THE GLOBAL DEVELOPMENT OF A CCS-BASED SERVICE AND TECHNOLOGY MARKET WITH A FOCUS ON THE US, FRANCE, AND CHINA

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* given the later submission date, some minor updates have been made with regards to some time-sensitive statements
Carbon Stock Engineering (CSE) was formed as a consulting firm specializing in carbon capture, transport, and storage (CCS) research and investment related services. The home office is currently established in Paris, France but the company is focused on expanding into the US and Chinese CCS project finance markets as the opportunities become apparent. An eventual expansion into other countries enthusiastic about deploying CCS is possible once CSE builds a respectable portfolio of projects in the US and China.

The founders of the firm are professional engineers and entrepreneurs with extensive experience within the oil and gas industry. As a result they have significant contacts and expertise dealing with the main companies that are currently interested in moving into carbon services, especially in France and in the US. The hope is to utilize these connections to position CSE as a bridge between the currently fragmented CCS services market and financing mechanisms for CCS projects. The founders, Jean-Pierre Foehn, Jean-Michel Fonck, and Thiery Gadou, provided an initial investment towards the start-up expenses associated with hiring Cameron McQuale, the lead market analyst. These costs were namely for start-up related administrative tasks, expert contact development, in-depth market research of the US, France, and China, and the creation of this report.

The Report

This paper was made possible by my position with Carbon Stock Engineering (CSE) and the financial support of its founders. The goal for CSE in sponsoring this report was to identify shortfalls in current service offerings and other pathways into the CCS service market. In pursuit of this information I was hired as an analyst to conduct the necessary research required to establish a base understanding of CCS technology, its global status, and the active projects and players in the countries concerned. The report itself was submitted to Ecole des Mines de Paris (Mines ParisTech) in France and Tsinghua University in Beijing, China in addition to the University of Pennsylvania as part of a cooperative international masters program in environmental management between those three institutions.
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ABSTRACT

THE GLOBAL DEVELOPMENT OF A CCS-BASED SERVICE AND TECHNOLOGY MARKET WITH A FOCUS ON THE US, FRANCE, AND CHINA

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The international discussion regarding those tasks that will be required for mitigating climate change has placed several new technologies on the table as possible means for upgrading the global energy and industrial infrastructure. That process will significantly reduce the current level of greenhouse gas (GHG) emissions, primarily carbon dioxide (CO₂). Carbon capture and storage (CCS), would add the capacity to capture and store all or most of the CO₂ emissions from both existing and planned new facilities. Carbon capture and geological storage (CCGS) describes a more specific technology within CCS, whereby captured CO₂ would be stored in geologic formations deep underground.

Effective storage sites would be located within porous formations, deep below the Earth’s surface, where the CO₂ would be trapped within pore spaces and prevented from escaping by an overlying impermeable geologic seal, in most cases the same seal whereby petroleum and natural gas were naturally trapped millions of years ago. Carbon dioxide has been injected routinely into hydrocarbon bearing reservoirs for enhanced oil recovery (EOR) projects during the past few decades. Thus, CCGS, a relatively new strategy, is based on fundamental concepts that are already in use.

The implementation of CCGS on a broad scale may lead to increased extraction of fossil fuels, as energy will be required to capture and sequester the CO₂ produced in combustion. Therefore, concern for the impact of mining on the local environment and the probability of oil spills will not be resolved. However, if the global energy industry will be restructured to measurably reduce CO₂ emissions on the time scale allotted to address climate change, CCGS will represent a significant component of that response.

To mitigate a significant fraction of the emissions expected between 2005 and 2055, Socolow and Pacala (2004) offered a strategy that has come to be known as the wedge concept: since no single mitigation strategy offers the potential to reduce CO₂ emissions to an acceptable level, Socolow and Pacala suggest that many mitigation strategies be implemented in parallel in a portfolio. Using the wedge model, the International Energy Agency considers CCGS technology a means of preventing approximately one fifth of the global GHG emissions expected under a business-as-usual scenario from now until 2050. The IEA estimate implies the construction of 3,400 projects that would couple both industrial and energy based infrastructure with the technology during that time period (IEA CCS Roadmap, 2009).

Several factors will have a significant effect on the time and capital investment needed for deploying CCGS at a scale that could impact global greenhouse gas (GHG) emissions. Although CCGS is safely deployed today; only five integrated, commercial-scale CCGS projects exist. Until
more commercial-scale demonstration projects are in operation, it will be difficult to estimate the real costs of this technology. The goals of this report are to explain the technology, give some examples of existing projects, and discuss current assessments of the CCS market with a focus on storage, as well as provide three country-based case studies: the US, France, and China.

Given the level of oil production across the US, interest in receiving CCS credit for injecting CO$_2$ as a means of EOR is growing, inspiring an increase in development of recovery-based CCGS opportunities. It should not come as a surprise that the two of the five existing commercial-scale projects where the US is active both involve EOR. Furthermore, the US has committed significant funding to projects that will demonstrate CCGS across the country. This mix of incentives has established the US as the most active country internationally in deploying CCGS technology on its own soil. However, because no commitment to a global emissions-capping treaty has been adopted, many major American players have thus been slow to get into the international storage market. For this reason the major storage actor present in the largest of the DOE projects is French.

Although France has a low carbon profile, major French players have significant investment in carbon-intensive operations outside the state’s borders, where they hope to employ CCGS as an emissions-mitigation tool. In addition, several major French oil and gas-based companies are active players in the developing global CCGS market. The French government is active in supporting this development, and as a result has deployed, along with additional funding set aside for CCS, several mechanisms, such as a carbon tax that will go into effect in 2010. With the breadth of French expertise in CCGS-related service and technology, France is now able to deploy the technology directly. The involvement of France in CCGS demonstration projects in China and the USA demonstrates the global reach that France has already achieved within the CCGS market.

The Chinese appear hesitant to commit publicly to reduction targets or to pursue a direct application of CCGS technology on their own and are soliciting international assistance. However, this picture is deceiving because China sees the value of developing its own expertise in CCS and Chinese companies are pursing projects without foreign involvement so as to remain competitive within this emerging market. Additionally, the IEA now estimates that China’s coal reserves will last ~50 years, at the current rate of extraction. The high energy penalty exacted by capturing, compressing, transporting, and injecting large amounts of CO$_2$ dictates that energy efficiency must be paramount in any CCGS industry. Thus, deployment of CCGS technology would achieve many things for the energy and environmental security of China.

The positions of France, China, and the USA in a global CCGS industry, can only be surmised at this early stage of development of the industry. Inasmuch as the CO$_2$ emissions of China, the US, and Europe combined represent ~50 percent of the emissions that the IEA identifies as capturable by 2050, the case studies developed in this report intend to assess the rate of development of this technology. One of the economic concerns that remains is that most discussions of CCS or CCGS mention only briefly the economic impact of the development of this new technology on consumption of such commodities as coal, iron, steel, wire, and cement. Past experience with the Three Gorges Dam in China and the nuclear power roll-out in the US during the 1960s and 1970s, should predict that prices and availabilities of these materials will be significantly affected by the global roll-out of CCGS. The extent to which this technology will to mature now lies in the hands of investors in CCGS technology and the regulators of CCGS deployment.
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Abbreviations

[ADEME] Agence de l'Environnement et de la Maîtrise de l'Energie - French energy and environment agency

[BAU] Business as Usual – continuing the current growth trends in terms of energy production and resource consumption

[BCG] Boston Consulting Group

[CAPEX] Capital Expenditures

[CCGS] Carbon Capture and Geological Storage

[CCS] Carbon Capture and Storage (or Sequestration)

[CFCs] Chlorofluorocarbons – a greenhouse gas

[CH₄] Methane – a greenhouse gas that can be burned to produce energy

[CMI] Carbon Mitigation Initiative at Princeton University

[CO₂ ] Carbon Dioxide – the most important greenhouse gas in terms of international climate agreements

[CO₂ CRC] Cooperative Research Centre for Greenhouse Gas Technologies (Australian)

[E&C] Engineering and Construction – designates a group of companies and do contracting work in these areas

[E&P] Exploration and Production – designates a group of companies and do contracting work in these areas

[ECBMR] Enhanced Coal Bed Methane Recovery

[EGR] Enhanced Gas Recovery

[EOR] Enhanced Oil Recovery

[EU ETS] European Union Emission Trading System – developed in order to implement Kyoto in the EU

[EUR] Euro

[GHG] Greenhouse Gas – large molecule gases that add to the atmosphere’s ability to trap heat

[Gt] Gigatons – unit used to designate quantities of CO₂ (or carbon) on a commercial or on the state and international scale

[GW] Gigawatts – unit used to describe power production capacity on a state scale


[IEA] International Energy Agency
[IGCC] Integrated Gasification Combined Cycle – Pre-combustion capture power plant that first gasifies a carbon rich energy source and then fires the gas to power a steam turbine

[IPCC] International Panel on Climate Change

[LNG] Liquefied Natural Gas – petroleum based methane gas that is cooled and pressurized so as to be transported and stored in liquid form

[MEA] Monoethanolamine – member of the group of chemicals called “amines” which are used to capture CO₂ in several post-combustion processes

[MIT] Massachusetts Institute of Technology

[MPa] Megapascals – European unit for describing pressure

[Mt] Megatons – Unit used for describing amounts of CO₂ (or carbon) at the individual project scale

[MW] Megawatts – Unit used to describe power production capacity at the plant scale

[NGCC] Natural Gas Combined Cycle – Natural gas fired steam turbine based power plant

[OGJ] Oil and Gas Journal

[PC] Pulverized Coal – Conventional type of coal fired steam turbine power plant

[PEI] Princeton University’s Environmental Institute

[Psi] Pounds per Square Inch – American unit used to describe pressure

[R&D] Research & Development – Used to describe research activities and the associated funding budgets within an institution

[RD&D] Research, Development, and Demonstration – Used to describe research activities put into application by an institution (and the associated funding budgets)

[SNG] Synthetic Natural Gas or Syn-Gas – Gas made from gasified coal, heavy petroleum, or biomass

[US DOE] United States Department of Energy

[USD] US Dollar

[WACC] Weighted Average Cost of Capital

[WRI] World Resource Institute
Introduction
The higher load of global human activities is rapidly changing today’s world. The increasing global population and especially the urban populations in developing countries are increasing their demands for resources and the associated services are increasing linearly or in some cases exponentially. One of the most essential of these resources is energy. Another is water, which is required to sustain human life and is inseparably linked to the production of energy as steam for turbines, a driver for hydropower, an oil production booster, a coolant, and perhaps one day a storage vector for energy in a hydrogen-based economy. Additionally, food production and transportation are two of the main uses of energy on the planet.

Securing the energy to provide access to food is vital and fresh water provision is also becoming increasingly dependent on energy. As a result, humanity arguably has rights to energy as means of survival. However, given the current natural resource availability, consumption trends, and observable and estimated ecological impacts of the current global energy system, the means by which this energy is supplied needs to change. In his book Hot, Flat, and Crowded, Thomas Friedman refers to the current period in history as it is briefly described above, as the Energy-Climate Era because it is a period where these two critical elements of human existence have become intrinsically linked (Friedman, 2008). However, it is important to understand the principles that provide the connection between these two systems: human energy production and consumption and the global climate.

Climate
The International Panel on Climate Change (IPCC) identifies in Climate Change 2007, three fundamental ways that the radiation balance of the Earth can be changed to affect the climate. This is an oversimplification of the reality, but gives some basic understanding as to how the Earth’s climate system works (Giegengack, Correspondence, 2009). One key factor is represented by the balance between the reflectivity of the planet and the absorbency of its atmosphere with respect to solar radiation. The Earth’s climate responds, directly or indirectly, to changes of these factors by means of a variety of feedback mechanisms so as to return to equilibrium (Le Treut, 2007).

Due to the limitations in current modeling technology, this model cannot adequately take into account the role of intrinsic solar variability and other global factors, which can have major influences on Earth’s climate over the time periods in which climate scientists are interested. For example, the thermohaline circulation of the oceans, which turns over every 1500 years and stores roughly 100 times more energy as the atmosphere, is difficult to consider in this model. The IPCC presents a simplified model of radiation balance because that is as far as the current modeling industry can go at the present level of technological development (Giegengack, Correspondence, 2009).

Carbon
One factor that regulates this absorbency dynamic is something known as the greenhouse effect and is caused by certain gases, most of which naturally present in the atmosphere. This effect is related to the bond length of these particular “greenhouse gas” (GHG) molecules, which allows them to absorb and store the infrared solar energy as it is reflected by the earth’s surface back to space. GHGs include water vapor, methane (CH₄), nitrous oxide, ozone, chlorofluorocarbons
(CFCs), and carbon dioxide (CO₂) - the gas that has become the most popular member of the group with respect to climate change.

CO₂ is one of the two most important GHGs, along with water (vapor), in terms of its effect on the climate due to the fact that these two GHGs are found in significantly higher proportions in the atmosphere than the other GHGs. With an actual horticultural greenhouse, which allows sunlight to enter and heat a typically translucent building were plants are grown, it is the closed structure that significantly slows the natural convection of that heat into the atmosphere. Conversely, the atmospheric greenhouse phenomenon, which is not based on convection, involves energy being trapped in the atmosphere because the wavelength of infrared radiation is caught as a vibration in the bonds of the GHG molecules, which lengthens its residence time and currently has the effect of keeping the global temperature at an average of 14 degrees Celsius. This is a positive effect with regard to maintaining the existing balance between the earth’s climate and eco-systems.

The concerns over the human factors driving climate change are the basis for the current climate negotiations, the Kyoto Protocol, and the resulting international treaty that aims at limiting the production of GHGs. Given the current international political trends, a truly global treaty that sets national production caps for of GHGs could be imminent. Global leaders met in December of 2009 in Copenhagen, Denmark to discuss the next steps and a global climate agreement to succeed the Kyoto Treaty, which would otherwise expire in 2012. Preparing for the possibility of such a treaty is therefore in the best interest of companies that produce these gases. If a global GHG emissions are regulated or “capped”, any progress in terms of developing alternatives to or solutions for activities that are GHG intensive will be prudent and even compulsory financially speaking. However, as the attendees of Copenhagen were unable to agree on a solution, the debate for an international political solution continues to be hotly debated.

Energy

The increase of fossil fuel-based energy production/consumption since the industrial revolution has resulted in a significantly elevated levels of GHGs, most notably CO₂ as a waste by-product. The resulting buildup of these human activity-related waste GHGs in the atmosphere has been documented by climate scientists. It should be noted that the increase of GHGs is at the very least an indication of a decrease in terms of the availability of carbon-based energy resources. According to Jefferies, an investment firm in New York, the power generation sector makes up over 60 percent of the industrial CO₂.

For the moment, despite extreme irregularity in fossil fuel supplies and prices, the major concern today arises from the effect that the increase of these gases is having on the global climate system and potential for these effects to increase if the concentration of GHGs continues to augment. Scientists appear to agree that the earth has been on an incremental global warming trend for thousands of years, i.e., since the end of the last Ice-Age. However, what is currently being documented is that there is an overall accelerated rate of temperature increase. In addition to the increased production/consumption of fossil fuels, global deforestation of rainforests is considered among the most significant of anthropogenic contributions to GHGs and the net global temperature increase, which is projected to increase by two degrees Celsius or more if the trends for emission and deforestation remain unchecked.
from business as usual (BAU). Again it is worth noting that deforestation has many negative aspects regardless of its contribution to the atmospheric GHG concentration.

Next, it is essential that a solution is found for what to do with all of the remaining emissions, which will prevent them from entering the atmosphere. At the current growth and expansion rates seen in the international industrial sectors that produce CO₂, it is expected that a minimum of 175 billion tons or Gigatons (Gt) of CO₂ will need to be eliminated by 2055 (Hotinski, 2007).

**Sustainability**

Simply giving the technological limitations facing those studying the climate issue is not an excuse for continued inaction. The fact is that the current system is simply not sustainable and the measures needed to move in a sustainable direction are time consuming, technologically complex, and often politically unpopular. Humanity therefore has two choices. People can use doubt and fear of change to justify continuing in an unsustainable fashion, until mankind is forced to change by the limits of the natural system. The second choice is to change by working with the tools available so to maintain, to the extent that is possible, a good quality of life for people across the planet by moving society, as quickly as possible, toward a more sustainable system.

The ideas being considered as a means for reducing GHG production are endless. However, the actual feasibility of these ideas, in terms of the physical, economic, and political resources needed to put the pieces in place, limits the scope of the possible solutions that are available if the aim of implementing GHG reduction goals is to be met. Although the expansion of renewable energy production is intended to at least reduce CO₂ emissions, an overall appreciable reduction will be extremely difficult within the short- to medium-term using these emerging GHG-free technologies. What this highlights most is a need for a dramatic increase in efficiency throughout the entire global system, so that the existing infrastructure is producing the least amount of GHGs physically possible.
The Argument for Carbon Storage

Paul Breeze, of Modern Power Systems magazine, presents a more serious situation than is presented by the 175 Gt by 2055 prediction. Breeze in 2006 stated that, “If the growth in demand for electricity continues unabated, and if the concentration of carbon dioxide within the atmosphere is to be stabilized, it may be necessary to capture, transport and [eliminate via storage] up to 350 Gt of carbon dioxide over the next 50 years (Breeze, 2006).”

Capturing the carbon and storing it with a portfolio of solutions commonly referred to as carbon capture and storage - or sequestration - (CCS) technologies, presents some options for industries that are currently tied to a carbon intensive production method. In order to build the requisite new CCS infrastructure or even outfit the current GHG producing industries with CO₂ capture and compression facilities will be an immense task. Construction alone will require a significant outlay of capital from governments and private investors, without even considering the transportation and storage capital and energy costs that are estimated as comparatively less than capture/compression but still important at the global scale and can become more significant if efforts are not coordinated.

According to the IPCC estimations, the amount of CO₂ to be stored is enormous but not unmanageable in terms of the global geological capacity for storage. What is important to understand when considering their initial estimations, seen in Table 1, is the pyramid of storage capacity versus volume certainly. Based on basic assumptions, such as the characteristics diagram for CO₂ provided in Figure 1 and the general pore volume observations for porous geological structures as seen in Figure 3, an estimate can be made such as the one by the IPCC. However, as John Kaldi, the chief scientist at the CO₂ CRC points out, as knowledge and precise data is obtained about the actual space where CO₂ will be stored, e.g. the amount of resident water, the injectivity, and other unpredictable factors are determined about the reservoir, the total amount of capacity decreases as is seen in Figure 2 (Kaldi, September 9, 2009). Nevertheless, some initial countrywide assessments have in fact increased estimates from the initial IPCC estimate, but these developments will

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>Global Capacity</th>
</tr>
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<tbody>
<tr>
<td>Deep Saline</td>
<td>1,000-10,000 Gt</td>
</tr>
<tr>
<td>Oil &amp; Gas Reservoirs</td>
<td>675-900 Gt</td>
</tr>
<tr>
<td>Unminable Coal Seams</td>
<td>5-200 Gt</td>
</tr>
<tr>
<td>Total</td>
<td>1,680-11,100 Gt</td>
</tr>
</tbody>
</table>

Table 1 - Global CO₂ Storage Capacity
Source: IPCC
be discussed in a later section.

The IEA estimates that 3,400 projects are required to achieve the goal of reducing emissions 50 percent from their level in 2005 (Kerr T. a., 2009). They place CCS investment as only 6 percent of the total amount required to achieve this 50 percent by 2050 goal. The outfitting of more than 3,000 projects with CCS technology alone, not to mention the other technology rollouts that will be required in tandem to the CCS scale-up, will require significant amounts of human capital and place significant strain on many global resources such as iron, steel, coal, and concrete and essential industrial items such as wire, valves, turbines, etc. As a result it is incredibly difficult to predict the real costs of deploying CCS. The next section discusses the overall picture in terms of what technologies will also be needed and will give some rough estimates as to the costs that should be expected.

**Carbon Capture and Geological Storage (CCGS)**

Before engaging in an explanation regarding the details of the market potential for CCS and examining the technology’s status in the US, France, and China, it is important to understand exactly what CCS is and also what it is not. To clear up confusion over terms of use, the focus of the discussion here needs to be précised to that of the capture of carbon dioxide from industrial point sources and its geological storage in porous media. This specific technology group should not be confused with other similar technology groupings, such as deep ocean storage and coal bed enhanced methane recovery (ECBMR). These technologies are perhaps similar to CCGS in many aspects and as a result are often categorized as forms of CCS. Nevertheless, they will not be discussed at length in this paper beyond a brief description of the merits and detractions of each relative to CCGS. The reason for excluding ECBMR is that this paper focuses on the geological storage aspect of captured CO₂ in porous media. As coal is not highly porous and the amount of GHG mitigation that can be achieved using this technology is comparatively small relative to standard sedimentary storage formations, ECBMR should not be considered seriously as a storage solution but more as a gas recovery method. Whereas ocean storage does address
the storage aspect, the fact that it is not geological results that the solution conflicts with several international regulations regarding waste disposal at sea. Ultimately, neither of these alternatives to CCGS is very attractive as a real option for addressing climate change due to their immaturity in the technological pipeline and the fact that they entail either higher risks or other significant regulation related hurdles.

The Basics
The CCGS concept is relatively simple and the individual processes involved in executing the full technology chain are already in use today throughout the industrial sector. In fact, with regards specifically to injecting CO₂ underground, some oilfield operators have already been engaged in this field since 1972, using CO₂ from natural and anthropogenic sources for enhanced oil recovery (EOR) by pumping the CO₂ into depleting oil formations so as to force out normally unrecoverable oil. However, only around the year 2000 did these companies begin to intentionally store the CO₂ used for their EOR operations permanently because as CO₂ is expensive it proved more economic to recover as much of the gas as possible (IEA GHG). It is important to clarify that extracting natural CO₂ and then injecting it to recover more oil is not CCGS and serves no purpose in terms of mitigating climate change as in fact the process increases the overall GHG production. CCGS technology in its simplest form involves three steps: 1) the CO₂ produced by a point source (e.g. an oil refinery, natural gas production facility, fossil-fueled power plant, steel mill, chemical or cement plant, or a waste treatment facility) is captured by using any one of a variety of technologies and methods, 2) the CO₂ is compressed and transported either via pipeline, or in the case of long distances via ocean tanker (in some early cases CO₂ has been transported by trucks or rail due to regulatory issues with the permitting and building of the necessary pipeline infrastructure but this is not cost effective at scale), 3) the CO₂ is injected underground using a specially designed well, similar to that used for re-injecting water into an oil field, and is stored in a deep geological formation, which can be located either onshore or offshore – far beneath the ocean floor. At this point, as well as after the storage reservoir has been filled and sealed, the reservoir that contains the trapped CO₂ is monitored for leaks and seismic issues. Continuous monitoring takes place for roughly 20 to 50 years after the storage site is closed and at that point, if the site is shown to be stable, the long term responsibility of the storage should in most cases ideally pass from the storage site operating company to the national government in a process called reclamation. At that point, monitoring would become minimal. It is important to note here that the regulatory frameworks for this process are not finalized for most countries and a large amount of work is required to put proper laws and policies in place.

Prior to transport, it is important that the CO₂ is purified to a quality level that prevents corrosion in a pipeline and the storage of non-GHG gases, but minimizes unnecessary cost. Paul Breeze outlines that, “Transportation will normally take place either under pressure in pipelines or by liquefying the gas and transporting it by sea...Underground storage could be carried out in three different types of geological structure, empty oil and gas fields, unmineable coal beds and within deep saltwater aquifers (Breeze, 2006).” In terms of actually geologically sequestering CO₂, the idea is to safely and permanently store as much of the gas as is possible for the lowest economic cost. The basic theoretical assumptions, based on existing research studies, demonstrate that 20-80 percent of the space in these reservoirs can be taken up by CO₂ and that the deeper the gas is stored, the denser the gas becomes until a depth of around two km, as can be seen in Figure 1 (Metz, 2005). Below 800-1000 meters of depth, the CO₂ remains supercritical due to the pressure and takes on some liquid-like flow characteristics but remains
buoyant like a gas. Most experiments aim at injecting the CO₂ to a sufficient depth so as to maintain this supercritical characteristic but some, like the US Midwest Geological Sequestration Consortium (MGSC) project in Hopkins County, Kentucky, where 8,000 tons of CO₂ are being stored at a depth of 580 meters, will explore the possibility of storing CO₂ as a gas (OGJ, 2009).

The first CCS project, called Sleipner, has been operated by Statoil in the North Sea since 1996 and stores 1 Megaton (Mt) or 0.001 Gt of CO₂ per year. There were some enhanced oil recovery (EOR) projects in the US prior to Sleipner but none were designed to permanently store significant amounts of the CO₂. In fact it was a benefit to recover most of the injected gas because it was expensive. EOR projects did not aim to store the injected CO₂ until much later, around the year 2000 as will be seen in the US case study (Lagneau, Second Advisory Meeting - Report Review, 2009). The project to construct a CO₂ treatment module at the Sleipner-T platform to treat the extracted natural gas produced by the operation, cost 350 million Euros. Sleipner does give an idea of the investment needed to take this technology to the commercial phase in that the investment will be significant to deploy CCS globally. However, Sleipner is perhaps not a great benchmark for price estimation since it was the first pilot of its scale and does not involve the same sort of processes that are most concerned by climate regulators, such as power plants, steel foundries, and cement production. The costs for CCS are expected to drop significantly as more pilots come online and experience is gained with deploying the technology, but this implies a significant number of these demonstration facilities coming online in the coming years (IEA GHG).

The Technologies

The source of the CO₂ is best for CCS if it is concentrated, because this reduces costs and allows for more capture methods. Jefferies has estimated the amount of CO₂ from common anthropogenic point sources and compared it to the concentration of the CO₂ in the flue gases of those sources in the Figure 4 to illustrate which sources are the best options for CCGS application. However, according to Sarah Forbes of WRI, it is not prudent at this point in the CCGS technology’s development to eliminate any source as too small or too dilute (Forbes, Correspondence, 2009). Each CO₂ point source should be engaged in research, development and deployment of carbon abatement technologies including CCGS. Nevertheless, with small sources such as ammonia and ethanol plant it may be better to utilize the high purity CO₂ for commercial purposes.

The reality beyond the Jefferies assessment in Figure 4 is that most ready sources for capture do not yet exist. Coal gasification plants (coal to SNG and IGCC) and the advanced pulverized coal (PC) boilers (i.e. supercritical and oxy-fuel PC) are not yet being built at commercial scale due to the extensive costs of these projects and the risk that they imply due to the uncertainties
associated with state level and international climate change politics. The risks are becoming high for building a carbon intensive plant without CCGS because this could put the project at risk of negative financial effects from a sudden passage of any significant climate legislation. Conversely, the costs of building the plant today fully-fitted with CCGS technology are too high without a climate treaty to place a price on carbon to ensure the competitively of the plant compared to the equivalent non-CCGS plants. The only cases that are at low risk are some special cases where EOR or some other economic benefit apply or in the case of Norway or Algeria where there are carbon emission taxes for the gas extraction operations. The strategy behind the Jefferies diagram is that sources with largest CO₂ emissions should aim to develop technologies that allow them to be capable of achieving high concentrations of CO₂, which would place them in a position, due to their scale, as the most appropriate targets for strategic commercial scale CCGS projects designed to reduce the overall global GHG emissions.

According to McKinsey, as seen in Figure 5, coal power plants make up 24 percent of the global CO₂ emissions resulting from fixed, man-made point sources. Of the capturable emissions, coal power represents 52 percent and this number is growing. Based on this assessment, the primary targets for CCGS will be regions or countries where significant amounts of their electricity needs are met by coal. An analysis of the coal consumption and electricity ratios globally in 2006 available from the International Energy Agency (IEA) and the US Energy Information Agency (US EIA) reveals the most probable locations for most commercial CCS projects in the event of a global emissions treaty. Figure 6 contrasts the overall use of coal with the dependence on that resource as an electricity source by country. As CCGS is a new technology option, in terms of it being applied at a commercial scale on plants that are for normal electricity production, the
results of this diagram indicate that the most significant coal-based CCGS market growth will most likely be seen in these countries. In fact, all of the countries that fall in the category of having high coal consumption and/or a high percentage of power from coal can be seen as pursuing CCS research projects, with the exception in the immediate term of India and Kazakhstan probably due to a lack of funding for CCGS projects there. This highlights the importance of adding CCGS projects to the list of “Clean Development Mechanism” (CDM) and Joint Implementation (JI) projects approved for accreditation under the Kyoto Protocol as an alternative means of developed countries achieving GHG reductions. The issue of CCGS currently being excluded from these programs will be important to resolve in terms of the policy design process for a similar cooperative mechanism under a future treaty if one is created at Copenhagen or thereafter. Despite many European countries being insignificant compared to other major coal countries, the European Union (EU-27) does consume a significant amount of coal as a whole (although this makes up a lower percentage of its electricity consumption). As a result the EU is also pursuing CCGS as a region and will award funding to 10-20 projects being pursued within member countries.

