Chapter 4 — Geological Carbon Sequestration

Carbon sequestration is the long term isolation of carbon dioxide from the atmosphere through physical, chemical, biological, or engineered processes. The largest potential reservoirs for storing carbon are the deep oceans and geological reservoirs in the earth's upper crust. This chapter focuses on geological sequestration because it appears to be the most promising large-scale approach for the 2050 timeframe. It does not discuss ocean or terrestrial sequestration[1,2].

In order to achieve substantial GHG reductions, geological storage needs to be deployed at a large scale.[3,4] For example, 1 Gt C/yr (3.6 Gt CO_2/yr) abatement, requires carbon capture and storage (CCS) from 600 large pulverized coal plants (~1000 MW each) or 3600 injection projects at the scale of Statoil's Sleipner project.[5] At present, global carbon emissions from coal approximate 2.5 Gt C. However, given reasonable economic and demand growth projections in a business-as-usual context, global coal emissions could account for 9 Gt C (see table 2.7). These volumes highlight the need to develop rapidly an understanding of typical crustal response to such large projects, and the magnitude of the effort prompts certain concerns regarding implementation, efficiency, and risk of the enterprise.

The key questions of subsurface engineering and surface safety associated with carbon sequestration are:

Subsurface issues:

- ☐ Is there enough capacity to store CO_2 where needed?
- ☐ Do we understand storage mechanisms well enough?
- ☐ Could we establish a process to certify injection sites with our current level of understanding?
- ☐ Once injected, can we monitor and verify the movement of subsurface CO_2?

Near surface issues:

- ☐ How might the siting of new coal plants be influenced by the distribution of storage sites?
- ☐ What is the probability of CO_2 escaping from injection sites? What are the attendant risks? Can we detect leakage if it occurs?
- ☐ Will surface leakage negate or reduce the benefits of CCS?

Importantly, there do not appear to be unresolvable open technical issues underlying these questions. Of equal importance, the hurdles to answering these technical questions well appear manageable and surmountable. As such, it appears that geological carbon sequestration is likely to be safe, effective, and competitive with many other options on an economic basis. This chapter explains the technical basis for these statements, and makes recommendations about ways of achieving early resolution of these broad concerns.

SCIENTIFIC BASIS

A number of geological reservoirs appear to have the potential to store many 100's – 1000's of gigatons of CO_2.[6] The most promising reservoirs are *porous and permeable rock bodies*, generally at depths, roughly 1 km, at pressures and temperatures where CO_2 would be in a supercritical phase.[7]

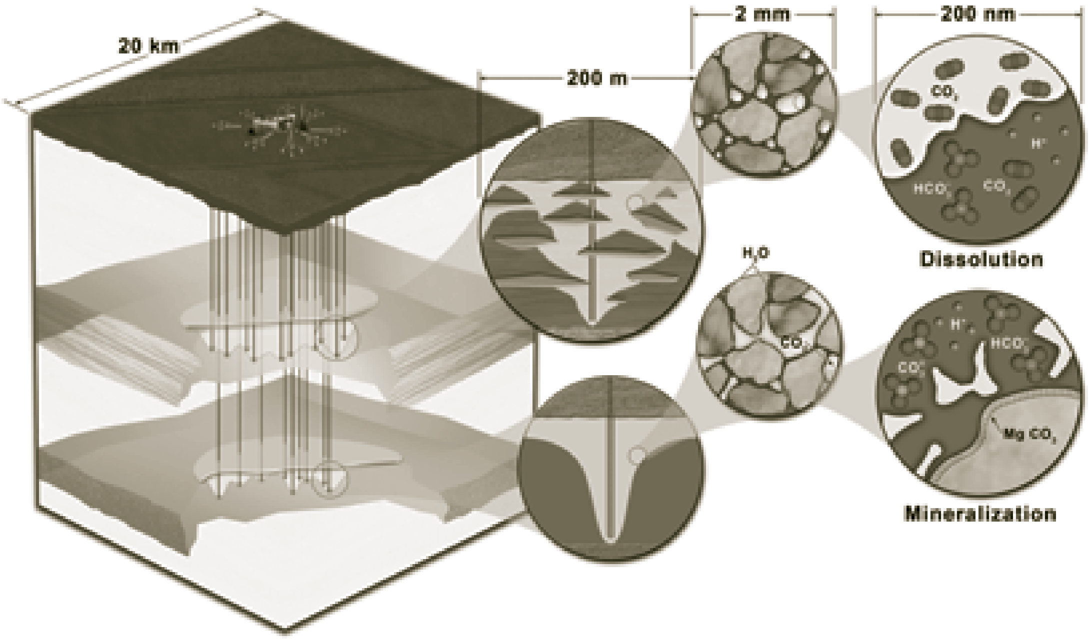
- *Saline formations* contain brine in their pore volumes, commonly of salinities greater than 10,000 ppm.
- *Depleted oil and gas fields* have some combination of water and hydrocarbons in their pore volumes. In some cases, economic gains can be achieved through enhanced oil recovery (EOR)[8] or enhanced gas recovery[9] and substantial CO_2-EOR already occurs in the US with both natural and anthropogenic CO_2.[10]
- *Deep coal seams*, often called unmineable coal seams, are composed of organic minerals with brines and gases in their pore and fracture volumes.
- Other potential geological target classes have been proposed and discussed (e.g., oil shales, flood basalts); however, these classes require substantial scientific inquiry and verification, and the storage mechanisms are less well tested and understood (see Appendix 4.A for a more detailed explanation).

Because of their large storage potential and broad distribution, it is likely that most geological sequestration will occur in saline formations. However, initial projects probably will occur in depleted oil and gas fields, accompanying EOR, due to the density and quality of subsurface data and the potential for economic return (e.g., Weyburn). Although there remains some economic potential for enhanced coal bed methane recovery, initial economic assessments do not appear promising, and substantial technical hurdles remain to obtaining those benefits.[6]

For the main reservoir classes, CO_2 storage mechanisms are reasonably well defined and understood (Figure 4.1). To begin, CO_2 sequestration targets will have *physical barriers* to CO_2 migration out of the crust to the surface. These barriers will commonly take the form of impermeable layers (e.g., shales, evaporites) overlying the reservoir target, although they may also be dynamic in the form of regional hydrodynamic flow. This storage mechanism allows for very high CO_2 pore volumes, in excess of 80%, and act immediately to limit CO_2 flow. At the pore scale, *capillary forces* will immobilize a substantial fraction of a CO_2 bubble, commonly measured to be between 5 and 25% of the pore volume. That CO_2 will be trapped as a residual phase in the pores, and acts over longer time scales as a CO_2 plume which is attenuated by flow. Once in the pore, over a period of tens to hundreds of years, the CO_2 will *dissolve* into other pore fluids, including hydrocarbon species (oil and gas) or brines, where the CO_2 is fixed indefinitely, unless other processes intervene. Over longer time scales (hundreds to thousands of years) the dissolved CO_2 may react with minerals in the rock volume to *precipitate* the CO_2 as new carbonate minerals. Finally, in the case of organic mineral frameworks such as coals, the CO_2 will physically *adsorb* onto the rock surface, sometimes displacing other gases (e.g., methane, nitrogen).

Although substantial work remains to characterize and quantify these mechanisms, they are understood well enough today to trust estimates of the percentage of CO_2 stored over some period of time—the result of decades of studies in analogous hydrocarbon systems, natural gas storage operations, and CO_2-EOR. Specifically, it is very likely that the fraction of stored CO_2 will be greater than 99% over 100 years, and likely that the fraction of stored CO_2 will exceed 99% for 1000 years[6]. Moreover, some mechanisms appear to be self-reinforcing.[11,12] Additional work will reduce the uncertainties associated with long-term efficacy and numerical estimates of storage volume capacity, but no knowledge gaps today appear to cast doubt on the fundamental likelihood of the feasibility of CCS.

Figure 4.1 Schematic of Sequestration Trapping Mechanisms



Schematic diagram of large injection at 10 years time illustrating the main storage mechanisms. All CO_2 plumes are trapped beneath impermeable shales (not shown) The upper unit is heterogeneous with a low net percent usable, the lower unit is homogeneous. Central insets show CO_2 as a mobile phase (lower) and as a trapped residual phase (upper). Right insets show CO_2 dissolution (upper) and CO_2 mineralization (lower)

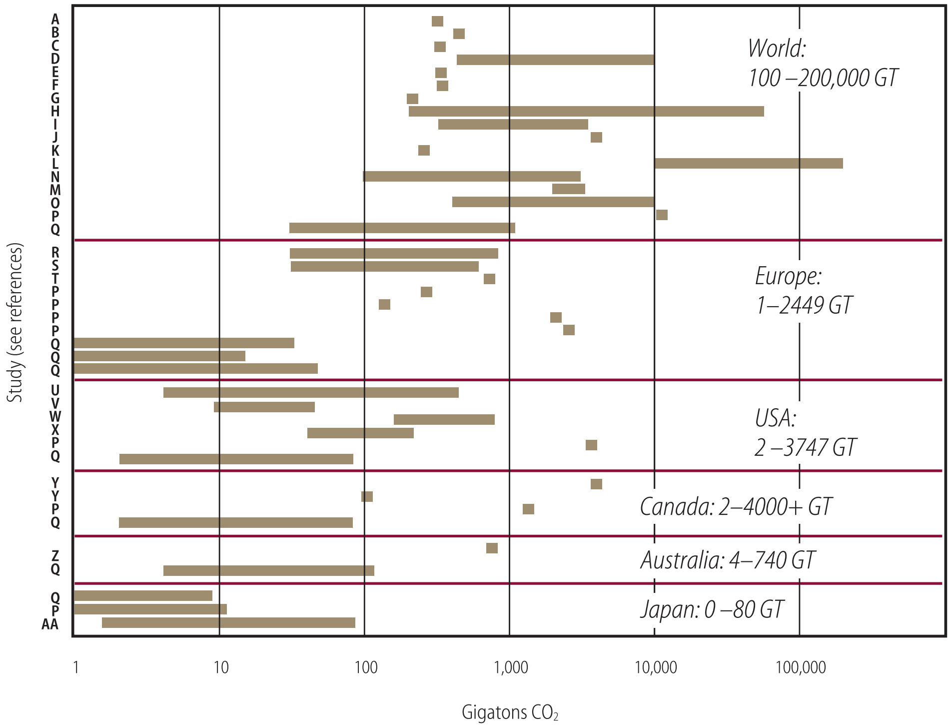
CAPACITY ESTIMATES

While improvement in understanding of storage mechanisms would help to improve capacity estimates, the fundamental limit to high quality storage estimates is uncertainty in the pore volumes themselves. Most efforts to quantify capacity either regionally or globally are based on vastly simplifying assumptions about the overall rock volume in a sedimentary basin or set of basins. [13,14] Such estimates, sometimes called "top-down" estimates, are inherently limited since they lack information about local injectivity, total pore volumes at a given depth, concentration of resource (e.g., stacked injection zones), risk elements, or economic characteristics.

A few notable exceptions to those kinds of estimates involve systematic consideration of individual formations and their pore structure within a single basin.[15] The most comprehensive of this kind of analysis, sometimes called "bottom-up", was the GEODISC effort in Australia.[16] This produced total rock volume estimates, risked volume estimates, pore-volume calculations linked to formations and basins, injectivity analyses, and economic qualifications on the likely injected volumes. This effort took over three years and $10 million Aus. Institutions like the US Geological Survey or Geoscience Australia are well equipped to compile and integrate the data necessary for such a capacity determination, and would be able to execute such a task rapidly and well.

Our conclusions are similar to those drawn by the Carbon Sequestration Leadership Forum (CSLF), which established a task force to examine capacity issues.[17] They recognized nearly two-orders of magnitude in uncertainty within individual estimates and more than two orders magnitude variance between estimates (Figure 4.2). The majority of estimates support the contention that sufficient capacity exists to store many 100's to many 1000's of gigatons CO_2, but this uncertain range is too large to inform sensible policy.

Figure 4.2 Published Capacity Estimates



Graph showing published estimates of CO_2 capacity for the world, regions, and nations.[17] Note the large potential range of in some estimates (greater than 100x) and the unreasonably small uncertainties in other estimates (none provided). Note that some national estimates exceed some global estimates.

Accordingly, an early priority should be to undertake "bottom-up" capacity assessments for the US and other nations. Such an effort requires detailed information on individual rock formations, including unit thickness and extent, lithology, seal quality, net available percentage, depth to water table, porosity, and permeability. The geological character and context matters greatly and requires some expert opinion and adjudication. While the data handling issues are substantial, the costs would be likely to be low ($10-50 million for a given continent; $100 million for the world) and would be highly likely to provide direct benefits in terms of resource management.[18] Perhaps more importantly, they would reduce substantially the uncertainty around economic and policy decisions regarding the deployment of resource and crafting of regulation.

Within the US, there is an important institutional hurdle to these kinds of capacity estimates. The best organization to undertake this effort would be the US Geological Survey, ideally in collaboration with industry, state geological surveys, and other organizations. This arrangement would be comparable in structure and scope to national oil and gas assessments, for which the USGS is currently tasked. This is analogous to performing a bottom-up CO_2 storage capacity estimation. However, the USGS has no mandate or resources to do CO_2 sequestration capacity assessments at this time.

The Department of Energy has begun assessment work through the seven Regional Carbon Sequestration Partnerships[19]. These partnerships include the member organizations of 40 states, including some state geological surveys. While the Partnerships have produced and will continue to produce some detailed formation characterizations, coverage is not uniform and the necessary geological information not always complete. As such, a high-level nationwide program dedicated to bottom-up geological assessment would best serve the full range of stakeholders interested in site selection and management of sequestration, as do national oil and gas assessments.

