR). Adding separated CO_2 to current sources and depleted reservoirs to current injection sites would accomplish sequestration with little change in current practice. The long-term stability of such reservoirs, however, is uncertain.

Deep coal beds contain methane adsorbed on coal surfaces, in quantities on the same order as global conventional gas reserves. Injected CO_2 can displace adsorbed CH_4 in a molar ratio of ~2:1, allowing the coal beds to serve as both a gas source and a highly stable CO_2 repository. Synergies between gas production and CO_2 sequestration are expected to yield low net costs of sequestration. A pilot-scale project in Alberta, Canada, aims to develop a zero-emission electric plant that exploits these possibilities (*10*).

The first large projects disposing of CO_2 to avoid emissions have sequestered the carbon in deep saline aquifers. Responding to Norway's carbon tax of \$170/tC, Statoil currently separates 300 ktC per year of CO_2 from a natural gas field and injects it into an aquifer under the North Sea. A similar project planned in Indonesia will inject 30 MtC/year, roughly 0.5% of present global emissions. Norway's tax has also elicited a vigorous industry response in developing projects to generate electricity from North Sea gas and sequester the resultant emissions.

Comparing Abatement Costs

Certain low-cost CM applications may be competitive with current energy sources. In addition to coal-bed methane production, these may include zero-emission plants burning waste fuels available at negative cost (*11*). Without such synergies, CM currently costs more than other options for small levels of abatement. Reductions of 10 to 20% from 2010 emissions—probably insufficient to meet the Kyoto targets—are likely available at marginal costs below \$50/tC, through efficiency improvements and switching to natural gas (*12*, *13*)

Stabilizing atmospheric CO_2 concentrations at currently proposed targets (350 to 750 parts per million) will require much larger reductions, implying major new sources of emission-free energy (*14*, *15*). Reductions beyond 10% from 1990 emissions will probably have sharply increasing marginal costs, well over \$100/tC, based on large-scale use of solar or nuclear energy (*13*, *16*). In this range, CM can substantially expand the abatement attainable at moderate marginal cost. In electric plants, even present CM technology can reduce emissions by more than 80%, at a cost similar to nuclear power and substantially less than present solar power (*5*). CM's costs will be lowest at large point sources, where the cost of separation dominates. With distributed sources, CM costs also include collection, which will be large for such highly decentralized sources as vehicles, home furnaces, or small distributed electrical generators.

To meet stringent abatement goals, however, the transport sector must participate. Unlike the electric sector, the required reorganization of the transport system would preclude incremental adoption of CM. Its costs are consequently much more uncertain, and may be dominated by transitional costs. Most nonfossil routes to steep transport abatement would require similarly difficult system reorganizations. Among low-emission transport systems, the high efficiency of thermochemical hydrogen production will likely give a fos-

E. A. Parson is at the Belfer Center for Science and International Affairs, John F. Kennedy School of Government. E-mail: Ted_Parson@harvard.edu. D. W. Keith is in the Department of Chemistry and Chemical Biology, Harvard University, Cambridge MA 02138, USA.

sil/CM system a substantial cost advantage over hydrogen derived from nonfossil electricity (*5, 8*).

Implications for Policy

Adoption of CM beyond synergistic applications will require modest policy-generated incentives to offset its cost penalty over current fossil energy, likely of the range of the ~\$50 to \$100 per tC that has been widely proposed to meet the Kyoto targets. Both CM's rapid recent development and continuing uncertainty over its desirable share of future abatement underscore the value of creating such incentives through policies that allow flexible response, such as taxes or tradable permits targeted at emissions. Industry's response to Norway's carbon tax vividly demonstrates the power of policies that apply substantial incentives to marginal emissions.

Because emissions are so heterogeneous and spatially distributed, however, taxes or permits applied at the point of emission are widely considered infeasible. Instead, approximations are proposed such as permits or taxes applied upstream, at the point of fuel extraction. Because CM changes relationships between emissions and upstream activities that have been strongly correlated, it requires that such policies grant credit at the point of sequestration—a tax rebate or creation of additional permits—as proposed for petrochemical feedstocks.

CM poses several problems for emission-accounting procedures, such as the national inventories required by the Framework Convention. Present inventories disregard or treat inadequately the CO_2 that is already actively managed (*17*). CO_2 currently separated at wellheads or refineries may be reinjected for EOR, sold for emissive uses, or vented. International CO_2 trade for EOR already occurs. Expanded CM will require inventories to account accurately for such CO_2 flows, transformations, and sequestration. Ocean injection will pose particularly acute accounting challenges associated with access to injection sites, the legal status of injection, and the uncertain site-specific rates at which sequestered CO_2 returns to the atmosphere.

Because low-cost CM is only available in new capital, its largest near-term opportunities lie in energy-sector growth in rapidly industrializing nations. Here, in addition to policies targeting marginal emissions, CM may also require financial aid or technology transfer to offset aggregate cost penalties. The Kyoto Protocol provides several mechanisms for such international cooperation. CM projects may be particularly suitable for the Clean Development Mechanism (CDM), which grants transferable credits for emissions avoided by investment projects in nations without emission targets. Defining a credible project baseline from which to grant credit has been considered a serious challenge to the CDM. CM projects, which sequester an observable quantity of emissions through a discrete technological choice, may allow an uncontroversial calculation of credit and so be more suitable for the CDM than other forms of energy investment.

CM in transport poses more extreme policy challenges. The required system transformation would call for a focused national effort and carry substantial economic, technological, and safety risks. Network externalities risk locking in inferior early technical choices, whether made as public policy or through decentralized market decisions. Such a system transformation may be more feasible in a rapidly industrializing country such as China, which arguably is not yet locked into a petroleum-based system (*7*).

CM may transform the political economy of abatement policy. By weakening the link between fossil energy and atmospheric CO_2 emissions, CM makes it feasible to consider a fossil-based global economy through the next century. By reducing the severity of the threat that emission reduction poses to fossil industries and fossil-rich nations, CM may ease current deadlocks in both domestic and international abatement policy.

The abatement required to stabilize CO_2 concentrations is immense and will require a fundamental transformation of global energy infrastructure. No clear path to such a future is evident. A serious effort to limit climate change will require pursuing multiple technological paths and aggressively exploiting the potential for early learning by doing. In the context of such an effort, CM's near-term potential is at least as great as that of nonfossil energy.

CM carries novel environmental risks, such as impacts on ocean chemistry and benthic ecosystems, and the rapid or slow release of injected emissions. Geological sites capable of sudden release would pose acute local risks. Sites subject to slow release would still reduce near-term peak atmospheric concentrations, even if all the injected CO_2 eventually returned—if a large long-term reduction in global emissions is achieved. Use of such sites would pose serious questions about equitable intergenerational distribution of risk, particularly because CM's energy penalty requires that more CO_2 be sequestered per unit of delivered energy, than would be emitted by conventional fossil-fuel combustion. Consequently, CM could reduce atmospheric CO_2 concentrations in the near term but increase them in the long term.

CM bears some resemblance both to conventional abatement and to geoengineering (*18*). This ambiguity and CM's character as an "end-of-pipe" technology foretell intense and proper controversy in global systems, as well as over CM's specific benefits and risks. Yet CM has so far received inadequate attention in climate assessments and policy debates. Large-scale adoption of CM would be a major technological and social choice that would be difficult to reverse. Continued rapid technical progress in CM and continued slow political progress on abatement pose the risk that this choice will be made without adequate reflection on its implications.

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