To give an overview of the existing capture technologies, there are currently three main categories for CO₂ capture methods: post-combustion, pre-combustion, and oxyfuel-combustion. This section briefly outlines each technology as it is used with current technology.

**Post-combustion capture** is performed in a way similar to that of several modern pollution mitigation schemes, e.g. for sulfur dioxide (SO₂) and particulates, in that it involves the separation of CO₂ from normal flue-gas. This capture method typically relies on a chemical that bonds with CO₂ when introduced to the end of a flue gas stream after other pollutants and particulates have been removed. The CO₂ is first captured by a special chemical and then released in a second process. The chemical, which most commonly is monoethanolamine (MEA), is typically recycled but many cost issues are related to contaminating agents in the process such as nitrogen degrading the capture chemical. The associated family of chemicals, known commonly as amines, is the subject of a large number of research, development, and deployment (RD&D) projects globally aimed at reducing the cost and increasing the efficiency of amine-based capture processes (Breeze, 2006). This type of capture will be applied most effectively to carbon point sources that already have high concentrations of CO₂ in the exhaust stream (see Figure 4 for examples). If the process is applied to retrofitted coal and natural gas fired power plants, it will potentially only prove cost effective (at this stage) on newer plants, because in many cases it would cost less to build a new, more efficient boiler along with a capture facility than to retrofit an older inefficient plant.

Post-combustion technology ideally removes 80 to 95 percent of the CO₂ from flue gases. However, there is a significant energy penalty lost as a result of the carbon capture process, which are estimated at 24%-40% for high efficiency pulverized coal plants and 11% to 22% for a natural gas combined cycle plant due to its lower carbon intensity (Breeze, 2006). The EU aims at reducing the current costs of post-combustion capture by 50 percent using amine-based chemicals. WRI in its “Capturing King Coal” report examined an MIT-developed efficiency comparison chart seen in Table 3, which gives an idea as to this loss of energy that should be expected due to the capture processes being added to a coal plant’s energy requirements. As is visible with the lower-efficiency plants, which burn coal at lower temperatures, fitting these plants with capture facilities would require an increase in construction costs by 61 to 74 percent (compared to the cost for building an equivalent plant new). The WRI report notes that the actual prices for new power projects are much higher per kW than the number’s presented by
MIT because of a recent increase in prices. Nevertheless, using the percentages for the expected increase in costs if fitting the plant with capture facilities is still useful in terms of roughly estimating what a plant needs to be prepared for when deciding whether or not to engage in a CCGS project.

<table>
<thead>
<tr>
<th></th>
<th>Subcritical PC</th>
<th>Supercritical PC</th>
<th>Ultra-Supercritical PC</th>
<th>IGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Capture</td>
<td>With Capture</td>
<td>Without Capture</td>
<td>With Capture</td>
</tr>
<tr>
<td>Generating Efficiency</td>
<td>34.30% 25.10%</td>
<td>35.50% 29.30%</td>
<td>43.30% 43.10%</td>
<td>38.40% 31.20%</td>
</tr>
<tr>
<td>CO2 emitted, Mt/yr</td>
<td>4.1 0.6</td>
<td>3.6 0.5</td>
<td>3.2 0.4</td>
<td>3.6 0.4</td>
</tr>
<tr>
<td>CO2 captured at 90%, Mt</td>
<td>0.0 5.0</td>
<td>0.0 4.3</td>
<td>0.0 3.7</td>
<td>0.0 4.0</td>
</tr>
<tr>
<td>Cost Increase</td>
<td>74%</td>
<td>61%</td>
<td>54%</td>
<td>32%</td>
</tr>
<tr>
<td>Costs</td>
<td>Total Plant Cost/s/kW</td>
<td>Investment</td>
<td>Fuel cost, cents/kWh</td>
<td>CO2 cost, cents/kWh</td>
</tr>
<tr>
<td></td>
<td>Without Capture</td>
<td>With Capture</td>
<td>Without Capture</td>
<td>With Capture</td>
</tr>
<tr>
<td></td>
<td>1,250</td>
<td>2,230</td>
<td>1,330</td>
<td>2,140</td>
</tr>
<tr>
<td></td>
<td>2.6</td>
<td>4.52</td>
<td>2.7</td>
<td>4.34</td>
</tr>
<tr>
<td></td>
<td>1.49</td>
<td>2.04</td>
<td>1.33</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>1.6</td>
<td>0.75</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>4.84</td>
<td>8.16</td>
<td>4.78</td>
<td>7.69</td>
</tr>
</tbody>
</table>

Basis: 500 MW plant net output, 85% capacity factor; for IGCC, GE radiant cooled gasifier for no-capture case and GE full-quench gasifier for capture case.

1. Efficiency = (3414 Btu/kWe-h) / (heat rate)
2. 90% removal used for all capture cases

Updated to 2005 dollars using CPI inflation rate. Current costs would be higher because of recent increases.

Paul Breeze outlined the market situation in 2006 regarding these technologies:

“There are currently three commercial processes available based on post-combustion chemical absorption. The Kerr-McGee/ABB Lummus Crest Process marketed by ABB employs a roughly 20% MEA solution has been used on small coke and coal-fired boilers. The Fluor Daniel Econamine Process, acquired by Fluor from Dow Chemicals in 1989, uses around 30% MEA solution as the chemical absorbent. The Kansai Electric Power Co, Mitsubishi Heavy Industries Process, meanwhile, uses specially developed amines that are tailored for particular industrial applications (Breeze, 2006).”

There are several other post-combustion processes under research now that are aimed at solving this and other efficiency and cost related issues. A medium to long-term solution to this cost issue are separation technologies such as membranes, which can be employed at higher concentrations of CO2 but this would require technology that releases much purer streams of CO2 than traditional boilers. The next two capture methods address the creation of purer CO2 streams.

Pre-combustion capture implies removing most of the carbon prior to combustion and therefore a change in the actual energy production process meaning the construction of a new plant. This technology is the entry step to a hydrogen based energy scheme: once the carbon is removed from any hydrocarbon you are left with hydrogen. If pure hydrogen is not the aim, a
more hydrogen rich fuel is an economic alternative, creating a gas similar to \( \text{CH}_4 \) from nearly pure carbon fuels like coal, or carbon intensive fuels like petroleum, and biomass. Biomass could prove a very interesting candidate for CCGS because if the bio-mass is harvested sustainably, this could lead to negative emissions in terms of carbon accreditation.

Using oxygen or high temperature steam with some sort of catalyst, fossil fuels can be caused to react and produce carbon monoxide and hydrogen in a mix called synthesis gas or syngas. If syngas is passed through a second steam reaction, hydrogen and \( \text{CO}_2 \) are produced with an efficiency rate of 76 percent for natural gas conversion and 64 percent for coal. If the \( \text{CO}_2 \) is made ready for transport and storage, an additional 3 percent of the efficiency is lost. Integrated gasification combined cycle (IGCC) plants are plants that today take heavy oil residues, coal, petroleum coke, etc. and gasify them, creating syngas. IGCC technology has a great potential for coupling with \( \text{CO}_2 \) pre-combustion capture. The efficiency comparison of an IGCC plant with the more traditional pulverized coal boilers can be seen in MITs analysis in Table 3. Another technology to watch in this sector is Greatpoint Energy’s coal and biomass gasification plant that makes “bluegas”, which is very similar to natural gas and can be sold commercially, and a very pure form of \( \text{CO}_2 \) that would be readily available for storage. The project is similar to a steam methane reformer but utilizes their patented catalyst to significantly reduce their energy costs for their demo plants they are building in Massachusetts and soon in Southern China (Greatpoint Energy, 2008-2009).

**Oxy-fuel combustion** is the remaining technology for capture and it is designed to address the problems that arise with burning a fossil fuel feedstock with normal air are that the combustion flue gases contain a significant number of other elements found in air, mostly (up to 75 percent) nitrogen. An oxy-fueled capture process uses air separators to remove the nitrogen from the intake air needed for combustion. Air typically contains roughly 80 percent nitrogen, 19 percent oxygen, and 1 percent argon with some other compounds found in very small quantities and this process removes the nitrogen (Lagneau, Second Advisory Meeting - Report Review, 2009). However this process creates two issues for CCS projects employing oxy-fuel. First, burning a fossil fuel with pure oxygen generates temperatures upwards of 3,500 degrees Celsius and so to resolve this issue, some of the \( \text{CO}_2 \) needs to be cycled back into the intake air stream to dilute the oxygen with a non-reactive additive. Second, with the removal of nitrogen the percentage of argon and other trace gases increases (argon to roughly 4.5 percent) and as it is a large gas this can prove problematic when it comes to storage. Air Liquide and some other gas separation specialists are working to address this purity issue. This technology requires further development at this stage but can prove promising for industrial retrofitting projects such as coal and gas power and also steel and cement plants.

The **transportation** of \( \text{CO}_2 \) takes place at a commercial scale already via onshore pipelines, especially in the US where it is already used since the 1970s for enhanced oil recovery (EOR) and the infrastructure that exists now takes \( \text{CO}_2 \) from both natural reserves and anthropogenic sources close to oil producing regions, especially in Texas (McKinsey, 2008). However, the viability of using \( \text{CO}_2 \) for this purpose was not widely published until much later, but this will be discussed in a later section. A pressure of 1450-2175 pounds per square inch (psi) or 10-15 megapascals (MPa) is needed to pipe the \( \text{CO}_2 \) in a supercritical liquid state, and the pipelines can be made of steel as long as the moisture is minimal to prevent extensive corrosion (Breeze, 2006).
The costs predicted for a large-scale deployment of CO₂ infrastructure depend on the method and distance as seen in Figure 7 and in Table 2, with offshore transport increasing costs by roughly 50 percent versus onshore, and with shipping becoming the economic choice after any distance over 1,500 km (Breeze, 2006) and (Alexander, 2009). However, these costs are hard to generalize because they represent the cost of transporting CO₂ and do not account for litigation and permitting and also do not take into account “trunk lines” where additional CCGS operations tie into an existing grid and contribute to the associated construction, operation, and maintenance costs of that line.

Jefferies lists the players in this existing merchant market as: Linde, Airgas, Praxair, Air Liquide, and EPCO (Alexander, 2009). In terms of existing pipelines, the Oil and Gas Journal (OGJ) has compiled a list of the existing pipelines, most of which exist in correlation to the existing CO₂ based EOR projects in the Southern United States. The current locations for the current global commercial onshore CO₂ pipeline infrastructure exist almost entirely in the US and Table 6 lists the most well know projects by location and operator expanded from OGJ. Norway has the longest offshore pipeline with 145 km of pipeline between its Snøhvit CO₂ storage demonstration and its Melkøya liquefied natural gas (LNG) processing plant (Acworth, 2006). Canada also has several smaller pipelines and is developing a more extensive network for its EOR operations there.

The current CO₂ high pressure pipeline in the US is made up of roughly 5,000 km with a capacity of 0.042 Gt per year of CO₂. To accommodate transporting carbon to storage sites in the US alone, Jefferies predicts a 10 to 50 fold increase or the construction of 95,000 to 245,000 km of pipe to hold a capacity of 0.42 to 2.1 Gt CO₂ (Alexander, 2009). Jefferies gives an estimate that, “to build a pipeline 50 [times] the current network in the U.S. would cost 180-360 billion USD in capital outlays, assuming no impact on the price of steel, molybdenum, valves, pipes, and other materials. Similarly, property rights and related litigation would surely increase this outlay.” To deal with some of the potential litigation issues CO₂ furthermore needs to be classified as a pollutant or a commodity for extensive interstate/province or international pipeline networks.

![Figure 7 - CO₂ Transport Costs in USD per ton](image)

**Table 3 - CO₂ Transport Cost Breakdown in USD**

<table>
<thead>
<tr>
<th>Transportation Method</th>
<th>Cost (USD per ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onshore Pipe (250 km)</td>
<td>1-8</td>
</tr>
<tr>
<td>Offshore pipe (250 km)</td>
<td>2-12</td>
</tr>
<tr>
<td>Up front capital cost</td>
<td>1.6-3.2 million USD per km</td>
</tr>
<tr>
<td>(USD per km of pipe)</td>
<td>(labor 26%, materials 25%, rights of way 14%)</td>
</tr>
<tr>
<td>Shipping</td>
<td>2-25</td>
</tr>
</tbody>
</table>
and this entails the consensus extensive national and international governmental bodies and agencies.

One major issue that is highlighted by Jefferies is that “there could be significant complications when investors attempt to scale up [CCS transport] projects.” This is because there is significant risk associated with dramatically expanding existing capacity, or building of any extensive new CO$_2$ infrastructure, because if the network of CO$_2$ pipelines becomes on par with the existing natural gas pipelines, this could entail an equal number of accidents, which they roughly estimate as 550 per year for natural gas in the US (Alexander, 2009). Understanding what this, other transport risks, and legal issues mean, in terms of what precautionary steps would be required to get such projects approved, is vital to any rollout of CCS at a commercial scale. A solution that could resolve many of these issues is if the storage sites can be found close to significant “clusters” of carbon intensive industries and power plants. If these clusters could combine their captured CO$_2$ emissions and inject them into a local formation, the need to transport CO$_2$ through populated areas and across major political borders could be avoided, as well as a need to create such an extensive network of high pressure CO$_2$ pipelines.

<table>
<thead>
<tr>
<th>Onshore Pipeline</th>
<th>Location</th>
<th>Operator</th>
<th>Capacity (Mt CO$_2$/yr)</th>
<th>Length (km)</th>
<th>Year</th>
<th>CO$_2$ Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortez</td>
<td>USA</td>
<td>Kinder Morgan</td>
<td>19.3</td>
<td>808</td>
<td>1984</td>
<td>McElmo Dome</td>
</tr>
<tr>
<td>Sheep Mountain</td>
<td>USA</td>
<td>BP Amoco</td>
<td>9.5</td>
<td>660</td>
<td>1984</td>
<td>Sheep Mountain</td>
</tr>
<tr>
<td>Bravo</td>
<td>USA</td>
<td>BP Amoco</td>
<td>7.3</td>
<td>350</td>
<td>1984</td>
<td>Bravo Dome</td>
</tr>
<tr>
<td>Canyon Reef Carriers</td>
<td>USA</td>
<td>Kinder Morgan</td>
<td>5.2</td>
<td>225</td>
<td>1972</td>
<td>Gasification Dome</td>
</tr>
<tr>
<td>Val Verde</td>
<td>USA</td>
<td>Petrosource</td>
<td>2.5</td>
<td>130</td>
<td>1998</td>
<td>Val Verde Gas Plants</td>
</tr>
<tr>
<td>Bati Raman</td>
<td>Turkey</td>
<td>Turkish Petroleum</td>
<td>1.1</td>
<td>90</td>
<td>1983</td>
<td>Dodan Field</td>
</tr>
<tr>
<td>Weyburn</td>
<td>USA &amp; Canada</td>
<td>North Dakota Gasification Co.</td>
<td>5</td>
<td>328</td>
<td>2000</td>
<td>Gasification Plant</td>
</tr>
<tr>
<td>Rangely</td>
<td>USA</td>
<td>Chevron/Exxon</td>
<td>3</td>
<td>283</td>
<td>1984</td>
<td>LaBarge Gas Processing Plant</td>
</tr>
<tr>
<td>In Salah</td>
<td>Algeria</td>
<td>Sonatrach/BP</td>
<td>1.2</td>
<td>60-100</td>
<td>2004</td>
<td>Gas Processing Plant</td>
</tr>
<tr>
<td>Lacq</td>
<td>France</td>
<td>Total</td>
<td>0.2</td>
<td>27</td>
<td>2000</td>
<td>Oxy-fueled Gas Power Plant</td>
</tr>
<tr>
<td>Offshore Pipeline</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snøhvit</td>
<td>Norway</td>
<td>Statoil</td>
<td>0.7</td>
<td>145</td>
<td>2008</td>
<td>Melkøya LNG Plant</td>
</tr>
</tbody>
</table>

Table 4 - Existing CO$_2$ Pipelines
Sources: SPE, Oil and Gas Journal, CO2CRC, BP, Chevron

As mentioned, the main focus of this report is on the storage aspect of CCGS and therefore storage will be outlined here only briefly in general terms, with more to follow in the next section. The concept of geological storage is that the CO$_2$ would, as outlined in the two previous sections, be compressed and piped (or even shipped) to various storage locations, either on- or offshore, and injected into the appropriate geological formations. This can be for an economic benefit, with locations such as depleted oil fields that can benefit from the EOR, or simply storage, in places such as saline reservoirs. All of the storage locations should be sufficiently
deep as to maintain the ideal pressure for keeping the CO₂ dense, to save space, and sufficiently sealed in by “cap-rock” formations, so that it does not infiltrate drinking water sources or migrate to the surface.

Currently there are several existing demonstration/pilot projects conducting CCGS for a variety of reasons in several different types of geologic formations and these will be illustrated in detail in the next section. The one type of geological formation that will not be discussed here, as mentioned earlier, is deep un-mineable coal seams where the idea is to boost methane (CH₄) recovery by replacing the CH₄ with the CO₂ molecules. There is also an emerging storage method that involves mineralization of the CO₂ either above ground in an industrial plant (ex-situ) or underground, where the CO₂ bonds naturally with basaltic formations, as is being looked at in the Hellisheidi project in Iceland and at several other locations worldwide. These are discussed further in the alternatives to CCGS section because they are viewed in this report as an unappealing GHG mitigation option at a global scale, based on current research on the existing technologies.

**CCGS Compatible Geology: Where Can Large Amounts of CO₂ be Stored?**

Any sufficiently porous media that is overlain by an impermeable cap-rock formation, which would prevent the escape of any gas (or pressurized liquid) residing there and is not overly saturated with water, should in theory work for CCGS. The majority of the current international focus - in terms of research studies, pilots, or projects moving towards the commercial scale - has been on three types of underground formations: depleted oil fields, depleted gas fields, and deep saline reservoirs. These vary in size and shape but physically all of these formations are of the same sedimentary rock types, the difference being that a hydrocarbon bearing formation has trapped oil or gas from a source rock below it and therefore is predisposed to preventing things stored there from escaping to the surface as it did with the hydrocarbon for millions of years. If any oil is still present, the type of oil may be or may not be conducive to CO₂ based enhanced recovery (EOR). Sarah Forbes, the CCS research specialist at the World Resource Institute (WRI), has confirmed saline reservoirs as ideal for storage sites, which is important because they are the most widely available globally and offer the best solution in terms of local storage options (Forbes, Phone Interview, 2009). The dissolved salts and metals of saline reservoirs make them of little value in terms of drinking water, given the high costs of current desalination technology. For this reason these have become of interest for the storage of not just CO₂ but also other substances such as natural gas. However, without an assigned price to carbon it is unclear if the storage of CO₂ will take place at a commercial scale without some economic benefit such as EOR.

To give a broad picture of what CCGS is, Figure 8 gives an idea of the different possible project scenarios, with on- and offshore setups, all three geological formations, and EOR/EGR taking place on the hydrocarbon formations. Many sources at this point state that for efficient injectivity, it is compulsory to attain a sufficient depth so as to maintain an adequate pressure range, ideally one equal to that of the transportation network of 1450-2175 psi (10-15 MPa) (Lagneau, First Advisory Meeting, 2009). However, other sources like WRI disagree stating that all cases need to be evaluated. In terms of storage principles, Geostock of France suggests a minimum depth of 500-2000 meters as a general reference for the storage of any gas, including natural gas, compressed air, and CO₂. However, as is suggested by the Jefferies diagram in Figure 3, this may not be ideal for maximizing storage capacity (Geostock). However, the Jefferies range conflicts with the transportation pressures and therefore a cost-benefit analysis
is needed to determine the true optimum depth range and this may not be possible except on a site-by-site basis according to Forbes.

It is held as important by many in the CCS field, such as John Kaldi of the CO2 CRC, that a depth be achieved to obtain pressures/temperatures to maintain the CO2 at a supercritical state. However, Forbes points to a DOE partner, the Midwest Carbon Sequestration Partnership (MCSP), project in Hopkins County, Kentucky in the US, which is attempting the storage of CO2 at a shallower depth of 580 meters, meaning this would be in a gaseous state (OGJ, 2009). The diagrams in Figure 9 allow for a comparison of a CO2 phase chart with the suggested depths given by various sources relative to an average hydrostatic pore pressure gradient [assumed at 1.4 psi/m (0.43 psi/ft)] and given a general geothermal temperature gradient range. The yellow section highlights the conditions needed for maintaining CO2 at a supercritical state but given that a reservoir can be overpressure or underpressure, meaning that due to other factors the observed pressure in the reservoir may be higher or lower than the standard pore pressure for that depth, some margin of safety should be established so that all ranges of pore pressure experienced within the reservoir will be manageable.
Sarah Forbes warns that until more projects come online for analysis and real regulations are formed, what remains paramount are the main criteria for using a geological formation for storing any gas and determining the storage formation rests directly beneath at least one, but ideally several, impermeable cap-rock layers that will prevent upward migration of the gas and protect overlying freshwater aquifers from CO₂ as is illustrated in Figure 8. It is also beneficial for the reservoir to have anticline characteristics so as to prevent extensive horizontal migration of the CO₂ to areas beyond the projects ability to monitor the site’s integrity. Monitoring must
take place throughout operation and continue for some time after the storage site is closed to additional CO₂, until the CO₂ is determined to have stabilized, so as to ensure long-term storage security.

According to WRI, “Careful characterization of potential storage sites is perhaps the single most important step to ensure that CCS projects can sequester CO₂ for geologic periods of time (Venezia, 2008).” Several projects have been completed estimate CO₂ capacity globally. GeoCapacity is a European consortium project that took existing GESTCO country data and then conducted investigations on many of the remaining countries of Europe, releasing a final report released in 2008. The Carbon Sequestration Atlas of the United States and Canada is a project by the National Energy Technology Lab (NETL) and the US DOE called the NatCarb Project and was completed in 2008. The results of the work indicate that the US, Canada, and Europe alone have the sufficient geological formations to store what the IPCC initially estimated as the global CO₂ capacity. Further work is underway to determine the possible storage capacities globally, including work in Australia by the CO₂ CRC collaborative effort and efforts by the GeoCapacity consortium and others to map East Asia. A recent report from the NRDC has released some estimates for China’s estimated capacity (Qian, 2009). Nevertheless, it is important to remember what was discussed earlier in the report regarding the storage capacity pyramid. This stage of national level estimations, although they are helpful in terms of giving a better picture of the existing formations that could be capable of CO₂ storage compared to the rough estimate given by the IPPC, it is still only the bottom of the pyramid meaning it is an exaggeration of the actual capacity. Further efforts need to now take place on the basin- and project- scale.

**The Key Demonstration Projects**

This section gives some examples of existing CCS projects that are in operation around the world. The characteristics of the early projects that follow must be taken as references only as first of all, many of the situations are naturally ideal, and secondly, these projects were not all developed explicitly to develop the CCGS technology portfolio – many having been due to other economic and political drivers. Because the reservoir types concerned by CCGS are broken down into three categories: deep saline reservoirs, depleted oil fields, and depleted gas fields, as a means of examining these formations more closely and the progress, the pilot projects are sorted by their formation type. Basalt is still being evaluated as a storage vehicle and therefore as a project of the same scale does not exist, it is not included here. The projects descriptions are given so as to understand why these projects were pursued and it should be noted that none of this projects are really completely integrated in that they are none of them was designed to be a standalone capture, transport, and storage project.

**Deep Saline Reservoirs: Statoil in North Sea and Snøhvit in Barents Sea**

StatoilHydro, the lead Norwegian oil producer, is a pioneer in the CCS field and established the first CCS project without commercial motivation (EOR) in 1996. Apparently, Sleipner is named after a mythical eight-legged horse that was the fleetest animal on Earth and the idea is now that it will lead the world in the development of CCS technology (Bazilchuk, 2007). The Sleipner project in the North Sea was undertaken because the Norwegian Government passed a tax on each metric ton of CO₂ emissions resulting from offshore gas field production. The high level of CO₂ at the Sleipner Gas Field (12 percent) with the CH₄ made the idea of capture and storage interesting because there is a limit of 2 percent CO₂ for commercial grade natural gas and so the CO₂ is removed anyway. The initial estimate was that it would cost slightly more than the tax to store the captured CO₂ in a saline reservoir within the Utsira Formation, so the project began
For the pure gain of the potential scientific benefit. However, once operations were underway the CO₂ storage costs ended up being less than the tax and so the project in fact saved money compared with venting the CO₂ and paying the tax, although the costs of the project’s construction were significant at 350 million Euros (Lagneau, First Advisory Meeting, 2009).

Because the project is the first to explore the storage of CO₂ in a saline reservoir formation, there is a great deal of interest as to how the gas will behave. Since the storage operations began in 1996, roughly one Gt CO₂ has been sequestered annually for the past 13 years. The saline reservoirs in the Utsira Formation used for the storage, are 200 to 250 meters thick and lie 250 km from the Norwegian coast and nearly 800 to 1,000 meters below the seabed (IEA GHG). The plume of CO₂ within the brine reservoirs at Sleipner is being monitored with the support of the IEA and many other members of the scientific community. The area of the CO₂ plume today is roughly 5 km in diameter (Audigane, 2009). The gas is slowly dissolving into the salt water and as this brine becomes saturated with CO₂, it will become heavier and sink to the bottom of the aquifer over about seven or more thousand years, making leakage even less likely. The gas also mineralizes to some extent, but this is at a much slower rate than it is dissolved into the brine (Audigane, 2009). The Sleipner saline reservoir sequestration scheme, illustrated in Figure 10, is looked to by the CCS community as a model, and is the basis for the Socolow “wedges scheme” target that calls for the creation of a global capacity of “3,500 Sleipners” or the ability to sequester 3500 Mt (3.5 Gt) per year of CO₂. It has been estimated that the Utsira formation could eventually store one to ten Gt of CO₂ and is looked at as a potential site for storage of the emissions from the new Norwegian Kårstø gas-fired power plant, north of Stavanger. According to the Norwegian Government, Kårstø will be outfitted with a carbon capture facility after its production stabilizes, but this remains to be seen.

It is important to take into account that Sleipner is a very ideal case in terms of injectivity, being that the Utsira formation is essentially loose sand. The geologic scenario found in the Utsira formation, in terms of porosity, permeability, and other factors, and is not by any means what is being found elsewhere or what should be expected in other formations. The Sleipner case is good to be used as an example, as is done by many research institutes such as BRGM (the French Geological Survey) who have modeled the Sleipner case to predict a 7,000 year period for absorption of the injected CO₂ into the brine or fixing of the carbon via mineralization (Audigane, 2009). However,
it should be used as one example among many and the reality is that there are really not enough examples at this point. Until the time when CCUS is more common place, no general rule should be followed and as Sarah Forbes of WRI recommends, each case should be examined within the context.

Snøhvit, another more recent Norwegian project, is taking place further north and this project is engaged in a different approach from what is performed at Sleipner. The Snøhvit case is also illustrated in Figure 10 because instead of an onsite gas separation unit, as was constructed offshore at the Sleipner-T CO₂ processing and injection station, the gas is shipped to a liquid natural gas processing facility called Melkøya, just outside Hammerfest. Because the CO₂ liquefies at a much higher temperature/lower pressure than CH₄, the separation process is probably facilitated by the LNG processing plant, but an amine chemical process is still required as is performed at Sleipner-T (Fonck, 2009). The separated CO₂ is then piped 145 km back out to the Snøhvit rig, in the longest existing offshore CO₂ pipeline. Once it reaches the Snøhvit rig, the CO₂ is stored below the gas field in a saline reservoir 2,600 meters below the sea floor. This reservoir is located within the Tubåen Sandstone Formation (Statoil, 2008). Injection of CO₂ began in 2008 and is estimated to reach 0.7 Mt per year at full capacity making it one of the five largest existing CCUS projects to date.

**Oil Field: Weyburn-Midale EOR Project, US-Canada**

Weyburn Oil Field in Saskatchewan Province, Canada was estimated to have 1.4 billion barrels of oil when it was first tapped in 1955. Oil production there peaked at 47,200 barrels per day in 1966 and then declined to only 9,400 barrels per day by 1986 (SEED, 2009). The injection of CO₂ began in 2000 to increase recovery (EOR) in tandem with water injection in a nine well production structure, with the central well serving as the injection point and the eight perimeter wells producing as is shown in Figure 11. A gasification plant in Buelah, North Dakota is currently contracted by EnCan, the company operating the Weyburn field, to ship its captured, 95 percent pure, CO₂ via a 330 km pipeline for the gas to be sequestered in the field. Since the CO₂ EOR began, at least 10,000 barrels of additional oil have been gained in daily production (this was the amount documented by 2005), which is an increase of about 60 percent from the point before injection began in 2000 (Lawrence, 2008). If the estimations are correct, it is expected the EOR will extend the Weyburn field’s life by 25 years and amount to about 120 million barrels in total, which is just under 10 percent of the estimated total reserve.