SITE SELECTION AND CERTIFICATION CRITERIA

Capacity estimates, in particular formation-specific, local capacity assessments, will underlie screening and site selection and help define selection criteria. It is likely that for each class of storage reservoir, new data will be required to demonstrate the injectivity, capacity, and effectiveness (ICE) of a given site.[20] A firm characterization of ICE is needed to address questions regarding project life cycle, ability to certify and later close a site, site leakage risks, and economic and liability concerns.[21]

Ideally, project site selection and certification for injection would involve detailed characterization given the geological variation in the shallow crust. In most cases, this will require new geological and geophysical data sets. The specifics will vary as a function of site, target class, and richness of local data. For example, a depleted oil field is likely to have well, core, production, and perhaps seismic data that could be used to characterize ICE rapidly. Still additional data (e.g., well-bore integrity analysis, capillary entry pressure data) may be required. In contrast, a saline formation project may have limited well data and lack core or seismic data altogether. Geological characterization of such a site may require new data to help constrain subsurface uncertainty. Finally, while injectivity may be readily tested for CO_2 storage in an unmineable coal seam, it may be extremely difficult to establish capacity and storage effectiveness based on local stratigraphy. Accordingly, the threshold for validation will vary from class to class and site to site, and the due diligence necessary to select a site and certify it could vary greatly.

OPEN ISSUES The specific concerns for each class of storage are quite different. For depleted hydrocarbon fields, the issues involve incremental costs necessary to ensure well or field integrity. For saline formations, key issues will involve appropriate mapping of potential permeability fast-paths out of the reservoir, accurate rendering of subsurface heterogeneity and uncertainty, and appropriate geomechanical characterization. For unmineable coal seams, the issues are more substantial: demonstration of understanding of cleat structure and geochemical response, accurate rendering of sealing architecture and leakage risk, and understanding transmissivity between fracture and matrix pore networks. For these reasons, the regulatory framework will need to be tailored to classes of sites.

MEASUREMENT, MONITORING, AND VERIFICATION: MMV

Once injection begins, a program for measurement, monitoring, and verification (MMV) of CO_2 distribution is required in order to:

☐ understand key features, effects, & processes needed for risk assessment

☐ manage the injection process

☐ delineate and identify leakage risk and surface escape

☐ provide early warnings of failure near the reservoir

☐ verify storage for accounting and crediting

For these reasons, MMV is a chief focus of many research efforts. The US Department of Energy has defined MMV technology development, testing, and deployment as a key element to their technology roadmap,[19] and one new EU program (CO_2 ReMoVe) has allocated €20 million for monitoring and verification. The IEA has established an MMV working group aimed at technology transfer between large projects and new technology developments. Because research and demonstration projects are attempting to establish the scientific basis for geological sequestration, they will require more involved MMV systems than future commercial projects.

Today there are three well-established large-scale injection projects with an ambitious scientific program that includes MMV: Sleipner (Norway)[22], Weyburn (Canada) [23], and In Salah (Algeria)[24]. Sleipner began injection of about 1Mt CO_2/yr into the Utsira Formation in 1996. This was accompanied by time-lapse reflection seismic volume interpretation (often called 4D-seismic) and the SACS scientific effort. Weyburn is an enhanced oil recovery effort in South Saskatchewan that served as the basis for a four-year, $24 million international research effort. Injection has continued since 2000 at about 0.85 Mt CO_2/yr into the Midale reservoir. A new research effort has been announced as the Weyburn Final Phase, with an anticipated budget comparable to the first. The In Salah project takes about 1Mt CO_2/yr stripped from the Kretchba natural gas field and injects it into the water leg of the field. None of these projects has detected CO_2 leakage of any kind, each appears to have ample injectivity and capacity for project success, operations have been transparent and the results largely open to the public. Over the next decade, several new projects at the MtCO_2/yr scale may come online from the myriad of projects announced (see Table 4.1). These will provide opportunities for further scientific study.

Table 4.1 Proposed CCS Projects at the Mt/yr scale

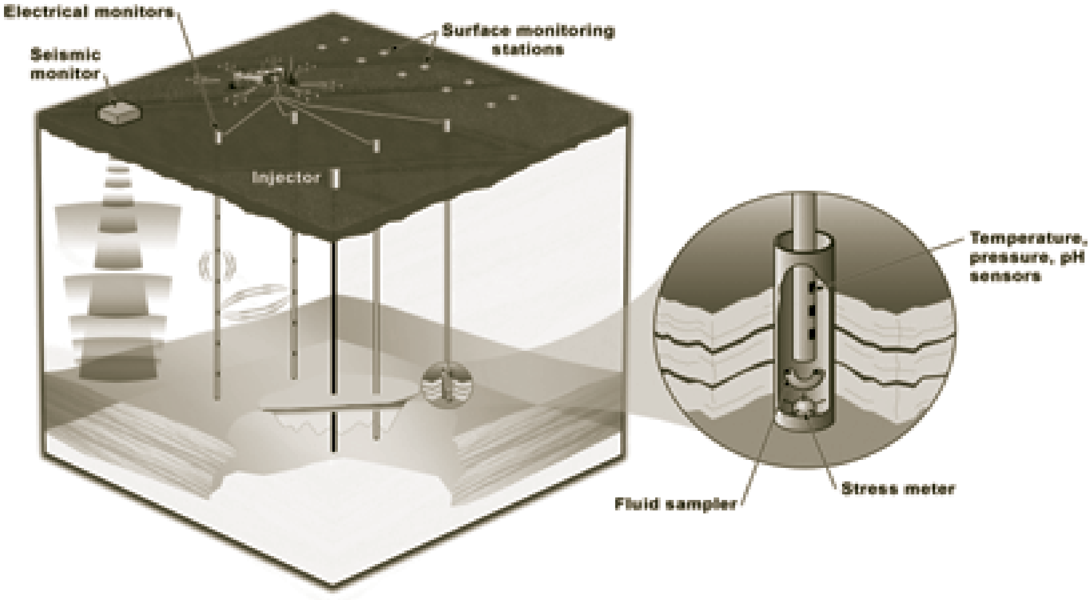
PROJECT	COUNTRY	PROJECT TYPE
Monash	Australia	Fuel
ZeroGen	Australia	Power
Gorgon	Australia	Gas Processing
SaskPower	Canada	Power
Greengen	China	Power
nZEC	China	Power
Vattenfall	Germany	Power
RWE	Germany	Power
Draugen	Norway	Power
Statoil Mongstad	Norway	Power
Snovit	Norway	Gas Processing
BP Peterhead	UK	Power
E.On	UK	Power
RWE npower	UK	Power (retrofit)
Progressive/Centrica	UK	Power
Powerfuel	UK	Power
FutureGen	USA	Power
BP Carson	USA	Power

Perhaps surprisingly in the context of these and other research efforts, there has been little discussion of what are the most important parameters to measure and in what context (research/pilot vs. commercial). Rather, the literature has focused on the current ensemble of tools and their costs.[25] In part due to the success at Sleipner, 4-D seismic has emerged as the standard for comparison, with 4-D surveys deployed at Weyburn and likely to be deployed at In Salah. This technology excels at delineating the boundaries of a free-phase CO_2 plume, and can detect small saturations of conjoined free-phase bubbles that might be an indicator of leakage. Results from these 4D-seismic surveys are part of the grounds for belief in the long-term effectiveness of geological sequestration.

However, time-lapse seismic does not measure all the relevant parameters, and has limits in some geological settings. Key parameters for research and validation of CO_2 behavior and fate involve both direct detection of CO_2 and detection through proxy data sets (figure 4.3). Table 4.2 provides a set of key parameters, the current best apparent measurement and monitoring technology, other potential tools, and the status of deployment in the world's three largest injection demonstrations

Importantly, even in the fields where multiple monitoring techniques have been deployed (e.g., Weyburn), there has been little attempt to integrate the results (this was identified as a research gap from the Weyburn effort).[23] There are precious few formal methods to integrate and jointly invert multiple data streams. This is noteworthy; past analyses have demonstrated that formal integration of orthogonal data often provides robust and strong interpretations of subsurface conditions and characteristics.[26,27] The absence of integration of measurements represents a major gap in current MMV capabilities and understanding.

Figure 4.3 Hypothetical Site Monitoring Array



Schematic diagram a monitoring array providing insight into all key parameters. Note both surface and subsurface surveys, and down-hole sampling and tool deployment. A commercial monitoring array would probably be much larger.

In addition to development, testing, and integration of MMV technology, there is no standard accepted approach (e.g., best practices) to the operation of MMV networks. This is particularly important in future commercial projects, where a very small MMV suite focused on leak detection may suffice. To be effective, it is likely that MMV networks must cover the footprint of injection at a minimum, and include sampling near the reservoir and at the surface. Within the context of a large-scale deployment, it is likely that determination and execution of monitoring will involve a four-phase approach.

1. **Assessment and planning:** During this phase, the site is characterized geographically, geologically, geophysically, and geochemically. Forward simulation of monitoring approaches will help to predict the detection thresholds of a particular approach or tool. Based on this analysis, an array can be designed to meet the requirements of regulators and other stakeholders.
2. **Baseline monitoring:** Before injection takes place, baseline surveys must be collected to understand the background and provide a basis for difference mapping.
3. **Operational monitoring:** During injection, injection wells are monitored to look for circulation behind casing, failures within the well bore, and other operational problems or failures.
4. **Array monitoring during and after injection:** This phase will involve active surface and subsurface arrays, with the potential for additional tools around high-risk zones. The recurrence and total duration of monitoring will be determined by the research goals, the site parameters, the commercial status and regulatory needs. Ideally, MMV data would be formally integrated to reduce operational cost and complexity and to provide higher fidelity.

The likely duration of monitoring is an important unresolved issue. It is impractical for monitoring to continue for hundreds of years after injection; a practical monitoring time

Table 4.2 Key MMV Parameters and Environments, Methods, and Large-Scale Deployments

PARAMETER	VIABLE TOOLS	WEYBURN	IN SALAH,[†]	SLEIPNER
Fluid composition	Direct sample at depth[§] (e.g., U-tube), surface sampling	some	??	no
T, P fieldwide	Thermocouples[§], pressure transducers[§], fiberoptic Bragg grating	no	??	no
Subsurface pH monitoring	Down hole pH sensors[§]	no	yes[§]	no
CO_2 distribution	Time-lapse seismic[§], tilt, ERT, EMIT, microseismic	one[§]	one[§] or more	one[§]
CO_2 saturation	ERT[§], EMIT[§], advanced seismic methods	no	no	no
Stress changes	Tri-axial tensiometers[§], fiberoptic Bragg grating	no	??	no
Surface detection	Eddy towers[§], soil gas, FTIRS, LIDAR, PFC tracing[§], noble gas tracing	one	??	one[*]

ERT = Electrical Resistivity Tomography,

EMIT = Electromagnetic Induction Tomography

[§] *Indicates best in class monitoring technology*

[†] *In Salah is still in the process of finalizing their monitoring array.*

[*] *The "surface" monitoring at Sleipner is different than other fields in that it is submarine rather than subaerial. Photo surveys and side-scan sonar surveys have not shown leakage*

period should be defined either generally or at each site before injection begins. Substantial uncertainties remain regarding the detection thresholds of various tools, since the detection limit often involves assumptions about the distribution, continuity, and phase of subsurface CO_2. Important issues remain about how to optimize or configure an array to be both effective and robust. This issue cannot be answered without testing and research at large-scale projects and without formal data integration.

LEAKAGE RISKS

Since CO_2 is buoyant in most geological settings, it will seek the earth's surface. Therefore, despite the fact that the crust is generally well configured to store CO_2, there is the possibility of leakage from storage sites.[6] Leakage of CO_2 would negate some of the benefits of sequestration.[28] If the leak is into a contained environment, CO_2 may accumulate in high enough concentrations to cause adverse health, safety, and environmental consequences.[29,30,31] For any subsurface injected fluid, there is also the concern for the safety of drinking water.[32] Based on analogous experience in CO_2 injection such as acid gas disposal and EOR, these risks appear small. However, the state of science today cannot provide quantitative estimates of their likelihood.

Importantly, CO_2 leakage risk is not uniform and it is believed that most CO_2 storage sites will work as planned.[33] However, a small percentage of sites might have significant leakage rates, which may require substantial mitigation efforts or even abandonment. It is important to note that the occurrence of such sites does not negate the value of the effective sites. However, a premium must be paid in the form of due diligence in assessment to quantify and circumscribe these risks well.

Wells almost certainly present the greatest risk to leakage,[34] because they are drilled to bring large volumes of fluid quickly to the earth's surface. In addition, they remove the aspects of the rock volume that prevent buoyant migration. Well casing and cements are susceptible to corrosion from carbonic acid. When wells are adequately plugged and completed, they trap CO_2 at depth effectively. However, there are large numbers of orphaned or abandoned wells that may not be adequately plugged, completed, or cemented (Chapter 4 Appendix B) and such wells represent potential leak points for CO_2. Little is known about the specific probability of escape from a given well, the likelihood of such a well existing within a potential site, or the risk such a well presents in terms of potential leakage volume or consequence.[35] While analog situations provide some quantitative estimates (e.g, Crystal Geyser, UT)[36], much remains to be done to address these questions. Once a well is identified, it can be plugged or re-completed at fairly low cost.

There is the possibility of difficult to forecast events of greater potential damage. While these events are not analogous for CO_2 sequestration, events like the degassing of volcanic CO_2 from Lake Nyos[37] or the natural gas storage failure near Hutchinson, Kansas[38] speak to the difficulty of predicting unlikely events. However, while plausible, the likelihood of leaks from CO_2 sequestration causing such damage is exceedingly small (i.e., the rate of any leakage will be many orders of magnitude less than Lake Nyos and CO_2 is not explosive like natural gas).

Even though most potential leaks will have no impact on health, safety, or the local environment, any leak will negate some of the benefits of sequestration. However, absolute containment is not necessary for effective mitigation.[28] If the rate and volume of leakage are sufficiently low, the site will still meet its primary goal of sequestering CO_2 to reduce atmospheric warming and ocean acidification. The leak would need to be counted as an emissions source as discussed further under liability. Small leakage risks should not present a barrier to deployment or reason to postpone an accelerated field-based RD&D program.[39] This is particularly true of early projects, which will also provide substantial benefits of learning by doing and will provide insight into management and remediation of minor leaks.

A proper risk assessment would focus on several key elements, including both likelihood and potential impact. Efforts to quantify risks should focus on scenarios with the greatest potential economic or health and safety consequences. An aggressive risk assessment research program would help financiers, regulators, and policy makers decide how to account accurately for leakage risk.

