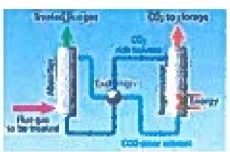
CO_2 Capture and Sequestration (CCS): Barriers to Deployment

N ("Maha") Mahasenan
Environmental Technology Manager
Rio Tinto Energy America

Carbon Capture & Sequestration



- Carbon Capture and Sequestration (also called Carbon Capture and Storage or CCS) refers to the separation of CO_2 from flue gas (in PC plants, cement plants, refineries, gas processing plants, etc.,) or from syngas (in gasification systems), and their injection into suitable formations, both geologic and deep ocean, for long term storage.
- In this presentation, CCS refers to storage in geologic formations only
- Energy intensive process, with decrease in net plant output
- The higher the CO_2 content in the flue gas, the more economic the process

How is the CO_2 injected / stored?

- Deep geologic formations need to be carefully chosen, and have following characteristics:
  - Generally at depths greater than 4000 feet
  - Target formation is free from significant fissures, cracks, faults, etc., and topped with one or more layers of impermeable "caprock"- this is the "seal" for the injected CO2
  - Target formation has good "injectivity" (sufficiently porous to accept the CO2).
- Suitable geologic formations include oil and gas basins (<u>E</u>nhanced <u>O</u>il <u>R</u>ecovery, <u>E</u>nhanced <u>C</u>oal <u>B</u>ed Methane), depleted oil and gas reservoirs, <u>deep saline formations</u> (DSF), unmineable coal seams, etc.,
- EOR and similar opportunities are geographically limited
  - Not long-term solution
  - There will be competition to sell to these opportunities
  - Ultimately, storage of CO2 will be a cost
- Total storage potential in deep saline formations is orders of magnitude greater than EOR, ECBM, etc.

APPENDIX 19

- CO_2 capture and sequestration is a cost, and will require an external signal to be deployed
- Economics has two parts:
  - Capture Costs:
    - Additional costs of capture from coal-fired power plants range from \$30-\$60/ton of CO_2
    - Capex requirements can be 40-80% higher compared to baseline plants, depending on technology and whether retrofit
  - Sequestration Costs:
    - Cost estimates for transport and injection vary from \$5-\$12 per ton of CO_2 in the literature

Favorable Economics

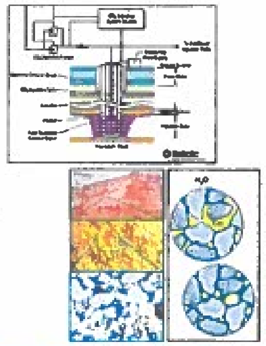
- **Bottom Line:**
- Early deployments will require significant cost sharing and/or financial assistance to proceed

A Few Final Thoughts

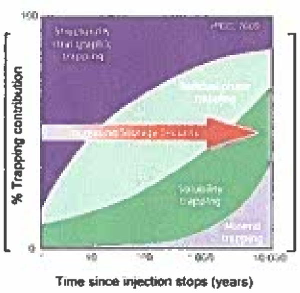
- While different components of CO_2 capture and sequestration have been tested or demonstrated at varying scales, it is important to recognize that substantive and necessary R&D is still on-going
- There is still a **very significant integration challenge** at commercial scale
- While technologies are evolving rapidly, they need an appropriate framework in order to be deployed successfully

What happens to the CO_2?

- Physical trapping:
  - The buoyant, supercritical CO2 will flow upward from injection to the caprock layer, which effectively traps the CO2
  - This mechanism is effective, unless the caprock is breached or compromised
- Residual trapping:
  - At low saturations levels, the CO2 occupies interstitial spaces in the formation, trapped by capillary forces
  - In this state, the CO2 is essentially immobile.
- Dissolution / Mineralization*
  - Over time, the CO2 will dissolve in the brine
  - This carbonic acid can react with minerals to form carbonates

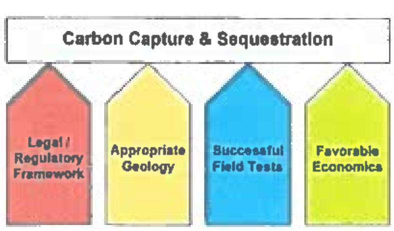


Storage security increases over time



- There are multiple mechanisms working over multiple timescales
- Over geologic time, the storage security increases
- Over time, the overall risk profile decreases

What are the pre-requisites for widespread deployment?



