Part I Introduction

Chapter 1

Climate Change and the Role of Carbon Capture and Storage in Mitigation

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1.1 Climate Change and the Need for Adaptation and Mitigation

The atmosphere of the Earth contains, among others, gases that are referred to as the greenhouse gases (GHGs). These gases are so called because, in the atmosphere, they both absorb and emit radiation. It is this process of absorption and emission of radiation in the atmosphere that is the fundamental cause of what is termed the greenhouse effect (Houghton *et al.*, 1990). The main GHGs in the Earth's atmosphere are carbon dioxide (CO_2), water vapor, methane (CH_4), nitrous oxide (N_2O), and ozone. Collectively the greenhouse gases significantly affect the Earth's temperature; scientists predict that without them, the temperature at the Earth's surface would average about 33°C colder than the present average of 14°C (Le Treut *et al.*, 2007).

Since the late eighteenth century, with the beginning of the Industrial Revolution in 1750, the atmospheric concentrations of these GHGs, CO_2 in particular, have risen substantially (Le Treut *et al.*, 2007). Since that time, the atmospheric concentration of CO_2 has increased from 280 to more than 400 parts per million (ppm). Since 1957, the atmospheric concentration of CO_2 has been measured at the Mauna Loa Observatory in Hawaii and is presented in what is known as the Keeling Curve. In May 2016, the National Oceanographic and Atmospheric Administration of the USA reported the highest ever monthly level of CO_2 in the air: 407.7 ppm. The increase in the concentration of CO_2 in the atmosphere is attributed to the increased use of fossil fuels, combined with the extensive deforestation observed since the Industrial Revolution. Atmospheric concentrations of CO_2 have not been observed at such levels for millennia. Scientific analyses suggest that atmospheric CO_2 levels reached as much as 415 ppm during the Pliocene Epoch, between 5 and 3 million years ago. In that period, global average temperatures have been estimated to be 3–4°C and as much as 10°C warmer at the poles than current levels. Sea levels have been estimated to have ranged between 5 and 40 m higher than today.

While CO_2 has the highest atmospheric concentration of the GHGs and its contribution to total radiative forcing is the largest of all the gases, that of the other GHGs cannot be ignored. The atmospheric concentrations of other GHGs have also risen significantly since the late 1980s. The atmospheric concentrations of CH_4 and N_2O in 2011 were 1803 ppb and 324 ppb, respectively, exceeding preindustrial levels by about 150% and 20% (IPCC, 2013).

The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific view on the current state of knowledge of climate change and its potential environmental and socioeconomic impacts (IPCC, 1988). The IPCC reviews and assesses the most recent scientific, technical, and socioeconomic information produced worldwide relevant to the understanding of climate change. It does not conduct any research nor does it monitor climate-related data or parameters.

The IPCC publishes its results in a series of Assessment Reports, the latest of which is Fifth Assessment Report (AR5), which was published in early 2014 (IPCC, 2014).

The AR5 indicates that global climate change has already had observable effects on the environment. Points highlighted by the report include:

- Warming of the climate system is unequivocal.
- Each of the past three decades has been successively warmer than any preceding decade since 1850.

- Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent.
- The rate of sea level rise since the mid-nineteenth century has been larger than the mean rate during the preceding two millennia.

  Over the coming decades, it is expected that

- Global surface temperature changes for the end of the twenty-first century will likely exceed 1.5°C relative to 1850 to 1900 and may even exceed 2°C.
- Warming over the twenty-first century will cause nonuniform responses in the global water cycle, increasing the contrast in precipitation between wet and dry regions and between wet and dry seasons.
- Continued warming of the global ocean will affect ocean circulation as heat penetrates from the surface to the deep ocean.
- The Arctic sea ice cover and the Northern Hemisphere spring snow cover extents, and the global glacier mass will all decrease further as global mean surface temperature rises.
- Increased ocean warming and loss of mass from glaciers and ice sheets will cause global mean sea level to rise at a rate that will very likely exceed that observed from 1971 to 2010.
- Climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere. Further uptake of carbon by the oceans will increase ocean acidification.