According to Paul Breeze, the injection rates started at 5,000t/day but are expected to fall to 3,000t/day by the end. Over this time about 23 Mt of CO₂ will be injected into the field and sequestered there (Breeze, 2006). EnCan quotes a higher figure of 30 Mt or 0.03 Gt for the Weyburn field. This amounts to over 1 Mt of CO₂ sequestered annually, but the exact amount changes depending on the source. The operation has been augmented by a second EOR-based storage project in the adjacent Midale Oil Field, operated by Apache, and recent reports say that together the new combined total amount of CO₂ stored annually by the Weyburn-Midale Project over 3 Mt, which translates to 8,800 tons of CO₂ injected daily by their reports. The Geological Survey of Canada quoted higher numbers for the overall injection amount in 2007 of 9,800 tons per day or 3.58 Mt annually, but it is important to consider the amount of new CO₂ purchased each day to know how much is being recycled. The state that the amount of CO₂ recycled is 21 percent for Weyburn (White, 2007). However, given that the purchase rate for CO₂ is 6,600 tons per day or 2.4 Mt, this is the amount of CO₂ that is actually being stored. This issue of CO₂ recycled versus purchased is discussed further under the US case study for the
Rangeley EOR project. This injection amount of 2.4 Mt nevertheless still places the project as the largest existing storage operation to date (IEA GHG, 2009). Several sources have raised the possibility that the CO$_2$ is in fact being absorbed by the sedimentary rock and while further investigation is necessary, this could mean that the CO$_2$ would remain trapped indefinitely. A similar project to the Weyburn-Midale effort is the Rangeley EOR project in Colorado which uses CO$_2$ taken from an Exxon operated gas sweetening plant at Shute Creek, Wyoming. However, the Weyburn project is especially important because, even though it is focused on EOR, it is the only large scale project that takes the emissions from an industrial operation, as opposed to natural gas processing, and stores them underground. This makes the commercial scale Weyburn-Midale project the closest thing to an example of an operating, fully integrated CCGS project.

Gas Field: In Salah, Central Sahara Region, Algeria

The success of the Sleipner project subsequently led Statoil to apply their emissions mitigation approach, in cooperation with BP, to the In Salah gas field in Algeria. In Salah is one of the largest dry gas joint-venture projects in Algeria and produces 9 billion m$^3$ of natural gas annually. The venture involves the development of seven proven gas fields in the southern Sahara, 1,200 km south of Algiers. The project’s major partners are Statoil and BP (each with a 32 percent share) and Sonatrach (the major Algeria oil company with a controlling 35 percent share). The natural gas produced at In Salah contains roughly 5 to 10 percent CO$_2$ and for the CCGS project and as such the project is similar to Sleipner and Snøhvit in that it is designed to separate CO$_2$ from the production of natural gas. However, in this case it is an onshore operation and the CO$_2$ is reinjected into the same formation where the gas originated, only it is not at the same location. An estimated 1.2 Mt of CO$_2$ from four gas production wells will be stored each year via three injection wells located roughly 60 to 100 km away in a depleted gas field near Kretchba as illustrated in Figure 12 (Wright, 2007). The depth of the target formation at the Krenchba Field is roughly 1,800 meters and injections began in mid 2004. However, unlike
Sleipner the project utilizes horizontal injection wells. This is because the injectivity is not as high in the Kretchba Field as it is within the Utsira Formation for Sleipner. The horizontal wells allow for multiple injection points throughout the formation so as to increase the otherwise more limited rate of injection (Forbes, Correspondence, 2009).

Together the partners estimate that 17 Mt (0.017 Gt) of CO₂ will be stored over the life of the project. The total cost of the CCGS development work was 100 million USD, with an additional 30 million USD allocated for CO₂ monitoring (Forbes, Correspondence, 2009). The idea is to demonstrate CCGS as a proven method of GHG reduction and as a result achieve approval of the technology for CDM and JI accreditation (Wright, 2007). As such In Salah is the first project of its scale to investigate onshore storage of CO₂ in a depleted petroleum reservoir without any economic benefit of enhanced recovery (EGR/EOR). The project’s goal of getting the technology approved under the current international regulation is vital, in terms of achieving the global scale-up that is needed, because then CCGS can more easily be found eligible for carbon credits in any emerging global climate treaty designed to replace Kyoto.

In addition to the early projects that are documented above, there are major efforts underway at the international scale. There are a sizable collection of projects that are planned or coming online now across the globe, which are concentrated in North America, Europe, and Australia, but are also visible in China, the Middle East, and elsewhere. The map that follows in Figure 13 illustrates where these projects are operating or are planned to be according to Worley Parsons who completed a project identifying and interviewing the project teams for the current CCS activities for the Global CCS Institute (GCCSI). This is a more complete combination than the maps developed by the Scottish Centre for Carbon Storage, MIT, the Oil and Gas Journal (OGJ),
the World Coal Institute, Bellona, and Canadian Geographic, but these maps also provide an interesting perspective on the global developments of CCS and detail the contain good information about the smaller CCS projects that exist today, are planned, or have failed for various reasons.

Further exploration into the reasons for some past projects having failed or gone offline is an important task in terms of understanding whether the causes were political, technical, financial, legal, or a mix of some or all of these factors. Being able to account for these “failures” is important to advancing the CCGS field to the global scale that is expected and more work should be done to catalogue these unsuccessful projects. There are also numerous smaller pilot CCGS projects, CO₂ injection for EOR, and CO₂ injection tests that have been completed at this point, and these can offer some insight as to what expect with CCGS and also provide insight for the final stages of injection and the sealing of storage reservoirs for future commercial projects.

**Comparing CCGS with other Similar Technologies**

If one considers the energy technologies available individually and compares them, there are a variety of solutions available that could in theory be used as a replacement for a roll-out of CCGS. However, as 88 percent of the current global energy production is made up of carbon-based sources and six percent of what remains comes from nuclear, a complete change is close
to impossible in the time frame being discussed within the climate context. The Boston Consulting Group sums up the situation today:

Most mitigation actions undertaken so far have focused on improving energy efficiency or deploying renewable or alternative forms of energy. Although both energy efficiency and renewable and nuclear energy must be pursued, conventional wisdom and the opinion of experts indicate that these efforts will not be sufficient to contain increasing global carbon emissions (Baeza, 2008).

Although the IEA estimate predicts that this would result in a 70 percent increase in costs, the basic wedges theory in fact does not preclude a solution assembled from a combination of wedges that do not include CCS at all. Given the position of coal and other carbon intensive fuels in the global energy mix it will be difficult to avoid addressing those emissions, not to mention the emissions implied in waste management as well as in steel, iron, cement, chemical production processes. Additionally, when comparing energy supplies, it is very important to understand what it is being compared and the compatibilities of the alternative technologies to CCGS in terms of their truly serving as an apt replacement solution. For instance, wind, solar and other new renewable technologies are important solutions in the global picture. However, these energies are intermittent and cannot be used to deliver base load power without significant advances in energy storage technologies. The following sections outline briefly both direct alternatives to CCGS, as well as solutions that would work in tandem with a CCGS outfitted global economy.

$\text{CO}_2$ absorption by the ocean has always taken place via several natural chemical processes involving partial pressures of gases present in the atmosphere for as long as there have been bodies of water on Earth. There is an increasing rate of this natural storage of $\text{CO}_2$, as a dissolved gas, within the ocean is due to an increase in global atmospheric $\text{CO}_2$ concentrations. One result of this is an observed incremental increase of the ocean’s acidity. $\text{CO}_2$ creates carboxylic acid when dissolved in water and the current documented changes in the ocean’s pH are already having significant impacts on coral and other sensitive marine life. This is largely because it makes them expend more energy to build their shells and carbonate structures. If the atmospheric levels of $\text{CO}_2$ were to change and go back down, a release from the dissolved $\text{CO}_2$ contained in the oceans as a result of a reverse equilibrium process could substantially prolong their stabilization at pre-industrial levels.

However, this is not at all the same process that would be taking place with “carbon capture and ocean storage” (CCOS). The concept of CCOS is fairly simple. Deep in the ocean there are similar levels of pressure as are found in deep geological formations. However, the temperature is close to 30 degrees Celsius, which is much lower than those found in cases of underground
storage. When the CO₂ is pumped from a pipe into the ocean at a sufficient depth, the supercritical gas is heavier than water. As a result, the gas sinks and forms a pool on the bottom as seen in Figure 14. How a system based on CCOS would work is that the CO₂ would be taken to a very deep part of the ocean, such as a trench, by a tanker loaded with the gas in a supercritical state, and then pumped down into a storage pool at the bottom of that trench. The only means of the gas returning to the surface is via the thermohaline circulation of the oceans, which turns over every 1500 years. Nevertheless, this current could serve to carry small amounts of the CO₂ to the surface but this would take place over very long periods of time.

Ocean storage is extremely difficult to pursue for a number of reasons. First, there is very little public support for ocean storage because it is admitted that it will have an impact at least on the immediate marine life, and possibly a wider effect. Second, it is forbidden to dump waste into the ocean by at least two international treaties: OSPAR, and the London Convention (Lagneau, First Advisory Meeting, 2009). However, these treaties are already being slightly modified for offshore CO₂ storage and it is therefore not inconceivable that they be altered for ocean storage if the first factor of marine life is disregarded (Kerr T. a., 2009). An announced project in Hawaii that would have injected 10 to 100 kg of CO₂ into the ocean was killed by substantial lobby efforts against it (Lagneau, First Advisory Meeting, 2009). The method was finally tested of the coast of California by the Monterey Bay Aquarium research division, but the experiment was kept for the most part out of the media and was only publicized afterwards.

**Enhanced coal bed methane recovery (ECBMR)** is an interesting concept that involves a process similar to enhanced oil recovery, in that CO₂ is pumped via an injection well into a deep geological layer to recover fuel. As is explained in Figure 15, the structure of coal is a lot of long tangled fibers resulting in a surface area of 200 square meters per gram. As the coal ages and reacts with its surroundings, methane is released. Some of this is trapped on the surface of these fibers due to an affinity of the CH₄ molecules to the coal molecules. However, when CO₂ is pumped into a coal bed, the CO₂ has a higher affinity than the CH₄ and as a result the methane gets replaced and is released from the coal and can be collected (Lagneau, Second Advisory Meeting - Report Review, 2009).

With the recovery process for CH₄, there are several issues to be considered. Coal is not highly porous and as a result the process of injecting CO₂ into a deep coal seam will need to be energy intensive. A second issue is that even if the energy intensity is reduced, there are major concerns as to whether ECBMR can serve as a GHG mitigation tool because the capture of any less than 95 percent of the CH₄ will defeat the purpose of the CO₂ storage. This is because CH₄ is also a GHG and stores 20 times the heat of CO₂ in the atmosphere (Lagneau, First Advisory Meeting, 2009). At the moment the technology is the least developed of all of the geologically based storage solutions and as a result there does not have
extensive research data on using coal beds as CO₂ storage vessels at this time. There are
nevertheless several ECBMR projects moving forward in the US, Australia, China, Europe, and
there is significant interest in South Africa. For the movement, the technology does not appear
to offer a significant storage solution and will probably remain as a methane production method
rather than a GHG mitigation technique.

An interesting proposal, known as in-situ mineralization or CO₂ fixation, uses chemical
reactions to bind the CO₂ with another substance. There are numerous experiments currently
underway designed to design a reaction that would combine CO₂ with some natural or man-
made substances, under the right temperatures and pressures, so as to trap the CO₂ within a
compound. However, this requires a great deal of energy and given current scientific
understanding of this process much more R&D is needed before this will be available at a
reasonable scale. However, this would potentially work in an area where free renewable energy
is abundant, e.g. with a high solar, wind, or geothermal rating but that is has a low enough
energy demand to allow for excess renewable energy be utilized for things besides electricity
production. Iceland is interested in the technology because they have abundant geothermal
energy and relatively low energy demands.

One way to get around this is to conduct “ex-situ mineralization” by injecting the CO₂ into
basaltic formation. The Hellisheidi Project in Iceland is conducting an experiment on a hybrid
storage/mineralization process that injects CO₂ into a basaltic formation at a depth of 400
meters. Here mineralization takes place naturally underground, i.e. without the high energy
cost. In the Hellisheidi case, as with several other experiments around the world, the hope is the
basalt will exhibit sufficient injectability so that the storage of large amounts of CO₂ will be
possible. The most interesting aspect of this unproven hybridized CCGS-mineralization process is
that it could allow for immediate storage of the CO₂, while causing a permanent bonding of the
gas with the formation in the medium-term as opposed to waiting thousands of years for
dissolution of the gas with the brine found in these formations (Lagneau, First Advisory Meeting,
2009). If this hybridized mineralization/storage technology proves to be promising, India could
be an interesting beneficiary for ex-situ mineralization because it could use its massive lava
flows, called “the Trappes”, to store its emissions.

Technologies and Developments that Compliment CCGS-fitted Energy Infrastructures
It must be noted that as CCGS is not an energy technology, it should not be compared with other
energy technologies as such. CCGS is an emissions reduction technology and therefore has many
applications outside the energy sector. However, the cases where energy installations are fitted
with CCGS are often held up in comparison to other options, e.g. renewable or nuclear or the
same installations without CCGS. In these cases it is vital to understand that CCGS fitted energy
production facilities will be part of a portfolio of solutions as mentioned by the wedges
argument and the IEA Bluemap Scenario. Nevertheless the other technology options will be
discussed here to emphasize the importance that all the technologies be used in tandem as
complimentary solutions rather than stand-alone options.

Nuclear for the moment is not a politically feasible option for the US or most of Europe due to
the issue of proliferation to hostile nations, the build-up of radioactive wastes for which there
currently exists no clear storage solution, and safety concerns based on the major accidents at
the nuclear plants of Chernobyl in Russia and Three Mile Island in the US (as well as a long
history of smaller accidents related to the use and transport of nuclear material) (Greenpeace,
1996). However, elsewhere in the world, where the technology has less stigma built up around
it, there are still possibilities of using the nuclear-produced power as a GHG mitigation energy option. Furthermore, it is important to note that there exists only 12 years of fissile material if the world overcomes the political hurdles, embraces a nuclear solution, and uses deploys nuclear using the technology at a global scale as it exists today. It would be necessary in such a scaling up of the technology to deploy nuclear reactors based on, as a minimum, “fourth generation” technology. Unfortunately, the only existing projects to test this technology, such as the Super Phoenix project in France, are still in development or have been canceled/“moth-balled” due to political concerns and high costs. With the use of fourth/fifth generation technology, there is feasibly enough fissile material to last the world for thousands of years. However, the technology would require much more investment for development to advance beyond where it currently stands. Compared to CCGS this would require much more research time and far more substantial global investment.

Most renewable energy sources, such as the sun, the wind, or the ocean are intermittent in terms of the energy that can be harvested from them. The constraint is simply that improved energy storage technology must be developed so as to allow the carbon-free energy to be obtained whenever and where-ever and then be shipped to where it is needed. Hydrogen is looked at as perhaps being capable of serving this storage purpose by some researchers, but there is almost no existing infrastructure for hydrogen transport, which would be much more complex and costly than CO₂ transport as required by CCGS. Furthermore, the cheapest means of producing the gas today is via fossil fuels. Interestingly, if the price on fossil fuels reflected their actual costs, including carbon waste/bi-product management (CCGS), this would in turn create a competitive demand for hydrogen (a carbon free energy source when burned for fuel – regardless of its source) and thereby reduce CO₂ generation. On these terms CCGS would allow for the beginning of a hydrogen based economy that could eventually be supplemented by, and in time completely supplied by, renewable energy sources. If wind does in fact prove to be less expensive than coal power fitted with CCGS, as will be shown in Figure 16, the technology could certainly compete for a larger share of the electricity mix. However, due to the issues with intermittency and storage, for now the baseload power supply will have to come from something more like a standard power plant, which can be coal, biomass, natural gas, fuel oil, or nuclear. Biomass does ultimately produce CO₂ and is less efficient than current coal and natural gas plants, but with an increase in gasification technologies biomass could be fitted to CCGS as well and provide a more sustainable solution than the limited fossil resources. Since nuclear proves a difficult political hurdle, the most probable cases for baseload power provision are coal, biomass, and natural gas. These energy sources will only be able to truly serve the mitigation goals set for dealing with the climate situation, if they are first coupled with CCGS.
Paul Breeze of Business Insights has made a comparison of nuclear, hydroelectric, and onshore wind power production costs to determine where the cheapest solution lies. He found that CCGS coupled with EOR is the cheapest, but without EOR the following comparison in Figure 16 gives the results of his analysis. His results demonstrate that given the uncertainty of natural gas prices, the other three options cost slightly less than a new generation pulverized coal (PC) plant or natural gas combined cycle (NGCC) plant retro-fitted with CCS, even with the structural costs of wind. However, it is noteworthy that hydropower is at about 60 percent of its capacity in the US and therefore cannot be depended on to provide the base load electricity that is needed.

**Efficiency** is the best option because it serves as either an immediate reduction in cost or, if significant investment is involved, the pay-back period is typically reasonably short, making the costs of efficiency negative. However, efficiency is more a principle than a strategy. There are significant inefficiencies that exist in the energy system today, including technology limitations, aging infrastructure, behavioral issues (i.e. leaving equipment running when not in use or using it at a higher rate than needed), etc. These inefficiencies range from temporary summer vacation housing that has become permanent but is never properly insulated, to shopping malls that due to “aesthetic” designs are extremely energy intensive. As for the power sector, the fact that half of the current coal fired power plant fleet in a wealthy nation like the US is on average more than 30 years old, does not bode well for the state of the rest of the world’s energy infrastructure and the resulting efficiency levels. If efficiency is not pursued by members of the energy system, it means the energy is too cheap to be properly valued. For the new generation of CCGS plants, efficiency will be compulsory in terms of the of plants’ ability to achieve the significant improvements necessary so as to minimize the inherent energy losses due to the capture, compression, and injection processes needed to manage their CO₂ emissions.

Embracing a new energy system is difficult technically, politically, legally, and socially, and will require significant investment from all sectors of society to become a reality. The goal should be to constantly improve the system and achieve new levels of efficiency, power output, revolutionary energy sources, cheaper means of delivery, and better means of production. Essential to this process again is to have each form of energy production reflect its actual costs, including nuclear, with regard to waste management and disposal. However, this is currently not the goal of the members of the global energy system. Thomas Friedman points to a line from *The Prince* by Machiavelli to explain this task: “It ought to be remembered that there is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in introducing a new order of things, because the innovator has for enemies all
those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new.” Friedman points out that during the Dot Com bubble of rapid development during the 1990s, the new information technology sector was receiving 80 billion USD per year in venture capital investments by the year 2000 in the US. Clean energy in the US on the other hand received 5 billion USD in 2007 (Friedman, 2008).

The problem is also that, at least in the US, there is little money returned from revenues by the energy sector into R&D. Thomas Friedman cites 8 to 10 percent as the typical range for R&D spending for a competitive industry, citing as an example the healthcare industry, which spends 8 percent of its revenues on R&D. However, Jeffery Immelt, the CEO for GE, revealed to Friedman in an interview that the entire energy industry spends about 2 percent in this area. That would make sense if there were low profits in that sector but for several years in a row now Exxon-Mobile has set records for highest profits in human history, with the other petroleum giants not far behind. Imagine if Exxon and its competitors matched the medical industry’s R&D investment.

For electric utilities the investment is even smaller, with only 0.15 percent of their revenues going to R&D. This is less than the amount spent by the American pet food industry (Friedman, 2008). It is clear from this trend that there is little incentive to compete or innovate in the energy industry. This will need to change if the types of numbers quoted as being required to a change to CCGS, which range in the hundreds of billions of USD.

**Energy Production Portfolios**

The Carbon Mitigation Initiative (CMI) at Princeton University’s Environmental Institute (PEI) was started by Robert Socolow and Stephen Pacala to develop a particle strategy to tackle the GHG issue and mitigate climate change. These two researchers created the concept of “stabilization wedges - 25 billion ton “wedges” that need to be cut out of predicted future carbon emissions in the next 50 years to avoid a doubling of atmospheric carbon dioxide over pre-industrial levels (Hotinski, 2007).” In this way, each wedge can be seen as a quantified goal to achieve the overall carbon abatement strategy that takes away from the doubled amount of emissions expected from business as usual (BAU). They have identified fifteen possible wedges that can be used, but only seven are required to achieve their mitigation goal of stabilizing CO₂ emissions at current levels. Three of the wedges have to do with CCS and all will involve geologic storage of the CO₂.

The World Resource Institute (WRI), a nongovernmental environmental research center, is working with the Goldman Sachs Center for Environmental Markets to take the wedge concept to the “next-stage” by evaluating the series of wedges and the financial, legal and environmental implications of each wedge as a policy choice. They attribute their work to Socolow and Pacala and the “solution-oriented framework [of] the wedges approach [that] has captured the imagination of those eager to tackle climate change (Wellington, 2007).” In their report WRI and Goldman distinguish that there are also negative wedges such as coal to liquids and oil shales that if pursued will increase emissions at a greater rate than the business as usual scenario and will therefore increase the costs of successful mitigation.

Overall, the wedges approach outlines much more tangible solutions to define the commitment required for scaling up CCS technology on a global scale, and requires the equivalent of 3,500 Mt per year CO₂ sequestration projects over that period. One Mt is currently the rough size of most of the five largest operating CCS demonstration projects, with the one exception being the
Weyburn-Midale project to be discussed later. A better means for understand what this 3,500 Mt represents is to think in terms of coal power plants. A rough estimate it is that in the US a typical coal power plant has a capacity of 1,000 Megawatts (MW) and this size plant produces 5 Mt of CO₂ each year (Lagneau, Second Advisory Meeting - Report Review, 2009). This means that the equivalent of seven hundred 1,000 GW coal plants would need to be fitted with CCS technology in order to achieve the goal for one CCS wedge. By a quick estimate given price average for new pulverize coal power plants in the US of 3,000,000 USD per MW taken from WRI and using MIT’s estimate that CCS increases costs by about 50 percent: if these 700 plants were to be built new, the total investment would be 3.15 trillion USD globally for deploying one CCS wedge, and that is only one seventh of what is needed to make up the full reduction goal.

A more recent take on the wedge theory can be seen in the latest report from the IEA, who have written several “roadmaps” that give the steps needed for all technologies identified by their BLUE Map modeling program as key for reaching the 50 percent by 2050 goal. The IEA outlines the basis for the BLUE Map model in Figure 17 as follows:

The IEA Energy Technology Perspectives (ETP) BLUE Map scenario describes how energy technologies may be transformed by 2050 to achieve the global goal of reducing annual CO₂ emissions to half that of 2005 levels. The model is a bottom-up MARKAL model that uses cost [optimization] to identify least cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. The ETP model is a global fifteen-region model that permits the analysis of fuel and technology choices throughout the energy system. The model’s detailed representation of technology options includes about 1,000 individual technologies. The model has been developed over a number of years and has been used in many analyses of the global energy sector. In addition, the ETP model was supplemented with detailed demand-side models for all major end-uses in the industry, buildings and transport sectors (Kerr T. a., 2009).

The IEA CCS Roadmap specifically outlines what needs to take place to see CCS come to scale globally. This is a much more detailed model then the theoretical model by PEI and uses a cost
benefit analysis to determine which wedges are needed and the size of each. This places CCS as necessary for addressing nearly one fifth of the expected emissions increase for a BAU scenario from 2005. The price tag for their CCS scale-up scenario is predicated to be about 2.5 to 3 trillion USD between now and 2050 for the construction of the 3,400 projects they estimate as needed to meet the 50 percent mitigation target. This is slightly less than the estimate from the PEI wedge cost of 3.15 trillion USD to cover CCS used for one seventh of the needed GHG mitigation activities, which makes sense as not all projects will need to be constructed new. The more precise CCS “wedge” from the IEA makes up roughly six percent of the total BLUE Map Scenario investment requirement, meaning that the total cost to achieve that goal is roughly 40-50 trillion USD in that 40 year period, or 1 to 1.25 trillion USD per year. It is important to note that without CCS, the IEA predicts a 70 percent increase in those emission reduction costs. Therefore, without CCS the costs would increase by 70 percent making the global investment closer to 70 or 85 trillion USD.

Bear in mind that these numbers are all based on the limited data that is available, due to the fact that only five commercial scale projects that are CCS currently exist at any sort of significant scale. However, one thing that should be made clear by these calculations is that if climate change is to be addressed and mitigated, a serious financial commitment must be made at the international level to place CCS and other GHG mitigation technologies as a priority. Furthermore, this highlights that firms with know-how about CCS related technologies and expertise will be in a position to take advantage of this massive outlay of capital. To give an idea of what kind of priority this would need to be, North America for instance, which would be responsible for 29 percent of the global CCS deployment according to the IEA CCS Roadmap, would need to spend roughly 350 billion USD per year to achieve the goal (assuming CCS is used). This is roughly 3.5 times what the US spends to operate in Iraq each year. To surmise, the goal of mitigating climate change could require funding on a tier perhaps equal to (or even greater than) what the current US budget allocates to its military. This is not meant to scare the reader or bring politics into this report, but merely to place these financial estimates of what is needed globally into terms that one can more easily gauge using know references.
Market Analysis

Although right now CCGS is seen as a very promising solution for addressing GHG emissions, there are significant costs entailed in building the infrastructure associated with a coupling of CCGS to fossil fuel energy production. The issue when considering whether or not it is feasible to bring CCGS to scale is the real cost of employing it as a solution to climate change, as compared with the predicted price of carbon, the cost of inaction, and the cost of other GHG mitigation technologies. Financial estimations of what costs should be expected, i.e. capture, transport, injection, storage, and monitoring, have been completed by groups interested in the CCGS solution and Table 8 outlines their finding in terms of a price to abate one ton of CO₂ and then the resulting cost of scaling the global energy sector to meet the goal of mitigating 25 Gt of CO₂ for one of the seven necessary climate wedges.

<table>
<thead>
<tr>
<th>Information Source</th>
<th>Average Initial CO₂ Cost</th>
<th>Stabilized CO₂ in USD (High)</th>
<th>Stabilized CO₂ in USD (Low)</th>
<th>Total Investment for a Wedge (25 B tons) in B USD (High)</th>
<th>Total Investment for a Wedge (25 B tons) in B USD (Low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business Insights (2006)</td>
<td>65</td>
<td>56</td>
<td>29</td>
<td>1,400</td>
<td>725</td>
</tr>
<tr>
<td>WRI/Goldman (2008)</td>
<td>-</td>
<td>60</td>
<td>40</td>
<td>1,500</td>
<td>1,000</td>
</tr>
<tr>
<td>McKinsey (2009)</td>
<td>105</td>
<td>67</td>
<td>42</td>
<td>1,675</td>
<td>1,050</td>
</tr>
<tr>
<td>BCG (2008)</td>
<td>63</td>
<td>42</td>
<td>42</td>
<td>1,050</td>
<td>1,050</td>
</tr>
<tr>
<td>Jefferies (2009)</td>
<td>55</td>
<td>145</td>
<td>32</td>
<td>3,625</td>
<td>800</td>
</tr>
</tbody>
</table>

Table 5 - CCGS Costs (1.4 USD = 1 EUR) - Sources: WRI/Goldman Sachs, BCG, Jefferies, McKinsey, Business Insights, IEA, Personal Analysis

Although Table 8 above simplifies the results of these institutions, it is difficult to compare the different reports because each took a different approach to the task of evaluating the cost of CCGS deployment. The following sections highlight the important aspects of financing CCGS as presented by the institutions compared in Table 8.

The World Resource Institute (WRI) and Goldman Sachs (Venezia, 2008)

What is made clear in WRI’s report “Capturing King Coal” is that “the transition to a lower-carbon energy economy is a long-term one (Venezia, 2008).” The team assessment by WRI and Goldman Sachs estimates that a period of 25 to 50 years is needed during which major capital outlays will be required to achieve a CCGS infrastructure that will have any impact on climate change. To the extent possible these outlays in capital investments need to be protected from cyclical political change and backed by government support in terms of incentives, research, development, and the deployment of demonstration projects, in order to attract serious investment in this field. What this implies is a broad reaching climate policy for the US and the EU and eventually at the global scale. US and EU policies are believed to be prerequisites to any overarching international treaty governing GHG emissions and they are the only means for bringing other major emitters such as China to the table.

In terms of this leading to CCGS development, a policy in the US and the EU will need to position CCGS as the “least-cost compliance strategy.” Otherwise emitters will simply pay the carbon fees and pursue the hope of possible cheaper alternatives and GHG abatement strategies. The WRI report outlines two methods for positioning CCGS in a favorable position for adoption on the global scale: pull and push policy and funding strategies that work in tandem to achieve the requisite market settings for a roll-out of CCGS. “A government ‘pull’ strategy would center on price incentives through cap and trade or taxation, whereas, a ‘push’ strategy would center
on research, development, and demonstration (RD&D); technology performance standards (such as efficiency standards); and subsidies (Venezia, 2008).”