SCIENCE & TECHNOLOGY GAPS

A research program is needed to address the most important science and technology gaps related to storage. The program should address three key concerns: (1) tools to simulate the injection and fate of CO_2; (2) approaches to predict and quantify the geomechanical response to injection; and (3) the ability to generate robust, empirically based probability-density functions to accurately quantify risks.

Currently, there are many codes, applications, and platforms to simulate CO_2 injection.[40] However, these codes have substantial limitations. First, they do not predict well the geomechanical response of injection, including fracture dilation, fault reactivation, cap-rock integrity, or reservoir dilation. Second, many codes that handle reactive transport, do not adequately predict the location of precipitation or dissolution, nor the effects on permeability. Third, the codes lack good modules to handle wells, specifically including the structure, reactivity, or geomechanical response of wells. Fourth, the codes do not predict the risk of induced seismicity. In order to simulate key coupled processes, future simulators will require sizeable computational resources to render large complex sedimentary networks, and run from the injection reservoir to the surface with high resolution in three dimensions. Given the capability of existing industry and research codes, it is possible to advance coupling and computation capabilities and apply them to the resolution of outstanding questions.

There is also a need to improve geomechanical predictive capability. This is an area where many analog data sets may not provide much insight; the concerns focus on rapid injection of large volumes into moderate-low permeability rock, and specific pressure and rate variations may separate reservoirs that fail mechanically from those that do not. This is particularly true for large-volume, high-rate injections that have a higher chance of exceeding important process thresholds. Fault response to stress, prediction of induced seismicity, fault transmissivity and hydrology, and fracture formation and propagation are notoriously difficult geophysical problems due to the complex geometries and non-linear responses of many relevant geological systems. Even with an improved understanding, the models that render fracture networks and predict their geomechanical response today are fairly simple, and it is not clear that they can accurately simulate crustal response to injection. A program that focuses on theoretical, empirical, laboratory, and numerical approaches is vital and should take advantage of existing programs within the DOE, DOD, and NSF.

The objective of these research efforts is to improve risk-assessment capabilities that results in the construction of reliable probability-density functions (PDFs). Since the number of CO_2 injection cases that are well studied (including field efforts) are exceedingly small, there is neither theoretical nor empirical basis to calculate CO_2-risk PDFs. Accurate PDFs for formal risk assessment could inform decision makers and investors regarding the potential economic risks or operational liabilities of a particular sequestration project.

In terms of risk, leakage from wells remains the likeliest and largest potential risk.[34,41,42] The key technical, regulatory, and legal concerns surrounding well-bore leakage of CO_2 are discussed in Appendix 4.B.

NEED FOR STUDIES AT SCALE

Ultimately, largescale injection facilities will be required to substantially reduce GHG emissions by CCS. Because the earth's crust is a complex, heterogeneous, non-linear system, field-based demonstrations are required to understand the likely range of crustal responses, including those that might allow CO_2 to escape from reservoirs. In the context of large-scale experiments, the three large volume projects currently operating do not address all relevant questions. Despite a substantial scientific effort, many parameters which would need to be measured to circumscribe the most compelling scientific questions have not yet been collected (see Table 4.2), including distribution of CO_2 saturation, stress changes, and well-bore leakage detection. This gap could be addressed by expanded scientific programs at large-scale sites, in particular at new sites.

The projects sponsored by the DOE are mostly small pilot projects with total injection volume between 1000 and 10,000 metric tons. For example, the DOE sponsored a field injection in South Liberty, TX, commonly referred to as the Frio Brine Pilot.[43,44] The Pilot received ~1800 t of CO_2 in 2004, and is slated to receive a second injection volume of comparable size in 2006. The Regional Partnerships have proposed 25 geological storage pilots of comparable size, which will inject CO_2 into a wide array of representative formations.[19] These kinds of experiments provide value in validating some model predictions, gaining experience in monitoring, and building confidence in sequestration. However, pilots on this scale cannot be expected to address the central concerns regarding CO_2 storage because on this scale the injection transients are too small to reach key thresholds within the crust. As such, important non-linear responses that may depend on a certain pressure, pH, or volume displacement are not reached. However, they will be reached for large projects, and have been in each major test.

As an example, it has been known for many years that fluid injections into low-permeability systems can induce earthquakes small and large.[45] It is also known that while injection of fluids into permeable systems can induce earthquakes, even with large injection volumes the risk of large earthquakes is extremely low. The best example is a set of field tests conducted at Rangely oilfield in NW Colorado, where an aggressive water-injection program began in an attempt to initiate and control seismic events.[46] Despite large injections, the greatest moment magnitude measured as M_L 3.1. Since that time, over 28 million tons of CO_2 have been injected into Rangely with limited seismicity, no large seismic events, and no demonstrable leakage.[47] These studies make clear that injections of much smaller volumes would produce no seismicity. Thus to ascertain the risk associated with large injections requires large injection, as do the processes and effects of reservoir heterogeneity on plume distribution or the response of fractures to pressure transients.

LARGE SCALE DEMONSTRATIONS AS CENTRAL SHORT-TERM OBJECTIVE

Ultimately, large-scale injections will require large volumes of CO_2 to ensure that injection transients approach or exceed key geological thresholds. The definition of large-scale depends on the site since local parameters vary greatly. In highly permeable, continuous rock bodies (e.g., Frio Fm. or Utsira Fm.), at least one million tons/yr may be required to reach these thresholds; in low permeability (e.g., Weber Sandstone or Rose Run Fm.) or highly segmented reservoirs, only a few 100,000 tons/year may be required. A large project would likely involve multiple wells and substantial geological complexity and reservoir heterogeneity (like In Salah and Weyburn). To observe these effects would likely require at least 5 years of injection with longer durations preferred.

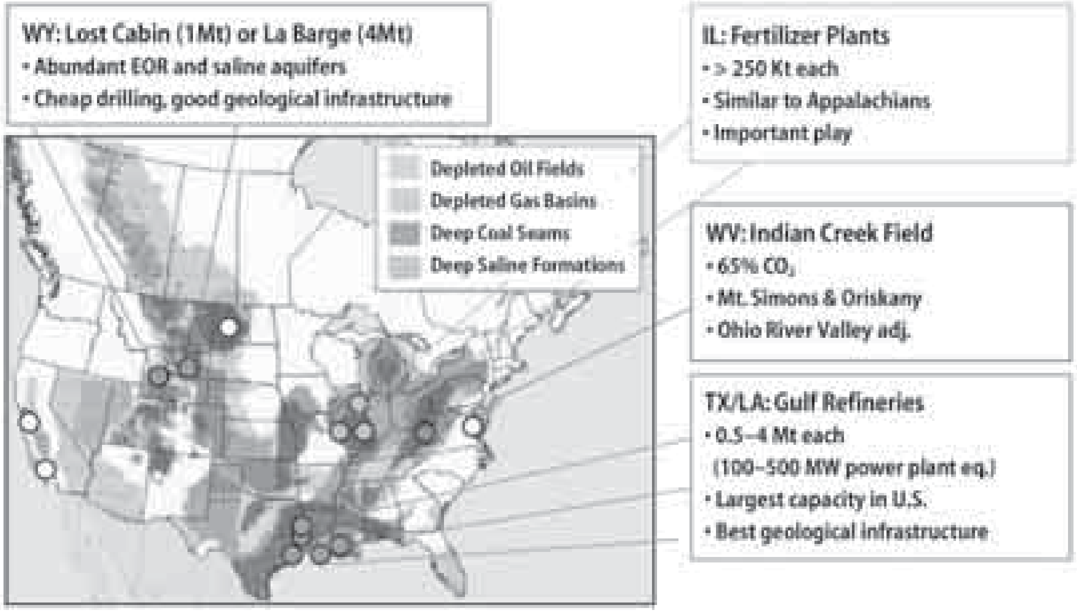
Because of the financial incentives of additional production, CO_2-EOR will continue to provide early opportunities to study large-scale injection (e.g., Weyburn). However, the overwhelming majority of storage capacity remains in saline formations, and there are many parts of the country and the world where EOR options are limited. Since saline formations will be central to substantial CO_2 emissions reduction, a technical program focused on understanding the key technical concerns of saline formations will be central to successful commercial deployment of CCS.

Costs for the large projects are substantial. For phase I, the Weyburn project spent $27 million, but did not include the costs of CO_2 or well drilling in those costs. Because of cost constraints, the Weyburn project did not include important monitoring and scientific studies. The cost of CO_2 supply could be low if one assumes that the CO_2 supply were already concentrated (e.g., a fertilizer or gas processing stream) and compression would be the largest operating cost. If CO_2 required market purchase (e.g., from KinderMorgan pipelines into the Permian Basin), then a price of $20/ton CO_2 would represent a likely upper cost limit. Total cost would include compression costs, well count, reworking requirements, availability of key data sets, and monitoring complement. **Based on these types of consideration, an eight-year project could achieve key technical and operational goals and deliver important new knowledge for a total cost between $100–225 million, corresponding to an annual cost roughly between $13–28 million.** A full statement of the assumption set and calculation is presented in Appendix 4.C.

In sum, a large well-instrumented sequestration project at the necessary scale is required to yield the important information. However, only a small number of projects are likely to be required to deliver the needed insights for the most important set of geological injection conditions. For example, in the US only 3-4 sites might be needed to demonstrate and parameterize safe injection. These sites could include one project in the Gulf Coast, one in the central or northern Rocky Mountains, and one in either the Appalachian or Illinois basins (one could consider adding a fourth project in California, the Williston, or the Anadarko basins). This suite would cover an important range of population densities, geological and geophysical conditions, and industrial settings (Figure 4.4). More importantly, these 3–4 locations and their attendant plays are associated with large-scale current and planned coal-fired generation, making their parameterization, learning, and ultimate success important.

The value of information derived from these studies relative to their cost would be enormous. Using a middle cost estimate, all three

Figure 4.4 Prospective Sites for Large-scale Sequestration Projects



Draft suggestions for 4 large UC storage projects using anthropogenic CO_2 sources. Basemap of sequestration targets from Dooley et al., 2004.

basins could be studied for $500 million over eight years. Five large tests could be planned and executed for less than $1 billion, and address the chief concerns for roughly 70% of potential US capacity. Information from these projects would validate the commercial scalability of geological carbon storage and provide a basis for regulatory, legal, and financial decisions needed to ensure safe, reliable, economic sequestration.

The requirements for sequestration pilot studies elsewhere in the world are similar. The number of projects needed to cover the range of important geological conditions around the world to verify the storage capacity is of order 10. Using the screening and selection parameters described in Appendix 4.C, we believe that the world could be tested for approximately a few billion dollars. The case for OECD countries to help developing nations test their most important storage sites is strong; the mechanisms remain unresolved and are likely to vary case to case.

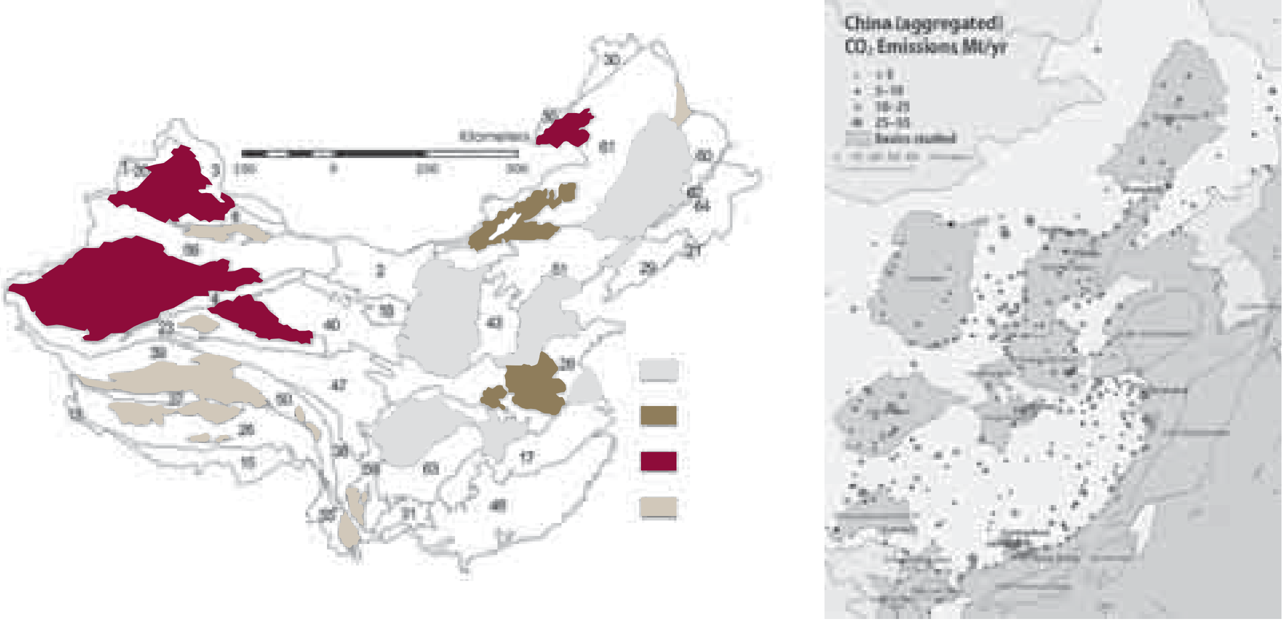
DEVELOPING COUNTRIES

Developing nations, particularly China and India, will grow rapidly in the coming decades with an accompanying rapid growth in energy demand. Both countries have enormous coal reserves, and have plans to greatly increase national electrification with coal power. Projections for CO_2 emissions in both countries grow as a consequence, with the possibility that China will become the world's largest CO_2 emitter by 2030. Therefore it is important to know what sequestration options exist for both nations.

China

The geological history of China is immensely complicated.[48,49] This history has produced 28 onshore sedimentary basins with roughly 10 large offshore basins (Figure 4.5). This presents a substantial task in geological assessment. However, many of these basins (e.g., Tarim, Junggar basins) are not near large CO_2 point sources or population centers and do not represent an assessment priority. Six on

Figure 4.5 Prospective CO_2 Storage Basins in China



LEFT: Tectonic map of onshore China; all colored areas are sedimentary basins. Yellow represent high priority for assessments; green represent second tier; blue represent third tier; fourth tier are purple. Ranking is based on closeness to CO_2 point sources, presence of hydrocarbons, and complexity of geology. (Map courtesy of Stanford University.) RIGHT: East China onshore and offshore basins with annual CO_2 emissions.[52]

shore and two offshore basins with relatively simple geological histories lie in the eastern half of China,[50] close to coal sources, industrial centers, and high population densities. These are also the basins containing the largest oilfields and gas fields in China.[51] Preliminary assessment suggests that these basins have prospectivity.[52] The initial estimates are based on injectivity targets of 100 mD, and continued assessment will change the prospectivity of these basins.