A recent report coauthored by the International Geosphere–Biosphere Programme (IGBP), the Intergovernmental Oceanographic Commission (IOC-UNESCO), and the Scientific Committee on Oceanic Research (SCOR) highlights the impacts of increased ocean acidification, the economic impact of which could be substantial.

Ocean acidification causes ecosystems and marine biodiversity to change. It has the potential to affect food security and limits the capacity of the ocean to absorb CO_2 from human emissions.

The Stern Review (2006) stated that climate change is the greatest and widest-ranging market failure ever seen, presenting a unique challenge for economics. The Review's main conclusion was that the costs and benefits of strong and early action on climate change far outweigh the costs of not acting. According to the Review, without action the overall costs of climate change will be equivalent to losing at least 5% of global gross domestic product (GDP) each year, now and in all the years to come. Including a wider range of risks and impacts could increase this to 20% of GDP or more, also indefinitely. Stern believed at the time that 5–6°C of temperature increase was "a real possibility."

We then have two options to follow: mitigation and adaptation. Mitigation addresses the root causes by reducing greenhouse gas emissions while adaptation seeks to lower the risks posed by the consequences of climatic changes

(IPCC, 2007b). In reality, we will follow a twin process because we expect that some 1 to 1.5°C of warming is already "locked in" (World Bank, 2014). Humans have been adapting to climatic changes throughout their evolution, but we probably now face a greater challenge to adapt than ever before. This chapter, however, concentrates on the issue of mitigation.

1.2 What Mitigation Options Are Needed?

The largest sources of global emissions are the power and industry sectors, which represent 56% of global GHG emissions, including fugitive emissions from fossil fuel mining, refining, and transportation. Of the global greenhouse gases, CO_2 accounts for 65% of these emissions, primarily from the use of fossil fuels. The discussion that follows therefore concerns the mitigation of emissions of CO_2 from the use of fossil fuel in the power and industrial sectors. It is important at this junction to stress that there are multiple mitigation courses of action in both of these sectors, and the aim of this discussion is not to select individual ones but to recognize that all the low-carbon technology options will be needed in combination to meet strict emission targets. It also follows that the portfolio and balance of low-carbon technology options will vary in different regions to account for national considerations. To be clear, there is no single low-carbon technology option that will reduce GHGs sufficiently on its own and there is no "one size fits all" low-carbon technology portfolio option either.