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Legal / Regulatory Framework

- Carbon capture and storage will not be deployed until all legal and regulatory issues have been addressed.
- In particular issues around long term liability and subsurface rights must be resolved
- Liability protection is a necessary pre-requisite for securing financing (and commercial deployment)
  - Timeframe mismatch necessitates statutory protection
- Subsurface rights need to be secured
  - How much is enough?
- Consistent regulatory requirements for injection, monitoring and closure
  - Federal guidelines would be preferable

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Appropriate Geology

- What is appropriate geology?
  - Contained, receptive target formation topped by one or more layers of impermeable caprock
- Formation needs to be well-characterized
  - Verified capacity, not estimated potential
  - Geologic properties (porosity, permeability, etc.,)
  - Cap-rock extent and properties
  - Knowledge of any prior incursions
- First sites may warrant additional requirements
  - Increased safety margin

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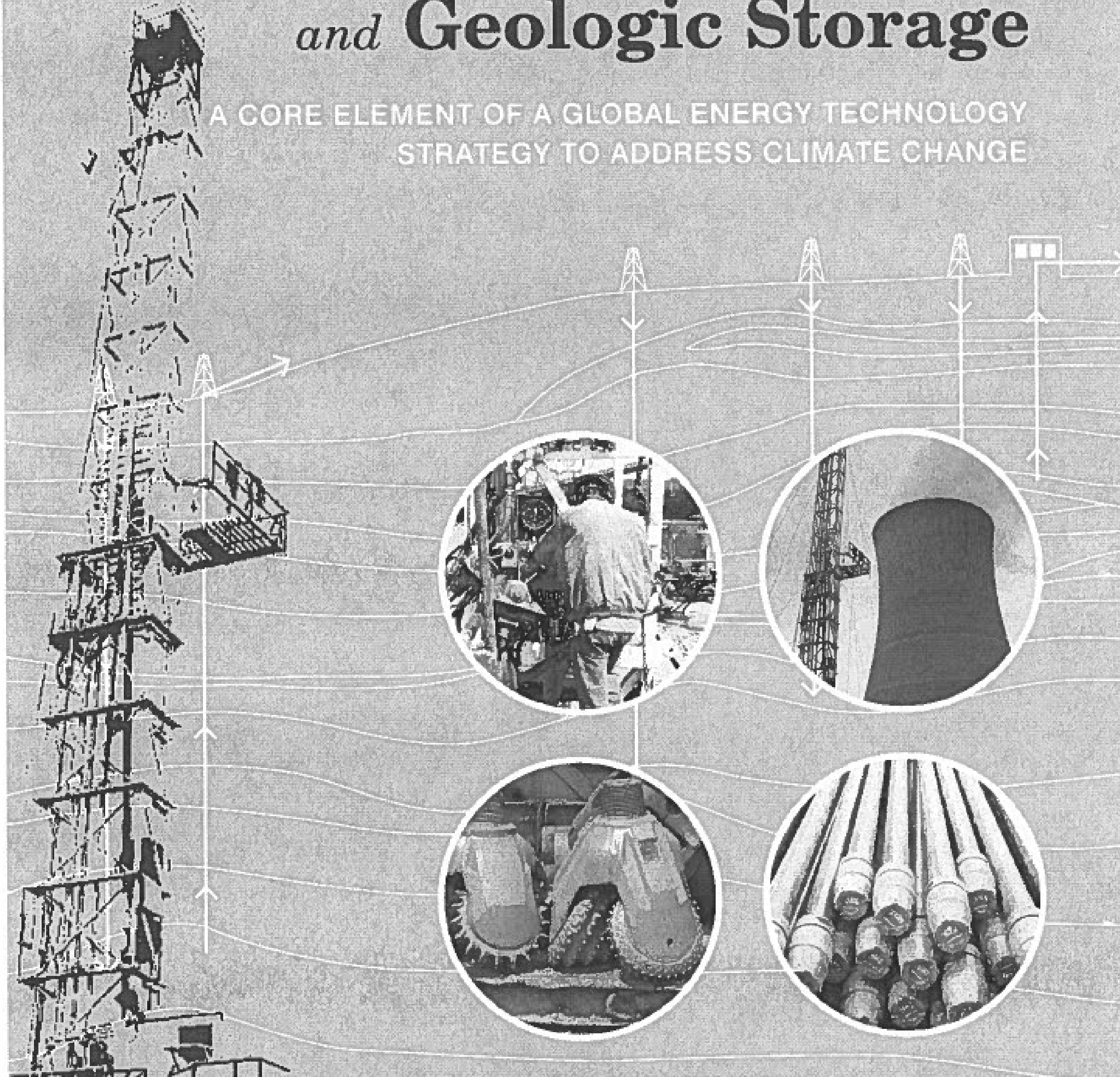
Successful Field Tests