A pull strategy would entail for the US adopting a carbon emissions trading scheme similar to the one in place in Europe already called the European Union Emission Trading System (EU ETS). The idea is that CO₂ emission point sources are allocated or secure via auction a certain number of CO₂ emission credits. These companies then either buy additional credits to cover their excess emissions from other companies that find a way to reduce their actual emissions, or likewise they sell their excess credits or “bank” them for a future period where the allocations may be stricter (17).

This is where the prices per ton of CO₂ in Table 8 come into play in that they are estimates as to what prices would bring CCGS into play as an economical emissions mitigation tool. The idea is summed up as follows, “If the net present value of a conventional coal plant, including the cost of cash outlays for cap-and-trade compliance over the life of the plant is greater than the net present value of a plant including CCS, there is no financial incentive for CCS deployment.” One roadblock to scaling CCGS is the concern that significant liability issues could arise with transporting and the long-term storage of significant quantities of CO₂. Governments will need to be able to take responsibility for this liability to cover costs of any potential emergency, especially for a closed site where the operating company is no longer in existence, so as to ensure investors that this risk would not fall completely on them.

Conversely, a push strategy would entail government RD&D, performance mandates, loan guarantees, and subsidies for private firms engaging in demonstration projects. Increasing performance standards can drive efficiency and emissions improvements throughout the existing industry and drive innovation in future projects, which may embrace CCGS as the method of meeting the standard. As for RD&D, the IEA estimates that in order to understand the technology at the scale that is required and achieve prices close to the lower estimates in Table 8, at least 10 major scale demonstration projects are necessary. Currently there are no major projects that incorporate capture and storage for a commercial scale power plant. It is only at the point where this future project is completed that the necessary infrastructure will begin to receive adequate investment. FutureGen in the US was just such a project and was slotted to receive 1 billion USD in government funding. However, the project was “moth-balled” in 2008, just after the final site was selected in Illinois, due to political issues and cost estimates increasing to 1.8 billion (20).

Government performance standards drive efficiency and emissions improvements throughout the existing industry and drive innovation in future projects that may embrace CCGS as the method of meeting the standard. However, from the private investment sector, the Carbon Principles published by Citi, JPMorgan Chase, and Morgan Stanley banks now outline these institutions’ new “environmental guidelines” that will be applied to investments due to the pending climate legislation. This is because this policy shift implies risk for carbon intensive projects and the guidelines encourage project developers to incorporate more efficiency and renewable energy considerations (29). At the very least, this push from the private sector means that Wall Street has begun to accept a future where carbon has a price tag and it gives a benefit to CCGS project developers.

Ultimately, WRI concludes that “a shift to a low-carbon energy future in the U.S. underpinned by an economically viable national CCS system is possible, but that such a fundamental shift will
likely only occur once definitive policies and incentives are put in place that reward investment in and capital formation around improved carbon performance (33).” The most important implications of the report on geological storage are those of who will take on the liability and what sort of “not under my backyard” issues might arise.


The McKinsey report focuses on new build coal power in Europe as the basis for its evaluation of CCGS. Retrofitting of plants is looked at as fairly inefficient since on a 20 year old plant, the life of the capture facility would be about 20 years (the same as the remaining life of the plant) making the initial CAPEX inefficient especially since the CCS costs compared to a new plant are 30 percent higher. The report highlights how public understanding is low and aims at bringing a clearer picture to the estimations of cost and what scaling up CCGS would entail. They estimate that 20 percent of Europe’s abatement potential lies in CCGS application. Their ideal scenario of 0.4 Gt of CO₂ reductions per year via CCGS is based on 80-120 commercial projects coming online by 2030 (7). Storage is a major factor of uncertainty in the report and although the efforts of the GeoCapacity project are recognized, their conclusion is that more extensive work is required.

One key figure described by the report and shown in Figure 18, was an idea of an economic gap in terms of anticipated costs of the initial and pilot scale projects, and the expected price of carbon that would allow these projects to recoup some of their costs. They estimate this gap at 0.5-1.1 billion Euros per project in terms of net present value, which would need to be covered by government subsidies or other funding (8).

In terms of cost, the McKinsey report sheds some light as to where costs are felt in a CCGS plant compared to a non-CCS plant in terms of the efficiency penalty and what that means in terms of additional total coal consumed to generate the same amount of output electricity and the associated increase in CO₂ emissions over all. Even though most of these (90%) emissions are captured, the overall increase is important to note in terms of the scale of storage that will be required and the increase in coal consumption. Furthermore, they breakdown the estimated cost of 35 to 50 Euros per ton of CO₂ into the various associated components of capture, transport, and storage. They give an anticipated storage cost of 4 to 12 Euros, or roughly 5.5 to 17 USD per ton CO₂ given the anticipated constraints of storage techniques, depths, and equipment. What is also interesting is that the costs of storage do not much change with the scale of deployment. With storage the major issue is uncertainty in terms of where the storage will take place, onshore having a significantly lower cost than offshore storage and saline reservoirs entailing 10-15 percent higher costs due to the extra geological mapping and exploration (27).
In terms of financing projects, the major cost sensitivity identified by McKinsey is the weighted average cost of capital (WACC) used by an investor could significantly affect the price per ton. In addition steel and engineering costs can be expected to increase (26). When looking to reduce costs, EOR and EGR are considered briefly by the report and the US estimated value of 25 to 35 USD per ton for EOR is looked at to be fairly irrelevant for Europe due to the limited amount of sites that could benefit from such activity (28). Nevertheless storage costs are looked at as a key factor for optimization so as to reduce the costs of CCS, along with capture CAPEX costs.

One of the most interesting aspects of the report is the discussion of a roll-out of CCGS in Europe. They envision that one storage area are identified, clusters of emissions sources could be identified and channel via a pipeline network to a central storage site so as to cut the costs of transport and injection. Due to the high level of uncertainly regarding storage in saline reservoirs, for which the capacity estimate ranges from 30 to 500 gigatons CO\textsubscript{2}, they are unsure about whether a storage scheme will focus on the established oil and gas reservoirs of the North Sea or if the saline reservoirs that exist across Europe can be counted on. The offshore scenario is estimated to double storage costs from 9 Euros to 18 per ton CO\textsubscript{2}. The scheme in Figure 19 was given in the report purely as an illustration of what such a capture and storage clustering scheme might resemble in Europe and nothing finite in terms of a plan and is in fact unrealisitic based on the current policy constraints of countries such as Germany with regards to transport. Nevertheless it gives a decent picture of the sort of road map that will be required for Europe to embrace CCGS as a solution.

In terms of what an actual roll-out of the technology, McKinsey estimates a 6-10 year lag time for projects in Europe to get started. They cite Prospx and Platts Powervision’s estimate that five new coal plants are planned per year from 2015 to 2030. The McKinsey team suggests that if along with these new builds, relatively new plants are retrofit for CCGS at an additional cost of around 10 percent compare to new plants, a goal of 0.2 to 0.4 Gt of CO\textsubscript{2} sequestered per year is feasible. This would entail for the 0.2 scenario that the first commercial projects would be operating in 2023, which would signal a commercial roll-out phase of five 1000 MW new CCGS coal plants per year or three of their example plants (900 MW) per year equally 70 percent of
the CO₂ abatement potential with retrofits and industrial projects each achieving 15 percent of the remaining CO₂ reductions (41). To reach the 0.4 Gt per year CO₂ abatement goal by 2030, two possibilities exist: one is to start the roll-out sooner in 2018 implying a more rapid development of commercial sized demonstration projects, the second is a nearly doubled rate of deployment after 2023 with the equivalent of ten or eleven 1000 MW plants being brought online each year and implying a great number of retrofits and industrial projects to make up the difference. In the end this would translate into 80 to 120 projects during the roll-out.

The report finishes by mentioning the major concerns already mentioned by WRI such as storage liability and legality with purity of CO₂ highlighted as a potential factor. Monitoring costs, responsibilities, and timeframes also remain unclear.

**Jefferies and Company (Alexander, 2009)**

The Jefferies analysis of the emerging CCS market is much more limited as it is part of an overview of a large selection of alternative energy technologies. Nevertheless it gives a sufficient picture of the US CCGS situation. The report again highlights that the technology is held hostage by the lack of any real global price on carbon. They place the start of a roll-out at 2025 with the possibility of legality issues delaying deployment further. They identify Fluor, Shaw Group, and the Washington Group subsidiary of URS Corporation as the E & C companies that would benefit probably as a result of their experience with hydrocarbon drilling projects. In terms of alternative uses for the CO₂, as opposed to storage or EOR, they have identified a 13.1 ton per year of liquid CO₂ business that is experiencing a 2 to 2.5 percent growth rate due to the increase of environmental standards requiring the use of less caustic chemicals.

As for storage, the report does mention the US DOE prediction that CCS will account for 40 percent of the US emission reductions by 2050 or 15 percent of all industrial emissions (182). The report is more enthusiastic with the results of the NatCarb storage capacity survey than McKinsey with the GeoCapacity project, noting that the survey results imply 300-950 years of storage. They mention that a depth of at least 760 meters is required to maintain the supercritical state of CO₂ that facilitates the largest and longest storage potentials but it is unclear whether the estimate of 300-950 years of storage based on the NatCarb assessment takes that into account. Extrapolating from IEA estimates and their own data, Jefferies predicts an ambitious 10,000 MW of CCGS demonstrative projects in the US by 2016.

The total price tag that the report assigns to a scale up of CCGS in the US is as follows: sequestering “50% of the stationary emissions from the U.S., assuming no need to build long-distance pipelines or resort to ocean storage, with an average cost of $55/t, would cost around $100bn a year, or 0.8% of GDP (186).” However, it is notable that their estimation for storage and monitoring costs fall in a range bellow one Euro per ton, which is extremely low compared to other cases.

**Boston Consulting Group (BCG) (Baeza, 2008)**

BCG highlights the promise of the European Union to partially fund 10-20 projects investigating CCGS. Japan aims at 0.2 Gt of reductions via CCS. The cost for storage is estimated at 4 to 5 Euros per ton. Large Investments in CCS cannot be exposed to a volatile carbon market. Not to be expected commercially give current development path until 2020-2030. The evolution of CCS is likely to be similar to that of natural gas distribution. First there will be standalone projects, with carbon dioxide capture, transport, and storage tied to a single-point source of emissions such as a power plant. Over time, more and more emission sources will connect through “trunk
lines,” and a grid infrastructure will develop. As with natural gas pipelines, regulation will be necessary to ensure open access to transport; in contrast, storage capacity is plentiful and likely to remain unregulated.
Case I: The United States of America

The United States is the largest developed market in need of a new energy strategy. The country has remained outside the core international debate concerning climate change abatement strategies and energy alternatives since the US Senate voted nearly unanimously against ratifying Al Gore’s signature on the Kyoto Treaty. The Bush Administration drew focus away from the ongoing climate debate, now centered in Europe, and Kyoto for eight years by diverting attention and resources to US military operations and to parallel alliances formed around the climate issue, such as the Asia Pacific Partnership on Development (APPD). In addition to the US, the APPD is comprised of China, India, Japan, South Korea, and Australia, and as such its members are responsible for 50 percent of the global GHG emissions (Rettman, 2005). However, the focus of this partnership was more of collaboration on technology development rather than an emissions limitation agreement like a direct carbon tax or a cap-and-trade scheme similar to what exists for SOx emissions and is already in place in the EU for carbon.

Individual states within the US are drawing separate conclusions from the federal government and as a result there are more localized efforts taking place across the country that aim to address the climate dilemma. There are currently three partnerships between groups of states in the US designed to implement regional cap-and-trade schemes: the Regional Greenhouse Gas Initiative (RGGI), the Western Climate Initiative (WCI), and the Midwestern Greenhouse Gas Reduction Accord (MGGRA). The RGGI, which includes ten US states, has already begun emissions trading allowances for its first three year compliance period as of January 1, 2009 and maintains the goal of reducing emissions by 10 percent from 2009 levels by 2018 (RGGI, 2007). The other two partnerships, WCI with six US states and three Canadian Provinces and MGGRA with six states and one Canadian province, will commence a cap-and-trade policy on January 1, 2012, with the WCI committed to reducing emissions 15 percent from 2005 levels and the MGGRA committed to 18 to 20 percent emissions reduction below 2005 (MGGRA Advisory Group, 2009) (WCI, 2009). There are numerous observants of these various regional efforts, which have not joined due to political and economic concerns, ranging from non-member US states and Canadian provinces but also several northern Mexican territories. A climate registry agreement has also been created to standardize emissions reporting by individual states as can be seen in Figure 20.

With the change of administration in the White House, there have been several developments that suggest a potential movement towards US adoption of a national GHG reduction policy or acceptance of a global climate agreement. The Obama Administration has reserved a significant portion of the 2009 Stimulus Funding Package for alternative energy research and projects deployment. In addition to recognizing the RGGI states for their efforts, the EPA has moved to establish a nationwide climate agreement to validate the existing efforts by the US Climate Registry state members and “on January 1, 2010, the U.S. Environmental Protection Agency will, for the first time, require large emitters of heat-trapping emissions to begin collecting greenhouse gas (GHG) data under a new reporting system. This new program will cover approximately 85 percent of the nation’s GHG emissions and apply to roughly 10,000 facilities (MGGRA, 2009).” There is also a growing development in the US Congress regarding a national climate policy. A bill called the American Clean Energy and Security Act of 2009 but known better as the Waxman-Markey Climate Bill has passed the House of Representatives and includes a cap-and-trade scheme that would aim to reduce emissions by 17 percent below 2005
levels by 2020 (Open Congress). If the bill’s counterpart passes successfully through the Senate, the bill would likely be signed into law by Obama but the Senate passage is a major hurdle. As of May 2010 the Senate version of the bill S. 1733 sponsored by John Kerry has still not passed through all of the six Senate committees responsible for it (Broder, Democrats Push Climate Bill through Panel without G.O.P. Debate, 2009). However, a new bill involving a dual “tax and trade” scheme, which changes depending on the type of emission point source, is being put forward by a bipartisan group and has oil company support. The most important conclusion to take from this is that the debate over whether the US will regulate emissions will need to be largely settled before any real hopes for a CCS rollout can be realized.

As the Copenhagen Climate Conference ended with no decisions as to whether there will be a global climate treaty, there are still hopes that the US will finally set a price on its CO2 by either implementing a federal climate agreement or by participating in an international agreement might. However, as can be seen with the current situation in the US Congress and the separate state efforts, there is little consensus as to how the US should address the climate issue. To better understand the politics behind the current roadblocks to either a national US GHG limitation policy and/or a signature on the existing/future climate agreements, it is important to
consider the US energy or more accurately GHG emissions profile. This profile is one based on three major factors: the US is a major petroleum producer and is a major player in the global oil and gas market, the US is the top coal producer and produces roughly half of its electricity from coal, and lastly the US has largely mothballed its nuclear program with no new plants receiving approval since 1978 (Broder, House Republicans Draft Energy Bill With Heavy Focus on Nuclear Power, 2009).

The US Energy Profile
The US became the original major oil exporter as a result of its discoveries in Texas and then in California at the turn of the 20th Century. Today the US remains among the top three producers along with Saudi Arabia and Russia but unlike the other top two producers, the US is not among the significant exporters of oil and gas as it is the top consumer of petroleum worldwide by a factor of three (Information Please Database, 2007). As a result of its national stocks of oil and gas, the US has maintained a strong economic dependence on oil, despite the oil shocks of the 1970s and 1980s. The US has pursued a strategy of international engagement rather than energy independence as a response to supply issues and as a result has maintained a strong presence in the Middle East and in South American oil producing states. However, with the recent increases in global demand due to rapidly increasing consumption by developing nations and issues with supply infrastructure, the limits of petroleum are beginning to be seen. The extreme fluctuations in gas prices seen in recent years illustrate the problems with complete dependence on this limited resource.

As only two percent of the US electricity supply comes from oil and most of the uses of petroleum involve non-fixed emissions, the country’s relationship with oil does not have a direct impact on the development of CCS except in the form of emission control for refineries and extraction operations. However, there are indirect negative and positive effects from the US petroleum sector on its development of CCS. On the one hand, the stance of big oil on climate change has confused the debate, which has now evolved from whether climate change exists to what extent an emissions reduction commitment will limit economic activity. However, with the decreasing productions of many US oil reserves, there has been strong development in the field of enhanced oil recovery (EOR) techniques and these include CO₂ based EOR. The US EOR activities will be developed further in a later section but it is important to realize that this has made the US a major player in the development of CCS globally and is driving many of its current DOE funded CCS related projects.

The most important factor in terms of passing a climate bill in the US or signing a global treaty is coal. Jeff Goodell, the author of Big Coal: the Dirty Secret behind America’s Energy Future, has described the US as the “Saudi Arabia of Coal” because the country maintains the world’s largest coal reserves: 27 percent of the global total. Not only does the US have the most coal in the world but it also is predicted to have one of the longest lasting reserves given its current production rates. Figure 21 puts this into perspective in terms of how other countries compare to the US in this regard. What is notable is that while China ranks third in terms of reserves, their production outstrips their overall reserves and leaves them with less than fifty years of domestic supply. The EU ranks low in both overall reserves and remaining regional supply for coal. As a result of this factor, it will be difficult to argue against the US pursuing coal based energy production and therefore its hesitance to sign any commitments that might limit its ability to capitalize on this resource are understandable. The EU is in a much more comfortable position to pursue emission reduction treaties as they have relatively few fossil based energy resources.
China is in the most difficult position as its current development relies nearly completely on coal for energy while it has one of the lowest domestic coal reserve life expectancies.

As a result of the relatively abundant fossil resources in the US, the country’s energy sector has been able to provide energy cheaply to the population fairly consistently for the last century. This also has meant a low rate of efficiency in the energy sector because it is perceived by most utilities that it is cheaper in the short-term to simply provide cheap energy using existing means than to incur short-term increases in costs so as increase efficiency and lower, more stable long-term prices. This has resulted in the trend, discussed by Thomas Friedman, with electric utilities reinvesting only 0.15 percent of their revenues in R&D. The diagram in Figure 22 gives the most recent breakdown for energy production by fuel type and consumption by sector in the US and was developed by the Lawrence Livermore National Laboratory from the DOE energy statistics. The calculations assume an 80 percent efficiency rate for average end-use energy consumption in the residential, commercial, and industrial sectors and 25 percent in the transportation sector. One issue of note should be the US produces more than twice the energy it consumes, with 58 percent of the energy being lost to inefficiencies. Although some of these inefficiencies are arguable unavoidable given technology constraints, valorizing less than half of the energy produced is excessive. Most of that is lost in electricity generation and this means that the energy can be provided so cheaply that there is little incentive to improve the generation process and increase efficiency. As nearly half of the electricity is produced by coal, a logical place to enforce efficiency standards or tax production so as to increase the value of the electricity that is produced or most specifically lost. Placing a price on carbon emissions would send a clear signal that operating at less than 50 percent efficiency is unacceptable. This would also prove true for the transportation sector that achieves even lower efficiency and would increase the demand for electric cars or plug-in hybrid vehicles (partially powered by batteries, partially by a combustion engine), which in turn would increase the demand for electricity. Figuring out a way to maximize resource consumption for energy purposes will be key.
The nuclear industry has been held hostage by several political issues for the past few decades. First, since the Chernobyl and Three Mile Island nuclear incidents, many people remain concerned about the technology’s safety. The Tennessee Valley Authority’s (TVA) Watts Bar 1, which came on-line in February 7, 1996 in Tennessee, was the last U.S. commercial nuclear power plant to go on-line. Second, there is the issue of global nuclear proliferation for the purpose of developing weapons. This is the major concern with countries like Iran and North Korea. Lastly, the industry was allowed to progress without presenting a proper solution for the waste it produced. Today as various governments search for a better solution, a large amount of radioactive material is stored onsite at nuclear plants and poses a local hazard. This has led to the rise of an anti-nuclear movement led by national and international non-governmental organizations such as Greenpeace and “Green” political parties, especially in Europe, which adamantly oppose the continued development of nuclear technologies or the construction of new plants.

In terms of the limitations of the technology itself, the main limiting factor is the availability of fissile material to power the reaction. At current consumption rates and using current nuclear electricity generation technologies, it is estimated that the existing supplies of fissile material will last roughly the same amount of time as the remaining petroleum reserves, which is to say roughly 30 to 60 years. If a significant expansion of nuclear energy capacity takes place globally by continuing to applying current or “third generation” technologies, the lifetime of global fissile supplies drops to approximately twelve years. What is needed is a rapid development of “fourth generation” nuclear technology that broadens the range of fissile material that can be used and increases the supply life to an estimated 1000 years or more. However, as a result of the current negative views on the technology, which are kept active by the global anti-nuclear movement, most of the projects to further develop the technology have encountered various issues or have been stopped mid-development. In the US the fourth generation technology was being developed as of 1984 via the construction of an “integral fast reactor” demonstration at US national labs in Idaho and Illinois but the funding was cut in 1994 by Congress due to concerns
about safety and proliferation. Another result of the anti-nuclear movement and the freeze on nuclear project approvals in the US since the 1970s, there is a steady decrease of nuclear engineers qualified to design, build, and operate new projects.

Notably, it is extremely difficult to site most new energy production projects in the US today, no matter what type of power will be produced there. This is partly a result of the climate debate and the risk of pending greenhouse gas emission caps, but is also due to a significant increase in construction prices and a large contingency of local resistance to most large industrial projects, which is referred to as a “not-in-my-backyard” or NIMBY mentality. People are concerned now about all aspects of these projects and these concerns are based on issues such as environmental impact, water consumption rates, local land devaluation, and landscape disfiguration. As a result, no one wants anything built in their backyard, whether it is a new coal plant, a pilot nuclear facility, or a wind turbine. A price increase on energy vis-à-vis carbon will place a greater pressure on citizens to consider the benefits to new infrastructure along with the currently dominating detracting points. The need for new options is now beginning to mount and as of the end of 2008 there were seventeen applications under review by the US Nuclear Regulatory Commission for new nuclear power projects (US EIA, 2009).

Drivers for CCGC Development in the US

There are several reasons for CCS’s development in the US currently. These primarily revolve around the abundant fossil resources located within the state’s borders. This is because the state not only stands to benefit from not only being able to continue to use these resources despite any future commitment to a climate treaty, but also in the recovery of energy from those resources as extraction becomes increasing difficult as the reserves are depleted. It is for this reason in fact that the technology that first injected CO₂ underground is enhanced oil recovery and not carbon storage for emissions reduction.

The early EOR operations in the US are not as well documented publicly, but there are extensive projects using CO₂ sources to increase production according to Oil and Gas Journal. This began in the 1970s with some projects in Texas around the Permian Basin oil reserves, which were found to be very responsive to the injection of CO₂ in the “tertiary” production period. The first production period is unaided and this is followed by a second production period, typically using water to flood the bits of oil remaining in the pore space. The tertiary production can be performed using a variety of methods that include several different gases and chemical agents. CO₂ has been found to be effective under certain conditions and with certain types of oil as was mentioned in the Weyburn example. With CO₂ EOR, the enhancement is normally done using a combination of CO₂ and water floods, known as a “water alternating gas” (WAG) flood. EOR can be done with a immiscible CO₂ at shallow depths, where the CO₂ remains in a gaseous state and simply increases the pressure in the formation which increases the flow of oil (and water) exiting via the production well. A second method that takes place in deeper formations is a miscible CO₂ flood, which is where the high pressure and temperatures cause the CO₂ to become supercritical and in that state the gas mixes with the trapper oil and increases the viscosity and this increases the rate of flow in the reservoir.

As these enhanced recovery aiding properties of CO₂ were discovered and experimented with in Permian Basin (and then elsewhere) one of the issues for the project operators became the CO₂ supply. Several firms such as Denbury Resources and Kinder Morgan moved into the CO₂ supply business by tapping into naturally existing CO₂ reserves in the country and building special CO₂ supply pipelines to deliver this natural CO₂ to EOR locations. As the industry developed, new
sources for the CO₂ were investigated such as industrial plants with high concentrations of CO₂ in their flue gases. This corresponded also with the growing concern about climate change resulting from CO₂ emissions but the two issues of climate change were not directly related. The primary reason for this is that given the limited number of CO₂ supply sources and providers, the gas was expensive and as a result the goal was to recapture as much as possible of the gas from the production well so as to re-inject it. Only a fraction of the gas was trapped residually in the formation and this would result in the need to purchase additional CO₂ but not in the same quantity as the total amount being injected. The map in Figure 23 gives an idea of the project activity in terms of what sources are used (natural or anthropogenic) and where the pipelines are. The map is non-exhaustive but has been slightly updated from the Oil and Gas Journal version and a more complete map of the US situation will be presented in the active projects overview. A more extensive list of Global CO₂-EOR projects can be found in the appendix.

As EOR was the first cause for the injection and monitoring of CO₂ into porous geological formation, it is the main precursor to the CCGS. However, EOR and EGR technology should not be looked at as synonymous with CCGS for two reasons. First, any project that recovers CO₂ already naturally trapped underground and then re-injects it to recover carbon intensive energy resources cannot be seen as a GHG mitigation technology and as such this type of EOR is not CCGS. Second, although CO₂ EOR technology that uses CO₂ from industrial sources performs all of the steps needed for CCGS, i.e. capture, transport, injection, and monitoring, prior to 2000 EOR was not focused on storage and in fact operators aimed to store as little or the gas as possible so as to minimize CO₂ costs. Some post-2000 EOR projects such as Weyburn-Midale also aim to store significant amounts of CO₂, however, the amount they are injecting (in the Weyburn case roughly 3 Mt per year) needs to be divided by a factor of three or even four to calculate the amount of CO₂ that remains trapped in the formation. Due to the market sensitivity of these projects, the actual amounts of CO₂ purchased new each year to supplement
the gas that is recycled for re-injection is not typically available in the public forum. Nevertheless, the merits of CO₂ EOR should not be forgotten as the technology has given many active players in the emerging CCS market valuable experience, which can be applied to the successful roll-out of the CCGS projects. Furthermore, it is the cause for the most extensive existing CO₂ pipeline network in the world pictured in Figure 23.

Since the US has decided to recognize climate change mitigation as a global concern under the Bush Administration and even as a political priority by the Obama team, the DOE has focused significant research and financing towards developing the technology. This support began with the regional partnerships to explore storage options and the FutureGen project to develop a zero emission coal-based IGCC power plant, but has now expanded to a variety of government supported projects across the country under the Recovery Act of 2009.

However, companies in the US have not taken the same perspective as their competitors in Europe. The US Focus has largely been on EOR and not on developing saline reservoir knowledge and storage expertise. For the capture and transport aspects of the CCS market, the technology providers and service contractors are competitive and on par with their global counterparts. However, the major US-based storage players are nearly all connected to the oil and gas industry and as such they are more interested in the CO₂ as a commercial opportunity than as a GHG mitigation technology. This is best seen best in the France-based oil exploration and production (E&P) contractor, Schlumberger, being the only storage expert involved in every single DOE partnership project - in most cases as a project leader. The US equivalents of Schlumberger are working to catch up with the investment and marketing the French oil service giant has already put behind its Carbon Services division. The section to follow gives an idea of who the various US CCS players are today.

There remain several concerns that stand in the face of a full-fledged CCS roll-out in the US, despite the extensive list of projects announcements that precede this section. This section will touch briefly on these concerns but they are all aspects that will need to be dealt with if the CCGS technology is to take hold among the portfolio of options.

One aspect of the US projects that have been announced is the large number of projects relating to EOR. This is largely due to the assessment seen in the market analysis section that CCGS only proves economical with EOR in the US. Conversely, it is difficult to get financing for a carbon-intensive project without CCGS built into the design due to the Carbon Principles mentioned as taking hold in financial institutions on Wall Street and elsewhere that decline financing to projects with a high emissions risk factor. This is resulting on a catch-twenty for energy project developers who do not know what to do, which has resulted in the Climate Action Partnership of industries who strive to achieve a fair cap-and-trade policy in the states. The DOE is working hard to facilitate the Obama Administration’s commitment to alternative energy development and clean coal technologies (CCS) by funding numerous projects across the country. However, a real adoption of carbon pricing schemes is needed before the technology truly begins to reach any significant scale. The various initiatives like the RGGI and the Climate Registry are preparing the country for the expected transition but the hope is this will come sooner rather than later.

Another major issue concerning CCGS project development is the perception of the technology by the American public. The primary issue is that most people have not heard of CCS at all. If they have heard of it, they often cannot link it to CO₂, do not understand what CO₂, i.e. they do not know it is in carbonated soda, or do not understand how it works. The ones who are made
more familiar with the technology often see it as synonymous with clean coal and therefore as an excuse to continue mining and see renewable energies as a preferred alternative. Many do not like the idea of storing CO₂ under their homes in what they image to be a big cave or balloon type formation and do not understand it would be done in the pore spaces of rocks. Others simply don’t support the use of CCS because they do not believe in climate change.