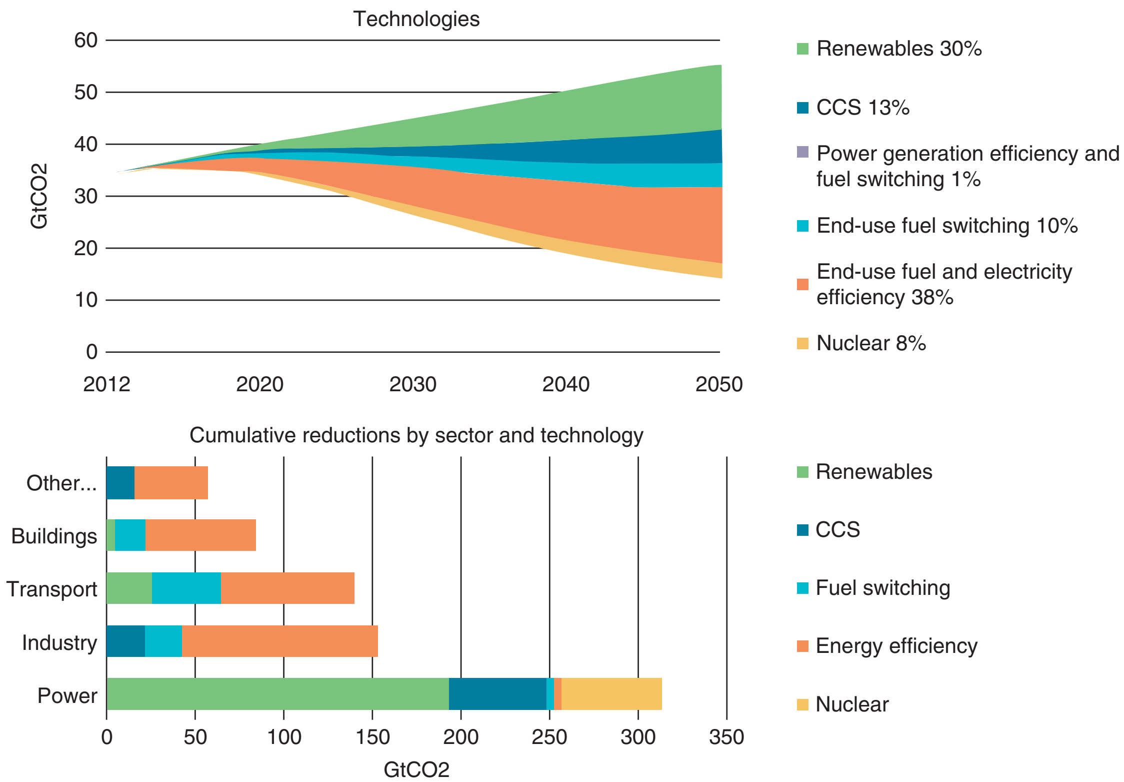

Figure 1.1 Key technology options to reduce global greenhouse gas emissions from the power sector for the IEA's 2-degree scenario.

To assess the mitigation needs, the international community has set itself temperature targets to limit the impact of global warming. These targets are framed and agreed on through the United Nations Framework Convention on Climate Change (UNFCCC), whereby countries meet annually at the Conference of the Parties (COP) to agree on international targets for climate change mitigation. Prior to COP21 in Paris, France in November 2015, the internationally agreed on target for limiting the increase in global average surface temperature rise target was 2 degrees centigrade (2°C Scenario [2DS]). The 2°C goal is achieved by limiting the concentration of GHGs in the atmosphere to around 450 ppm of CO_2.

Considerable work has been done by many organizations that have modeled the energy sector and looked at the technology options that could meet such a temperature target. One such organization that has been very active is the International Energy Agency (IEA). For example, 2DS is the main focus of IEA's Energy Technology Perspectives (ETP) book series. ETP's annual analyses aim to set out sustainable energy transition pathways that incorporate detailed and transparent quantitative analysis and thus provide targeted reading for experts in the energy field, policy makers, and heads of governments.

The 2DS lays out an energy system deployment pathway and an emissions trajectory that are consistent with an at least 50% chance of limiting the average global temperature increase to 2°C. The 2DS limits the total remaining cumulative energy-related CO_2 emissions between 2015 and 2100 to 1000 $GtCO_2$. The 2DS reduces CO_2 emissions (including emissions from fuel combustion and process and feedstock emissions in industry) by almost 60% as compared to 2013 levels by 2050, with carbon emissions being projected to decline after 2050 until carbon neutrality is reached.

An example of the modeling outputs as provided in ETP 2016 is given in Figure 1.1. The figure shows the key technologies that can be used to mitigate GHG emissions from the power sector and the relative contribution between 2013 and 2050 to meet the 2DS compared to a business-as-usual scenario (6DS). As indicated earlier, to achieve the required GHG emission savings a portfolio of technologies will be deployed that include nuclear power, fuel switching and energy efficiency, carbon capture and storage (CCS), and various renewable options.

For industry, there is a similar picture that CO_2 emissions in the 2DS will be achieved through a combination of lower carbon fuels, energy efficiency improvements, and CCS.

The IEA's analysis is not a unique one. Another example is the recent Global Energy Assessment (GEA) 2012, which also works from setting a "business–as-usual" base case but uses a different assessment approach than the IEA. The GEA report shows that there are many combinations of energy resources, end-use, and supply technologies that can simultaneously address the multiple sustainability challenges. One of the report's key findings is that energy systems can be transformed to support a sustainable future through (a) radical improvements in energy efficiency, especially in end use; and (b) greater shares of renewable energies and advanced energy systems with CCS for both fossil fuels and biomass (Johansson *et al*., 2012).