- Learning-by-doing is a necessary and critical component of technology deployment.
- Field-testing improves confidence of industry, regulators, stakeholders and the financial community.
- Field-testing can take several forms:
  - Pilot scale
    - Necessary first step
    - Early test bed for technologies
    - Regional partnerships are a good example
  - Commercial scale
    - FutureGen: research platform for integration of state-of-the-art gasification, cleanup and CO_2 capture and sequestration
  - Need more

Carbon Dioxide Capture *and* Geologic Storage

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE



A TECHNOLOGY REPORT FROM THE SECOND PHASE OF THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM

GTSP

Global Energy Technology Strategy Program

Printed in the United States of America

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JJ Dooley (Lead Author), RT Dahowski, CL Davidson,
MA Wise, N Gupta, SH Kim, EL Malone

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THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM

The Global Energy Technology Strategy Program (GTSP) began in 1998 with the goal of better understanding the role that energy technologies might play in addressing the problem of global climate change. The GTSP is a unique, global, public and private sector research collaboration, whose sponsors and research collaborators are drawn from around the world.

The completion of the first phase of the GTSP in 2001 was marked by the release of a seminal report during a special session of the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change. This report, *A Global Energy Technology Strategy Addressing Climate Change: Initial Findings from an International Public-Private Collaboration,* demonstrated the importance of technology development and deployment as key cornerstones of a broader set of activities designed to address climate change.

A central conclusion was that a robust "technology strategy" required the development of a *technology portfolio.* It found no evidence for a single technology whose development promised to "solve" the climate problem. That is, *a priori*, there is no technological "silver bullet." Rather, the GTSP concluded that a variety of technologies and technology systems show promise for making substantially expanded contributions to the global energy system in a climate-constrained world. These include biotechnology, hydrogen energy and other advanced transportation technology systems, nuclear power, renewable energy technologies, end-use energy technologies, and carbon dioxide capture and storage.

The first phase of the GTSP produced ground-breaking research, including many results that have made their way into the frequently cited literature. The first phase of the GTSP successfully added to the dialogue about responses to climate change a new, previously missing, element—technology.

But building productive, long-term, real-world technology strategies to address climate change requires a deeper understanding of technologies and their potential. Thus, the GTSP launched its second phase in 2002. GTSP Phase 2 is pushing the frontiers of our knowledge to gain a much deeper understanding of how these key carbon management and advanced energy technologies will deploy in practice, and the means for launching and sustaining a meaningful global energy technology strategy. GTSP Phase 2 is in the process of distilling important lessons gleaned from research on the potential roles of six carbon management technology systems in the context of a competitive future global energy system. These summaries of key research insights will take the form of "capstone reports" for each of the six technology areas. This is the first capstone report—on Carbon Dioxide Capture and Geologic Storage. In addition, a set of overall conclusions will be drawn from the complete body of the GTSP work and will be published in 2006.