The best example of this in the US is the DOE Phase III project meant to take place near Greenville, Ohio. The townspeople were rallied behind an anti-CCS group called “Citizens Against CO₂ Sequestration” who argued that 1) climate change was not something they saw as an issue for the town, 2) the new ethanol plant where the CO₂ was coming from was not adding much to the community in terms of economic gain, and 3) the storage would be dangerous. The project used a variety of techniques to explain the project and the CCS concept to the town but in the end the project was canceled.

For this type of issue to be dealt with prior to additional project facing opposition several subjects need to be discussed in the public forum. First, climate change needs to be explained with specific local relevance. Second, CCS needs to be placed in a portfolio solution to explain that it is not merely a choice between one power type and another but that many different types must be employed together to meet demand at a cost that is reasonable to ratepayers. Third, carbon capture needs to be talked about and explained so that people know more about the technology in terms of what it is and what it is not. This is not to say that the technology should be marketed but that it should be explained on its own merit in terms of being an economic bridge-technology to a low-carbon world that does not stop the mining of coal or the use of fossil fuels but does help place a price on CO₂, which in turn will make renewables more competitive and start to take over larger sectors of the power supply. Lastly, locals need to be engaged in the project to the greatest extent possible, perhaps not as project decision makers but at least as significant stakeholders with the ability to voice concerns and affect some changes if needed.

As the US operates in a federal system, there are three tiers of laws that can affect CCGS expansion within the country. Laws at the local, state, and national level need to be examined so that CCGS is allowed to move forward in a safe and properly regulated way. For example, this means looking at the pipeline permitting process, property ownership statues, interstate waste regulations, etc. Jurisdictions need to be set in terms of who takes responsibility for the CO₂ throughout the CCS operations chains, as well as long-term liability statutes such as already exist in Australia.

On the policy agenda regarding CCS lay several main priorities. The most important of these is one that places a price on carbon, either via a national law or compliance under and international treaty but the best case would be a combination of the two. These issues can be seen as coming to a head over the conflict between whether the EPA or Congress will regulate CO₂, which is a situation that only serves to highlight the need for the US government to decide where it stands on climate change. However, for CCGS technology to be properly accredited as a climate change mitigation solution several practices must be changed. Efficiency standards need to be adopted for power production to address the issues discussed at the beginning of this case study. CO₂ EOR needs to be limited to anthropogenic sources either via direct prohibition of using natural sources or the more feasible solution of not granting carbon credits to operators using natural CO₂ or treating natural sources as emission point sources and taxing them accordingly.
The Players: The US as CCS Deployment Stage

With the amount of money being poured into CCGS projects from the US government, many international firms have been attracted to the US to test their expertise. Nevertheless, there remain a significant number of American firms, research institutes, agencies, universities, and various other organizations involved and this section gives a basic description of who these players are and their roles in the development of CCGS activities in the US.

There are numerous national agencies and research institutions run by the government or by public and private universities involved in the development of CCGS technology in the US. The following examples are the most important but there are many more. The main funder for CCS projects and R&D work is the US Department of Energy (DOE). Under the Bush Administration they developed the FutureGen project and the regional partnerships to be detailed in the following section. Under the Obama Administration the support of the DOE extended to additional projects to develop CCS under the stimulus funds of the Recovery Act passed in 2009. The National Energy Technology Laboratory (NETL) is the 15th research lab for the DOE and was commissioned as such in 1999 to develop solutions for fossil fuel based energy production while pursuing increased energy independence.

The US Environmental Protection Agency (EPA) is responsible for environmental policy development and enforcement. Currently their main efforts relating to CCS are in the creation of a mandatory CO₂ emissions accounting scheme that would directly support the potential creation of a GHG emissions limitation policy in the US or at the international level. There is also potential for CO₂ to be classified as an air pollutant under the Clean Air Act, which would place the limitation of the gas into the domain of the EPA but this is still being decided by Congress and the Supreme Court. The EPA is also involved in several of the NETL/DOE regional partnerships for CCS development.

These government laboratories are located across the US and are involved with research and development of many topics relating to energy, including CCS and nuclear technologies. A variety of National Labs are involved with the projects and partnerships relating to CCS in their regions. Battelle is an international organization that started in the US to develop steel technologies but now is involved with R&D laboratories across the US, in the UK, and elsewhere. They are also contracted by the US Government to manage several of the national labs such as the Lawrence Livermore and the Pacific Northwest National Laboratories (LLNL and PNNL) that are both involved with CCS development. It is important to note that not only the Battelle run labs are involved nevertheless Battelle has taken a clear lead in this field.

So as to better divide the task of surveying the country and determining storage capabilities, the DOE has sponsored seven “regional partnerships” to conduct storage tests across the US. These partnerships will be detailed further under the DOE projects section but in general they are consortiums made up of US national labs, state geological surveys, the regions industries, national and international corporate interests, regionally active NGOs, and the local universities. They are supported by the DOE and its National Energy Technology Laboratory (NETL). The seven partnerships are listed here will be described in greater detail under the Phase II project descriptions.

The Big Sky Carbon Sequestration Partnership (Big Sky) is responsible for Idaho and parts of Montana, Oregon, South Dakota, Washington, and Wyoming. The West Coast Regional Carbon Sequestration Partnership (WESTCARB) maintains as members both US states and Canadian
provinces: California, Arizona, Nevada, Oregon, Washington, Alaska, Hawaii, and British Columbia. The Midwest Regional Carbon Sequestration Partnership (MRCSP) includes Ohio, Maryland, Pennsylvania, New York, and Michigan and parts of Kentucky, Indiana, and West Virginia. The Midwest Geologic Sequestration Consortium (MGSP) is a smaller but very well organized group hailing from Illinois and parts of Kentucky and Indiana. The largest partnership that is again between the US and Canada is the Plains CO₂ Reduction Partnership (PCO₂ R or PCOR) that includes Iowa, Minnesota, Missouri, Nebraska, North Dakota, Wisconsin with Alberta, Saskatchewan, and Manitoba in Canada, and parts of Montana, South Dakota, and Wyoming. In the south there is the Southeast Regional Carbon Sequestration Partnership (SECARB): Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia and parts of Kentucky, Texas, and West Virginia. Then to the west is the Southwest Regional Partnership for Carbon Sequestration (SWP): Colorado, Kansas New Mexico, and Utah with parts of Arizona, Texas, and Wyoming.

Before the regional groups formed around the CCS issue, the FutureGen Alliance was brought together to design the country’s first zero emissions coal fired power plant. Today FutureGen is an international consortium of coal and utilities companies designed to support the construction of a near zero-emission coal-fired power plant. The location of the plant is set to be Mattoon, Illinois and the goal is to demonstrate both the technical and economic feasibility of building a commercial-scale, CCGS-based IGCC power plant. However, there were so issues with the approval of the plant that will be detailed in the project description to follow. The current members are made up of coal producers and energy utilities. In terms of US coal companies there is the US-based Peabody Energy, which is the world’s largest private-sector coal company, CONSOL Energy Inc, which is the largest producer of high-Btu coal in the US, and Alpha Natural Resources, a top US metallurgical and thermal coal supplier. In addition there is Anglo American Services, a UK-based global mining and coal supplier, BHP Billiton Energy Coal, a global coal company from Australia, Rio Tinto Energy America Services, the US subsidiary of UK coal company, and the Australian Xstrata Coal that serves as the world’s largest exporter of thermal coal. In terms of utilities there is a US subsidiary of E.ON, the German investor-owned energy provider, and the China Huaneng Group that is the largest energy producer in China.

As this report’s primary focus is on storage, the following section on storage engineering firms aims to give a fairly detailed description of the more significant US actors, their areas of expertise, and their level of involvement in CCS. Many other actors are involved but their activities are not as easily substantiated.

Advanced Resources International (ARI) was an early entrant into the CCS arena, beginning with global sequestration capacity assessments in oil and gas reservoirs and coal seams for the IEA GHG Program in the mid-1990’s. Since then, ARI has become a leading provider of technical and consulting services regarding geologic carbon storage for both R&D and commercial projects. They are involved in the WESTCARB, SWP, and SECARB regional partnerships and provide consulting services to several major contractors like Schlumberger and Halliburton and the major oil companies involved with CCS.

Baker Hughes is best known for its rig-counts service but besides that it is a major contender in the oil services market. As such Baker Hughes sees a need to move into the CCS services market to provide injection well and monitoring related services to remain competitive. However, despite the company’s involvement in the MGSC, SECARB, and PCO₂ R partnerships, they are not as established in this area with respect to CO₂ specifically. For instance, compared to
Vice offer Texas, result. and of description, own in seismic monitoring assessment, contracts Schlumberger companies. The reservoir activities. has services, project technologies test Sandia with geotechnical the assist CCS US customers be given the CCS storage the field. Nevertheless involved big ambitions in the CCS arena.

The drilling professionals at the Gas Technology Institute (GTI)’s drilling test facility near Tulsa, help customers find ways to reduce exploration and production costs. They offer a wide range of services, from the evaluation of advanced drilling to formation evaluation and completion technologies associated with the drilling of natural gas and oil wells. As such they are positioned to assist in CCS storage project design and consulting as well as monitoring services. They are a partner in the SWP.

The US oil services giant Halliburton is involved in SECARB but the group is also visible the realm of CCS on a global scale. There precise involvement is not completely clear but the project involvement is less than that of Schlumberger based on Halliburton’s own relation of their CCS project history. They are more active in the US than elsewhere in the world with CCS and it can probably be assumed that most of this expertise lies in their drilling and reservoir management contracts that must have led them to engage in some of the EOR projects but it appears that they are not involved in many projects relating only to storage. The group recently purchased Pinnacle Technologies and this company is listed as a partner in the SECARB and SWP and this may be the basis for Halliburton’s claim to involvement in SECARB. Halliburton is not a trusted brand in the US at least due to many allegations surrounding its former CEO and the former US Vice President Dick Cheney, the Iraq War, and Halliburton receiving numerous government contracts there. This could also explain involvement in the sensitive CCS topic is more under the Pinnacle brand. Nevertheless the company has big ambitions in the CCS arena.

Sandia Technologies is involved in SECARB and is reported to be involved with a lot of the geotechnical field required in those projects. There origins lie in geological waste disposal, which has given them some significant advantages in terms of experience, know-how, and actual tools in the CCGS field. Besides being competent in geologic/reservoir evaluation services, they also offer specifically services relating to CCGS. They are also involved in the FRIO project and their own DOE supported CCGS project that will both be detailed to follow and was an early feasibility test of storage in the US.

The alternative energy solutions company, Sage Resources, is interested in CCGS due to its existing activity with geothermal energy projects, which can involve similar geological assessment, drilling, and re-injection needs. They are involved in the Big Sky partnership as a result. TGS, another Houston company, offers geological data services to many of the major E&P companies and is involved in the PCO₂ R partnership.
Weatherford Advanced Geotechnology is a software service division of the oil services company Weatherford International. It is involved with the PCO₂ R partnership in the US, which make sense because the group’s most stated involvement in CCS is in Canada despite its origins being Texas. As such the group appears to be less involved in the US CCS market than its competitors in well services like Halliburton, Schlumberger, and Baker Hughes. However, in Canada the group is a member of the Canadian CCS Alliance and there it states more clearly its ability as E&P service provider.

Blue Source is not a storage company per se but is still a significant player in the emerging CCS market in the US and they are involved in CCS in three different areas: the financing of CO₂ pipelines, project development, and voluntary carbon credits (specifically TERs). They are partners in WESTCARB, SWP, MGSC, and PCO₂ R but are also involved in a wide range of GHG abatement projects. Their focus in terms of transport is taking CO₂ from industrial sources to potential storage sites. To coordinate this activity they are also involved in the project development side of CCS and the TERs come into play for financing these early projects.

As the key aspect of the developing CCGS infrastructure chain, transport technology providers and operators are important players in this market. There are some companies included in this section that are also storage operators in that they use the CO₂ for EOR applications and as such have the ability to expand their expertise into CO₂ EOR for storage and pure storage projects.

Denbury Resources’ involvement in the CO₂ transport sector arose from the initial CO₂ EOR projects in Texas and then elsewhere in the US. The company is originally a field acquisition and production company but as a result of its oil, gas, and CO₂ pipeline construction projects it is now well positioned as a CO₂ transport operator and also an end-user of the CO₂ for EOR projects. One thing that is interesting about their business model is that they began with natural CO₂ for their EOR. Now, as they add anthropogenic sources to their supply, the natural CO₂ domes they acquired originally could serve as both supply to supplement their anthropogenic supplies and as storage if the supply of anthropogenic CO₂ becomes greater than their existing demand from EOR.

The Denbury group recently acquired Encore who was also involved in CO₂ EOR but in the northwestern parts of the US, which increases Denbury’s range of influence. Encore has a few operations that are employing or at least considering CO₂ for EOR in Montana. Denbury is involved in SECARB but Encore gives the group access to the PCO₂ R. They also have several projects that they are completing with industrial partners as a result of US stimulus funding from the DOE and all this will be documented in the project section. Its biggest project relating to transport currently is the construction of the “Green Pipeline” that will bring CO₂ from near New Orleans in Louisiana for EOR near Galveston Bay in Texas by mid-2010 and beyond that point later that year. This project has a good potential for expansion via trunk-lines to the areas other CCGS activity, which is extensive. They are currently negotiating with some CO₂ sources in Illinois in order to link them to their EOR activities near the gulf.

Kinder Morgan is similar to Denbury Resources in that they began as a supplier of natural CO₂ for EOR operations in Texas and as such these two are the main competitors in the US CO₂ supply and transport market. Kinder Morgan also produces oil in Texas but its main activities are as one of the largest natural gas transporters and storage operators, the largest independent terminal operator, the largest transporter and marketer of CO₂, and the largest handler of petroleum coke in the US. The company is a member of WESTCARB, SWP, and SECARB. Its main
CO₂ pipeline operations are mostly developed around natural CO₂ sources, which can prove problematic if CCGS is to be looked to as a GHG mitigation technology. The expansion of Denbury into more anthropogenic CO₂ sources could prove as a real advantage in this competition. Also, although Kinder Morger is involved in DOE partnerships, they have not pursued their own projects as Denbury has done.

Rooney Engineering is a general engineering firm specializing in pipelines. They are mostly involved in the construction of complete transportation systems, including not only the pipes but also compression stations and metering and are familiar with right-of-way acquisitions, and as such will be well positioned to participate in the CCS transport market. They are a partner in WESTCARB. Spectra Energy specializes in all natural gas related infrastructure, which is very closely related to that required for CO₂. As such they are involved in the MGSC and PCO₂ R groups. Similarly, the Williston Basin Interstate Pipeline Company performs both natural gas transportation, and underground storage services in the Northwestern US around the Williston Basin, which lies between North Dakota, Montana, and Wyoming and also extends into Canada. It is not clear if the company was involved in the pipeline construction from the Dakota Gasification Plant in Beulah to the Weyburn-Midale EOR operations in Canada, but as these operations are also in the Williston basin this involvement would be logical.

There are several consulting operations that have adopted CCGS into their portfolio of activities and they engage in various aspects of advising companies how to adopt the technology or for government regulators to help design CCGS policy. As of now there do not appear to be any sizable pure and specifically CCGS-based consultant groups based in the US. Melzer Consulting maintains a focus on EOR operations arising from the Texas experience but is not engaging on purely storage related activities. ICF has taken on a more regulatory role by working with the EPA to develop carbon policies and storage regulations. The following paragraph gives many of the more active purely consulting-based firms involved in the US, however it is important to understand that many project developers and contractors, such as Blue Source or Halliburton, have in-house consultants or consultant partners that they use for projects such as these.

The Applied Sciences Lab (SECARB) engages in environmental systems evaluation and planning and do some software development. Bevilacqua-Knight (WESTCARB) are engineering and project communications consultants. CRL Energy conduct energy and environmental research and consulting with a capture focus. GEO Consultants specialize in environmental services. Nexant (PCO₂ R & WESTCARB) provide technology management and development consulting. Renewable Fuel Technologies (WESTCARB) do have a renewables focus but also consult on CCS. SFA Pacific (WESTCARB) advises on power generation and environmental control and Summit Energy (Big Sky) provides natural gas and related risk consulting.

One key aspect for CCGS project success is introducing the storage and transport aspects of the project to the local community in a way that does not create anti-CCS bias due to fears relating to a lack of understanding regarding the concepts involved. Many social scientists from universities and private firms are involved in studying the perceptions of CCS, the knowledge of the technology (or lack thereof), the effect of pseudo-opinions that are formed by those with no prior-knowledge of the technology so as to evaluate it in surveys, etc. Several cases exist globally where CCS projects have failed or have been severely hindered due to public resistance and as a result many project developers have begun to hire public acceptance consultants to assist with educating the local population on the CCGS topic and engaging them in the decision-making process. The following firms are the main examples from the consultant groups doing
this type of work for the regional partnerships. AJW of MRCSP has become recognized as an expert in CCS related public relations and outreach, with their partner Sarah Wade working closely with the DOE and NETL to provide the latest public engagement tools and tips to CCS project developers and regulators alike. EnTech Strategies (SWP & Big Sky) also engages in technology acceptance consulting and RMS Strategies (SECARB) provides marketing and public opinion strategy services.

There are many players in the capture technology, equipment, and chemicals sector as well as in the transport and commercial gas supply market. Because the list is already so populated in the US this report will not attempt to list the major players as the focus here is again storage. Many NGOs are involved in various aspects of CCGS development, policy, and research. As such they are difficult to classify, this section presents some of the more interesting cases in terms of environmental policy development relating to energy and climate change. The Electric Power Research Institute (EPRI) has developed a recommended portfolio of energy production technologies as a recommendation to energy policy developers at the state and national level. They are also engaged in several capture studies taking place across the US and Canada and support broadly the application of capture and CCS technologies to power infrastructure. The World Resource Institute (WRI) is visible in nearly every international effort regarding CCGS policy recommendations and its CCS expert Sarah Forbes as well as former WRI researchers like John Venezia are well respected voices in the CCS world and appear as advisors and co-authors on most global CCS related papers. WRI is seen as an unbiased research institute and as a member of the Climate Action Partnership (CAP), which is comprised of industrial and environmental interests and can be viewed as a bridge between environmental advocacy groups such as Greenpeace and NRDC and big industry.

Environmental Defense and the Natural Resources Defense Council (NRDC) began as opponents to CCS like Greenpeace, advocating a completely renewable-based solution. However, they have now accepted the technology at least as part of a complete solution for the climate change issue. The NRDC and Environmental Defense have also joined along with WRI the CAP in the US, in the hopes on reaching a compromise on the cap-and-trade policy issue by working together with industrials. The NRDC, like WRI, has also engaged in China and this may be one of the key reasons why NRDC has become interested in CCS as part of a global strategy as opposed to simply being a US policy issue. Nevertheless they have become active in influencing US CCS policy and as a result have supported research on topics like EOR and CCS project quality standards. The Pew Climate Center also engaged in developing CCS project standards.

Most of the projects in the US concerning CCS are focused on capture from energy projects for underground storage. There are some that are interested in industrial applications for the gas that would replace the need for storage and others who are pursuing industrial applications for the technology. The following examples are taken from the regional partnerships.

A new company called Abengoa Bioenergy is interested in using micro algae to capture the CO2. The algae then can be used for a variety of applications including being dried and burnt for biomass energy and also as fish food for large aquaculture operations. CEMEX is perhaps the only cement company worldwide engaged in a project to adapt CCGS to the cement production context. In France, Lafarge is also interested in this but has apparently not as of yet engaged in developing its own specific project and is more focused on biomass. As the sole developer in this area, CEMEX stands in a good position to market this technology globally once they have
developed a pilot as will be discussed in the project section. **Continental Carbonic Products** is interested in another method to dealing with carbon: finding other industrial applications for the gas. Dry ice is frozen CO₂ and as such continental carbonic products has joined the MGSC in the hope of using captured CO₂ as a source for its products and services. This could have interesting financial implications in terms of carbon credits if a price is assigned to CO₂ within the US.

As the US has been involved in oil production from the beginning of the petroleum age, the oil companies in the US are numerous and cover a very broad range in terms of the size and scope of the companies and their activities. Many of these companies are purely interested in the development of CCS for enhancing their production and possible gaining additional benefits from tax credits, carbon credits, and investment from parties concerned about the climate change issue. However, several of the larger companies have begun to at least speak to the topic of becoming energy companies in the larger sense of the word and as such are working to develop their expertise for application in storage for the sake of GHG emissions reduction without any additional benefit. This is less common with the big US players compared to BP (with their new slogan: Beyond Petroleum), Shell, and Total. Smaller E&P companies like Denbury Resources, **Advanced Resources**, and **Rosetta Resources** are more visibly involved with non-EOR related CCGS technology development.

As the US presents such a large market and deployment stage for CCS, with a variety of government programs and incentives for the technology, many foreign actors are involved as well within the country. Some of the major influences are from France, e.g. Schlumberger, Alstom, Air Liquide, and Oxand (a smaller firm typically involved with Schlumberger), but these companies will be discussed in the French case study. What is most notable is that Schlumberger is the only commercial actor to be involved in all of the regional partnerships and most of the other CCGS projects in the US. There are also a variety of Canadian actors as a result of the extensive oil and gas E&P activities in the US’s northern neighbor. However, they are mostly involved in bilateral partnerships like WESTCARB and PCO₂ R who are developing projects in the US and Canada.

**The Projects: Current CCGS Activity within the United States**

Despite perhaps appearances that the US has the least amount of commitment compared to other developed nations in terms of developing solutions to climate change, it has by far the largest amount of capital invested on its soil for developing CCGS. This is mostly reflected in the recent Economic Recovery Act stimulus package that sets aside a good deal of funding for alternative energy projects. The reason for this is however not due as much to the concern about rising temperature but more so to the desire to increase domestic oil production using CO₂. This is best seen in the early project development where EOR projects have been more successful and the major saline storage projects have had more trouble.

As was discussed under the EOR section the initial CCS-related projects in the US centered on the CO₂ -based EOR work in **West Texas**, with the concept gradually being applied by oilfield operators in other states. Two of the major EOR project operations are now cited by the IEA as among the only truly commercial scale projects in existence today as was revealed in the introduction. However, the Gulf Coast Carbon Center has been established to facilitate regional education and technical information transfer on the potential for scale-up to use develop EOR in the region as an early, economically viable method of greenhouse gas emissions reduction for this industrial corridor.
The actual amount of CO₂ being stored each year must be estimated based on CO₂ recycling rates combined with information on the total injection and annual CO₂ purchases. A rule-of-thumb could be established to estimate new CO₂ injection, for instance by using the 21 percent recycling rate estimated for the Weyburn-Midale project, this could be applied universally to guess the size of the “storage” aspect of an EOR project. However, a general rate is difficult to establish and should be calculated on a case-by-case basis for actual mitigation and carbon crediting purposes.

The Weyburn-Midale project detailed earlier was an example of CCGS but it is important to remember that the storage project is Canadian with the North Dakota Gasification plant only being concerned with capture. For a US example, Chevron is operating an EOR project at Rangeley in Colorado, which is listed by the IEA as one of the five commercial-scale CCS projects existing today. The field was first discovered in 1901 and then commercially developed in 1943 with the depths ranging from 150 and 520 meters (Energy and Minerals Field Institute, 2005). CO₂ EOR began in 1986 and with the added boost from CO₂ an additional 114 million barrels are expected to be produced.

The CO₂ is piped from the Exxon LaBarge gas sweetening plant in Wyoming via first the Exxon pipeline for 77 kilometers (48 miles) and then a Chevron operated pipeline for 207 kilometers (129 miles) and the capital investment for this pipeline was 158 million USD. The CO₂ compression facility was one of the largest parts of this initial investment and continues to be a significant operating cost.

The injection rates for CO₂ are typically given for the US in million standard cubic feet per day (MMSCF/D or MMCFD) In terms of the amount of CO₂ captured as opposed to recycled, the CO₂ purchase rates for Rangeley began at 1.8 Mt in 1986, peaked in 1990 at just less than 3 Mt, and now have decreased to 1.2 Mt (50 MMCFD) as of 2007 (Energy and Minerals Field Institute, 2005). The water, CO₂, and other gases used at Rangeley are apparently reinjected after processing but it is not clear if this implies 100 percent reinjection for the CO₂, which could have implication for GHG mitigation accreditation.

Returning to the FutureGen topic, this time as a project rather than the organization, in terms of the technology the IGCC coal gasification process for FutureGen involves a controlled mixture of coal, oxygen, and steam in series of reactors. Then, similar to an oxy-fired plant, an air separation unit supplies the gasifier with a stream of oxygen without nitrogen. In high temperature and pressure gasifier, a reaction converts the coal and oxygen into a syngas (H₂ and CO). The syngas is passed through a second “water-gas-shift” reactor to convert the remaining CO into more H₂ and fairly pure CO₂. There are a variety of applications for the H₂ but the important aspect of this plant is that the CO₂ stream is relatively pure and ready for geological storage. Another benefit is that many of the byproducts of the process would have commercial value for regional industries. The efficiency of the plant is derived from the combined use of gas and steam turbines to produce electricity. First the hydrogen-rich syngas is fed into a gas turbine to generate electricity. Next, the waste heat from the gas turbine is used to power a steam turbine (FutureGen, 2008).

Originally, in 2003 the FutureGen project was announced by the Bush Administration as a front running US effort to develop clean energy technology. The project was meant to be a group of industrial partners from the US coal and utilities companies with some international involvement from relevant developing countries, like China, who depend on coal as an energy

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source and would benefit from the demonstration project. The first four years were dedicated to planning the plant and selecting a site for the project and the preliminary cost estimate for the project was set at 1 billion USD, with the DOE contributing roughly three fourths of the funding. The Washington Group, which was then purchased by URS Corporation, was selected to lead the project’s design and construction.

In the final site selection, the possibilities were narrowed down to two sites in Texas and two in Illinois. Shortly after the Mattoon was chosen at the end of 2007, the DOE withdrew its funding promise for the project. Among the concerns were a more recent estimate of the project’s cost predicted an increase to roughly 1.8 billion. The US Energy Secretary at the time of the cancelation in early 2008 argued that the money could be better spent between several CCS pilot projects rather than just on one large project. Several members of the US Congress from Illinois accused the Energy Secretary of following directions to kill the project after it was not awarded to the president’s home state of Texas.

The FutureGen alliance lost some members but has continued to maintain the prospect of moving forward in Mattoon. Obama’s support for clean coal was elicited after the election and in the summer of 2009 the project was again taken up by the DOE under the Recovery Act funding and is in a restructuring period until early 2010, so as to complete the site specific design/subsurface work and expand the partnership.

The Department of Energy's total anticipated financial contribution for the project is $1.073 billion, $1 billion of which comes from Recovery Act funds for carbon capture and storage research. The FutureGen Alliance’s total anticipated financial contribution is $400 million to $600 million, based on a goal of 20 member companies each contributing a total of $20 million to $30 million over a four to six year period. The Alliance, with support from DOE, will pursue options to raise additional non-federal funds needed to build and operate the facility, including options for capturing the value of the facility that will remain after conclusion of the research project, potentially through an auction of the residual interests in the late fall.

This field test of CO₂ sequestration into the Frio Formation in Texas was the first example of a saline reservoir test in the US. It is a part of the three state of the international GEO-SEQ project, which is designed to improve injectivity and capacity predictions for saline and depleted gas formations. There are three CCGS cases that fall under the GEO-SEQ project: Frio, the Otaway Basin Project in Australia, and In Salah in Algeria. According to GEO-SEQ:

In [fiscal year 2008], the third year of a five-year cycle, we will continue to advance understanding of CO₂ migration in brine formations and depleted gas reservoirs, and investigate geomechanical effects of industrial-scale CO₂ injection. Although the three projects are carried out in distinct geological environments, the scope of GEO-SEQ is integrative with strong cross-task communication and application of common tools and approaches in related projects. The overall objective of the GEO-SEQ project is to gain knowledge of geologic CO₂ storage processes and mechanisms and how to monitor and simulate them while making results available through publications and conference participation. Advances derived from GEO-SEQ efforts also support the DOE Regional Partnership Projects through the involvement of the investigators in various Partnership projects, and will likely be used in commercial-scale CO₂ operations in the future (IEA GHG).
As the first task in GEO-SEQ, Frio is designed to explore as well a major storage location for the very carbon emissions intensive region around Texas, due to the significant oil and gas production and processing there. The project phase I was reservoir characterization followed by 100 days of CO₂ injection. Phase II, currently underway, involves monitoring compared to a pre-injection baseline established at the end of 2002. The goals are to prove the security and safety of saline formations for CCGS, track the CO₂ plume that results in such a formation, compare real results with conceptual models, and develop the experience needed for future saline projects.

The project is funded by the DOE and the NETL and there are several key players involved as partners in the Frio injection test including Sandia Technologies, Schlumberger, and three of the national labs. BP, the Texas American Resources Company, and Transpecto also were involved with the test. Frio is a Carbon Sequestration Leadership Forum (CSLF) Endorsed Project. CSLF is an international climate change initiative that is focused on development and improvement of cost-effective technologies for the CCS and for this purpose it has endorsed 10 international projects it believes support its overall goal.