At a recent COP, COP21 in Paris, the delegates agreed to a new temperature rise target of less than 2° C, with the intent of limiting global surface temperature rise to 1.5°C. This sets an even stronger need to reduce emissions, and the technologies discussed previously will all be required. Discussions in the post-Paris environment indicate that negative emission technologies (NETs) will also be required. These are technologies that remove more emissions from the atmosphere than they put in. A variety of NET options are being considered that include afforestation, enhanced weathering, ocean fertilization, BioChar, direct air capture, and BioCCS, among others. However, unlike those discussed under the 2DS model, most of the NET technologies have not been tested at any realistic scale and thus require considerable development in the coming centuries if they are to be successful in significantly mitigating GHG emissions.

1.3 CCS as a Global Mitigation Option before and after the Paris Agreement

CCS is the process of capturing produced carbon dioxide CO_2 from large point sources, such as fossil fuel power plants, transporting it to a storage site by pipeline or ship, and injecting it where it will be prevented from entering the atmosphere, normally in an underground geological formation. In this way release of large quantities of CO_2 into the atmosphere can be prevented (IPCC, 2015).

The analyses by IEA and GEA discussed earlier have shown that CCS is a key low-carbon technology and has a strong role to play as part of the global low-carbon technology portfolio in reducing global GHG emissions.

The IPCC Fifth Assessment report made two strong points regarding the importance of CCS (IPCC, 2014). First, it showed that most of the global assessment models could not reach the 2°C temperature rise target without the inclusion of CCS in the global technology portfolio. Second, the IPCC analysis indicated that the cost of meeting the 2°C temperature target would be 138% higher without the incorporation of CCS.

With the discussion beginning to unfold regarding a 1.5°C target and the need for negative emissions, both BioCCS and Direct Air Capture (DAC) become relevant to future demand for CCS. Recent work to assess the global potential for BioCCS has suggested the technical potential is large and, if deployed, could result in negative emissions up to 10 Gtonnes of CO_2 equivalents annually. The key obstacle to the implementation of the technology is the absence of a price for stored biomass-based CO_2. There is, therefore, a need for policy developments in this area to assist global adoption of the technology (IEAGHG, 2011a). The implementation of DAC will require the utilization of geological storage space to store CO_2 that has been directly removed from the atmosphere. Consequently, the development of the transportation and storage components of CCS will aid in advancing this technology.

1.4 Geological Storage of CO_2

Geological storage of CO_2 is generally accomplished by injecting it in dense form into rock formations below the Earth's surface (it may well be possible to inject the CO_2 into shallower formations as a gas as well; certainly publications such as Chapter 17 by Juhlin *et al*. in this book demonstrate the safety of shallower traps). Porous rock formations that hold or, as in the case of depleted oil and gas reservoirs, have previously held fluids, such as natural gas, oil, or

Table 1.1 Storage capacity for several geological storage options

Reservoir type	Lower estimate of storage capacity ($GtCO_2$)	Upper estimate of storage capacity ($GtCO_2$)
Oil and gas fields	675[a]	900[a]
Unminable coal seams (enhanced coal-bed methane)	3–15	200
Deep saline formations	1000	Uncertain but possibly 10^4

From Johansson *et al.* (2012).

[a] These numbers would increase by 25% if "undiscovered" oil and gas fields were included in this assessment. Source: IPCC SRCCS 2005.

brines, are potential candidates for CO_2 storage. Suitable storage formations can occur in both onshore and offshore sedimentary basins (natural large-scale depressions in the Earth's crust that are filled with sediments). Coal beds also may be used for storage of CO_2 where it is unlikely that the coal will later be mined and provided that permeability is sufficient (IPCC, 2005).