For more information about the GTSP, please contact

Jae Edmonds
Laboratory Fellow and Chief Scientist
Battelle, Joint Global Change Research Institute
8400 Baltimore Avenue, Suite 201
College Park, MD 20740 USA
jae.edmonds@battelle.org

TO THE READER

The findings presented in this report stem from more than ten years of research at Battelle's Joint Global Change Research Institute (JGCRI) to better understand the significant potential of carbon dioxide capture and storage (CCS) technologies in addressing climate change. A central focus of this report is on actions that will allow CCS technologies to transition from their current status as *potential solutions* to climate change to the point where these systems are deployed widely and have become *safe, effective, and trusted cornerstones of the global energy system.*

CCS technologies are increasingly seen as critically important elements of a global portfolio of advanced energy technologies needed to address climate change. One sign of the significant interest in CCS technologies is the recent publication of the Intergovernmental Panel on Climate Change's *Special Report on Carbon Dioxide Capture and Storage* (2005). While acknowledging the significant contributions being made by many other research groups, national governments, state agencies, and private firms who are pushing forward the development and early commercial deployment of CCS technologies, this document is meant to summarize research performed under the Global Energy Technology Strategy Program (GTSP), and therefore principally focuses on CCS research carried out at Battelle and JGCRI during the first and second phases of the GTSP.

Overall, this document fulfills the GTSP objective of articulating the cost and environmental performance targets for CCS, as well as the institutional means that will enable its commercial deployment in a greenhouse-gas-constrained world. The report establishes that CCS technologies can make a significant contribution to reducing greenhouse gas emissions. The report also describes the cost, performance and other key characteristics of the component technologies comprising a complete CCS system. Included in this is an examination of deep underground geologic sites and the permanence of injected carbon dioxide storage. Market and economic cost analyses are presented to elucidate the potential deployment of CCS technologies. Finally, the report explores how the world—especially industries, such as electricity generators—would make decisions about using CCS under a policy that places a value on carbon dioxide emissions.

Our CCS research has been supported by numerous firms, nongovernmental organizations, and government agencies. We are grateful for their support, which has enabled us to pursue this important work. However, JGCRI, GTSP and James J. Dooley, who leads JGCRI and GTSP's research related to CCS technologies, along with the other authors are solely responsible for the content of this report. Also, we would like to acknowledge and thank the many peer reviewers who freely gave their time to comment on earlier drafts of this document. Their thoughtful review helped to significantly improve this document.

For more information about the GTSP's program on CCS, please contact

James J. Dooley
Senior Staff Scientist
Battelle, Joint Global Change Research Institute
8400 Baltimore Avenue, Suite 201
College Park, MD 20740 USA
dooleyj@battelle.org

GTSP Phase II—
Program Objective

To articulate the cost and environmental performance targets for technologies and technology systems in a greenhouse-gas-constrained world, and the institutional means of implementation.

A Note on Terms: CCS technologies, as used here, do not include planting trees, increasing soil carbon, or other bio-based activities. These activities are more commonly referred to as "carbon sequestration." This report will not use the term "sequestration" in order to avoid any possible confusion.

EXECUTIVE SUMMARY The Role of Carbon Dioxide Capture and Storage Technologies in Mitigating Climate Change

THE CHALLENGE OF CLIMATE CHANGE AND THE TECHNOLOGY PORTFOLIO RESPONSE

Addressing climate change is a large-scale, global challenge to reduce and avoid the release of enormous amounts of greenhouse gases (GHGs) over the course of this century. Currently, the world's economies annually emit approximately 26 gigatons of carbon dioxide ($GtCO_2$) to the atmosphere from the combustion of fossil fuels. In the absence of explicit efforts to address climate change, rising global populations, higher standards of living, and increased demand for energy could result in as much as 9,000 gigatons of cumulative CO_2 being emitted to the atmosphere from fossil fuel combustion over this coming century.

However, to stabilize CO_2 concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system" as called for in the United Nations Framework Convention on Climate Change, the cumulative amount of CO_2 released to the atmosphere over this century would need to be held to no more than 2,600 to 4,600 $GtCO_2$—a substantial reduction and formidable challenge.

The Global Energy Technology Strategy Program (GTSP) has shown conclusively the value of developing an enhanced portfolio of energy technologies in meeting this challenge. Some aspects of this portfolio will involve continued energy efficiency improvements in homes, offices, and automobiles, as these technologies not only reduce CO_2 emissions but also help to improve economic efficiency, competitiveness, and local environmental quality. Renewable energy, advanced bioenergy and biotechnologies, advanced transportation including hydrogen production and fuel cell technologies, and nuclear power have also been shown to be key aspects of the broad portfolio of energy technologies needed to address climate change. GTSP research has demonstrated that all aspects of this portfolio need to be capable of delivering significant and sustained reductions in CO_2 emissions over the course of this century.