There are a number of active sequestration projects in China. RIPED, CNPC, and other industrial and government entities are pursuing programs in CO_2-EOR. These are driven by economic and energy security concerns; continued study will reveal the potential for storage in these and other fields. Some western companies are also pursuing low-cost CO_2 projects; Shell is investigating a large CO_2 pilot, and Dow has announced plans to sequester CO_2 at one of its chemical plants. There is a 192 tonne Canadian-Chinese ECBM project in the Quinshui basin. However, there is much greater potential for very large CO_2 storage tests using low-cost sources. China has many large coal gasification plants, largely for industrial purposes (e.g., fertilizer production, chemical plants). A number of these plants vent pure streams well in excess of 500,000 tons/y, and many are located within 150 km of viable geological storage and EOR targets.[53]

A program to determine the viability of large-scale sequestration in China would be first anchored in a detailed bottom-up assessment. The data for assessments exists in research institutions (e.g., RIPED, the Institute of for Geology and Geophysics) and the long history of geological study and infrastructure[54,55] suggests that Chinese teams could execute a successful assessment in a relatively short time, which could be followed by large injection tests. Given the central role of China's emissions and economy in the near future and the complexity of its geology, this should involve no less than two large projects. One might target a high-value, high chance of success opportunity (e.g., Bohainan basis; Songliao). Another might target lower permeability, more complicated targets (e.g., Sichuan or Jianghan basin). In all cases, large projects do not need to wait for the development of IGCC plants, since there is already enormous gasification capacity and large pure CO_2 streams near viable targets. As with any large target, a ranking of prospects and detailed geological site characterization would be key to creating a high chance of project success.

India

Geologically, India is a large granitic and metamorphic massif surrounded by sedimentary basins. These basins vary in age, complexity, and size. The largest sedimentary basin in the world (the Ganga basin) and one of the largest sedimentary accumulations (the Bengal fan) in India are close to many large point sources. In addition, a large basaltic massif (the Deccan Traps) both represents a potential CO_2 sink and also overlies a potential CO_2 sink (the underlying basins).

Currently, there is one CO_2 storage pilot planned to inject a small CO_2 volume into basalts. There are currently no plans for a detailed assessment or large-scale injection program. However, the IEA has announced a program to conduct an assessment. Many governmental groups have relevant data, including the Directorate General for Hydrocarbons, the Geological Survey of India, and the National Geophysical Research Institute. Several companies appear well equipped to undertake such work, including the Oil and Natural Gas Company of India. Despite the Indian government's involvement in the CSLF and FutureGen, it has not yet made the study of carbon sequestration opportunities a priority.

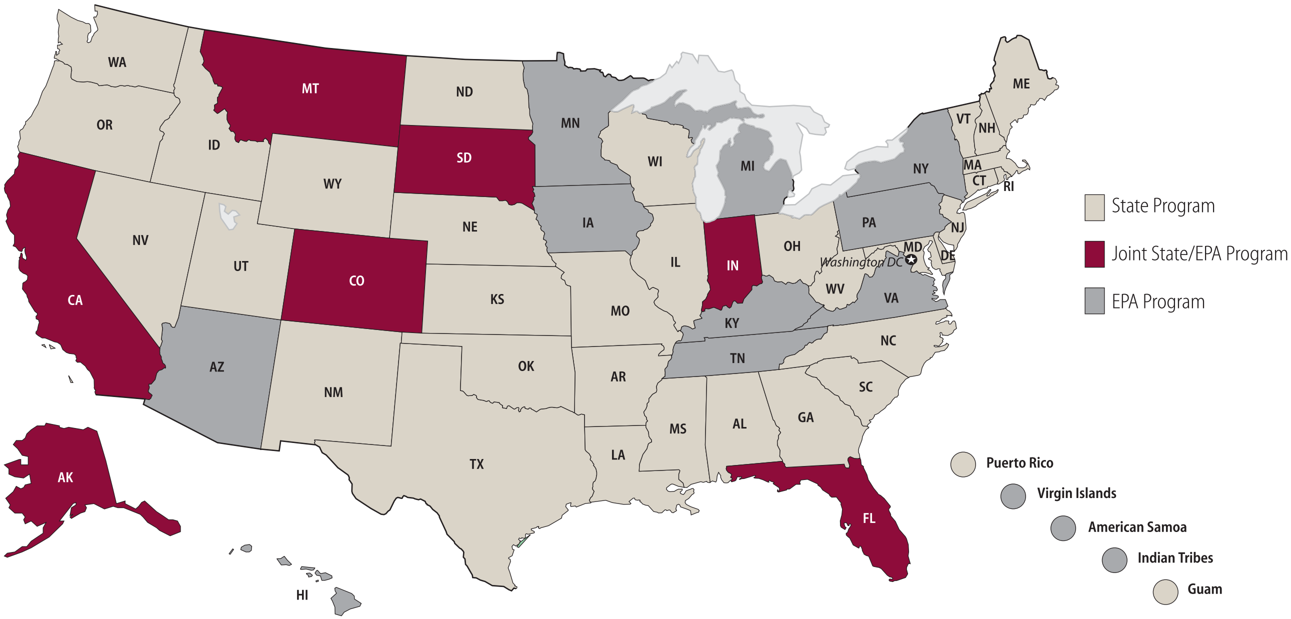
CURRENT REGULATORY STATUS

At present, there is no institutional framework to govern geological sequestration of CO_2 at large scale for a very long period of time. At a minimum, the regulatory regime needs to cover the injection of CO_2, accounting and crediting as part of a climate regime, and site closure and monitoring. In the United States, there does exist regulations for underground injections (see discussion below), but there is no category specific to CO_2 sequestration. A regulatory capacity must be built, whether from the existing EPA underground injection program or from somewhere else. *Building a regulatory framework for CCS should be considered a high priority item.* The lack of a framework makes it more difficult and costly to initiate large-scale projects and will result in delaying large-scale deployment

In the United States, there is a body of federal and state law that governs underground injection to protect underground sources of drinking water. Under authority from the Safe Drinking Water Act, EPA created the Underground Injection Control (UIC) Program, requiring all underground injections to be authorized by permit or rule and prohibiting certain types of injection that may present an imminent and substantial danger to public health. Five classes of injection wells have been set forth in the regulations, none specific to geological sequestration. A state is allowed to assume primary responsibility ("primacy") for the implementation and enforcement of its underground injection control program if the state program meets the requirements of EPA's UIC regulations. As shown in Figure 4.6, thirty-three states have full primacy over underground injection in their state, seven states share responsibility with EPA, and ten states have no primacy. A state program may go beyond the minimum EPA standards; in Nevada, for example, injection is not allowed into any underground aquifer regardless of salinity, which negates a potential sequestration option (Nevada Bureau of Mines and Geology, 2005).

The UIC achieves its primary objective of preventing movement of contaminants into potential sources of drinking water due to injection activities, by monitoring contaminant concentration in underground sources of drinking water. If traces of contaminants

Figure 4.6 Current State and EPA Underground Injection Control Programs



Source: EPA

are detected, the injection operation must be altered to prevent further pollution.

There are no federal requirements under the UIC Program to track the migration of injected fluids within the injection zone or to the surface.[56] Lack of fluid migration monitoring is problematic when the UIC regulatory regime is applied to geological sequestration. For example, one source of risk for carbon sequestration is that injected CO_2 potentially leaks to the surface through old oil and gas wells. For various reasons, such as existing infrastructure and proved cap rock, the first geological sequestration projects in the US will likely take place at depleted oil and gas fields. These sites possess numerous wells, some of which can act as high permeability conduits to the surface. Plugs in these wells may be lacking, poor, or subject to corrosion from CO_2 dissolved in brine. The presence of wells at sequestration sites greatly increases the chance for escape of injected gas. Regulations will be needed for the particular circumstance of CO_2 storage. This will involve either modification of the UIC regulations or creation of a new framework.

Unlike onshore geological sequestration, which is governed by national law, offshore geological sequestration is governed by international law. Offshore sequestration has not been specifically addressed in any multilateral environmental agreements that are currently in force, but may fall under the jurisdiction of international and regional marine agreements, such as the 1972 London Convention, the 1996 Protocol to the London Convention, and the 1992 OSPAR Convention. Because these agreements were not designed with geological sequestration in mind, they may require interpretation, clarification, or amendment by their members. Most legal scholars agree that there are methods of offshore sequestration currently compatible with international law, including using a land-based pipeline transporting CO_2 to the sub-seabed injection point and injecting CO_2 in conjunction with offshore hydrocarbon activities.[57]

LIABILITY

Liability of CO_2 capture and geological sequestration can be classified into **operational liability** and **post-injection liability**.

Operational liability, which includes the environmental, health, and safety risks associated with carbon dioxide capture, transport, and injection, can be managed within the framework that has been successfully used for decades by the oil and gas industries.

Post-injection liability, or the liability related to sequestered carbon dioxide after it has been injected into a geologic formation, presents unique challenges due to the expected scale and timeframe for sequestration. The most likely sources of post-injection liability are groundwater contamination due to subsurface migration of carbon dioxide, emissions of carbon dioxide from the storage reservoir to the atmosphere (i.e., non-performance), risks to human health, damage to the environment, and contamination of mineral reserves. Our understanding of these risks needs to be improved in order to better assess the liability exposure of operators engaging in sequestration activities.

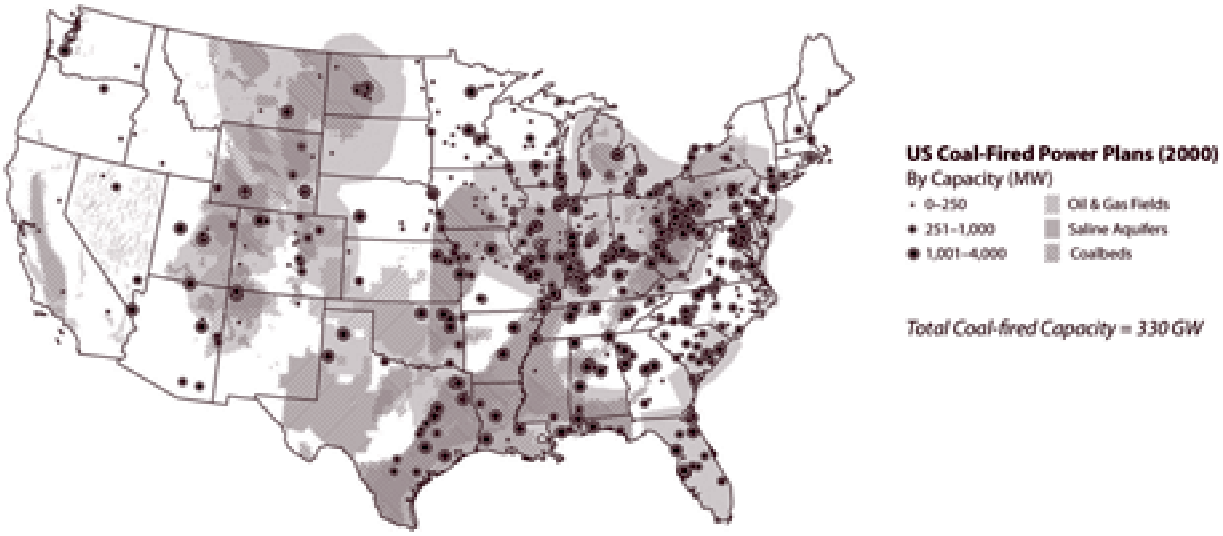
In addition, a regulatory and liability framework needs to be adopted for the closing of geological sequestration injection sites. The first component of this framework is monitoring and verification. Sequestration operations should be conducted in conjunction with modeling tools for the post-injection flow of carbon dioxide. If monitoring validates the model, a limited monitoring and verification period (5-10 years) after injection operations may be all that is required, with additional monitoring and verification for exceptional cases. The second component of the framework defines the roles and financial responsibilities of industry and government after abandonment. A combination of a funded insurance mechanism with government back-stop for very long- term or catastrophic liability will be required. Financial mechanisms need to be considered to cover this responsibility. There are a number of ways in which the framework could proceed. For example, in the case of nuclear power, the Price-Anderson Act requires that nuclear power plant licensees purchase the maximum amount of commercial liability insurance available on the private market and participate in a joint-insurance pool. Licensees are not financially responsible for the cost of any accident exceeding these two layers of insurance. Another example would be the creation of a fund with mandatory contributions by injection operators. We suggest that industry take financial responsibility for liability in the near-term, i.e. through injection phase and perhaps 10-20 years into the post-injection phase. Once certain validation criteria are met, government would then assume financial responsibility, funded by industry insurance mechanisms, and perhaps funded by set-asides of carbon credits equal to a percentage of the amount of CO_2 stored in the geological formation.

SEQUESTRATION COSTS

Figure 4.7 shows a map of US coal plants overlayed with potential sequestration reservoirs. The majority of coal-fired power plants are situated in regions where there are high expectations of having CO_2 sequestration sites nearby. In these cases, the cost of transport and injection of CO_2 should be less than 20% of total cost for capture, compression, transport, and injection.

Transportation for commercial projects will be via pipeline, with cost being a function of the distance and quantity transported. As shown in Figure 4.8, transport costs are highly non-linear for the amount transported, with economies of scale being realized at about 10 Mt CO_2/yr. While Figure 4.8 shows typical values, costs can be highly variable from project to project due to both physical (e.g., terrain pipeline must traverse) and political considerations. For a 1 GW_e coal-fired power plant, a pipeline must carry about 6.2 Gt CO_2/yr (see footnote 1). This would result in a pipe diameter of about 16 inches and a transport cost of about \$1/tCO_2/100 km. Transport costs can be lowered through the development of pipeline networks as opposed to dedicated pipes between a given source and sink.