Today the DOE and the NETL work most closely with the Regional Carbon Sequestration Partnerships (RCSPs), hereafter referred to as the Regional Partnerships, but the DOE is involved with nearly every CCS project being undertaken in the US with efforts such as Frio and FutureGen where the DOE has taken a funding role but also with the Recovery Act of 2009. There was significant funding allocation for CCS projects in this Act and the DOE has selected additional projects in addition to its own Regional Partnership Phase III projects to receive stimulus support.

DOE/NELT carbon source and storage possibilities atlas “Carbon Sequestration Atlas of the United States and Canada” that was mentioned earlier in the report to give the storage capacity for the US and Canada was the core aim of the Phase I of the regional partnerships project. This phase included the gathering of available geological data so as to begin to better estimate the storage capacity US and Canada. Phase II of the partnerships was designed to continue to the course up the pyramid given from CO₂ CRC at the beginning of the report to the regional, basin-wide, and even site specific level by engaging in smaller injection tests across the country. The overall goal has been to test the various capacities for the different formation types, including coal beds, and also for terrestrial sequestration projects in forests or wetlands. However, in terms of actual CO₂ injection these tests have given a more reservoir specific and site specific knowledge, which was severely lacking for saline reservoirs and was not certain even for the oil and gas formations for CO₂ specifically. The DOE list for the Phase II tests is given in Figure 24 and the projects are divided into geological and terrestrial tests and then further by the specific storage mechanism, i.e. formation or biomass type.

The major goal of the Phase III tests is to verify the storage potential with injection rates and amounts resembling the amounts anticipated by a commercial operation (DOE, November). The following paragraphs attempt to outline where these projects stand.
The focus of this partnership’s phase III project is testing some Jurassic sandstone formations throughout the region from Wyoming to Northern New Mexico. These formations are about 60 meters thick and the project will inject two Mt of CO₂ over four years to test the large shale deposits that will act as cap-rocks using a variety of monitoring techniques.

This test has two locations within the Tuscaloosa Massive Sandstone that are 320 km apart to test the effect of the formations heterogeneity on the injectivity. The first location will be to inject 1.5 Mt into the saline portion of a formation lower down or “down-dip” from an oil field already employing CO₂ EOR to trace the CO₂ ‘s movement in the saline reservoir. This test has two locations within the Tuscaloosa Massive Sandstone that are 320 km apart to test the effect of the formations heterogeneity on the injectivity. The first location will be to inject 1.5 Mt into the saline portion of a formation lower down or “down-dip” from an oil field already employing CO₂ EOR to trace the CO₂ ‘s movement in the saline reservoir.
injection has begun already. A second location will inject CO₂ from an existing coal plant fitted with post-combustion capture. This CO₂ will be injected for six years directly below the plant.

**PCO₂ R**: The largest of the seven partnerships is working in the US and Canada and as a result it will complete large-scale tests in both countries. The Canadian project involves the “largest gas production plant in North America” and 1.8 Mt of its CO₂ and hydrogen sulfide (H₂S) will be injected in Northwest British Columbia into a saline sandstone formation within the Alberta Basin. The US test will be within the Williston Basin into an oil-bearing reservoir in a carbonate formation at a depth of 3048 meters for EOR. The partnership will specifically be working with Basin Electric and their post-combustion capture facility and Encore, now owned by Denbury, who is currently producing oil at the field of concern where one Mt of CO₂ will be injected annually.

**MGSC**: Archer Daniels Midland Corporation and Schlumberger will be injecting one Mt of CO₂ from a biofuel fermentation plant into the Mount Simon formation to test its capacity to serve as the major storage formation for the region. The Mount Simon formation is ideal in that it is 450 meters thick and highly permeable and porous, but little information is known about the formation as a whole. The primary injection well is already drilled and the injection will be 1800 meters below the surface at the base of the formation and is planned for early 2010. The DOE has also committed 1,480,656 USD of Recovery Act funding to this project.

**MRCSP**: This phase III project has not pinned down where the injection location will be due to public resistance to the first selected site near Greenville, Ohio. The original idea was to inject one Mt of CO₂ annually from an ethanol plant, which produces a fairly pure stream of CO₂ naturally without extensive capture equipment. This would also have been within the Mount Simon Sandstone formation. The issues with this project will be discussed further in the public acceptance and engagement section.

**WESTCARB**: This project will test the San Joaquin basin in central California by injecting 1 Mt over four years. The source will be a Clean Energy Systems 170 MW oxy-fired IGCC plant that will be using coal and biomass in Kern, County. The injection location will be on site with the CO₂ stored directly below the plant in one of several feasible formations.

**Big Sky**: This project will test the Nugget Sandstone formation with the injection of 2 Mt to CO₂ at a depth of 3352 meters. The location will be at Riley Ridge near Exxon’s LaBarge platform and the Cimarex Energy Company’s planned helium and natural gas processing plant is expected to be the source for the CO₂. The sandstones in the region are hoped to eventually be able to hold more than a century’s worth of the regions point source emissions.

As already mentioned, the Economic Recovery Act of 2009 has promised a significant amount of funding for alternative energy projects and research. Among these technologies, a large percentage of the money will go directly to CCS related projects, including FutureGen. The following projects are the projects selected to receive these funds that have as of yet not been mentioned in this case study in another context (DOE, 2009).

Air Products and Denbury Resources have agreed to work together to capture more than 1 Mt of CO₂ from two steam methane reformers Port Arthur, Texas and transport it via Denbury’s planned Green Pipeline system for EOR applications, e.g. in the Oyster Bayou and Hastings oilfields in Texas. The DOE has promised just less than million USD of funding for this project.
Fluor will be employing its “Econamine Plus” post-combustion capture solution specially tailored to accommodate the emissions from a plant burning a Boise White Paper industry bi-product called black liquor fuels that are made during pulp production. This Battelle Memorial Institute project will explore injection into deep flood basalt formations in Washington State, probably close to the paper plant’s location. The DOE will contribute 0.5 million USD to this project.

A Bay Area, California-based project headed by C6 Resources, which is an eco-minded spin-off from Shell, will be injecting a total of one Mt of CO\textsubscript{2} from several facilities in the area into a 3220 meter deep saline formation with the help of two national laboratories and 3 million USD of DOE funding.

CEMEX is partnering with the oil and gas E&P contractor RTI International to demonstrate a dry sorbent CO\textsubscript{2} capture technology at one of its cement plants in the United States. The CEMEX plant will work to design and construct a dry sorbent CO\textsubscript{2} capture and compression system, pipeline (if necessary), and injection station apparently near to the plant. This is hoped to be a demonstration CCGS project at a scale of one Mt of CO\textsubscript{2} stored annually and if successful will allow CEMEX to market its technique to cement industry players globally. The project will receive 1.1 million USD in funding from the DOE.

ConocoPhillips aims to capture the CO\textsubscript{2} from a 683 MW IGCC plant firing petroleum coke in Sweeny, Texas for this CCGS commercial-scale project. Only 85 percent of the CO\textsubscript{2} produced will be captured but this will amount to over 5 Mt of CO\textsubscript{2} stored, probably for EOR in an oil or gas field nearby. The project was awarded a little more than 3 million USD by the DOE.

Leucadia Energy and Denbury Resources have received a DOE pledge of support for two projects they will pursue jointly. The first project, which was awarded 540,000 USD from the government, will be to capture the CO\textsubscript{2} from a co-generation plant that will make methanol from petroleum coke to be located near Lake Charles, Louisiana. The project will send the 4 Mt of CO\textsubscript{2} for EOR by building a 19 kilometer (12 mile) trunk-line to connect it to Denbury’s proposed Green Pipeline. The second project, with 840,000 USD from the DOE, will involve a Leucadia affiliate, Mississippi Gassification, petcoke-based synthetic natural gas plant in Moss Point, Mississippi. Similar to the first project this plant will capture 4 Mt and probably also truck in to the Green Pipeline.

Praxair with BP and Denbury Resources plan to capture one Mt of CO\textsubscript{2} per year from a hydrogen-production facility at an oil refinery in Louisiana planned along the path of the Green Pipeline. The DOE will support this project with 1.7 million USD.

Shell’s Chemical Capital Company will work to coordinate the capture of one Mt of CO\textsubscript{2} from facilities located along the Mississippi River between Baton Rouge and New Orleans. It could be that these are all chemical production facilities and as such do not require significant capture related modifications because they already produce relatively pure streams of CO\textsubscript{2} and are thus “low hanging fruit” economically for the CCGS roll-out. The project will receive 3 million USD from the DOE. It is not yet clear if it is up to Shell to store the CO\textsubscript{2} themselves or, as the project is located close to the proposed route of Denbury’s Green Pipeline, to dispense of the CO\textsubscript{2} that way.

A University of Utah team will work with several proposed CO\textsubscript{2} EOR locations in Kansas. To test the CCGS concept, more than one Mt of CO\textsubscript{2} will be captured annually from a variety of industrial sources. The project aims to then compress and transported the gas via two new
intra-state pipelines to bring it to the EOR locations. Below each EOR location also lies a deep saline reservoir that spans most of Kansas and will be used to store the CO₂ produced in addition to the EOR production needs. The DOE’s share of funding for this effort is 2.7 million USD.

Wolverine Power Supply Cooperative will be building a 600-megawatt circulating fluidized bed power plant near Rogers City, Michigan and this project will investigate the use of advanced amines and other capture chemicals from DOW and Hitachi to capture 0.3 Mt of CO₂ per year. The storage for this project is apparently not yet determined but it is notable that there are already some CO₂ based EOR activities in the state. The DOE will contribute 2.7 million USD to the project.

In addition to the projects discussed, there are several other CCS projects across the US that are either funded via some other government mechanism not discussed here or are privately funded. These projects have been discovered using the CCS project maps supplied by MIT, the World Coal Institute, and the Scottish Centre for Carbon Storage and additional research. In the appendix is a list of the global commercial projects as given by the GCCSI but a comprehensive map in Figure 25 give all of the sizable project activity in the US.

Ultimately, for the US several things should be made clear by this case study. First, the country’s energy system is severely limited by a variety of technical, financial, and political factors. The US infrastructure is aging and needs to be revamped, which means a significant concentration of national efforts on projects to improve many systems and foremost among these systems is the energy system. However, other updates will increase the overall efficiency and decrease energy demand.

Second, climate change needs to be recognized at the national, state, and local level across the country and the implication this has on the energy options available to the country needs to be made clear to decision-makers. It is important that a choice be made to move forward with a solution and economics point to CCGS as able to deliver a significant piece of that solution. But it must be realized that CCGS is only the beginning and that a long-term strategy be developed to increase the energy independence and security in the US. The recent BP oil spill accident in the Gulf of Mexico places a great deal of pressure to move away from offshore drilling and could lead to increased interest in onshore EOR using CO₂.

Third, within the alternative energies market the US is placing its firms at a disadvantage by not adopting higher efficiency standards and carbon pricing mechanisms. Whether or not climate change needs to be addressed becomes irrelevant if the energy security of the country is considered. Furthermore, although coal is apparently abundant, it would be unwise for the country to focus its entire R&D effort on inefficiently burning a dirty resource that is scarce and will be taxed elsewhere on the planet if it hopes to remain competitive internationally. Coal is believed to be a constant and reliable source for energy but some studies indicate supply issues arising in the next couple decades and some new natural “shale gas” discoveries could lead to a favoring of natural gas projects over coal and diminish the need for CCS given relatively low carbon constraints.

The general lack of foresight with respect to climate constraints in the US can already be seen as taking effect with the loss of alternative energy companies to more politically supportive counties like Germany and cheaper production countries like China. In terms of CCGS specifically
it is a French company, Schlumberger, which is managing most of the US storage projects. As one of the major oil market players, a potentially fast democratic system, and one of the largest national budgets, the US has great potential to be highly competitive in the emerging CCGS market but without strong policies supporting the potential national players this market will pass into the hands of others eager to act today.
Case II: The French Republic

France is an interesting case when considering its stance on climate change for several reasons. First, as an influential member of the European Union, the country offers an opportunity to observe the larger picture of EU policies regarding climate change and CCS. Second, France is largely energy independent, in terms of its grid electricity production, due to its significantly nuclear-based power sector. The severe effects of the oil crises of the 1970s caused the country to pursue a route towards energy independence early, which moved it away from fossil fuels for electricity production and towards alternative energy solutions like nuclear, hydroelectric, and geothermal. As a result, the fixed point source (non-transport related) carbon dioxide (CO₂) emissions of the country are drastically lower than most other developed countries.

Nevertheless, given the significant number of cars and trucks in its transportation sector and its expertise in the petroleum industry France remains tied to carbon due to its high stake in the international oil trade. Total, France’s main oil provider, is listed as one of the six global “supermajors”, which is a title designated for the world’s largest petroleum companies. The other big oil industry names in France are Schlumberger and Technip, which are worldwide service providers for the industry. Second, in addition to the oil players, Air Liquide is a global commercial gas supplier with an interest in carbon dioxide management. Lastly, given the number of turbines and power equipment supplied by France’s Alstom, who serves as a global technology provider, the company claims that, “One in four of the world’s light bulbs is powered by Alstom technologies (Alstom, 2009).” These two divergent profiles, one with comparatively low CO₂ emissions and the other with a high stake in carbon production, make the prospect of a strong carbon capture and geological storage (CCGS) market sector emerging within France uncertain without further investigation.

One pattern that can be observed globally is that many existing companies within oil and gas sector are currently positioning themselves to provide the servicing and expertise to deploy the various technologies associated with CCGS. The aforementioned French companies are all, to some extent, vying for a piece of the emerging CCGS market. On the other hand, the clientele and project locations for this market appear for the moment to be developing largely outside of France, due to the low carbon profile of the country. As such, due to the economic interest in the sector from the French industrials, the current situation in France is one of embracing the technology on the small scale, giving the country a technical advantage in CCGS, so that CCGS can be applied by French experts on a larger scale elsewhere on the globe. This report will outline what the positions are of potential CCGS experts within France, the French pilot projects that are coming online or are planned, the involvement of French industry giants in these projects, and the applicability of these projects both within the country and at a global scale.

The Background: France’s CO₂ Profile and the Reason for CCGS Development in France

France currently maintains a very low profile in terms of its CO₂ produced per capita. Compared with the top per capita CO₂ emitters, Australia and the US, France produces less than one third of the emissions of these coal dependant countries. To place this in perspective, Australia produces 20.5 tons of carbon dioxide per capita and the US follows closely with an annual average of 19.7. These two are closely followed by Canada, the Netherlands, and Saudi Arabia whose per capita emissions continue historic increase trends or are now beginning to stabilize (Lauder, 2009). On the other hand, France’s per capita emissions have decreased since the 1970s and are stabilized around an average of 6 tons per capita during the 1990s. Although this trend is more due to a decision to pursue energy independence rather than a dedication to
reducing climate change; it nevertheless places France in a more comfortable position in terms of meeting the demands of a global climate treaty such as the Kyoto Treaty and its potential successor that is to be agreed upon at Copenhagen in the coming months. Nevertheless, regardless of the results from the Copenhagen Conference, the European Commission (EC) has set a target of a 20 percent reduction in greenhouse gas emissions by 2020 (30 percent if other developed nations join in on meeting a similar reduction goal). “As part of its Climate Action package adopted on January 23, 2008, the Commission mentions CO₂ capture and storage (CCS) as one of the most promising techniques available in terms of its potential contribution to their targets for greenhouse gas (GHG) emissions reduction. It recently put forward a regulatory framework for this technology and is encouraging the installation of demonstration pilot units to improve knowledge (Veolia, 2009).”

The EC has now announced that it will select ten to twelve CCS projects planned within its member states that will receive European funding (Munier, 2009). These projects are currently encouraged to be larger than 0.5 Mt but there is a possibility that, due to the immaturity of the technology in terms of existing integrated CCS projects, there will be no minimum. In France, complimenting the interests of the EC, there are several policies going into effect to incentivize the reduction of GHGs. The French President Nicholas Sarcozy has committed the country to adopting a carbon tax beginning in 2010. The recent environmental law passed in August of 2009 states in section VI,

*Tout projet de construction d'une centrale à charbon devra être conçu pour pouvoir équiper celle-ci, dans les meilleurs délais, d'un dispositif de captage et stockage du dioxyde de carbone. Aucune mise en service de nouvelle centrale à charbon ne sera autorisée si elle ne s'inscrit pas dans une logique complète de démonstration de captage, transport et stockage du dioxyde de carbone (Prorogeant le mandat des membres du Conseil économique, social et environnemental et de programmation relative à la mise en œuvre du Grenelle de l'environnement, 2009),*

which means that all new coal plants constructed within France must be coupled with CCS. In addition to this, by 2015 3.6 GW of France’s existing coal plants are scheduled to be decommissioned so as to respect new EU air quality standards. Lastly, the new “Grenelle Environment Round Table” is backed by several state funded agencies like ADEME, which is also encouraging CCS technology development by offering funding to five projects being planned within France. However, given the country’s overall emission’s profile, it is not necessarily clear at an initial glance why the country has adopted CCS as such a major priority.

As a result of France’s decision to move away from fossil fueled electricity production in the 1970s, the country is now the global leader in terms of the percentage of its national energy supplied from nuclear power. This is visible in Figure 27, which illustrates the significant reductions of solid fuels like coal from the French complete energy makeup. The most notable increase lies with liquid fuels, which represents the burgeoning transport sector that is mostly made up of cars and trucks and less so by rail transports as is seen in Figure 26. The significant decrease in the use of solid fuels, namely coal results directly from the buildup of nuclear power in France, which now ranks second behind the US for the total amount of electricity produced from nuclear fuel. Nuclear power made up 41 percent of the country’s energy supply in 2004. This leaves only 4 percent of the energy supply coming from coal, which in most cases is the likely target for CCGS in other countries.
Nevertheless, France has made a commitment to utilize CCGS in its climate change solution portfolio. There is a notable increase in the use of gas fuels, which would mostly represent the usage of natural gas and this can be coupled with CCGS if the technology is current, given that 15 percent of the current energy production comes from this resource. Most of what is addressable by CCGS lies within the solid and gas fuels because these are more likely to be tied to a fixed source as opposed to liquid fuels that are mostly used to power mobile vehicles. This is good news in that France utilizes a good deal of electrically based rail for transportation needs but this is nowhere near the amount of transport that takes place on roads and therefore utilizes liquid fuels as seen in Figure 26. Briefly, what could change this is a switch in the transportation sector to an electric based system for road vehicles, but such a change would require a equivalent increase in power from the electricity sector and the source of this new power scenario is difficult to predict, but it is not certain that such a build-up would be made up of nuclear power and for now these emissions will remain unaddressed by this report.

The unanswered question of why CCS should develop in France is therefore a logical one in that the most likely candidates for CCS, coal, is in limited use within the country and makes up only five percent of the energy production in France, with this number scheduled to decrease in 2015. In terms of applicability of CCGS within France, the most notable energy source of interest
for the application of the technology after coal is natural gas combustion. However, natural gas is not very carbon intensive in terms of energy production, when compared with coal or fuel oil-based boilers. Furthermore the security of the natural gas supply is not completely clear and a major build-up of capital intensive natural gas CCGS-coupled power plants tied to a resource that might not last for the life of that infrastructure would be unwise.

Observing energy via consumption by sector, rather than by fuel type, gives another perspective and reveals an additional target that could benefit from CCGS. Although the five percent of the energy sector that is made up by coal perhaps seems unappealing initially as a target, if one examines industry as a whole by combining the eight percent of greenhouse gas emissions that result from industrial processes with the thirteen percent from energies used (and therefore normally produced locally) by the industries, the resulting nearly one quarter (23 percent) of France’s emissions. As seen in Figure 28, this number becomes an attractive target for GHG reduction strategies. Mineral products, metal production, and the chemical industry make up over 60 percent of the industrial process emissions, and most of the coal consumption would be contained within this sector (Le Treut H. e., 2007). Because the EU has selected many of these industries as major targets for the union’s emissions reductions, there exists significant interest in technologies that could mitigate the potential increase on emissions or a price increase on carbon in the Emissions Trading System (EU ETS) or from the pending French carbon tax. This makes companies like the cement giant Lafarge, the steel major Arcelor-Mittal, and the waste and water services provider Veolia, along with the energy providers GDF-Suez and EDF, who are the more typical clients for CCGS, all very eager to see the technology develop.

**The Players: CCGS Service Providers and Global CO₂ Producers**

In addition to these pressing national concerns about emission reduction strategies within the state, the aforementioned French-based global corporations are a group of companies based in France who are interested in CCGS as potential service providers. Beyond the mere provision of capture, transport, and storage services for the CO₂, there are others who hope to develop and sell low-CO₂ industrial methods. Groups and consortiums are forming across the lines of the government, education, research, and private sectors so as to maximize the expertise of each and facilitate the necessary steps to bring CCGS online. As a result, several CCGS projects are in the initial and planning stages and a variety of efforts are now underway currently to map the geological potential of the country for CCGS deployment.

France has a large potential to be successful in terms of realizing an edge on the CCGS service and technologies market. Most of this is seen within the energy sector, but there are other groups interested in providing aspects of the technology to the major industrial GHG emitters.
These interests are pulling in the support of universities, government agencies, and non-governmental research groups, so as to share the expenses and workload among those with the highest level of expertise in each area. The following section gives an overview of these various organizations and corporations, their core activities, and their connection or potential expertise within the emerging CCGS market.

Oil and gas companies and their associated exploration and production (E&P) and engineering and construction (E&C) contractors have the most experience with the technologies required for capturing, transporting, storing, and monitoring CO₂. They are familiar with the construction of infrastructure such as on- and off-shore pipelines, offshore rigs, injection and extraction wells, and above- and below-ground storage facilities needed for CCGS but that also allow the extraction of oil and gas for domestic and commercial use. They also gain expertise from their familiarity with the geological formations relevant to CCGS, because these are the same as the ones that are typically targeted either for oil and gas extraction or for the storage of gas reserves after it is extracted and purified. This gives them a significant amount of knowledge and experience dealing with underground engineering. The builders of power-plants and other industrial installations also have the technical knowledge for capture and often work with the oil and gas companies for that reason helping them purify their natural gas production by removing contaminants like CO₂. As a result, all of these companies have a significant lead on the members of other industrial sectors who are hoping to enter the CCS market and is the reason why they are the ones who are most involved with the current and planned CCGS demonstrations. The following companies are the most significant players in the energy sector regarding CCS.

Alstom, as was mentioned, is the global leader of integrated power plant production, in terms of the equipment and technology required to build them. They are also a global leader in many other sectors, including nuclear power plants, hydro power, high-speed trains, and urban transport, with global orders totaling 24.6 billion Euros (Alstom, 2009). Their position in the power plant market has compelled them to pursue development in terms of carbon capture technologies, often by creating alliances with the other key players who compliment their technology with the necessary gases or chemicals used to capture the CO₂. Alstom lists its expertise in this area with two of the three types of capture: post-combustion and oxy-combustion. The third technology of pre-combustion capture is not currently covered by Alstom technologies but it is only applicable to new plants, whereas the other two can be built new or retrofit to existing installations (Sonnois, 2009).

Alstom’s post-combustion technologies currently at the demonstration phase include chilled ammonia scrubbing and advanced amines. Some of the amine based capture techniques, as was described in the CCS overview, are projects that Alstom is developing jointly with partners such as Dow Chemical Company. The second technology uses chilled ammonia in a similar process that cools the flue gas, but treats it instead with ammonium carbonate in solution, which reacts with CO₂ to form ammonium bicarbonate. The compounds are again reheated to release pressurized CO₂. An advantage to this technology appears to be that there is no degradation for the globally available and therefore inexpensive reagent (ammonia) and no emission of trace contaminants, leaving a highly pure stream of CO₂ for storage. Alstom is currently in the early stages of developing with ARMINES (the research wing of Mines ParisTech) an “anti-sublimation” capture technology, which will be discussed further in the following section (Lagneau, First Advisory Meeting, 2009).
As for the oxy-fuel technologies, the concept is one of removing the agent (nitrogen) within air that is the cause of a large percentage of the impurities within flue gas that make normal CO₂ post-combustion capture difficult. Here an air separation unit is employed to provide a pure stream of oxygen to the boiler, for which Alstom partners with companies like Air Liquide. The main advantages to this technology are that it covers all fuel types. Most of the components already exist at commercial scale and so the technology needs merely to be adapted to the power generation or industrial settings. As a result the technology, according to their own reports, can be scaled-up rapidly after demos are completed and it is currently the most conducive technology for retrofitting existing power or industrial plants with carbon capture (Sonnois, 2009).

Air Liquide’s specialty lies originally with the supply of various gases of commercial interest. As a result, the company has entered into the oil and gas sector with respect to the gas based enhanced oil recovery (EOR) activities in the US. To supply the CO₂ for several US projects, Air Liquide developed some CO₂ transport experience as well. With the rise of oxy-combustion technology, the company has recognized and capitalized on the emerging need for oxygen separation equipment. This has led to their involvement with Alstom in projects such as Total’s integrated oxy-fueled CCS Project at Lacq that is detailed in a following section. They are currently engaging in solving the issue of increased argon and trace gases after nitrogen is separated and removed from intake air for oxy-fueled projects.

According to their profile, “To oil and gas companies worldwide, Schlumberger is the leading oilfield services provider, trusted to deliver better results in any location to help customers improve [exploration and production] performance.” They back this with their 80 year history of subsurface evaluation and engineering experience and advertise that they have been involved with CO₂ injection since the mid 1990s (Schlumberger Carbon Services, 2009). Schlumberger’s core professional activity is the provision of formation characterization and monitoring services, but they also are very capable of managing all aspects of underground engineering and they contract out the work they cannot do themselves. This has led them to exposure to nearly every existing CCGS project to date, because most of the early projects are run by oil companies.

As a result of their initial exposure, Schlumberger today has the biggest name globally in terms of providing CCGS solutions, participates to nearly every existing consortium concerned with CCS, and speaks as experts on the topic at countless CCS conferences, forums, and workshops. Schlumberger has embraced this role and now has developed an explicit Carbon Services division with 100 million Euros worth of R&D investment, so as to provide CCGS solutions to all interested parties and expands their customer base to more than the oil and gas sector (Lagneau, Second Advisory Meeting - Report Review, 2009). What this means is they hope to manage the drilling and technical outfitting of carbon injection wells. They also engage in the wide range of seismic and monitoring solutions that could be required for storage sites once they are in operation. Their services could potentially expand into the operation of the physical storage facilities once they are constructed and injection is underway, but this currently does not appear to be their core focus. As a result of their marketing on the subject of CCS, their involvement with so many of the current projects, not to mention their expensive network within the oil and gas industries, Schlumberger will remain one of the key players in CCS as the market continues to develop.

Total has an interesting position in the CCGS field in that the Oil and Gas giant has been involved in CCGS projects since the beginning, as it was a partner with Statoil on the Sleipner project. The
company also has the capital to engage in expensive demonstration projects without so much assistance from other funding sources. Total also has a broad knowledge of the geological characteristics of the reservoirs it has explored for its various oil and gas operations. As such the company is moving forward on a project in the southwest of France, which will be detailed in the following section. This project is one where it will act as director and utilize the experience it has gained from Sleipner and other CCGS projects it has involved itself in. However, the individual pieces of the project will be provided by the traditional array of oil and gas E&P contractors. Total is also pursuing a major storage project for the Northwest of France, the details of which are also to follow.

The reason for the oil giant’s involvement in the business is not clear in terms of what they hope to achieve with the expertise they may gain. However, it does not seem logical that the company will pursue CCS as an additional core activity, as it is currently already extensively engaged in oil and gas extraction and this is already an immense business. There are two possible reasons for their interest in CCGS development in France. First, Total is involved significantly in oil and gas extraction activities in Canada where the more of the world’s oil-sands are located. However, recovering this oil is extremely carbon-intensive and as Canada hopes to comply with its ratification of the Kyoto Protocol, continuing to extract oil resources there may require a change in method so as to limit the resulting emissions. CCS offers a potential tool for achieving this goal and also the CO₂ is becoming valuable as a means of EOR in Canada. For this reason, Total could wish to prove expertise in this area. Second, Total operates refineries and other oil related facilities in the northwest of France. As these facilities are carbon-intensive they are at risk of being negatively affected by the pending carbon tax and by future climate treaty statutes Total is interested in the possibility of storing their emissions via CCS. If the company is going to engage in a significant storage project for its own needs, it could benefit from increasing the scale of such a project so as to accommodate the emissions from other industries located in proximity to Total’s own operations (Lagneau, Second Advisory Meeting - Report Review, 2009).

**Geostock** is not on the same scale as the previously mentioned French oil and gas related companies. Nevertheless, it does have a strong name in its field of expertise, which is underground storage. Geostock is owned by Total (50%), BP (25%), and Entrepose Contracting (25%) and is prolific in France, but also has extensive international project experience, with several holdings in European companies, an office in the US, and major contracts active in Singapore, Korea, and elsewhere in Asia. As such, at least in terms of France, Geostock has been involved with many of the early storage capacity estimation and methodology development projects. Geostock has now created, in a partnership with the French Geological Survey (BRGM) and the French Petroleum Institute (IFP), a commercial firm specifically focused on the topic of carbon transport and most especially storage.