The IPCC Special Report on CO_2 Capture and Storage (IPCC SRCCS, 2005) undertook the first review of the global potential for CO_2 storage in geological formations (IEAGHG, 2011a). The IPCC SRCCS considered in detail three types of geological formations that had at that time received extensive consideration for the geological storage of CO_2. The three options were storage in oil and gas reservoirs, deep saline formations, and unminable coal beds.

At the time of the IPCC SRCCS several other possible geological formations or structures were considered, such as basalts, oil or gas shales, salt caverns, and abandoned mines. However, it was believed at the time that these represented only niche opportunities or had not been sufficiently studied at that time to assess their potential. This conclusion is still largely valid today, although interest in shale formations for CO_2 storage is growing.

The estimates of the technical potential for different geological storage options from the IPCC SRCCS are summarized in Table 1.1. While there have been numerous studies on the individual storage options since the IPCC SRCCS, the fact that the largest CO_2 storage potential globally lies in deep saline formations still remains a core conclusion to this day.

Since the IPCC SRCCS, our knowledge on how these storage resources can be developed has advanced. Gas fields hold a greater storage potential than oil fields. Compared to deep saline formations, both gas and oil fields are much better explored and have a background data set of both geological and operational/production data. On this basis, they both should be more suitable for early application of CO_2 storage than deep saline formations. Storage in oil fields is typically carried out as part of enhanced oil recovery operations (EORs). In such systems, the injection of CO_2 is used to maximize oil production, not for storage of the injected CO_2 (see, e.g., Chapter 14 in this book by Davis *et al.*). However, incidental storage does occur within the reservoir that can amount to 90% of the CO_2 injected (Whittaker and Perkins, 2013).

From the time of the release of the IPCC SRCCS there has been little research in the potential for geological storage in coal seams. In the past few years, interest in using shale has also surfaced as a potential storage option. Again, it is too early to decide whether this is a promising option for the future or not (IEAGHG, 2013a).

While deep saline formations represent a tantalizing resource for global storage of CO_2, they remain relatively unexplored in most regions of the world. Deep saline formations require much more extensive characterization because, in general, they are "virgin" formations not previously investigated. Because of this, they require much longer lead times, potentially up to 15 years of preexploration, to be considered as viable for geological storage of CO_2 (IEAGHG, 2011b). Chapter 12 by Halland in this book demonstrates the importance of having a catalog of storage opportunities in anticipation of the need for geosequestration in the future.

Storage efficiency, for example, depends on the characteristics of the storage aquifer and confining caprock, operational characteristics of CO_2 storage, and regulatory constraints. Based on these combined factors, storage efficiency can vary widely, with values ranging from less than 1% to greater than 10%. This wide variation in storage efficiency correspondingly impacts storage capacity. In the IPCC SRCCS storage capacity estimates were based on a conservative 1% estimate of pore

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Table 1.2 IEA GHG CO_2 monitoring selection tool

				deep	shallow	Plume location / migration	Fine scale processes	Leakage	Quantification
Seismic			3D/4D surface seismic						
			Time lapse 2D surface seismic						
			Multi-component surface seismic						
	Acoustic imaging		Boomer/sparker profiling						
			High resolution acoustic imaging						
			Micro-seismic monitoring						
	Well based		4D cross-hole seismic						
			4D vertical seismic profiling						
Sonar bathymetry			Sidescan sonar						
			Multi beam echo sounding						
Gravimetry			Time lapse surface gravimetry						
			Time lapse well gravimetry						
Electric/electromagnetic			Surface EM						
			Seabottom EM						
			Crosshole EM						
			Permanent borehole EM						
			Crosshole ERT						
			Electric spontaneous potential						
Geochemical	Fluids	Downhole /Springs	Downhole fluid chemistry						
			pH measurements						
			Tracers						
		Marine	Sea water chemistry						
	Gases		Bubble stream chemistry						
		Atmosphere	Short closed path (NDIRs & IR)						
			Short open path (IR diode lasers)						
			Long open path (IR diode lasers)						
			Eddy covariance						
		Soil gas	Gas flux						
			Gas concentrations						
Ecosystems			Ecosystems studies						
Remote sensing			Airborne hyperspectral imaging						
			Satellite interferometry						
			Airborne EM						
Others			Geophysical logs						
			Downhole Pressure / temperature						
			Tiltmeters						