Figure 4.7 Location of Coal Plants Relative to Potential Storage Sites



Map comparing location of existing coal-fired power plants in the US with potential sequestration sites. As stated earlier in the report, our knowledge of capacity for sequestration sites is very limited. Some shaded areas above may prove inappropriate, while detailed surveys may show sequestration potential in places that are currently not identified.

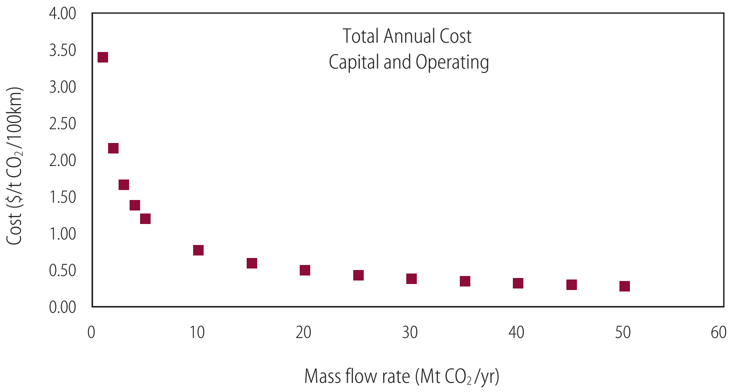
Costs for injecting the CO_2 into geologic formations will vary on the formation type and its properties. For example, costs increase as reservoir depth increases and reservoir injectivity decreases (lower injectivity results in the drilling of more wells for a given rate of CO_2 injection). A range of injection costs has been reported as \$0.5-8/tCO_2.[6] Costs will also vary with the distance transported, the capacity utilization of the pipe, the transport pressure and the costs of compression (which also produces CO_2).

It is anticipated that the first CCS projects will involve plants that are very close to a sequestration site or an existing CO_2 pipeline. As the number of projects grow, regional pipeline networks will evolve. This is similar to the growth of existing regional CO_2 pipeline networks in west Texas and in Wyoming to deliver CO_2 to the oil fields for EOR. For example, Figure 4.7 suggests that a regional pipeline network may develop around the Ohio River valley, transporting much larger volumes of CO_2.

RECOMMENDATIONS

Our overall judgment is that the prospect for geological CO_2 sequestration is excellent. We base this judgment on 30 years of injection experience and the ability of the earth's crust to trap CO_2. That said, there remain substantial open issues about large-scale deployment of carbon sequestration. Our recommendations aim to address the largest and most important of these issues. Our recommendations call for action by the U.S. government; however, many of these recommendations are appropriate for OECD and developing nations who anticipate the use CCS.

Figure 4.8 Cost for CO_2 Transport Via Pipeline as a Function of CO_2 Mass Flow Rate



1. The US Geological Survey and the DOE, and should embark of a 3 year "bottom-up" analysis of US geological storage capacity assessments. This effort might be modeled after the GEODISC effort in Australia.
2. The DOE should launch a program to develop and deploy large-scale sequestration demonstration projects. The program should consist of a minimum of three projects that would represent the range of US geology and industrial emissions with the following characteristics:
    - Injection of the order of 1 million tons CO_2/year for a minimum of 5 years.
    - Intensive site characterization with forward simulation, and baseline monitoring
    - Monitoring MMV arrays to measure the full complement of relevant parameters. The data from this monitoring should be fully integrated and analyzed.
3. The DOE should accelerate its research program for CCS S&T. The program should begin by developing simulation platforms capable of rendering coupled models for hydrodynamic, geological, geochemical, and geomechanical processes. The geomechanical response to CO_2 injection and determination or risk probability-density functions should also be addressed.
4. A regulatory capacity covering the injection of CO_2, accounting and crediting as part of a climate regime, and site closure and monitoring needs to be built. Two possible paths should be considered — evolution from the existing EPA UIC program or a separate program that covers all the regulatory aspects of CO_2 sequestration.
5. The government needs to assume liability for the sequestered CO_2 once injection operations cease and the site is closed. The transfer of liability would be contingent on the site meeting a set of regulatory criteria (see recommendation 4 above) and the operators paying into an insurance pool to cover potential damages from any future CO_2 leakage.

CITATIONS AND NOTES

1. From a technical perspective, ocean sequestration appears to be promising due to the ocean's capacity for storage (IPCC 2005). Presently, because of concerns about environmental impacts, ocean sequestration has become politically unacceptable in the US and Europe.
2. Terrestrial storage, including storage in soils and terrestrial biomass, remains attractive on the basis of ease of action and ancillary environmental benefits. However, substantial uncertainties remain regarding total capacity, accounting methodology, unforeseen feedbacks and forcing functions, and permanence.
3. Pacala, S., and Socolow, R., Stabilization Wedges: Solving the Climate Problem for the Next 50 Years Using Current Technologies, *Science*, 2004, v.305, pp. 986
4. US Dept. of Energy, Climate Change Technology Program Strategic Plan, 2005, Washington, 256 p. http://www.climatetechnology.gov/
5. A 1000 MW bituminous pulverized coal plant with 85% capacity factor and 90% efficient capture would produce a CO_2 stream mass of 6.24 million t/yr. If injected at 2 km depth with a standard geothermal gradient, the volume rate of supercritical CO_2 would be 100,000 barrels/day (for comparison, the greatest injection rate for any well in the world is 40,000 bbl/d, and typical rates in the US are <3000 bbl/d). This suggests that initially either multiple long-reach horizontal wells or tens of vertical wells would be required to handle the initial volume. Over 50 years, the lifetime typical of a large coal plant, this would be close to 2 billion barrels equivalent, or a giant field for each 1000 MW plant.
6. Intergovernmental Panel on Climate Change, IPCC Special Report on Carbon Dioxide Capture and Storage, 2005, Interlachen, http://www.ipcc.ch/
7. Bachu S., Sequestration of Carbon Dioxide in Geological Media: Criteria and Approach for Site Selection, *Energy Conversion and Management*, 2000, v.4, pp. 970
8. Stevens, S. 1999. *Sequestration of CO_2 in Depleted Oil and Gas Fields: Barriers to Overcome in Implementation of CO_2 Capture and Storage (Disused Oil and Gas Fields)* IEA Greenhouse Gas R&D Programme, IEA/CON/98/31.
9. Oldenburg, C.M., S.H. Stevens, and S.M. Benson, Economic feasibility of carbon sequestration with enhanced gas recovery (CSEGR), *Energy*, 29,1413–1422, 2004 LBNL-49762
10. Jarrell, PM, CE Fox, MH Stein, SL Webb, *Practical Aspects of CO_2 flooding*. Monograph 22. Society of Petroleum Engineers, Richardson, TX, USA., 2002
11. Johnson, J.W., Nitao, J.J., Knauss, K.G., *Reactive transport modeling of CO2 storage in saline aquifers to elucidate fundamental processes, trapping mechanisms, and sequestration partitioning*, in R. Gieré & P. Stille (eds.), *Energy, Waste, and the Environment - A Geochemical Perspective*. Geological Society of London, Special Publication, 2004
12. Johnson, J.W., Nitao, J.J., Morris, J.P., *Reactive transport modeling of cap rock integrity during natural and engineered CO_2 storage*, in S. Benson (ed.), *CO_2 Capture Project Summary Volume* (2), Elsevier, 2005

13. Bergman, PD, and Winter, EM, Disposal of carbon dioxide in aquifers in the US, *Energy Conversion & Management*, 1995, v.36, pp. 523.

14. Dooley, JJ, and Friedmann, S.J., A regionally disaggregated global accounting of CO_2 storage capacity: data and assumptions, Pacific Northwest National Laboratory, Report PNWD-3431, 2004

15. Gibson-Poole CM, Lang SC, Streit JE, Kraishan GM, Hillis RR, Assessing a basin's potential for geological sequestration of carbon dioxide: an example from the Mesozoic of the Petrel Sub-basin, NW Australia; Keep, M. & Moss, S.J. (eds). *The Sedimentary Basins of Western Australia 3*: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 2002, pp. 439

16. Bradshaw J, Allison G, Bradshaw BE, Nguyen V, Rigg AJ, Spencer L, Wilson, P., Australia's CO_2 Geological storage potential and matching of emission sources to potential sinks. In: Greenhouse gas control technologies: Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1–4 October 2002, Kyoto, 2003

17. Carbon Sequestration Leadership Forum, Discussion Paper on Capacity Estimation, Technical Working Group, Olveida, Spain, 2005. http://www.cslforum.org/presentations.htm

18. Friedmann, S.J., Dooley, J.J., Held, H., Edenhofer, O., The low cost of geological assessment for underground CO_2 storage: Policy and economic implications, *Energy Conversion Management*, in press

19. US Dept. of Energy, Carbon Sequestration Technology Roadmap and Program Plan for 2006, Morgantown, WV, 2006, 39p.

20. *Injectivity* is the rate at which CO_2 injection may be sustained over fairly long intervals of time (months to years); *Capacity* is the total volume of potential CO_2 storage CO_2 at a site or in a formation; *Effectiveness* is the ability of the formation to store the injected CO_2 well beyond the lifetime of the project.

21. Friedmann SJ, The ICE framework for CO_2 storage site characterization, NETL 5th Annual Conference on Carbon Sequestration, Alexandria, VA, ExchangeMonitor Publications, 2006

22. Arts, R., O. Eiken, A. Chadwick, P. Zweigel, L. van der Meer, B. Zinszner, Monitoring of CO_2 injected at Sleipner using time-lapse seismic data, 2004, *Energy*, v.29, pp. 1383

23. Wilson M, Monea M. (Eds.), IEA GHG Weyburn CO_2 Monitoring & Storage Project Summary Report 2000-2004, 2004, 273 p.

24. Riddiford, F, Wright, I, Espie, T, and Torqui, A, 2004, Monitoring geological storage: In Salah Gas CO_2 Storage Project, GHGT-7, Vancouver

25. Benson SM, M Hoversten, E Gasperikova, M Haines, 2004, Monitoring Protocols and life-Cycle costs for Geological Storage of carbon Dioxode, GHGT-7, Vancouver

26. Hoversten, G. M., Gritto, G., R.; Daily, T.; Washbourne, J., 2002, Fluid saturation and pressure prediction in a multicomponent reservoir by combined seismic and electromagnetic imaging SEG Expanded Abstracts 1770-1773

27. Ramirez, A, and 8 others, 2005, Stochastic inversion of electrical resistivity changes using a Markov Chain Monte Carlo approach, Journal of Geophysical Research, v. 110, B02101

28. Herzog, H., K. Caldeira and J. Reilly, "An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage," *Climatic Change*, Vol. 59, No. 3, pp 293-310, August (2003).

29. Snodgrass, WR, Physiological and biochemical differences between children and adults as 5 determinants of toxic exposure to environmental pollutants. In *Similarities and differences between children and adults: Implications for risk assessment*. Guzelain, P.S., C.J. Henry, S.S. Olin (eds.), ILSI Press, Washington, DC, USA., 1992

30. National Institute for Occupational Safety and Health (NIOSH): Pocket Guide to Chemical Hazards. DHHS publication no. 97-140. US Government Printing Office, Washington, 25 DC, USA, 1997

31. Rice, SA. Human health risk assessment of CO_2: survivors of acute high-level exposure and 40 populations sensitive to prolonged low level exposure. Poster 11-01 presented at 3rd Annual conference on carbon sequestration, 3-6 May 2004, Alexandria, VA, USA.

32. Knauss, KG , JW Johnson, YK Kharaka, Preliminary Reactive Transport Modeling and Laboratory Experiments Conducted in Support of the Frio Pilot Test, NETL 4th Annual Conference on Carbon Sequestration, 2005, Alexandria VA, ExchangeMonitor

33. Bradshaw, J, Boreham, C, and la Pedalina, F., 2004, Storage retention time of CO_2 in sedimentary basins; examples from petroleum systems, GHGT-7, Vancouver

34. Gasda, S.E., S. Bachu, and M.A. Celia, "The Potential for CO_2 Leakage from Storage Sites in Geological Media: Analysis of Well Distribution in Mature Sedimentary Basins", *Environmental Geology*, *46* (6-7), 707-720, 2004.

35. Scherer, G.W., M.A. Celia, J.H. Prevost, S. Bachu, R. Bruant, A. Duguid, R. Fuller, S.E. Gasda, M. Radonjic, and W. Vichit-Vadakan, "Leakage of CO_2 through Abandoned Wells: Role of Corrosion of Cement", in *The CO_2 Capture and Storage Project (CCP), Volume II*, D.C. Thomas and S.M. Benson (Eds.), 823-844, 2005

36. Gouveia, F.J., M. Johnson, R.N. Leif, S.J. Friedmann, 2005: Aerometric measurement and modeling of the mass of CO_2 emissions from Crystal Geyser, Utah; NETL 4th Annual CO_2 sequestration conference, Alexandria

37. Kling, MA Clark, HR Compton, JD Devine, WC Evans, AM Humphrey, EJ Doenigsberg, .P Lockword, ML Tuttle and GW Wagner,: The lake gas disaster in Cameroon, West Africa, *Science*, 1987, v.236, 4798, pp. 169–175

38. Lee, AM, 2001: The Hutchinson Gas Explosions: Unravelling a Geologic Mystery, Kansas Bar Association, 26th Annual KBA/KIOGA Oil and Gas Law Conference, v1, p3-1 to 3-29.

39. Dooley JJ, Dahowski RT, Davidson CL, Wise MA, Gupta N, Kim SH, Malone EL, 2006, Carbon dioxide capture and geologic storage: A core technology element of a global technology strategy to address climate change, GTSP Technology Report, www.battelle.org/gtsp

40. Pruess, K, J Garcıa, T Kovscek, C Oldenburg, J Rutqvist, C Steefel, T Xu, Code intercomparison builds confidence in numerical simulation models for geologic disposal of CO_2, *Energy*, 2004, v29, pp 1431–1444.

41. Ide, ST., SJ Friedmann, HJ Herzog, 2006, CO_2 Leakage through Existing Wells: Current Technology and Regulations, 8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway.