**Geogreen** was created in August of 2007 and is currently headed by Gilles Munier (CEO), formerly of Geostock, and Dr. Pierre Le Thiez, formerly of the IFP. The company’s connections within its founding partners (IFP, Geostock, and BRGM) and its new collaboration with others interested in the CCS market like Technip and TNO, a Dutch climate research group, have led to a rapid scaling up the company’s activities in the CCGS world. According to Mr. Munier, Geogreen is involved with roughly 20 projects worldwide and will be creating an office in the US early in 2010 and hopefully will have a presence in China within about one year’s time. They are also involved in the Middle East and in South America. The group appears to be operating in a
niche market with designs of moving to a larger level of involvement at a time when CCS will be deployed internationally at a commercial scale.

Technip’s expertise lies with its on- and offshore as well as subsea construction experience in the oil and gas E&C sector. This entailed the construction of offshore platforms, facilities, moorings, offshore pipelines, and other various infrastructures. The company also has some experience in constructing some onshore plant installations and pipelines. The company is eager to engage in CCGS service contracts and has signed an agreement with Geogreen, so as to provide together the complete chain of carbon services as it has been a little more slow in entering the CCS game than many of its competitors.

There exist others companies and groups that are or hope to be involved in the new CCGS market and lie outside the oil and gas world. There are nevertheless some aspects of the technology that are not covered by the oil and gas E&P and E&C groups, namely the industrial application of low-carbon production via improved efficiency and carbon capture and also the more intellectual aspects of CCGS such as various sorts of risk assessment and legal issues. The following companies listed here are given due to their stated involvement in CCGS related RD&D work.

The state electricity company, Electricité de France (EDF), seems perhaps an odd candidate for an interest in CCS due to the earlier sections of this case study, which revealed how little of France’s electricity, with nearly 90 percent being produced by nuclear or renewable sources, comes from carbon-based energy resources. Much of what remains of France’s coal power production will probably be shut down anyhow after 2015, being too old to retrofit with CCS. However, an interesting aspect of many French state-run companies is that as they have grown, they have been permitted to expand by gaining holdings in other countries, much like a private company would do. EDF maintains ownership of electricity infrastructure in several other countries throughout Europe. One particular investment made by EDF in a variety of coal plants during the deregulation of some Eastern European countries, which were formerly pieces of the Soviet Union. Now with these countries joining the EU, they are subject to the EU ETS and will have to comply with any other European statues regulating CO₂. As a result, developing some experience or at least contributing toward the major research efforts surrounding CCS technology could prove very strategic in terms of addressing the company’s coal plants outside of France.

Veolia is originally one of two municipal services companies in France, the other being Suez that has now merged with GDF. Today the company is, along with being a water supplier and a public transport company, a major waste management firm, with 100,000 locations of activity across the globe. Veolia’s waste operations are estimated to account for one one-thousandth of the total global CO₂ emissions and as a result the company hopes to patent, utilize, and potentially sell via its environmental services group, Veolia Environment, GHG reduction technologies related to this industry (Quisel, 2009). The solutions it is developing for waste processing facilities on the global market will be grant the unique ability for these facilities to couple energy and waste recovery/recycling via concepts such as methane/landfill gas capture, combined heat and power plants, industrial symbiosis, with CCGS. The idea is that if these waste operations can be made carbon neutral (they produce no CO₂) or even carbon negative (they have a net-effect of reducing the amount of carbon in the atmosphere) in terms of carbon credit accounting purposes there could be significant financial incentives for other waste sites to employ the
techniques Veolia is developing. At present however, the group contracts the carbon storage engineering and facilities design work to others such as Geogreen.

The global steel producer was formed by a merger between the French steel group, Arcelor, with the Mittal steel company Arcelor-Mittal from India. The company is now one of Europe’s top steel producers and as a result is directly impacted by the EU’s commitments to the Kyoto Protocol. As such the group is keen to develop low carbon steel production techniques and is pursuing this via the ULCOS consortium that is detailed in a following section.

GDF or Gaz de France was the gas equivalent of EDF before its recent merger with Suez. Similarly to EDF, GDF has developed holdings in other countries and as a result has equivalent sister companies in countries such as Belgium and the Netherlands. However, prior to the merger the gas provider was involved in the K-12B project discussed earlier, which aims at very deep offshore EGR just off the coast of the Netherlands. It is also a partner for several of the pilot projects planned in France.

Oxand does risk assessment work and therefore is interested in assessing the various types of risk that will unavoidably be associated with CCS projects. These risk include not only the financial risk of projects dependant on a price on carbon and global climate treaties, but also the geological risk, public acceptance, transport risk, etc. The company apparently involved with this topic on a global scale and has worked with Schlumberger in CCS projects such as the In Salah project in Algeria (Van Der Beken, 2007). Its competitors in the field are companies such as the Norwegian Det Norske Veritas (DNV), who has gained more exposure as a CCS risk assessment company due to its association with Statoil and the Norwegian Government.

Lafarge is a global cement supplier based in France and as cement is a major emitter of GHGs, the company maintains an active interest in the CCS discussion in France (ADEME, 2009). However, it would appear for the moment that the company has no direct projects related to CCS that it is engaged in as opposed to its American equivalent of Lafarge: CEMEX (DOE, 2009).

There is a strong level of communication between the private sector and a long list of public and private research institutions within France. The following list compiles a brief description of some of the more important ones based on their current involvement in the topic. The **Bureau de Recherches Géologiques et Minières (BRGM)** is France’s governmental geological expert and is similar to the United States Geological Survey (USGS). They maintain detailed records of the geology throughout the state and therefore have been implemenetal to assessing the CO₂ capacity within France.

The **Institut Français du Pétrole (IFP)** is like the American Petroleum Institute (API) except that it is a public sector research group with an attached university whereas API is purely a trade association that funds petroleum based research and initiatives. IFP is involved deeply in the French CCS activity and is also pulling France into the CCS activities happening on the national scale, quite often in cooperation with BRGM. They participate to several European CCS research initiatives and also are involved in China and in the US with CCS developments there (like the Regional Partnerships in the US and the Coach Project in China that will be discussed in the case studies associated with those countries).

The **École Nationale Supérieure des Mines de Paris** is a member of the French Grande École group and as such is top university in engineering, especially in areas related to the management of resources. The school is involved with several projects on both the capture and
the storage side and works closely with the major private sector companies in these areas such as Alstom, EDF, Total, and GDF-Suez.

The interest of so many French players in CCS has resulting in the creation of some groups designed to share ideas and work together on the development of CCS technologies within the country and in Europe. Club CO₂ is a group put together with a focus on capture and storage by ADEME, the French energy agency, which begins to approach the type of collaboration seen in the US regional partnerships. It includes three types of entities within France and the categories can be seen as CO₂ producers, CO₂ mitigation service providers, and research organizations involved with the CO₂ topic. The group is not meant as a federation and is more a forum where the members can share information they feel will not jeopardize their position in the market. ADEME uses the group as a means of distributing pertinent information regarding the CCS topic to the members and holds fairly regular meetings with representatives from a wide variety of groups to discuss relevant developments within the topic. The largest of these are the ADEME CCS Symposia designed to provide cutting edge lectures from the experts in the field to those seriously interested in the CCS topic.

ULCOS (Ultra Low Carbon Steelmaking) is a European effort, headed by the European Technology Platform on Steel (ESTEP) and major steel producers of France, Germany, and Luxembourg, for the development of low CO₂ steel technology, with the explicit goal of reducing the overall CO₂ emissions of the steel industry by 50 percent in the long term (AFP, 2009). The effort, led by Arcelor-Mittal, has an announced short to medium term budget of one billion Euros and initially involves a small pilot plant in Germany, with then a larger demonstration operation to be implemented in France that will be detailed in the following section. The technology is hoped to be ready for application at commercial steel sites starting in 2020.

The Projects: CCGS Activity within France

France has a high level of ambition when it comes to CCGS, but not without reason. As can be seen in the last section, there is a strong support network of experts from all steps of the CCS technology chain. Many of these experts are global corporations who have a high potential to act as international CCGS service providers as the technology is accepted and implemented across the globe. In order to reach this stage, or even to effectively use CCGS as a GHG mitigation tool within France as part of the portfolio of solutions to meet the country’s Kyoto commitments and the commitments that will follow under the future climate treaty, a rigorous schedule needs to be followed by those participating in the research and development and demonstration activities. Figure 29 outlines what this progression should look like.

The first projects in France worked to estimate the countries capacity ranging from the site to a national scale. The goal was to estimate not only the total capacity of France but also to understand in the French context how injection took place. The “Pléage du CO₂ dans les réservoirs géologiques, en France” (CO₂ Trapping in Geological Reservoirs, in France) or PICOREF project is a two year project began in 2005 and had an allotted budget of 3.75 million Euros. It was meant to determine application within France of the previous 4 year study (PICOR) by the RTPG (Réseau des Technologies Pétrolières et Gazières - a network of oil and gas technology providers) that was designed to research the available knowledge and tools that could be applied to storing CO₂ (Lund, 2008).

GETSCO was a European effort designed to give an initial estimate of the European carbon storage capacity in terms of saline aquifers, oil and gas reservoirs, and deep coal beds in a select
group of European nations including France, Germany, Etc. This project is what was expanded into the GeoCapacity project to estimate the storage for the entire EU. These projects hailed cooperation by a wide range of groups across Europe.

A project more specific to France and therefore more precise called “Méthodologie de sélection des sites de stockage du CO₂ dans des réservoirs souterrains en France” or METSTOR was completed by a partnership containing BRGM, CIRED, Ecole Nationale Supérieure des Mines de Paris, Gaz de France, Geostock, IFP, INERIS, and IPGP. This group worked to further identify geological storage sites in France and provide a public interface at metstor.fr, a site where interested parties can learn about the CCGS field, where the storage sites could be, what is taken into account when storing the gas, etc. This work was mostly focused on two potential storage formations within the Paris Basin: the Dogger and Trais (Lagneau, Second Advisory Meeting - Report Review, 2009). These were selected due to the broad range and depth of knowledge surrounding these formations as a result of the extensive exploration of them for oil and gas, as well as for geothermal resources. This project was completed in 2008 (Ha-Duong, 2009).

Total’s project at Lacq was the first CCGS project to come online in France and is the first fully integrated CCGS demonstration utilizing oxy-combustion capture technology at a gas-fired power plant in the world. Lacq is Total’s first project where the company serves as the project director, but the company has served as partner for many other projects such as Sleipner and Snøhvit in Norway. “The project has three key objectives: to improve mastery of the oxyfuel combustion process, particularly with a view to applications in the production of extra-heavy oils, to halve the cost of carbon capture compared to existing processes, to develop monitoring methods and instruments to demonstrate on a larger scale the reliability and sustainability of long-term CO₂ storage technology (Lund, 2008).” The plan for Total is to fit a gas boiler with oxyfuel-based CO₂ capture technology at its location near the Lacq gas field in the Southwest of
France near the Pyrenees. The 0.15 Mt of annual CO₂ emissions from the gas plant will then be shipped to the neighboring depleted Rousse gas field, which lies more than 4000 meters below the surface (Total, 2008).

The creation of this oxy-fired gas plant contributes to the EU goal of creating low CO₂ fossil fuel-based power, known as the Zero Emission Fossil Fuel Power Plant (ZEP) goal, as defined by the European Technology Platform of which Total is a partner (Lund, 2008). The pipeline to be used is about 27 kilometers long and is already built, being once a natural gas pipeline for the gas production operations that Total operated in the Lacq area. The project counts a wide range of partners, including Alstom who will design the oxy-boiler for the gas plant retrofit and Air Liquide, who is also involved in the oxy-combustion technology application. Because IFP and BRGM are also involved with the project, it seems logical to deduct that Geogreen is the company that did the initial geological assessment and was probably chosen to operate the storage for the project. The injection was scheduled to commence in late 2009, but due to some problems with a down-well monitoring device the injection has been temporarily delayed (Agrinier, 2009).

With Lacq, France has now progressed to the pilot and demonstration phase of the CCGS timescale, despite the current complications that have temporarily delayed the project (Agrinier, 2009). In Tandem, ADEME has made a call for five projects in France, which it will contribute research funding of up to 60 percent of the project costs. Some sources believe this funding will in fact be much lower and will not be given directly as cash but will be realized via tax incentives or other fiscal mechanisms. In addition to Lacq and these five ADEME projects, there are a few European supported efforts and potential projects announced, but not confirmed, on some scale by other parties interested in CCS. The map in Figure 30 to follow gives a broad estimate of where the various planned CCS related projects are located in France, with a brief summary of each project following.

Veolia, with significant expertise in the area of waste management, is in charge of a waste incinerator and landfill site at Claye-Sulley that is noted as one of the largest in Europe. They wish to explore two solution possibilities for their CO₂ emissions at this site: the first being CO₂ capture, transport, and industrial recovery; and second being CCGS. The first investigation involves recycling the CO₂ produced by the incinerator by capturing it and then piping it to a local chemical production plant that needs a source of CO₂. The second project is to capture biogas being produced at the landfill and valorize the energy in a combined heat and power plant (CHP), while capturing and storing the resulting CO₂ emissions (Harel, 2008). As a result of the project’s implications for CCS in France, they approached ADEME for funding towards this 150 million Euro CCGS proposal, which when completed will engage in a full chain CCGS project for their landfill facility at Claye-Sulley (Agrinier, 2009). The resulting 200,000 tons of annual CO₂ emissions will be captured and transported just a few kilometers away to be stored in a saline formation at about 1,500 to 2,000 meters below the surface (Les Echos, 2009).

The project was planned for 2011 with the injection commencing in 2014, which would have made it the third project involving CO₂ injection in France, after Lacq and one other, and in fact will be the largest at 0.2 Mt CO₂ injected per year. However, this original schedule is no longer sure. Nevertheless, Veolia is now engaged in investigating the proximity of its other operations worldwide to identified geological formations with CO₂ storage potential (Wecsteen, 2009).
**Alstom** is building a plant in a partnership with the French State electricity provider EDF and some other partners. The project is one of five projects that are receiving ADEME funding to encourage CCGS in France but beyond that there is currently not publically available information concerning the location of the project or the type of plant it will be applied to. The goal of the project is to explore the use of a new family of **advanced amines** in a post-combustion capture facility.

Alstom is also putting funding, along with EDF, GDF, and ADEME into a research project called **“Pil Ansu”** developed by an Ecole des Mines researcher on the topic of carbon capture. This technology currently exists at the laboratory stage (at a scale of 1/100th of an industrial sized application) and involves a of cooling flue gases at a pressure more or less equal to atmospheric pressure at a temperature such that the carbon dioxide passes directly from the vapor state to the solid state via an “anti-sublimation” (Pil Ansu) process. This is a technology that Alstom supports and hopes to add to the repertoire of capture methods it has on the market and as such this project would be an application of this process to a roughly 30 MW power plant near Le Havre.

The project by Arcelor-Mittal is within the context of its ULCOS project. It will keep open the steel operation in **Florance**, is in the Northeast of France near Germany, which was originally scheduled for closure by 2010 or 11 as part of Arcelor’s “Apollo” plan (Arcelor Mittal, 2008). Arcelor with ULCOS support is first planning to test this technology at a smaller scale at Eisenhüttenstadt, Germany from 2010 to 2014. The company will keep the plant open at Florange and begin a larger ULCOS demonstration project there, if the initial feasibility studies prove positive, in 2011. This project will cost an estimated 400 million Euros over the four years needed to complete the low carbon steel plant by 2015. This project has also been selected to receive ADEME funding and hails Air Liquide as a partner, which suggests it will utilize oxy-combustion technology. Along with the steel technology engineering company Paul Wurth of Luxembourg will be performing the steel-related design work.

There are activities underway, run by Total under the project heading of **“France Nord”**, to determine a feasible storage location for the industries of the Paris area and the cities of Le Havre and Lille near the coast. These locations form a triangle that rests atop the Paris Basin, where Total hopes to discover a suitable storage site for this large amount of emissions. This project has the benefit of being a follow-up project on the heels of PICOREF and METSTOR. It also coincides with a project called “AQUA-CO₂ “, which is headed up by IFP and several other European partners to find a sizable CO₂ storage location in each participating country (Lutzky, 2009). A second source cites a similar project that could be conducted offshore, close to the Normandy Coast, with a similar goal of supplying storage space for the Paris and Le Havre industrial CO₂ sources (Les Echos, 2009). The connection to the Geostock studies and the IFP work suggests that this project might involve Geogreen as the storage expert but according to Geogreen, Total is in fact not yet working publically with any other companies on this project for the moment (Munier, 2009). Nevertheless, the project should receive ADEME funding as one of the five sponsored projects.

At the moment there exist two additional projects that are also rumored to take place in France that could prove interesting for the advancement of the CCGS field. Vermillion energy of Canada has operations at two locations within France. The first is in the South West on the Atlantic Coast and involved taking its petroleum products and burning them in a combined heat and power (CHP) installation build to power tomato greenhouses. The heat and power will be
utilized for the greenhouses and the emissions of CO₂ will be circulated through the greenhouses in sync with a specially timed lighting scheme that will cause the tomatoes to have an increased CO₂ absorption rate. They basically plan to engage in bio-sequestration via tomatoes.

A second operation for Vermillion is in the Paris Basin, where they own one of the larger oil concessions in the area. The group according to one source has spoken loosely about the potential to capture CO₂ and store it in some of their depleted reservoirs for either the aim of pure storage or enhanced oil recovery (EOR). This information is only speculative at this point. The Soufflet Group is engaged in the production of biofuels and especially biodiesel. As a member of Club CO₂ they had expressed an interest in pursuing CCS at one of their operations near Paris at Nogent-sur-Seine but they have not released any more information (ADEME, 2009).
The sum up of the French situation is divided into two different areas. On the one hand there are national industries eager to do their parts to meet the requirements set by Kyoto or a future climate treaty. These include EDF, Veolia, Groupe Soufflet, and others who are looking to invest in pilot projects at their operations in France, or even outside of the country. The second group is one of major service providers who are hoping to get all of the experience they can on the topic of CCS so that they can move onto the global market or improve their existing position within that market. There are even those like Schlumberger who appear to be more active outside of France than within. Ultimately this technology if successful will prove very profitable for France.
Case III: the People’s Republic of China
The region that is today known as the People’s Republic of China (PRC) has maintained a significant population when compared with other areas across the world throughout history. An undeveloped and loosely associated semi-colony, split apart by imperial powers in the early part of the 20th Century; China’s rapid transition to a massive independent economy at the start of the 21st has significantly changed how that population is perceived. In terms of development and global impact, it was not until the last few decades that that the PRC began to be considered and treated as a global power.

China presents the most interesting case when considering climate change and the applicability of CCGS technology. Although its decision to act or not could potentially have the most significant impact globally, the country has taken a vague stance in terms of climate change mitigation commitments. As a result, it is unclear to what extent the country will pursue CCGS. This case study will explore what the implications are of China’s actions and inactions, what opportunities can be found there for the development of CCGS technologies, and what the risks and benefits are from China’s engagement in this sector.

The Background: China and Climate Change
According to Wired, “If China’s carbon usage keeps pace with its economic growth, the country’s carbon dioxide emissions will reach 8 gigatons a year by 2030, which is equal to the entire world’s CO₂ production today.” China surpassed the US around 2006 or 2007, depending on how one counts emissions, to become the world’s top emitter of GHGs. This ranking does not indicate the amount of emissions related to products that are consumed in China, as many of the products are then exported to countries with apparently low GHG counts. Nevertheless, it is still important to realize that the largest source of the GHGs produced on earth today is China. This has tended to draw greater attention to China’s actions, or its inaction, with respect to international climate change mitigation efforts. Whereas before China was listed among the developing countries who would not be directly bound by the emissions limitations set by a global climate treaty, now there is mounting international pressure for China to join the developed “Annex I” countries in devising and implementing a solution. The Annex I countries, who had been designated by Kyoto as the actors most responsible for addressing GHG emission mitigation, predict that any actions under a new treaty, as was hoped for from the Copenhagen talks, will be for naught if China refuses to participate at a meaningful scale.

As the US and China are currently the most important states in terms of GHG emissions, generating more than 40 percent of the global output, it is important to understand what they are discussing in terms of reductions. Leading up to the Copenhagen Conference in December 2009, US President Barak Obama stated that he hoped to commit the US to reduce emissions by 17 percent of 2005 levels by 2020, which was in line with the commitments contained in the most recent climate bill passed by the US House of Representatives. China, in response to the US statement, committed to reducing emissions intensity by 40 to 45 percent in that same period (Lash, November 26, 2009).

A notable counterargument is that compared to developed countries like the US, China has produced significantly less emissions on a historical basis. To date China is responsible for 66 percent less emissions than the US has produced a historic basis, which is calculated in terms of the total GHG emissions released by either nation throughout their development histories. If
one uses the IEA and WRI recorded data for annual and historic CO₂ emissions respectively, it is possible to put these commitments into perspective, as is shown in Figure 31. Given the trends for a business as usual (BAU) scenario, China will not overtake the US in terms of historic emissions until 2034, even if the US caps its emissions according to its recent commitment.

The historical emissions argument proved beneficial for the PRC during the Kyoto Protocol negotiations, which took place at the turn of the 21st Century and resulted in China’s being listed among the developing nations who would not be limited by the treaty and who could benefit from the “Clean Development Mechanism” (CDM). This mechanism of the Kyoto Treaty allows the Annex I countries, i.e. those listed as sufficiently developed to have their emissions directly limited by the treaty, to invest in approved emissions mitigation projects in countries not listed on Annex I. The logic here is that to ease their domestic emission reduction measures, Annex I countries can offset their existing emissions by instead helping a developing country reduce their emissions instead and so in the end - at least in theory - the overall achieved reduction is the same. China still holds historic emissions as a key negotiating point and as a means of placing the responsibility of reducing emissions on developed countries: namely the US, but also EU member states.

As another counterargument to the increasing demands that it take a leadership role in addressing increasing global emissions, China points to the fact that its CO₂ profile per capita is still very low compared to most developed countries. Compared to the top fifteen major
emitters, which using 2006 data make up 75 percent of the total global GHG emissions, China ranked number one for overall emissions but thirteenth for its per capita emissions. In 2008, China's National Development and Reform Commission (NDRC) estimated that the country's per capita emissions of CO₂ would probably remain below US levels until at least 2025. “This will mean less pressure from the international community for more drastic measures, and it allows China to pursue a more flexible model for rapid economic development," said a senior official with the NDRC. With a population more than four times as large as the US, the NDRC claims the per capita figures are more meaningful and that after the necessary catch-up period, “From 2030 to 2050, China will enter a period of extremely strict environmental controls [to tighten environmental regulations and reduce emissions].” This argument would demand that China only decrease its emissions by less than 5 percent so as to match the global average.

This type of argument is becoming increasingly difficult to support given the rapidly increasing share of emissions global emissions coming from China. In addition, while it is important to recognize that global emissions are not equally distributed across the globe, the danger of designating emissions responsibility on a per capita basis, while continuing to also divide them by state borders, is that the result will be just as unbalanced and arbitrary as to simply do so based on borders alone. To comply with such a “per capita emissions standard”, while the US would still need to reduce its emissions by around 80 percent, India, who ranks fourth in terms of total emissions, would need to increase its emissions by more than 200 percent to meet this same global average-based standard. The problem also lies in that a per capita basis makes assigning the state responsibilities for meeting a global cap very difficult. It allows multi-national companies to simply move to “developing” states where the treaty is not as harsh. There they can continue to produce unregulated cheap goods with high emissions without providing major development benefits to the poor citizens of that country who are holding down the average. Nevertheless, China’s position and the implications of per capita and historic emissions should be addressed by a climate treaty: but in a way that is constructive and not in one that simply allows China to continue to prosper and widen the trade deficit by depressing its currency and allowing unrestrained development and goods production.

The reality that essentially any agreement will result in restrictions on current development trends leaves China in a difficult position in terms of international negotiations on the climate issue, which is probably why Chinese officials continue to only give commitments in terms of emissions intensity. Emissions intensity is generally calculated in terms of emissions versus gross domestic product (GDP). As such there is no implied reduction of overall emissions because decreasing intensity is only an increase of the efficiency with which things are produced and in Figure 32 it is shown that China’s recent

![Figure 32 - China and US Commitments to Global GHG Reductions](Nov 2009) | Data Sources: IEA, WRI, and Chinability.com
commitment implies no change for its current development trends.

However, in the next rounds of negotiations, as it now ranks as a major economy and as the largest emitter of CO₂, it will be increasingly difficult for China to maintain this position of making no promises. If an agreement is finally reached between the developed countries on GHG emissions limitations and China refuses to comply, such a move could prove damaging to the state’s economy if the participating states use mechanisms to properly tax the carbon implied by imports coming for countries that are not abiding by the treaty.

**Chinese Domestic Issues and Drivers for CCGC Development in China**

China is in a more difficult position than it may appear in terms of addressing the domestic side of the climate issue. The socio-economic reality behind the arguments China provides for refusing to agree to a set limit on its emissions is that the state government believes it must maintain a steadily growing GDP so as to provide jobs to the increasing number of people entering the workforce each year. For this reason, the economy is the top priority for the country and all commitments for emissions reductions are placed in terms of emissions intensity. However, leaving that same workforce with unlivable environmental conditions is equally destabilizing. The increasing access for common citizens to information from outside China only serves to emphasize that higher standards should be expected.

As with most developing nations, China needs to deal with and provide for a burgeoning population. The state has addressed the overpopulation issue to some extent with the “one-child” policy that is predicted to stabilize the population at 1.4 billion, as opposed to India where this kind of population stabilization is not taking place. The issue now is to sustain this immense population. Moreover, the critical problem today in China is the rate of urbanization, which unlike its population growth is not stabilizing. In tandem to the urbanization trend is an increasingly large Chinese middle class, which means there are more people demanding more resources. This problem can be seen globally but is especially relevant for the Chinese case according to Thomas Friedman. He describes the global problem as a conflict between two trends: an increase in the number of “Americums” that exist on the planet, i.e. US-sized groups of middle class consumers who are using resources at a similar rate, versus a decrease in resources meaning a decrease in the number of “Americums” the planet can sustain (Friedman 2008).

When traveling through the Chinese heartland, what one sees out the window – versus what is accounted for on a map – is not the same reality. Armies of cranes appear in the middle of nowhere, deployed there to literally construct a city there “over-night”. The current annual rate of urbanization in China is 2.7 percent, which is more than twice the US rate of 1.3 percent and more than triple the 0.8 percent rate in France (US CIA, 2009). After analyzing the current trend, McKinsey gave the following assessment:

*China's urban population will expand from 572 million in 2005 to 926 million in 2025 and hit the one billion mark by 2030. In 20 years, China's cities will have added 350 million people—more than the entire population of the United States today. By 2025, China will have 219 cities with more than one million inhabitants—compared with 35 in Europe today—and 24 cities with more than five million people (McKinsey, 2008).*

To power this burgeoning economic growth, the Chinese are depending on their most abundant energy resource, coal, to produce the needed electricity and as a result are the largest
consumers of coal in the world. China is also one of the largest importers of coal, as seen in Table 9, with most of this coming from Australia. China’s concern driving this is that if the economy does not have the energy needed to prosper and grow, the resulting unemployment will be destabilizing for the country. In addition to coal, the PRC is now, after the US, the world’s second largest consumer of petroleum. The other electricity sectors in China are expanding as well, including solar, wind, and nuclear. As a result of its nuclear ambitions, China has also recently begun to buy up a large number of uranium reserves in Australia and elsewhere. The Australian news group, The Age, documents this as follows:

*China is shaping as a multibillion-dollar new uranium export market as it looks to Australia to supply the resources it needs to underpin a massive expansion in its nuclear power industry. Chinese officials this week announced they would start building five extra power plants this year on top of the 24 already under construction and 11 already in operation. Chinese analysts say the country’s dearth of uranium is “the tiger in the road” to fulfilling its nuclear power ambitions and that Australia is the most obvious solution (Garnaut, 2009).*

In the short-term, the Chinese economy is still largely tied to coal especially as an increasing number of items demanded by its growing middle class require electricity. What this means is an unprecedented rate of coal-fired power plant construction in China, which the New York Times estimates place near to one plant per month, adding that, “China now uses more coal than the United States, Europe and Japan combined (Bradsher, May 10, 2009).” In fact, China’s consumption is 25 percent larger than the mentioned regions.

Coal is not the only resource that is being used in large quantities to power Chinese growth. Thomas Friedman recounts the Three Gorges Dam project in China that increased the scrap iron demand so much that exports to China surged globally and resulted in some strange thefts of such things such as manhole covers, with several cases resulting in injuries due to pedestrians falling into the exposed manhole (2008). The number of resources needed to continue the rate of China’s growth and the shortages/supply strain that will result can only increase given current trends.