Dark pink = method suitable; pink = less suitable; white = not applicable.
From IEA GHG (2010).

volume utilization. Research related to pressure buildup and brine displacement has demonstrated that injection-induced pressure changes can propagate in the injection aquifer much farther than the CO_2 plume itself and can therefore limit storage capacity. Geomechanical effects of pressure buildup can include microseismicity and ground deformation, but pressure management strategies exist. The knowledge base on capillary, or residual, trapping of CO_2 has increased substantially. Laboratory observations confirm that CO_2 will occupy at least 10%, and more typically 30%, of the pore volume. Dissolution of CO_2 at the interface between CO_2 and aquifer water can be significantly accelerated. Taken together, these factors have the effect of reducing the amount of free-phase mobile CO_2 and increasing storage security because dissolved CO_2 is no longer buoyant and prone to leakage.

In summary, the reviews in the Special Issue updating the IPCC SRCSS indicate that CO_2 storage is by and large a safe operation if storage sites are properly selected, characterized, and managed. This should go a long way to alleviating concerns by policy makers, the public, and other stakeholders' concerns that geological storage is a safe and permanent option from the removal of CO_2 from the atmosphere.

1.5 Ensuring Storage Integrity and the Need for Monitoring of Injected CO_2

Storage integrity has been and will continue to be a critical consideration for the storage of CO_2 in the subsurface. In part this is a public issue, as people have concerns about the safety of storage, and in part this relates to the ability to demonstrate predictable conditions in the subsurface prior to any transfer of the project to the public sector in the future. To do this, good monitoring of the project is needed to determine the fate of the injected CO_2 (IPCC SRCCS, 2005).

Table 1.2, taken from the IEA Greenhouse Gas R&D Programme, is a general list of the techniques available for monitoring the state of the CO_2 plume and, in particular, evaluating possible leakage from the storage horizon. The table identifies a number of points salient to this book. The first is the usefulness of geophysical techniques both onshore and offshore. The second is the lack of applicability of all the techniques when it comes to quantifying the amount of CO_2 that exists in the subsurface. In other words, the amount of CO_2 entering the subsurface can be measured with a high degree of accuracy, but quantification of the amount in place in the subsurface is difficult, if not impossible, to measure with any accuracy. These techniques do, however, allow for the identification of the CO_2 plume and will provide a high degree of certainty on the movement of the plume and hence the predictability of the plume migration in the subsurface for eventual handover to public authorities.

The first requirement of any monitoring program is to create a baseline such as was undertaken at Sleipner (Chadwick *et al.*, 2009) and Weyburn (Wilson and Monea, 2004) against which future surveys can be compared. This is quite consistent with standard oil field practices using a variety of techniques to understand the processes operating in the subsurface and applying history matching to predict future production. Indeed, with enhanced oil recovery, the use of time-lapse seismic surveys has become relatively routine (Weyburn, Wilson and Monea, 2004) and this type of process has been applied in storage areas such as Sleipner (Chadwick *et al.*, 2009). This process is clear in the chapters, particularly the case studies, in this book.

Recognizing the need to ensure storage integrity requires that appropriate monitoring takes place and, as noted, that all changes are referenced back to a baseline set of data. Table 1.2 identifies the monitoring technologies that can be used. These technologies include surface techniques to measure possible CO_2 leakage at the surface (ocean bottom or land surface), shallow CO_2 presence (particularly in potable water zones), and remote sensing of the deeper subsurface to identify leaks and leakage pathways early. These pathways are identified in the IPCC SRCCS 2005 report. While direct measurement techniques can be applied at the surface and near-surface, this is not effective in the deeper subsurface. It is here in the subsurface that geophysical techniques, and particularly seismic surveys, demonstrate their value to ensure that we have storage integrity and that we can predict movement of the CO_2 in the subsurface. Seismic technology also allows for an evaluation of potential leaks and leakage pathways, particularly understanding such features as sealed versus open faults, thinning of caprocks, and other potential natural hazards that may result in CO_2 crossing formational boundaries and migrating toward the surface, economic zones, or potable water zones. Active monitoring is a way of understanding the flow path of the CO_2 and the potential for it reaching man-made or natural routes out of the storage formation.