42. Gale, J. (2004), "Geological storage of CO_2: What do we know, where are the gaps and what more needs to be done?" *Energy* 29, 1329-1338

43. Hovorka SD, Collins D, Benson S, Myer L, Byrer C, Cohen K, Update on the Frio Brine Pilot: Eight months after injection, 4th Annual Conference on Carbon Capture and Sequestration, Alexandria, Virginia May 2–5, 2005

44. Shinichi Sakurai, T. S. Ramakrishnan, Austin Boyd, Nadja Mueller, Tom Daley, Mike Hoversten, John Peterson, Integrated Evaluation for Measuring, Monitoring, and Verifying CO_2 Distribution, 4th Annual Conference on Carbon Capture and Sequestration, Alexandria, Virginia May 2–5, 2005

45. Healy, JH, Griggs DT, Rubey WW, Coakley JM, 1968, Science, v. 161, 1301

46. Raleigh, C, JH Healy, JD Bredehoeft, 1976, An experiment in earthquake control at Rangely, Colorado, Science, v. 191, 1230-1237

47. Klusman, R.W. 2003b. Rate measurements and detection of gas microseepage to the atmosphere from an enhanced oil recovery/sequestration project, Rangely, Colorado, USA. App. Geochem., 18, 1825-1838

48. Carroll, AR, Graham, SA, Hendrix, MS, Ying, D, Zhou, D, 1995, Late Paleozoic tectonic amalgamation of northwestern China; sedimentary record of the northern Tarim, northwestern Turpan, and southern Junggar basins, *GSA Bulletin*; May 1995; v. 107; no. 5; p. 571-594

49. Gilder, S. and 9 others, 1996, isotopic and paleomagnetic constraints on the Mesozoic tectonic evolution of south China, Journal of Geophysical Research, Volume 101, Issue B7, p. 16137-16154

50. Quanmao, C., and Dickinson, W., 1986, Contrasting nature of petroliferous Mesozoic/Cenozoic basins in Eastern and Western China, AAPG bulletin, v70, p 263-275

51. Desheng, L, 1984, Geological evolution of petroliferous basins on continental shelf of China, AAPG Bulletin, v68, p 993-1003

52. Newlands, I.K., Langford, R., 2005. CO_2 Storage Prospectivity of Selected Sedimentary Basins in the Region of China and South East Asia, Geoscience Australia, Record 2005/13. 223 p

53. Meng K, Celia M, Williams RH, 2005, Opportunities for Low-Cost Carbon Capture and Storage Demonstration Projects in China, , 4th Annual Conference on Carbon Capture and Sequestration, Alexandria, Virginia May 2–5, 2005

54. Zhai G. 1997, Petroleum Geology of China, 680 p.

55. Zhang W, Yan D., 1993, Petroleum Geology of China-Bohai Gulf Basin, v.1 of 20, 157p.

56. Wilson E, Johnson T, and Keith D, 2003: Regulating the ultimate sink: managing the risks of geologic CO_2 storage, Envtl. Sci. Tech. 37: 3476-3483.

57. International Energy Agency, Legal Aspects of Storing CO_2 (2005).

Chapter 5 — Coal Consumption in China and India

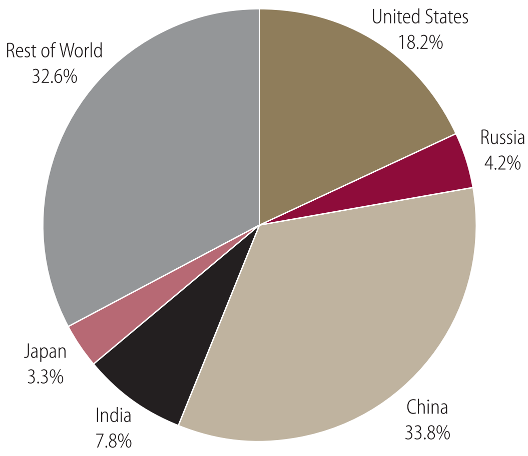
INTRODUCTION

China is expected to account for more than half of global growth in coal supply and demand over the next 25 years. The implications for the global environment are both complex and substantial. This chapter explores the circumstances under which China might constrain its carbon emissions from coal significantly below the currently forecast range. India, with a population comparable to that of China, a rapidly growing economy, and large domestic coal reserves, may one day come to rival China as a source of carbon emissions from coal. Like China, India derives over half of its commercial energy from coal, and together the two countries are projected to account for over 68% of the incremental demand in world coal through 2030.[1] Today, however, India consumes only about a fifth as much coal as its neighbor, and for the foreseeable future the consumption gap between the two countries will remain wide. The main focus of this chapter is thus on China, but in the final section we briefly compare patterns of coal use in the two countries.

Coal is today China's most important and abundant fuel, accounting for about two thirds of the country's primary energy supply. Coal output in China rose from 1. 30 billion tonnes in 2000 to 2. 23 billion tonnes in 2005,[2] making China by far the world's largest coal producer (the next largest, the United States, produced 1.13 billion tonnes last year). All but a few percent of this coal is consumed domestically, and China's coal use amounts to nearly a third of all coal consumed worldwide (see Figure 1). Electricity generation accounts for just over half of all coal utilization in China, having risen from 22% of total consumption in 1988 to over 53% in 2002.[3] Coal currently accounts for about 80% of China's electricity generation, more than 50% of industrial fuel utilization, and about 60% of chemical feedstocks. Forty-five percent of China's national railway capacity is devoted to the transport of coal.[4] The central government has announced its intention to reduce the country's reliance on coal, but for the foreseeable future it will remain China's dominant fuel, and will very likely still account for more than half of the country's primary energy supplies in the year 2030. The largest contributor to future growth in China's demand for coal will be the electric power sector.

The recent growth of the Chinese power sector has been dramatic. Electricity generation grew at a rate of 15.2% in 2003, 14.8% in 2004, 12.3% in 2005, and 11.8% (on an annual basis) in the first quarter of 2006.[5] Total generating capacity increased by nearly a third in the last three years and is expected to double between 2002 and 2007. In 2005, about 70,000 MWe of new generating capacity was brought into service. A similar completion of new plants is projected for each of the next two years.[6] At this rate, China is adding the equivalent of nearly the entire UK power grid each year. Most of the existing and new generating capacity is fueled with coal, and China's coal-fired power plants are the main cause of the rapid increase in its greenhouse gas emissions, which are already the world's second largest after the United States.

Figure 5.1 World Coal Consumption, 2004



Source: Energy Information Administration, International Energy Page (Table Posted July 12, 2006)

Chinese energy statistics—including those pertaining to coal consumption and power generation—suffer serious problems of reliability. Data reported by both official and unofficial sources exhibit substantial variation and numerous inconsistencies. Indeed, different figures for annual coal consumption are noted in this chapter and in Chapter Two. But there is no dispute about the general trend exhibited by the data: Chinese energy consumption is trending rapidly upward.

The supercharged recent growth rates in the power sector may moderate in coming years, but the general trend of strong growth is likely to continue for a long time to come. Electricity consumption per capita in China, at about 1,700 kilowatt hours per year, is still only 20% of the average per capita consumption in the world's advanced economies. Rapid economic development is changing the lifestyles and energy needs of hundreds of millions of Chinese citizens. Future demand growth on a large scale seems assured.

A full understanding of China's current energy situation—including the types of fuels being consumed, the kinds of technologies employed, the effectiveness of environmental regulation, and the international reach of its enterprises—starts with three key characteristics of the Chinese system.

- *First, especially at the national level, China's energy-related governmental bureaucracy is highly fragmented and poorly coordinated.* Responsibility for energy pricing, for the approval of infrastructure projects, for the oversight of state energy companies, and for long-term energy policy is spread across many agencies, most of them seriously understaffed, and some of which—given their very recent emergence on the scene—are notably weak in relation both to other agencies and to the players they are supposed to be regulating.

- *Second, under these conditions the state energy companies—the national oil corporations and the national power generating groups—are the most coherent entities.* These are the organizations that are most capable of defining their own interests and that are most likely to act, making decisions that their ostensible state regulators and overseers can barely keep up with and sometimes do not even monitor. At the same time, and reflecting China's increasingly deep integration with the global economy, these corporate entities are hardly simple organizations themselves. Listed on both domestic and foreign stock exchanges, the state energy corporations encompass complicated groupings of stakeholders, including state-appointed senior executives, domestic and foreign corporate board members, major financiers from the global investment banking community, and international institutional investors. Textbook examples of shareholder-driven corporate governance they are not, but neither are they simple puppets of the state—in no small part because the state itself is so fragmented and lacks a clear voice on energy policy. In essence, the central government in Beijing today has neither a coherent national energy strategy nor much capacity to monitor, support, or impede the actions of state-owned energy companies—actions that are often misunderstood by outsiders as merely echoing government policy.

- *Third, and most important, the remarkably rapid growth of energy consumption in China has been possible because a host of infrastructural issues are being resolved very quickly by individuals and organizations operating well below the level of national energy corporations.* Almost daily, actors at the grass roots level are making key decisions about China's physical and technological infrastructure—decisions with profound consequences for its long-term energy development.

Thus, it is a mistake to attribute China's aggregate energy demand growth—or even the actions of the state-owned energy companies—to central government agendas or geopolitical strategy. What many outsiders see as the deliberate result of Chinese national 'energy strategy' is in fact better understood as an agglomeration of *ad hoc* decisions by local governments, local power producers, and local industrial concerns. These local actors are primarily motivated by the need to maintain a high rate of economic growth and few, if any, have the national interest in mind. They are rushing to fill a void left by the absence of a coherent national-level energy strategy. Amidst surging energy demand and frenetic local decision-making, agencies and individuals in the central government are scrambling simply to keep abreast of developments on the ground. China's astonishingly rapid energy development may well be spinning the heads of outsiders, but it is vexing, perplexing, and even overwhelming to Chinese governmental insiders too.

METHODOLOGY

The main conclusions of this chapter are based upon fieldwork conducted in China by a team based at the MIT Industrial Performance Center beginning in 2002, but concentrated primarily in 2005. Our goal was to study decision-making in the Chinese power and coal industry sectors. The study primarily employed a case-based approach, supplemented by extensive interviews at various levels of Chinese governmental, academic, and commercial circles. The cases center primarily on the electric power sector and they were selected to represent three general modes of energy-related problem solving in the Chinese system: (1) relatively standard coal-fired power generation by municipal-level plants; (2) "within the fence" self-generation (co-generation) by industrial users or other commercial entities operating outside of what is generally understood as the energy sector; and (3) more future-oriented regional efforts by China's wealthiest coastal provinces to build a natural gas infrastructure.

(1) In the municipal power utility category, we focused our efforts on two sites, the 250 MWe Xiaguan Power Plant in Nanjing (Jiangsu Province) and the 1,275 MWe No. 1 Power Plant in Taiyuan (Shanxi Province). The Xiaguan facility, though formally owned by the national Datang Enterprise Group, is managed and administered primarily at the provincial and municipal levels. The facility is located in the downtown area of Nanjing, the capital of Jiangsu Province and a city of 1.8 million persons (the city has an additional 3.5 million suburban residents). Jiangsu, located on the east coast of China and encompassing much of the Yangtze River Delta, is among the most prosperous and industrialized regions of the country. Industry accounts for over 77% of provincial electricity consumption and (including the power sector) 92% of coal consumption, with residential following a distant second at 11% and 4.2%, respectively.[7] Jiangsu is a center for numerous clusters of domestic and foreign-owned manufacturing operations, and relies primarily on coal imported from interior regions of China to meet its needs. In 2003 about 79% of the province's total coal supply was imported.[8] Nanjing consumes one quarter of Jiangsu's electricity supply.

Nanjing's Xiaguan Power Plant dates originally from 1910, but underwent a substantial rebuild from 1998 to 2000. Approximately 30 percent of the rebuild costs were devoted to the installation of a LIFAC (<u>L</u>imestone <u>I</u>njection into <u>F</u>urnace and <u>A</u>ctivation of <u>C</u>alcium oxide) flue-gas desulfurization system. At the time of our research, three such systems were operating in China, two in the Nanjing facility and one in a 125 MWe power plant in neighboring Zhejiang Province. Xiaguan's system was supplied by the Finnish firm POCOTEC Pollution Control Technologies, and was financed by soft loans from the Finnish government and grants from the Jiangsu provincial government. The system produces no secondary wastewater, and the fly ash is used for road construction and cement production. The Xiaguan plant generally burns coal with a sulfur content of 1.0 to 1.5 percent. The LIFAC system has achieved a 75% sulfur removal rate, and for the first five years of operation averaged more than 95% availability. Though a loss maker commercially over the past three years—a condition not unusual for Chinese generators—the plant has become something of a model nationally for advanced emissions control.

The second case in this category, the No. 1 Power Plant on the outskirts of Taiyuan City, Shanxi Province, is a more typical facility along a number of dimensions. Taiyuan is the capital of Shanxi, a landlocked province in North China and the largest coal-producing region in the country, supplying 27% of China's coal in 2003.[9] Mining is far and away the largest industry in the province, though a concentration of traditional, state-owned heavy manufacturing is clustered in Taiyuan City. The province, among the poorest in China in terms of urban income, has gained notoriety as the center of some of the country's worst environmental problems, especially atmospheric pollution and acid rain. Approximately 70 percent of annual provincial production of energy resources are exported and sold to other provinces. Taiyuan City, with an urban population of about 2.3 million, consumes 40% of the province's electricity supply. The city is covered in soot and has been ranked as having the worst air quality (particulates and sulfur dioxide) of any city in the world.[10] In 2002, despite various regulatory efforts, reported average daily SO_2 concentrations in Taiyuan equaled 0. 2 milligrams per cubic meter (mg/m3), over three times the PRC's Class II annual standard (0. 06mg/m3).[11] The Taiyuan No. 1 Power Plant, one of the largest sources of airborne pollutants in the city, went into operation in 1954, though the six units currently in operation—four 300 MWe generators, one 50 MWe generator, and one 25 MWe generator—date from the 1990s. The plant sources all its coal from within Shanxi province, and reports an inability to secure low-sulfur and low ash content coal. Flue-gas desulfurization facilities (wet limestone and gypsum spray injection systems imported from Japan) have been installed only on the 50 MWe unit and one of the 300 MWe units. The plant reports sulfur dioxide emissions of approximately 60,000 tonnes annually, about 20 percent of Taiyuan municipality's annual total. The local Environmental Protection Bureau has routinely assessed emission fines on the No. 1 Power Plant which, when combined with low tariffs for power delivered to the grid, makes the facility uneconomic. Nevertheless, the facility is planning a major expansion, involving the addition of two 600 MWe generators. This expansion is driven in part by electricity shortages both within the inland province itself and in the Northern coastal areas to which power generated by the plant is dispatched. Shanxi Province exports approximately 25 percent of its electric power to coastal areas, with generators in the province facing particular pressure to dispatch to the distant, but politically powerful cities of Beijing and Tianjin. Our team also interviewed the state-owned Shanxi Grid Corporation to examine issues surrounding dispatch.