Carbon dioxide capture and storage (CCS) technologies, which are the focus of this report, have the potential to be central elements of this advanced energy technology portfolio. CCS technologies are capable of deploying widely across the globe in many different economic sectors and in many different locales. These technologies are capable of delivering deep, cost-effective, and sustained emissions reductions. This report seeks to conclusively demonstrate the technical feasibility and potential economic value of CCS in this broader portfolio of advanced energy and carbon management technologies.

POTENTIAL TO DELIVER BENEFITS TODAY, TOMORROW, AND WELL INTO THE FUTURE

CCS systems offer several unique benefits as part of a climate change mitigation portfolio:

- In the near term, CCS systems help the owners, operators and beneficiaries of established, economic production methods—which lie at the heart of the modern industrial economy—to find a financially viable pathway forward into a world in which there are significant constraints on CO_2 emissions. CCS may be pivotal in helping reduce the emissions from fossil fuel-fired electricity generation, steel and cement manufacturing, refining, and chemicals production. Without CCS technologies, many of these firms may see efforts to address climate change as threats to their businesses. The potential cost savings from using CCS systems opens the dialog with these industries about how best to address climate change in the future.
- In the medium term, the implementation of CCS technologies allows for a smoother transition of the global economy to a low-GHG emissions future. Established production methods and existing infrastructure can continue to be utilized, and the costs of transitioning to a lower-emitting energy system can be minimized.

- In the long term, CCS will help make valuable commodities like electricity and hydrogen cheaper than they would otherwise be. This is the key merit; CCS technologies are not ends in themselves but a means—a means of realizing abundant energy and industrial production, without CO_2 emissions.

CURRENT MARKET DEPLOYMENT

Many component technologies for CCS systems already exist, including CO_2 capture, transportation via pipeline, and injection into geologic formations deep underground. However, both the scale of existing CCS systems and the number of CCS commercial and field demonstration projects are very small compared to the scale necessary for significant and sustained CO_2 emissions reductions. The very newness of CCS systems and a lack of real-world operational experience in essential markets such as electric power generation are current impediments to the expanded adoption of CCS technologies.

Globally, there are currently more than 8,100 large CO_2 point sources (accounting for more than 60% of all anthropogenic CO_2 emissions) that could conceivably adopt CCS technologies as a means for delivering deep and sustained CO_2 emissions reductions. These 8,100 large CO_2 point sources are predominantly fossil-fueled electric power plants, but there are also hundreds of steel mills, cement kilns, chemical plants, and oil and gas production and refining facilities. A very small number of these facilities are already capturing and selling CO_2, suggesting that in certain niche applications it is already profitable to deploy some CCS component technologies. However, the vast majority of these existing facilities have not adopted CCS systems. Moreover, the vast majority of the new power plants and other large industrial CO_2 point sources that are now being built or that are in various stages of early development are also not planning to adopt CCS systems. This reveals an important point; the deployment of CCS technologies is almost exclusively motivated by the need to significantly reduce greenhouse gas emissions, and, therefore, their large-scale adoption depends upon explicit efforts to control such emissions.

CO_2 STORAGE CAPACITY

Our research and that of many other research groups demonstrate that potential deep geologic CO_2 storage sites exist around the world, although the distribution of these candidate storage sites is quite uneven (as is true for many other types of natural resources). Our preliminary estimate of the potential global deep geologic CO_2 storage capacity is nearly 11,000 $GtCO_2$. Assuming that other advanced energy technologies are developed and deployed along with CCS systems, this potential capacity should be more than enough to address global CO_2 storage needs for at least this century. In many places, candidate CO_2 storage formations are near large groupings of power plants and other industrial facilities, which should lower the cost of deploying CCS systems.

COST AND ECONOMIC VALUE

For most applications, assuming the adoption of currently available CCS component technologies, the cost of employing CCS systems most likely lies below $50/$tCO_2$ including capture, transport, injection, storage and monitoring. At this cost level, CCS systems are capable of reducing the costs of climate stabilization by trillions of dollars because these technologies allow for the continued use of fossil fuels and enable the deployment of other key mitigation technologies such as large-scale, low-emissions hydrogen and synfuels production. GTSP research also confirms that the costs of CCS systems should be competitive with—and in some cases significantly less costly than—other potential large-scale CO_2 emissions reduction and abatement technologies.