1.6 Practical Experience in Monitoring CO_2 Storage Formations

At the time of the IPCC SRCCS there were three operational commercial scale CO_2 injection projects globally: Sleipner in the North Sea, the Weyburn CO_2 EOR Project (with an associated research project, the IEAGHG Weyburn CO_2 Capture and Storage Project) in Canada, and the In Salah Project in Algeria. Two of these, Sleipner and InSalah, were injecting CO_2 into deep saline formations, while Weyburn was a CO_2 flood in a depleting oil field (IEAGHG, 2011a). All three of these projects had substantive monitoring projects running alongside their commercial operations.

Since that time the number of CO_2 injection projects has grown considerably. A recent analysis undertaken by the IEA Greenhouse Gas R&D Programme has shown that there were, as of mid-2012, 45 small-scale injection projects and 43 large-scale projects (IEAGHG, 2013b). Small-scale projects were considered to be those injecting less than 100 000 tonnes, though many projects inject considerably less (less than 15 000 tonnes). Large-scale projects were injecting more than 100 000 tonnes/year.

Figure 1.2 provides an overview of the global distribution of the small or pilot CO_2 injection projects.

While there are several individual projects in Australia, China, Europe, and Japan, the majority of these projects are in North America, principally in the USA. The reason for the large number of projects in the USA is that in 2003, the U.S. Department of Energy (DOE) awarded cooperative agreements to seven Regional Carbon Sequestration Partnerships (RCSPs). The seven RCSPs were tasked to determine the best geological and terrestrial storage approaches and apply technologies to safely and permanently store CO_2 for their specific regions (Rodosta, 2016).

The RCSP Initiative has been implemented in three phases:

1. Characterization Phase (2003–2005): Initial characterization of their region's potential to store CO_2 in different geological formations
2. Validation Phase (2005–2011): Evaluation of promising CO_2 storage opportunities through a series of small-scale (less than 500 000 metric tons CO_2) field tests to develop understanding of injectivity, capacity, and storability of CO_2 in the various geological formations within a wide range of depositional environments
3. Development Phase (2008–2018+): Implementation of large-scale field testing involving at least 1 million metric tons of CO_2 per project

The RCSP program, as of April 2010, has six operational 1 Mtonne CO_2 injection projects, with two more in preparation. This is the largest geological storage demonstration program in the world (IEAGHG, 2013b).

Together the pilot projects around the world have played a fundamental role in enhancing our substantive knowledge of monitoring the storage integrity of the CO_2 storage component of the CCS system. Once again, the experience gained in monitoring over the last 10 or so years has been summarized in the Special Issue of the *International Journal of Greenhouse Gas Control* (IJGGC, 2015). The present book seeks to enhance our understanding of the seismic aspects of monitoring still further.

The Special Issue of IJGGC has shown that

1. Monitoring and verification have developed many shallow monitoring methods in parallel with the assessment of environmental impacts, reflecting societal concerns about leakage to the near-surface.
2. Very significant progress has been made in the deep-focused monitoring techniques, particular examples being marine seismic monitoring at Sleipner and the combination of pressure and seismic imaging at Snøhvit.
3. In the case of Sleipner, both conformance and containment have been convincingly demonstrated by innovative analysis of an impressive data set. Snøhvit is a textbook case of pressure monitoring detecting nonconformance and a mitigation strategy being successfully adopted.
4. Another success for monitoring of reservoir-level processes was at In Salah, where ground surface displacements were detected by the new (in terms of application to CCS) method of interferometric synthetic-aperture radar (InSAR), the measurement of ground surface displacement from satellite platforms. The interpretation of those results in terms of geomechanical processes was subsequently shown to be consistent with microseismic observations and time-lapse seismic imaging,