(2) In the category of co-generation for primary power by industrial firms, the research team focused on the coastal Southern Chinese province of Guangdong, where much development of this type has taken place. Guangdong, arguably the first Chinese province to undergo economic reform, is now one of the most economically liberal and internationally integrated regions of China. The province includes a number of major manufacturing clusters, many of which emerged only after the onset of economic reform and thus have avoided many of the historically-rooted problems of China's northern and northeastern industrial

‘rust belt’ regions. The research team focused on two primary cases in this region.

One of the cases is a major Guangdong subsidiary of a Hong Kong-based global apparel concern. This subsidiary employs 23,000 individuals in a major production site in the city of Gaoming. The company’s factories in Gaoming and nearby Yanmei consume about 170 thousand megawatt-hours of electricity and 600,000 tonnes of steam annually, accounting for 8–9% of total operating costs. The firm was confronted with electricity shortages which were constraining its expansion, and in 2001 elected to build its own 30 MWe coal-fired co-generation plant. The plant became operational in 2004. The plant burns low sulfur coal sourced from Shanxi and Inner Mongolia. Coal costs for the company have risen substantially over the last two years (from 330 RMB/ton to 520 RMB/ton), making the in-house plant’s electricity costs only marginally lower than grid electricity. Unlike the grid, however, the in-house plant provides reliable energy, as well as substantial quantities of steam, which avoids the need for costly and environmentally problematic heavy oil burners.

The second self-generation case involves the Guangdong manufacturing site of a U. S. consumer products company. This firm faced similar energy constraints, albeit on a smaller scale, at its production facilities outside the provincial capital, Guangzhou. The bulk of the site’s energy use is accounted for by the heating, ventilation and air-conditioning requirements of its climate-sensitive manufacturing facilities. In the last two to three years, the firm has routinely received electricity-shedding orders from the regional grid company, requiring a shift in production schedules to avoid periods of peak power consumption. The shedding orders have ranged from 30 to 70 percent of total load, thus challenging the firm’s HVAC requirements and threatening its manufacturing operations. Fearing further energy-related disruptions, the firm elected to purchase dual Perkins diesel-fired generators, each rated at 1.8 MWe.

To supplement these case studies, the team conducted interviews with major multinational suppliers of diesel generators to the China market, as well as with industrial and governmental purchasers of diesel generators in North China, a region in which these generators are usually employed as back-up sources of power.

(3) Members of the research team have also undertaken a multi-year effort into the third category of energy decision-making, gas infrastructure development in coastal East China. Interviews and discussions have been conducted with a variety of involved entities, including overseas fuel suppliers, Chinese national oil and gas majors, port facility and pipeline development companies, national and local governmental development agencies, domestic bank lenders, and overseas investors. This is a large topic that extends beyond the scope of the chapter. However, we include it as an important illustration of the politics of energy-related issues in China, as an important indicator of future energy infrastructure trends in the country, and as a bridge between China’s domestic energy imperatives and global energy markets.

CAPACITY EXPANSION IN THE ELECTRIC POWER SECTOR.

Capacity expansion in China’s electric power sector provides us with some of the clearest evidence of how energy-related decisions are actually being made on the ground. On paper, the story is straightforward. Most power plants belong to one of five major state-owned national energy corporations, enterprise groups that in theory answer upward to the central government while issuing orders downward to exert direct financial and operational control over their subsidiary plants. This chain of command should mean that for a new power plant to be built, the state-owned parent must secure the necessary central government approvals, and demonstrate that the new project meets relevant national technical standards, stipulations about what fuels to utilize, and, once the plant is up and running, national operational requirements, including environmental regulations.

The reality, however, is far more complex. For example, as central government officials themselves acknowledge, of the 440,000 MWe of generating capacity in place at the beginning of 2005, there were about 110,000 MWe of 'illegal' power plants which never received construction approval by the responsible central government agency (the Energy Bureau of the National Development and Reform Commission, a part of the former State Planning Commission.)[12] These plants were obviously all financed, built, and put into service, but nobody at the center can be sure under what terms or according to what standards.

Local government dynamics are critical to an understanding of China's fragmented energy governance. In China today, localities in high growth industrialized regions like the coastal provinces Zhejiang and Guangdong desperately need electricity. Local officials, long accustomed to operating in a bureaucratic system that for all its confusion has consistently emphasized the maximization of economic growth and consistently tolerated 'entrepreneurial' ways of achieving that goal, are the key players in power plant construction and operation. For example, the parent national energy corporations provide only about 25% of the capital required for new power plant investment. Much of the remainder comes in the form of loans from the municipal branches of state-owned banks. These banks in theory answer to a headquarters in Beijing, but in practice are likely to respond to the wishes of local governmental officials, partly because local officialdom exerts substantial control over personnel appointments within local bank branches. Another important source of capital is even more directly controlled by the locality. These are municipally-owned energy development corporations—quasi-commercial investment agencies capitalized through various fees and informal taxes levied by local government.

Thus, regardless of formal ownership ties running up to the center, power plants built for the urgent purpose of meeting local demand are often built with locally-controlled financing. It should not be surprising, then, to find municipal governments providing construction approval to get the plants online as quickly as possible, while simultaneously shielding them from the need for further approvals from the center that might well require stricter technical, environmental, or fuel standards. Similarly, parent power firms and local governments will often break apart plant investment filings in an attempt to lower artificially the plant's recorded capacity and therefore avoid the need for central government approval. The fact that 110,000 MWe of installed capacity is 'illegal' means neither that the plants are hidden in a closet nor that they lack any governmental oversight. What it does mean is that they are not part of a coherent national policy, that they frequently operate outside national standards, and that they often evade control even by their ostensible owner at the national corporate level.

In this system, the lines of operational accountability and responsibility are often blurred. On the one hand, power plants that are supposed to be controlled by a parent national firm end up dealing with the parent at arms length. The parent provides some investment and working capital funds to the plant, and some profits are returned upward. In accounting terms, the financial performance of the plant is subsumed within the integrated financial statement of the parent corporation. On the other hand, financing and project approval come primarily through local agencies that are intent on ensuring power delivery regardless of the commercial ramifications for the plant or the parent group. Thus, power plants can and do operate at a loss for years on end, further complicating incentives for plant managers. Indeed, because of the lack of clarity in the governance structure these operators sometimes themselves engage in creative financial and investment strategies. Central officials acknowledge that it is not unusual for power plants to operate sideline, off-the-books generating facilities, the profits from which can be hidden from the parent energy group and thus shielded from upward submission. As one Chinese government researcher recently observed, the electric power sector may be a big loss maker on the books, but people in the sector always seem to have a great deal of cash. Of course, the high rates of capacity increase mentioned earlier could not happen without local government compliance, if not outright encouragement. China's fastest growing cities are effectively pursuing a self-help approach to meeting their power needs, and blurred lines of governance and accountability abet them in this.

ENVIRONMENTAL REGULATION.

Chinese environmental administration is also characterized by a pattern of de facto local governance. For example, the central government has established extensive legal restrictions on emissions of sulfur dioxide. The 1998 and 2000 amendments to China's Law on the Prevention and Control of Atmospheric Pollution set stringent national caps on total sulfur emissions and required coal-fired power plants to install pollution-reducing flue gas desulfurization systems.[13] To promote the utilization of these technologies, which add significantly to plant capital and operating costs, the central government imposed mandatory pollution emission fees on power plants. Yet today, the central government estimates that only about 5,300 MWe of capacity has been equipped with FGD, a small fraction of the total capacity subject to the anti-pollution laws. Another 8,000 MWe with FGD is currently under construction, but even once completed, the resulting total will still only equal about 5.4% of thermal capacity.[14] Even more troubling, researchers could only guess at how often the equipment is actually turned on.

Once again, the fragmented, *ad hoc* system of energy-related governance in large part explains how this could happen. Environmental policy at the national level is primarily the responsibility of the State Environmental Protection Agency (SEPA), a relatively weak organization, though one that has been gaining authority recently. But implementation and enforcement come under the authority of provincial and municipal-level arms of SEPA. As with the local bank branches, personnel appointments in these local environmental bureaus are for the most part controlled by local governmental officials rather than by the parent central agencies. If the locality's main goal is to achieve economic growth, and cheap electric power is needed to fuel that growth, then environmental enforcement will play a secondary role. Local environmental officials who take a different view are likely to run into career difficulties. Moreover, budget allocations for local environmental bureaus are very tight, so bureau officials are often forced to resort to self-help mechanisms of financing just to survive. To keep up staffing levels and ensure that their employees are paid, they must rely either on the collection of local pollution emission fees or on handouts from the local government. In practice, this translates into incentives for local environmental regulators either to allow emitters to pollute (as long as they compensate the local SEPA office with the payment of emission fees) or to accept payment from the local government in return for ignoring emissions entirely.

WITHIN-THE-FENCE GENERATION.

In the fastest-growing and most power-hungry areas of China the self-help approach goes right down to the level of the industrial enterprises that account for so much of the growth in electricity demand. In provinces like Guangdong and Zhejiang, major industrial cities have grown up out of what only recently were small towns or villages. In the absence of adequate municipal or regional power infrastructure, large numbers of manufacturers in these areas have been installing their own diesel-fired generators. The diesel fuel is expensive, and the electricity is more costly than from a large coal-fired power plant. But the factories have little choice. Many of them are tightly integrated into global production networks and are scrambling to meet overseas demand for their products. They cannot afford to shut down for lack of power. Some of them operate sensitive production processes that do not tolerate power interruptions. The scale of such activities is considerable. In Zhejiang province, for example, it is estimated that 11,000 MWe is off-grid. China is now the world's largest market for industrial diesel generators, and the country's consumption of diesel fuel, much of it produced from imported crude, has climbed substantially. Generator manufacturers estimate that ten percent of China's total electric power consumption is supplied by these 'within-the-fence' units. Local officials have generally tolerated and in some cases actively supported such solutions, and environmental regulation of these diesel generators has lagged behind that of central station power plants.

THE PATH FORWARD: COAL VERSUS OIL AND GAS.

The complicated, fragmented governance of China's energy sector will also have a major bearing on one of the most important aspects of its future development: the relative roles of coal, on the one hand, and oil and natural gas, on the other. The vast scale of China's demand suggests that all economic energy sources, including nuclear power and renewables, will be used heavily. But in China, as in the world as a whole, fossil fuels will dominate the supply side for the foreseeable future. (China's ambitious plans for nuclear power underscore this point. If current plans come to fruition, and nuclear generating capacity is increased from its current level of about 9,000 MWe to 40,000 MWe by the year 2020, more nuclear plants will be built in China over the next 15 years than in any other country. But even then, nuclear energy will still only provide about 4% of China's generating capacity. Fossil-fired plants will account for much of the rest.[15])

The inevitable dominance of fossil fuels in China is not good news for the global climate. But the severity of the problem will depend on the proportions of oil, gas, and coal in China's future energy mix, and that is much less certain. In one scenario, China, like almost every country that has preceded it up the economic development ladder, will rapidly shift from reliance on solid fuels towards oil and gas, with gas playing an increasingly important role in electric power generation, in industrial and residential heating, and potentially also in transportation.

In an alternative scenario, China will remain heavily dependent on coal for electric power, for industrial heat, as a chemical feedstock, and increasingly, for transportation fuels, even as demand continues to grow rapidly in each of these sectors. The prospect of continued high oil and gas prices make the coal-intensive scenario more plausible today than it was during the era of cheap oil.

These two scenarios pose very different risks and benefits for China and for the rest of the world. For the Chinese, the heavy coal use scenario would have the merit of greater energy autonomy, given China's very extensive coal resources. It would also mean less Chinese pressure on world oil and gas markets. But the impact on the environment would be substantially greater, both locally and internationally. In the worst case, the heavy environmental toll inflicted by today's vast coal mining, shipping, and burning operations, already by far the world's largest, would grow much worse as China's use of coal doubled or even tripled over the next 25 years. More optimistically, China would become the world's largest market for advanced clean coal technologies, including gasification and liquefaction, and eventually also including carbon dioxide capture and storage. But these technologies will add considerably to the cost of coal use, and, in the case of carbon capture and sequestration, are unlikely to be deployable on a large scale for decades.

The high oil and gas use scenario would not prevent these problems, but it would make them more manageable. A modern gas-fired electric power plant is not only cleaner than its coal-fired counterpart, but also emits 70%

less carbon dioxide per unit of electrical output. A petroleum-based transportation system emits only about half as much carbon dioxide per barrel as it would if the liquid fuels were produced from coal. But the high oil and gas scenario would also force China, with few resources of its own, to compete ever more aggressively for access to them around the world. In that case, the recent tensions with Japan over drilling in the East China Sea and the flurry of deal making in Iran, Africa, Central Asia, South America, and elsewhere may in retrospect come to seem like a period of calm before the storm.

Much is riding, therefore, on which of these scenarios China will follow more closely. There are already some indications of which way China will go. China's coal is for the most part located inland, far from the major energy consuming regions along the coast. So a clean-coal-based development strategy would require a national-scale energy infrastructure, with large-scale, technologically-advanced, highly efficient power plants and 'polygeneration' facilities (producing a mix of chemical products, liquid transportation fuels, hydrogen, and industrial heat as well as power) located in the coal-rich areas of the north and west, and linked to the coastal regions via long-distance, high-voltage transmission networks. But although numerous demonstration projects have been proposed or even in some cases started, both participants and other domestic advocates frequently express frustration at the slow pace of development and inconsistent government support for these efforts. Despite years of deliberation, many of the highest profile projects are still held up in the planning or early construction phases.