SAFETY AND ENVIRONMENTAL EFFICACY

At a properly designed and well-managed CCS facility, the chance of appreciable CO_2 leakage from the deep geologic storage formation is very small. The principal task for the measurement, monitoring, and verification of stored CO_2 centers on how to demonstrate the long-term retention of stored CO_2 to regulators and the public. New and improved measurement and monitoring techniques and standards for their use need to be developed to provide proof of public and environmental safety and of each CCS project's effectiveness in mitigating climate change.

ADOPTION AND DEPLOYMENT WITHIN THE ELECTRIC POWER INDUSTRY

Early adopters of CCS systems will likely lie outside the electric utility industry and will seek opportunities that move beyond today's niche markets in CO_2-driven enhanced oil recovery. However, if there were an explicit climate policy in place that called for substantial and sustained emissions reductions, the electric power industry would likely become the largest market for CCS systems. GTSP research has shown that CCS systems will be most economic when deployed with large baseload power plants. These plants operate around the clock with only occasional brief outages for routine maintenance. For these facilities, a key criterion for locating suitable storage reservoirs is that those reservoirs have sufficient capacity to hold perhaps more than 50 years' worth of the facility's CO_2 plus some margin for growth. Because of this need for large quantities of reliable CO_2 storage, decade after decade, CCS-enabled electric power plants will most likely look to deep saline formations, which tend to offer large storage capacities.

THE VALUE OF CONTINUED R&D

The next five to ten years constitute a critical window in which to amass needed operational experience with CCS technologies in real-world conditions. Planned CCS field demonstrations, a handful of early commercial CCS projects, and continued laboratory-based research are all needed to advance the state of the art across a number of CCS-related areas, so that CCS technologies can deploy safely and effectively in as many locales and configurations as needed to meet the challenge of stabilizing atmospheric CO_2 concentrations. Important areas of research identified by GTSP include the following:

- Continually improve CO_2 capture technologies and ensure that they are being developed and tuned to a wide array of industrial sectors that can potentially benefit by adopting CCS systems.

- Survey global candidate CO_2 reservoirs so that we can better understand the nature and distribution of the world's deep geologic CO_2 storage reservoirs. This is particularly crucial in rapidly developing countries such as China and India. Helping developing nations site new long-lived electricity generation or other large CO_2-emitting industrial facilities while giving forethought to potential deployment of CCS will allow them to avoid stranding those assets should there be a need to adopt CCS systems at those facilities at some point in the future.

- Develop a broader and more advanced set of measurement, monitoring, and verification (MMV) technologies for stored CO_2 than currently exists in order to meet the needs of a potential future large-scale deployment of CCS systems with CO_2 being stored in many different kinds of formations and circumstances. New MMV technologies need to be invented and the cost, performance, and other operating characteristics of existing MMV technologies need to be improved.

- Obtain more experience with end-to-end CCS systems in real-world conditions and make specific efforts to utilize the opportunity presented by these early commercial and research demonstration CCS facilities to increase our understanding of the behavior of CO_2 in the subsurface, develop a base of empirical data to facilitate the development of MMV systems and their regulation, train and educate a larger cadre of individuals who are capable of running commercial-scale CCS systems, garner public support for CCS deployment, and otherwise lay the foundation for the larger scale deployment to come.

THE EFFORT REQUIRED FOR LARGE-SCALE COMMERCIAL DEPLOYMENT

Fulfilling the potential that the large-scale use of CCS technologies could hold will take significant effort. Despite recent technical successes and growing budgets for the development and critical field demonstration of CCS technologies, much hard work remains to transition them—perhaps quickly—from their current status as potential solutions to climate change to safe, effective, and trusted cornerstones of the global energy system. If the world can do this, then our research suggests that CCS systems hold promise to be an economic, cost-effective means for facilitating the stabilization of greenhouse gases in the atmosphere as part of a portfolio of technologies to address climate change.

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College Park, MD 20740 USA

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