1 BSCSP Basalt	16 MGSC Sugar Creek EOR Phase II	32 SECARB - Mississippi Saline Reser
2 Carbfix	17 MGSC Tanquary ECBM Phase II	33 South West Hub (Collie South West
3 CarbonNet	18 Mountaineer PVF	34 Surat Basin CCS Project (Previousl
4 CIDA China	19 MRCSP Appalachian Basin (Burger) Phase II	35 SWP San Juan Basin Phase II
5 CS Energy Callide Oxyfuel Project	20 MRCSP Cincinnati Arch (East Bend) Phase II	36 Teapot Dome, Wyoming
6 CSEMP	21 MRCSP Michigan Basin Phase II	37 Lacq-Rousse
7 Fenn/Big Valley	22 Nagaoka Pilot CO2 Storage Project	38 West Pearl Queen
8 Frio, Texas	23 Otway I (Stage I)	39 WESTCARB Arizona Pilot (Cholla)
9 JCOP Yubari/Ishikari ECBM Project	24 Otway II Project (Stage 2A,B)	40 WESTCARB Northern California CO
10 K12B	25 PCOR Lignite	41 WESTCARB Rosetta-Calpine test 1
11 Ketzin	26 PCOR Williston Basin -Phase II (NW McGregor Field)	42 WESTCARB Rosetta-Calpine test 2
12 Marshall County	27 PennWest Energy EOR Project	43 Western Kentucky
13 Masdar/ADCO Pilot project	28 Recopol	44 Zerogen Project
14 MGSC loudon Field EOR Phase II	29 SECARB - Black Warrior Basin Coal Seam Project	45 East Canton Oil Field
15 MGSC Mumford Hills EOR Phase II	30 SECARB - Central Appalachian Coal Seam Project	46 PCOR Zama Field Validation Project

Figure 1.2 Global distribution of pilot-scale CO_2 injection projects as of December 2013.

all suggesting initiation and reactivation of fractures.

The common theme to these examples, which has now emerged from many projects at all scales, is the ability of the available techniques for monitoring and interpretation to test containment and conformance. Shallow-focused monitoring methods have also been exploited extensively and have played an important role in countering leakage allegations at Weyburn and providing assurance that environmental impacts of hypothetical leakages are undetectable above natural variability in key parameters.

The pilot projects have led to the production of several best practice documents and guidelines, which vary in scope and technical detail. A number of non–site-specific best practice guides have also been produced, such as the National Energy Technology Laboratory (NETL)'s risk assessment and site selection manuals and the World Resources Institute (WRI)'s CCS guidelines that outline the entire process. There are also best practice guidelines that consider learnings taken from particular projects, such as the Saline Aquifer CO_2 Storage Project (SACS) best practices for the storage of CO_2 in saline aquifers, which uses learnings from the Sleipner storage site in the North Sea. Other examples of best practice guides are the QUALSTORE best practice guide and the EU Guidance documents. There are several documents outlining issues regarding public communication including guidelines from NETL and WRI. The Global CCS Institute commissioned CO2CRC to produce a summary of best practice guides, including a summary of the varying areas of coverage and technical detail (CO2CRC, 2011).

Pilot projects have played a key role in helping build public confidence in geological storage (Romanak *et al.*, 2013). It is safety/integrity of storage sites that principally gets raised in public debates on CCS. These pilot projects have assisted through

- Establishing visitor centers at sites so the public can get first-hand experience of storage operations
- Enabling direct local dialogue with farmers and other key stakeholders
- Enabling the public to meet the scientists involved so people can learn and speak openly about their concerns
- Providing the opportunity to disseminate information at a local level

Through these actions the pilot projects have helped build public confidence in CCS at a local/regional level, which is important for the success of projects and CCS globally.

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Excerpt
More Information

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