A major obstacle is that these clean-coal-based strategies require a strong central government role, centralized funding, and substantial cross-regional coordination, all of which are lacking in China's energy sector today. Instead, China's most-developed coastal regions, rather than waiting for a national strategy to emerge, are moving forward with their own solutions. Many municipalities are simply building conventional coal-fired power plants as fast as they can, often with subpar environmental controls. While they are willing to import coal from the poorer inland provinces, they are not willing to invest in the large-scale infrastructure that would make them dependent on electricity generated in those interior regions. It is commonly observed that in China everybody wants to generate power, and nobody wants to rely on others for it.

More developed provinces like Zhejiang and Guangdong, or provincial-level municipalities like Shanghai, under pressure to provide adequate power supplies but also facing growing demands by an increasingly sophisticated public for a better environment, recognize the need for cleaner approaches. However, these wealthier regions are investing not in clean coal, but rather in a burgeoning natural gas infrastructure, based mainly on liquefied natural gas (LNG) imports. In this, their interests coincide with those of the state petroleum companies, which have become significant investors in—and builders of—the infrastructure of port facilities, terminals, LNG regasification plants, pipelines and power plants, frequently partnering in these projects with the energy development arms of the municipalities and provinces. Since the viability of these investments depends on the availability of natural gas, the state petroleum companies have recently been focusing their overseas acquisition activities at least as much on gas as on oil. CNOOC's recent bid for Unocal, for example, was motivated as much or more by Unocal's natural gas reserves than by anything having to do with oil.

In effect, commercial and quasi-commercial interests at the local and national levels—almost always in cooperation with international investors—are moving China's coastal regions, if not China as a whole, down a natural gas-intensive path. Recent increases in the price of gas are playing a key role in these decisions, but that role is by no means straightforward. As noted previously, many of the key decision-makers—particularly those at the grassroots level who are influencing national policy through 'fait accompli' commercial deals and investment programs—often simultaneously play the roles of policy designer, regulator, investor, commercial operator, and commercial fuel supplier. At times, their commercial stakes extend across the supply chain, from ownership of overseas fuel assets to management of shipping and logistics, investment in domestic port and infrastructural facilities and ownership of power generation. Thus, a given decision-maker may simultaneously view the prospect of higher-priced gas imports negatively from a regulatory perspective and positively in commercial terms.

In fact, more than any other players in the Chinese system, those who are participating in the gas and petroleum supply chains are the organizations with cash, commercial sophistication, links to global partners, access to global fuel supplies, and ready entrée to downstream infrastructure and major energy consumers. It is they who are making national energy policy, whether by design or—simply by virtue of the speed with which they are executing commercial strategies—by default. And none of them—not the national fuel and power firms nor the decision-makers in the leading coastal provinces—has much incentive to advocate advanced coal-based solutions or technologies. For the state petroleum firms, which increasingly see themselves as gas companies and hold substantial cash reserves, coal is a substitute for their products and the coal industry a competitor. Large-scale clean coal solutions are unlikely to be much more appealing to the national power companies, the nominal parents of most of China's coal-burning plants. Large-scale clean coal is associated with power generation at the mine mouth, which in turn is associated with control by the mining industry, and the power companies have little interest in yielding control of their industry to mining concerns.

Finally, even though price will surely be important in the long run, powerful provincial and municipal governments along the industrialized coast, facing rapidly growing local power demand and able to draw on substantial investment resources to meet it, seem at present to be opting for dependence on foreigners for gas over dependence on interior provinces for coal. The Shanghai government last year banned the construction of new coal-fired plants, while at the same time working to build an LNG infrastructure. Some coastal municipalities have little choice but to rely on coal from the interior in the near term, though even here they maintain control over power generation through the exercise of financial and regulatory power, and by building new coal plants scaled to serve only local or intra-provincial needs. However, the real trend-setters over the long term, the richer and more advanced municipalities like Shanghai, are pursuing self-help on a grand scale by investing in natural gas infrastructure. In effect, they are tying themselves to overseas natural gas supplies while maintaining a regulatory and financial stake in the downstream gas infrastructure. As they partner in these projects with national energy companies, they become at once investors, producers, consumers, and regulators of the natural gas business. This is all done in lieu of national-scale advanced coal solutions which would remove from their control not only the fuel but the power generation business as well.

THE OUTLOOK FOR CHINA

In light of this fragmented system of governance, what can the West expect of China in those aspects of its energy development that matter most to us? What, if anything, might be done to influence China's energy development in a favorable direction?

First, we should recognize that the Chinese government's capacity to achieve targets for reducing hydrocarbon consumption or pollutant releases, or Kyoto-like limits on greenhouse gas emissions, is in practice quite limited. Neither louder demands for compliance by outsiders nor escalating penalties for non-compliance are likely to yield the desired results. China's national leadership may eventually be prepared to enter into such agreements, but if so those undertakings should be understood primarily as aspirational. China's system of energy-related governance makes the fulfillment of international commitments problematic. Nevertheless, those commitments can serve as an important source of domestic leverage for leaders seeking to strengthen internal governance in the long run.

The Chinese central government's recently announced goal of increasing national energy efficiency by 20 percent over the next five years can be understood in analogous terms. Key actors within the central government have grown increasingly aware of China's energy vulnerabilities and of the urgent need for more sustainable utilization of energy resources. Public commitments to efficiency targets, by putting the central government's reputation on the line, suggest at the very least serious aspirations—probably a necessary condition for real change to occur, though by no means a sufficient one. The question now is whether, given the nature of governance obtaining across the system—vast decentralization, ambiguous boundaries between regulatory and commercial actors, and overriding norms of economic growth maximization—there exists systemic capacity to meet the center's aspirational goals.

Second, the authoritarian nature of the Chinese state does not mean that the state itself is internally coherent or effectively coordinated. Indeed, even with regard to the recent energy efficiency targets, substantial differences of opinion persist among various agencies and actors at the central level. One result of China's particular path of reform is that the boundaries between state and non-state, public and private, commercial and non-commercial, and central and local have all become blurred. China's increasingly deep integration into the global economy is even blurring the distinction between foreign and domestic. The Chinese energy companies are majority-owned by the state (though who actually represents the state is open to debate), but they also list on overseas stock exchanges, have foreigners among their corporate directors, and receive financing and guidance from international investment banks. As a practical matter, the number of actors exercising de facto decision-making power over energy outcomes in China is large, and they are not exclusively confined within China's borders. We should not reflexively invest the actions even of the ostensibly state-owned Chinese energy entities with geostrategic intent. Nor should we assume that those in the center who do think in terms of crafting a national energy policy actually can control the very large number of entities whose actions are often driving energy outcomes.

For those outside China who have a stake in the direction of China's energy development, the governance situation we have described here has both positive and negative implications. On the one hand, this is not a system that is capable of responding deftly to either domestic or international mandates, particularly when such mandates call for dramatic near-term change, and particularly when such change carries economic costs. Indeed, the response by subordinate officials to dictat from above is more likely to come in the form of distorted information reporting than actual changes in behavior. The response by local officials in the late 1990s to central mandates for closure of locally-owned coal mines—a response that generally involved keeping local mines open but ceasing to report output to national authorities—is indicative of how the system reacts to dictat. The many players, diffuse decision making authority, blurred regulatory and commercial interests, and considerable interest contestation in the energy sector combine to make dramatic, crisp changes highly unlikely. It is illusory to expect that the world's carbon problem can somehow be solved by wholesale changes in Chinese energy utilization trends.

On the other hand, this is also system in which players are emerging at every level who have a stake—whether political or commercial—in achieving more sustainable energy outcomes. That some central agencies have been able to establish more stringent national energy efficiency targets, that citizens in China's more advanced cities like Shanghai (a municipality with a per capita income comparable to Portugal's) are demanding cleaner air, and that domestic energy companies are positioning themselves commercially for an environmentally-constrained market are just some of the indicators of this. Although these players are not well coordinated, and often represent competing interests themselves, they are frequently looking outside, particularly to the advanced industrial economies, for guidance and models to emulate. Moreover, they are doing so in the context of a system that is highly integrated into the global economy, to the point that foreign commercial entities are often deeply involved in domestic decision making. This is particularly apparent with respect to corporate strategy (including the strategies of the state energy companies), investment preferences, and technology choices. In short, there may be significant opportunities, especially through commercial channels, for foreign involvement in China's pursuit of sustainable energy development.

Perhaps most important, for all its faults the Chinese system is highly experimental and flexible. Those entities that are seeking more sustainable energy solutions in many cases actually have the ability to pursue experimental projects, often on a large scale and often involving foreign players. For example, several municipalities, including Beijing itself, have taken advantage of aspects of the national Renewable Energy Law to establish cleaner, more efficient, large-scale biomass-fueled power plants. The specific terms of such projects—who pays for them, who designs and controls them, and so on—are always subject to ambiguity, negotiation, and ad hoc interpretation. This is, after all, a nation that has an institutional tolerance for "systems within systems" and a wide array of quasi-legal, gray area activities. Experiments on the sustainable energy front are certainly possible, and in some cases are beginning to happen. Those most likely to succeed will not be national in scale, but localized, replicable, and able to propagate to other localities. These experiments should also be consistent with trends in advanced economies, and indeed, should be supported by players from those economies. China's economic and commercial development is now so dependent on global integration that it will not be an outlier in terms of its energy system.

Finally, we should recognize that China's energy system is in its own way as politically complex, fractured and unwieldy as our own. And we would be unwise to expect of the Chinese what we do not expect of ourselves.

CHINA AND INDIA COMPARED

India, with a population almost as large as that of China (1.1 billion compared with 1.3 billion) and with a similarly rapid rate of economic growth, will also be a major contributor to atmospheric carbon emissions. Like China, India has extensive coal reserves (see Figure 2.1), and it is the world's third largest coal producer after China and the United States. Coal use in India is growing rapidly, with the electric power sector accounting for a large share of new demand. However, India's per capita electricity consumption, at 600 kWe-hr/yr, is only 35% of China's, and its current rate of coal consumption (460 million tonnes in 2005) is about a fifth that of China.

India's total installed generating capacity in the utility sector in 2005 was 115,000 MWe, of which 67,000 MWe, or 58%, was coal-fired. Coal currently accounts for about 70% of total electricity generation. (The comparable figures in China were about 508,000 MWe of total installed capacity, with coal plants accounting for over 70% of installed capacity and about 80% of generation.) In India, as in China, self-generation by industry is also a significant source of coal demand.

A large fraction of future growth in the electricity sector will be coal-based. Current government plans project growth in coal consumption of about 6%/year.[16] At this rate, India's coal use would reach the current level of U.S. coal consumption by about 2020, and would match current Chinese usage by about 2030. This suggests that there may be time to introduce cleaner, more efficient generating technologies before the greatest growth in coal use in the Indian power sector occurs.

Further information on India's patterns of coal use is provided in Appendix 5.A.

CITATIONS AND NOTES

1. IEA, *World Energy Outlook* 2004, p. 34.
2. Wei Yiming, Han Zhiyong, Fan Ying, Wu Gang (eds.). 2006. *China Energy Report* (2006). Beijing, China: Science Press. (Zhongguo Nengyuan Baogao: Zhanlue yu zhengce yanjiu (2006), Beijing: Kexue Chubanshe).
3. Pu Hongjiu, Lu Yanchang, Lu Yaohua, Zhou Xiaoqian (eds.). 2004. *China Electric Power and Coal*. Beijing: Coal Industry Press. Zhongguo dianli yu meitan. Beijing: Meitanqiye Chubanshe. P. 309.
4. National Bureau of Statistics. 2005. *China's Economy and Trade Yearbook*. Beijing: China Economy and Trade Yearbook Press. p . 99; UNDP/World Bank Energy Sector Management Assistance Programme (ESMAP). June, 2004. "Toward a Sustainable Coal Sector in China", p. 4.
5. Wei Yiming, Han Zhiyong, Fan Ying, Wu Gang (eds.). 2006. *China Energy Report* (2006). Beijing, China: Science Press (Zhongguo Nengyuan Baogao: Zhanlue yu zhengce yanjiu (2006), Beijing: Kexue Chubanshe). p. 12; National Bureau of Statistics. 2004. China Electric Power Yearbook. Beijing: China Electric Power Press p. 671; Energy Bureau, National Development and Reform Commission. November 28, 2005. "A Comparison of World and Chinese Energy Statistics". Shijie yu Zhongguo de nengyuan shuju bijiao. http://nyj. ndrc. gov. cn/sjtj/t20051128_51344. htm. http://www.sp-china.com/news/powernews/200605110002. htm.
6. State Council Information Office. June 8, 2006. http://www. gov. cn/xwfb/2006-06/08/content_303550. htm
7. National Bureau of Statistics. 2004. *China Energy Statistical Yearbook*. Beijing: China Statistics Press. p. 183.
8. National Bureau of Statistics. 2004. *China Energy Statistical Yearbook*. Beijing: China Statistics Press. p. 183.
9. National Bureau of Statistics. 2004. *China Energy Statistical Yearbook*. Beijing: China Statistics Press. pp. 34, 158.
10. National Bureau of Statistics. 2003. *China Energy Statistical Yearbook*. Beijing: China Statistics Press, p. 307.
11. Richard Morgenstern, *et. al.* "Emissions Trading to Improve Air Quality in an Industrial City in the People's Republic of China". Resources for the Future Discussion Paper 04-16. April 2004. p. 6.
12. A 2005 Merrill Lynch report estimated the corresponding figure at 80-140 GWe (China Daily,"Illegal Power Plants to be Cracked Down". February 15, 2005. http://www. chinadaily. com. cn/english/doc/2005-02/15/content_416510. htm.)
13. Richard Morgenstern, *et. al.* "Emissions Trading to Improve Air Quality in an Industrial City in the People's Republic of China". Resources for the Future Discussion Paper 04-16. April 2004. p. 15.
14. National Bureau of Statistics. 2005. *China's Economy and Trade Yearbook*. Beijing: China Economy and Trade Yearbook Press. p . 102.
15. Ma Kai (ed.) *Strategic Research on the Eleventh Five-Year Plan*. Beijing: Beijing China Science Technology Press. October 2005. "Shiyiwu" guihua: Zhanlueyanjiu. Beijing: Beijing kexiejishu chubanshe.
16. "Draft Report of the Expert Committee on Integrated Energy Policy". Planning Commission, Government of India. New Delhi, December 2005. http://plannningcommission. nic. in/reports/genrep/intengpol. pdf.