<table>
<thead>
<tr>
<th>Coal by Country:</th>
<th>Imports</th>
<th>Production</th>
<th>Exports</th>
<th>Consumption</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0</td>
<td>59.257</td>
<td>4,627.030</td>
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<td>0</td>
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<td>446.627</td>
<td>15.589</td>
<td>1,689.652</td>
</tr>
<tr>
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<td>8,203.105</td>
<td>33.571</td>
<td>9,425.496</td>
</tr>
<tr>
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<td>3,355.581</td>
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<td>23,789.510</td>
<td>1,303.749</td>
<td>22,507.970</td>
</tr>
<tr>
<td>Mainland China (PRC)</td>
<td>793.958</td>
<td>52,803.472</td>
<td>1,702.600</td>
<td>52,031.825</td>
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<tr>
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<td>1.852</td>
<td>6.349</td>
<td>668.063</td>
</tr>
<tr>
<td>Russia</td>
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<td>6,143.047</td>
<td>2,181.760</td>
<td>4,554.692</td>
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<tr>
<td>Canada</td>
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<tr>
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<td>31.561</td>
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</tr>
<tr>
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<td>23.156</td>
<td>592.082</td>
</tr>
<tr>
<td>Netherlands</td>
<td>462.136</td>
<td>0</td>
<td>133.218</td>
<td>314.487</td>
</tr>
</tbody>
</table>

Table 6 - Coal Market by Top Importers
Source: IEA

80
Returning to coal, it is interesting to consider how much of the resource the country has in terms of domestic reserves. Returning to the diagram in the US case study, where Figure 21 places China as holding the second largest coal reserves in the world after the US, it was important to note how the PRC only has a predicted 55 years maximum for its coal reserves at the current consumption rate (IEA, 2008). Even if the two major exporters of coal to China, Australia and Indonesia, contributed all of their recoverable reserves as of 2005 and China capped coal consumption at 2006 rates, the state’s coal supply should not be expect to last more than 95 years. On the contrary, the projections from the IEA show China as doubling its coal-based electricity capacity by 2030 and the new push in 2010 by Volvo and Honda to sell electric cars China will certainly not decrease this demand.

It should be noted that China has made significant strides in terms of improving its emissions intensity and efficiency; however, there are many reasons why the state still hopes to be allowed to function as a developing economy under a new climate treaty. Another driver for China’s current stance on climate change is that the state could hope to use a “developing” status to appear incapable of creating solutions on its own. Because China is still regarded as a developing country in many respects by OECD countries, such a strategy might continue to encourage developed economies to transfer technology to China with agreements like the CDM. Additionally, by keeping its developing status, the international attention due to China’s being known as the largest emitter can draw significant clean investment projects and aid to China that might have gone to other countries otherwise.

Again, it is true that a strong economy is certainly an important factor for maintaining political stability, but the state can see that forgoing a livable environment is just as destabilizing. Regardless of its international posturing, there are social and environmental issues that also are driving China to deploy some solutions domestically at a rate that is faster than foreign actors are able to bring them. Air quality issues and fresh water availability, especially in major cities, are serious concerns in China and the state is working hard to develop and implement solutions for the pollution problem. China not online understands the position the environment holds domestically, it also knows what neglecting it does for the global perception of the state and as such the leaders want to demonstrate that the state is making strides to meet this challenge.

China is interested in exploring the CCGS route, but the commitment to gaining a strong position in this market has not arrived at the same extent in China to which it has in the US or even France and the EU. The state has begun to deploy some CCS related projects but some actions are more superficial, such as the demo capture projects (to be detailed) in Beijing and Shanghai led by the Huaneng Group for the Beijing Olympics in 2008 and the Shanghai Expo in 2010 respectively. These are arguably more in response to the image issue, rather than a strong desire to scale-up CCS. However, China has adopted CCS into its current Five Year Plan and several other policy agendas and there are several CCS projects underway across the country, mostly involving the enhanced oil recovery.

The potential for CO₂ -EOR to increase China’s domestic production are significant and the desire to pursue CCS as a strategic move for the state is clearer with these efforts. Many projects exist to begin exploring the benefits of CO₂- aided oil production as will be detailed in the following sections. Another driver is the international concern relating to China’s deployment of coal gasification and coal to liquids (CTL) infrastructure, which are significantly more carbon intensive than more traditional coal power production and threaten to significantly increase the rate of increase in China’s emissions trajectory.
With respect to the environmental implications from CCGS development, systems that capture CO$_2$ from flue gases necessarily imply a more efficient and cleaner operation for the industrial process concerned and so this offers an incentive to develop CCS technology regardless of any climate agreement. In this way the technology corresponds well to China’s “circular economy” i.e. industrial ecology based policy to close the loop by increasing the overall efficiency of its production systems. Increasing the efficiency of its plants while decreasing the overall emissions, including not only CO$_2$ but also sulfur, NO$_x$, and mercury emissions that are causing so many of the countries environmental problems, can only prove to be a win-win situation for China. First, the country would benefit economically from the needed technology transfer of countries hoping to deploy their capture technologies as CCGS moves towards scale globally and also from beginning to design its own solutions that it could then market to other countries adopting the solution. Second, the environmental benefits of becoming a truly green and efficient economy should stand on their own merit: a quick trip to China and then Western Europe to compare the environmental quality differences and the effects this must have on someone needing to live there should make this clear.

The Players
One interesting situation is that China is becoming increasingly dependent on imported petroleum and as such the state is pursuing an extensive coal to liquids (CTL) development program. These liquefaction plants produce petroleum-like fuels and will supplement the waning supply of national oil. These plants essentially capture the CO$_2$ as part of the process in that the resulting flue steam is very pure and as such they offer low-cost opportunities for capture. Likewise, CO$_2$ -EOR in China is viewed as an early opportunity to demonstrate CCGS. These types of projects have been identified as targets for foreign-Chinese cooperation on CCGS due to the economics possible in China and the ability of the government to move quickly with few non-addressable regulatory hurdles (Light, 2009). However, China also stands to benefit from developing its experience with CCGS if it applies capture technologies to these CTL plants and deploys CO$_2$ -EOR. Once the experience has been gained from China-based projects, Chinese companies involved with these early projects would be highly competitive in the CCGS market as they will probably be able to underbid many of their competitors.

The situation of simply China waiting for technology to be given to the state by foreign actors via a CDM-style agreement does not paint an entirely accurate picture. Clean-technology development is strategic and difficult to do entirely in the lab and as such in order to develop its own solutions China will have to act quickly to deploy pilot projects of its own. In fact, the country is pursuing CCS independently in many cases without foreign company involvement. Many foreign companies, like Schlumberger and Shell, have recognized this and are pushing to be allowed to participate in these “Chinese-only” projects, but their success remains to be seen (Loizzo, 2009).

China began to explore EOR using untreated flue-gases and then purer CO$_2$ in the late 1990s. As a result of the growing international pressure and interest in China addressing climate change, the amount of project activity in this area is increasing rapidly, with a variety of national and foreign actors becoming involved. This section will give an overview of the major Chinese actors in this sector, the foreign actors and resulting international partnerships, and the project activities across the state. PetroChina is the international wing of CNPC, one of four state petroleum companies. The company is pursuing a variety of EOR projects in the northeastern oilfields of China using CO$_2$ . As a result of this activity, the company has been sought out by
several of the international partnerships as an early stage potential user/storage operator for currently capture-focused CCGS projects. The **Huaneng** Group is the state’s largest utility company and was founded in 1985. It created Huaneng International Power as a public entity listed on the Hong Kong, Shanghai, and New York stock exchanges in 1998. The company is the most active in developing clean-coal technology in the country, with two demonstration projects, and is the leading member of the GreenGen consortium to develop a CCGS-equipped IGCC plant. The **Shenhua** Group, formed in 1995, is the largest coal producer in China and is a vertically integrated energy company in that it operates the coal supply chain from the mine, to the transport, and all the way to the end sale to the purchaser. The company is looking to expand internationally with investments in coal in Australia, Indonesia, and (Outer) Mongolia (McGregor, 2007). They are developing a large coal-to-liquids sector across China and for these projects it is looking for international partners for possibly capturing and storing the emissions.

**The Projects**

Due to the economic benefit possible by using CO₂ for EOR, this type of project is the primary cause for Chinese engagement in CO₂ storage at the present time. The following projects outline what activities are currently taking place or are planned in this area. According to a report from the China University of Petroleum, CO₂ injection technology has been applied as an EOR technique only recently due to the lack of readily available CO₂. Today some discoveries of natural CO₂ sources have been made in recent years, found in the Jiangsu, Shengli and Jilin oilfields. Most oilfields in east China are entering the “late-life production” stage and as a result they require EOR in order to maintain production rates making CO₂ EOR increasingly attractive. “CO₂ injection technology has been studied in China since the late 1980’s, and pilot tests were conducted in the eastern Sanan of Daqing oilfield, Jiangsu oilfield and Xinli 288 area of Jilin oilfield[3-5] and satisfactory results were obtained. Unfortunately, there has been little study of injection CO₂ for heavy oil reservoirs in China so far, especially for reservoirs at their late stage of cyclic steam stimulation (Luo, 2005).” The **Shengli** Oil Field is the second largest in China and is located in the Yellow River Delta and produces approximately 500,000 barrels of oil per day. According to Canadian Geographic, pilot testing using CO₂ EOR began in 1998, implemented using both polymer flooding and steam and gas injection (Canadian Geographic, 2008). The **Liaohe** Oil Field, an EOR pilot project to recovery heavy oil located in the Bohai Sea near Liaoning, has undergone several phases of testing since 1998 (Canadian Geographic, 2008). The project employs “combustion EOR” which injects steam and boiler flue gasses, containing 12 to 13 percent CO₂, into the reservoir to increase production (Luo, 2005). Liaohe is the third largest oil field in China and comprises six percent of the national oil supply. The project is operated by Liaohe Petroleum and Huafu High-Tech with possible involvement from Panjin Liaohe Oilfield Tianyi Petroleum Equipment Company and CNOOC/COSL.

China has taken two international events, the 2008 Olympics and the 2010 World Expo, and recognized them as venues for showcasing their efforts on many aspects of clean technology, including CCS. Huaneng began to engage in CO₂ capture with Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) just before the 2008 Olympics that were held in Beijing. They built a demonstration plant that captured and sold CO₂ for commercial purposes, namely for carbonated drinks. The demo employs a post-combustion capture retrofit at the **Huaneng-Beijing Gaobeidian** 845 MW co-generation power plant and it captures up to 3000 tons of CO₂ per year. Expanding from the Beijing pilot plant, Huaneng has expanded to a larger Shanghai demonstration project for the Expo. “The world’s largest carbon capture project launched by a coal-fired power plant broke ground in July in Shanghai. After completion, which
is scheduled before the end of this year, the project will capture as many as 100,000 tons of carbon dioxide annually (Ying, 2009).” The location for the project is on the outskirts of the city at the Shanghai Shidonkou Second Power Plant, a subsidiary of Huaneng. In terms of the possible end-uses for the captured CO₂, in the short-term it is expect to be disposed of locally via commercial gas sales to food production and industrial companies, with a possibility open that the excess emissions could eventually be piped for offshore EOR.

Although the international involvement in China is extensive, the state is engaged in several CCGS related programs that do not involve a good deal of international involvement. The following two projects give some examples of China’s independent actions, but there is a good possibility that there are efforts taking place for developing this technology that are beyond the seight of the global public. Shenhua Group, as already mentioned, is moving quickly to deploy a significant number of CTL plants as are shown in Figure 33, which is only a small part of the development in this sector in China. Coal to liquids is recognized as a major CO₂ emissions point source and the technology is listed by WRI as a negative wedge in terms of GHG mitigation, meaning that it will potentially require an additional wedge worth of mitigation efforts if deployed globally at a significant scale. Shenhua recognizes this issue to some extent and is developing partnerships with many foreign companies like Shell, Sasol, and GE so as to develop capture and storage options for its plants. However, the group has also acted on its own in developing a demonstration project in Erdos, Inner Mongolia, which appears to use a Rectisol coal conversion process adapted from American, German, and Japanese processes. Plants such as this plant capture the CO₂ as part of the process and emit practically pure stream of the gas. The plant is already in operation but the storage demonstration is hoped to come on line before 2011, with 100,000 tons being stored in the Erdos Basin in saline reservoirs and possibly being used for EOR. If the storage is successful at the pilot level, the project should expand to store 3.9 Mt per year.

The GreenGen group is a corporation formed from a national partnership, headed by the Huaneng Group (with 51 percent ownership), the other four state power companies, and with Shenhua and China Coal holding the remaining shares. Peabody Coal applied to join the corporation and was only recently approved as the sole non-Chinese partner. The goal of the corporation is to build an IGCC plant at a demo scale of 250 MW by 2011 in Tianjin, with this expanding to 650 MW using capture by 2013 and storing the emissions via EOR in the Dangang or Shengli fields by 2015. Saline reservoir-based storage will be investigated for the long-term (GreenGen Co., 2006).

Just as China has a vested interest in pursuing CCGS on its own, foreign interests have identified the Chinese market as an ideal stage for initial CCGS projects due to the low costs of materials,
labor, and a variety of other factors. There is also less of an issue with public acceptance of projects. As a result there are two kinds of international cooperation efforts that are visible in China. The first kind is represented by a variety of consortiums, which work to support the deployment of CCS and can be seen as alliances between China and either singular states or groups, e.g. the European Union. The second type is a more direct agreement between companies in an effort to transfer technology to China in a mutually beneficial relationship.

The following groups have been identified from among many that can be found to exist today and are estimated to be the most important broad arrangements between state-level interests in the field of CCGS in China (Zhang, 2009). COACH is an EU funded effort that is led by the IFP and dominated by French and British corporate actors. It is comprised of a wide range of Chinese and European institutions but the key players are oil and gas based: Schlumberger, Alstom, Air Liquide, BP, Shell and Statoil with one smaller Argentinean chemicals company involved called Atanor. The other organizations are mostly national geological or petroleum survey groups from Europe and then Tsinghua University, a top engineering and management school in Beijing, heads of the list of Chinese organizations (COACH, 2007). The main goal appears to be to developing technology transfer by setting up a variety of memorandums of understanding (MOUs) and this project was set to end December 2009.

Japan, as one of the early movers in CCGS project demonstration, has approached China to perform CCS based EOR in the Northeast province of Heilongjiang near Daqing oil field as part of a Japan-China development cooperation agreement. The two countries signed an agreement in May of 2008 that aims to store 3 to 4 Mt to CO₂ from two post-combustion capture based 600 MW power plants for EOR in a major oilfield nearby. The Japanese industrial partners are led by Japan’s Ministry of Economy, Trade and Industry (METI), include: JGC Corporation (a supplier for the In Salah project), Japan Coal Energy Center, Toyota Motors, and Mitsubishi Heavy Industries (MHI) who are working with CNPC/PetroChina and the local Daqing Oil Field Company, the Harbin Utilities Company, and the Huadian Corporation that is another of the top five state electricity companies. It is estimated that this project will cost 300 million USD.

The Near Zero Emissions Coal for China (NZEC) project is originally a UK-China partnership and remains that way for the first phase of the project, which is designed to explore the possibilities and options open for demonstrating CCGS in China and increasing the overall CCGS capacity. The second and third phases of this project are to be taken on by the European Commission, expanding the scope of this partnership to EU-China collaboration. Phase II will work to develop specifically identified capture and storage options in a lead-up to Phase II that will be a demonstration plant, probably near the Songliao or Subei basins for EOR and eventually saline-based storage. Songliao is already home to two EOR projects at the Jilin and Daqing oilfields but the Yangzhou oilfield in Subei is also a possibility, which is why the project end location is not decided yet. This final phase is hoped to begin in 2014.

In addition to the FutureGen project, which involves Chinese participation in the US, the US has engaged in several US-China partnership efforts to expand CCS in China. First of all, the US State Department has supported WRI to create CCS guidelines similar to those completed for the US and WRI has established an office in Beijing to go about this task and to become more involved with CCS there in general. Secondly, a group of research partners including the U.S./China Energy and Environmental Technology Center, Tsinghua University, the Institute of Rock and Soil Mechanics of the Chinese Academy of Sciences, Leonardo Technologies, the Battelle managed Pacific Northwest National Laboratory (PNNL), and Montana State University, have worked to
identify regional opportunities for CCGS in China. This larger effort is led by the Ministry of Science and Technology of the People's Republic of China (MOST) and the US DOE.

In addition to the broad international collaborations, the second type of international cooperation effort is comprised of several industry level agreements or MOUs between foreign and Chinese actors. This type of agreement has also been shown to be a strong method for ensuring protection of patented technologies by having the Chinese actors gain a vested interest in protecting their exclusive right to the technology and defend this right on the state level.

As mentioned previously, many MOUs involve the Chinese coal giant Shenhua, who has signed agreements with Shell, DOW, GE, and Sasol in regards to several of its CTL projects and many of these companies are already speaking to the issue of CCS for the plant they are involved with across the state (Sun, 2008). EEStech was formed in Delaware in the US in 2000 as a sustainable and environmental technology patent acquisition company. As such it has acquired a technology for carbon management and storage and is working to apply this technology in Asia. The company has signed an agreement with Dagang Huashi Power Generation Company to build a capture/compression addition onto a 330 MW Dagang plant in Tianjin and transport the emissions for EOR in the Dagang oilfield and/or storage (Zhang, 2009).

**Figure 34 - China’s CCGS Activities**

Greatpoint Energy has rapidly expanded its base in the US with and now has moved to try and develop a plant in Southeast China with Datang Power, another of the top five state producers.
One of the main benefits of the “bluegas” hydro-methanization technology is that the CO₂ is left pure at the end of the process and ready for storage so it makes sense that any operation employing the technology will seek to store its emissions using CCGS. The demonstration plant in China was expected to come online within the next three years; however, the plant would have cost between $100 million and $200 million and this was found to be too exorbitant and the project was scrapped. It was going to be located at a coal-fired power plant operated by Datang Huanyin Electric Power and would have been designed to convert 1,500 tons of coal a day into natural gas, according to the CEO of Greatpoint (La Monica, 2009).

This case study has hopefully brought several issues to light about China’s position with regards to climate change and its stance on the CCGS roll-out as a result. To sum up from the last few sections, the map in Figure 56 gives the approximate location of the CCGS projects in China identified within this report. As was stated earlier, there are a probably a good number of projects that the state is pursuing out of the media’s focus to maintain a strategic position on this emerging market, especially in the area of technology development if not true demonstration and deployment.

China has claimed that the finances do not exist for funding a major CCGS scale-up on its own. However, the state is in a position, if it decides to give priority to the technology, to become a serious leader in the global CCGS market. The biggest potential for China’s industrials would be in developing the technologies needed to build the CCS chain. One reason for this potential is because the most significant expansion in the Chinese exports can be seen in capital goods, as a change from a consumption goods based export market 15 years ago as seen in Figure 35, which along with parts and components has grown to represent 50 percent of their export market versus less than 20 percent in the early 1990s. However, as the Chinese market does not appear to have a significant service sector, or at least not one as developed as those found in developed countries the storage market potentially remains fairly unpopulated by Chinese firms. The advantages lie in that the financial, legal, regulatory, and public acceptance issues will not be as severe in China making a roll-out of full scale CCGS there much more feasible on the storage side of things. Nevertheless, there are other issues that exist in terms of the political system in terms of cooperation between regional and local governments and the central government in Beijing that could prove as stumbling blocks to the otherwise relatively unimpeded possibilities for exploring and demonstrating storage possibilities at a commercial scale in China.
What should be clear is that even though the Chinese are resisting a public international commitment to reducing emissions and as such as promising only to achieve what is feasible within the scope of what they intend on doing anyway development wise. However, as they are aware of the implications of being cut out of the export market by a price on carbon that could drastically affect the competitively of their products and also of their potentially strong position as a capital goods supplier in the emerging CCGS roll-out, they will not completely disregard the climate change and CCGS issues. What seems more likely is that they will delay for as long as possible any formal signature to an international commitment while they also pursue emissions reductions employing many technologies, including many types of CCS, CCGS, and especially carbon capture, use, and storage (CCUS), at their own pace. Based on this situation, it can be argued that the pace China will engage in this task, as can be seen in just about anything China engages in, will be significantly faster than would be achieved elsewhere and certainly faster than the rest of the world thinks is possible.

If a policy is adopted that charges a tax on emissions embodied in goods, imports coming from China will probably need to have their carbon accounted for and appropriately taxed. This could be similar to the REACH Regulation on Chemicals that was recently adopted by the EU. As a result of the regulation, foreign chemical producers in countries like the US and China that do not have as strict regulations regarding chemicals must comply if they wish to sell on the European market based on a “no-data-no-market” principle. With regard to CO₂ emissions, if China does commit to the decreases decided upon at Copenhagen and the US and EU do, China’s emissions associated with the production of exported goods could place these products at a disadvantage compared to goods produced in EU and US that will potentially embody fewer emissions in this case.
Final Case Comparison and Conclusion

In light of the climate situation, the economic implications of decreasing carbon emissions, and the overall status (technologically and economically) of the various solutions available today for addressing that situation, CCGS should play a significant role as a means of achieving a long-term solution. However, the technology is not a solution in and of itself, and in most cases will have a limited life expectancy – approximately the same as the life of the first generation of commercial plants. In reference to the estimation by the IEA, the construction of 3,400 CCGS projects globally will be the end of development for CCGS except in unique cases of steel, cement, petrochemical, and chemical production that may continue to require GHG emissions control systems as necessary feedstocks for many products.

Adding a price to CO₂, with a direct carbon tax or an economy-wide cap-and-trade system alike, is essentially taxing GHG emissions. No matter how it is implemented, any argument that takes into account the social implications of such a fee must do so on a social basis, not a state-basis. If the entire world wishes to join a climate treaty that essentially establishes an enforcement power, higher than any state government, that can regulate GHGs; only at that point could the global population be divided along the lines of rich/carbon-intensive versus poor/low-carbon individuals. Under such a system, brackets could be drawn for individual carbon intensity profiles to place the greatest responsibility on the upper brackets that would be designed to contain the richest people with the highest emissions. However, as the current national governments would never agree to such a loss of power, climate regulation policies must be developed at the state level and as such state emissions must be considered in their totality and not in terms of any per capita argument.

In line with this fundamental political reality, another interesting argument could be to examine state emissions not by how much that state produces, but instead by how much of emissions are embodied in the products that are consumed within its borders. For instance, when one ton of steel is produced and it generates one ton of CO₂ as a result, it is the eventual buyer of that steel that is responsible for those carbon emissions and not the steel plant in China. Calculating China’s emissions, “On a consumption rather than a production basis both lowers its responsibility for carbon-dioxide (CO₂) emissions in 2006 from 5,500 to 3,840 Mt CO₂ and reduces the growth rate of emissions from an average of 12.5 [percent per year] to 8.7 [percent per year] between 2001 and 2006 (Pan J., 2008).” This means that 30 percent of China’s CO₂ emissions and 4 percent of the resulting growth rate for these emissions are embodied in its exports.

To not consider emissions in this way creates significant problems that can be seen today throughout the global economy and are referred to as carbon leakage. With no global treaty regulating emissions, the strong desire in most developed countries to go green coupled with a need to do so as economically as possible, together are driving a significant shift in production to developing countries. The industries of developed countries already are forced to compete with the low wages and artificially low currency of China. Increased pressure for companies to produce their products more cleanly and with less GHG emissions serves to underscore the existing difficulty they face by operating in a country with stricter environmental controls, higher wage and working standards, and higher exchange rates. Although countries with large amounts of carbon-free energy production capacity (like France - with its large nuclear fleet and just over six tons of CO₂ per capita) appear to lead in the green energy movement, it is the countries who do not really embody such desires to go green (like China) or with small industrial sectors (like
Switzerland - with its dominant banking sector powered by hydroelectricity) who benefit the most. While China gains from the industries that give up on achieving the higher standards in their home country and move their production centers to within its borders, Switzerland has little industry to lose and gains by financing the moves. France is actually at the greatest disadvantage because it is constrained by a European emissions regulation and has a sizable industrial sector while the US remains in limbo, caught between the European example of how to run a green economy regardless of the cost and the Chinese example of how to maintain consistent GDP growth regardless of the environmental consequences. The risk is that in the end developing countries will be powered by green energy technology all made in China and while the EU and the US suffer from unemployment and budget deficits and China suffers from severe environmental degradation and social inequality, the whole world will have achieved nothing with respect to lowering GHG emissions.

Assigning the onus of emissions to the countries where the products that embody those emissions are consumed significantly alters the picture. According to a Stanford study, if one looks at emissions on a consumption basis the numbers shift slightly. While the emissions for the US is responsible increases by 13 percent and China’s decrease by roughly one third, France’s emissions increase by nearly 50 percent and Switzerland’s emissions more than double. Despite the potential attractiveness of this kind of accounting, it creates massive carbon crediting problems in terms of assigning a price to carbon because it relies on life cycle analysis to calculate not only what a product’s carbon is but also to determine from which country these emissions were added to the products overall embodied carbon. Moreover, the fact still potentially ends with a drastic shift away from buying the now expensive, carbon-intensive, products from China no matter whether a carbon tax is placed on products at the production end or the consumption end. These various means of describing who is to blame for the climate issue in the end need to decide if it is a global priority to cap emissions and stabilize the GHG concentrations in the atmosphere. Once this can be agreed to, the responsibility of each nation must comply with the overall cap agreed upon will no longer be a moral argument but one based on economics and a commitment to global wellbeing.

It should be noted as well that CCGS is not only a climate change mitigation-based solution and that the technology serves as a market mechanism for moving towards a new energy system; one no longer based on fossil fuels. As these resources are becoming increasingly scarce (in terms of long-term resource management) it is apparent that policies and financial incentives need to be put in place that not only encourage the development and deployment of new energy production methods but also the discouragement of inefficient and polluting technologies that currently make up most of the 88 percent of the global energy production relying on fossil fuels.

With respect to the cost of the technology itself, the technological costs are quickly moving down the curve for capture technologies. At the same time however, the costs of transport and storage are becoming less and less certain as projects encounter legal, regulatory, and public acceptance issues. One issue that has become prominent is that it is not sufficient for projects to simply be “capture ready”. A “capture ready” project with no feasible transport or storage options is a waste of time and capital. Rather, projects that first assess a region/locality in need of CCGS should, given the industrial/emissions make-up of that area, pursue from the start a geological assessment to determine storage options. Once this is completed, the region should
be examined using an industrial ecology-based approach to determine the most cost effective means for treating and storing the CO₂.

In terms of the three countries examined in this report, the situation becomes more complex in terms of when and why a CCGS roll-out will be realized by each country. For the US, it is in the best position with respect to getting a return on an investment in CCGS-coupled energy production because it has the largest coal reserves, both in terms of quantity and anticipated longevity. The technology will therefore serve as a key aspect in the decision making process for how the state will engage in a global climate treaty. Despite the lack of any federal level limitations on emissions, the US has engaged rapidly in developing CCGS projects across the country, assisted by the surge in federal funding facilitated by the economic recovery package and the DOE. Most of these projects are related to enhanced oil recovery (EOR), but there are still a significant amount of them that are pursuing storage purely for mitigation reasons.

For France CCGS has merits in certain cases, such as for the carbon intensive port of Le Havre due to the large amount of fossil fuel use and processing based there. However, the country does not have any apparent desire to re-embrace carbon intensive energy technologies due to the implications this would have for its energy independence. Therefore, the basis for significant CCGS development work by multinational corporations headquartered in France, is with the goal of applying the technology either to their operations abroad or to sell services relating to the technology to projects elsewhere, especially in the US and in China but also potentially in India and South America, which are also anticipated to become major targets for commercial CCGS deployment.

China is the most complicated case in terms of CCGS in that the state is somewhere in between a developing and developed nation at the moment. As such the Chinese government recognizes the technology as a means to encourage support from developed nation in terms of technology transfer and project development. However, the state also appears to recognize the strategic implications of CCGS technology along with green technology in general globally and sees a need to develop its own competence in this area so as to remain competitive in the rapidly developing markets that service this expanding sector. Furthermore, with only a limited amount of coal reserves given the expansion of China’s consumption of this resource, which is estimated to leave the country with 50 years or less of its national supply, a solution is needed to facilitate a change to a new energy source and as a result China has strong ambitions in the area of nuclear and renewable technology development. In light of this limit on China’s coal, CCGS should be seen much more as a bridge technology than a solution for energy, as opposed to in the US where the coal reserves are more substantial.

Ultimately, after the legal and acceptance issues are addressed for the global rollout of CCGS, the main concern will be resource and energy consumption by building the 3,400 projects implied by the CCS wedge. Substantial work needs to be done in terms of the life cycle of CCGS projects. Given past experience with technology scale-ups and major projects, it should be anticipated that resources like steel, cement, coal, technical supplies like wire and valves, and manpower will be affected in terms of availability and price. However, this will not serve to decrease CCGS technology’s competitively relative to other core base-load energy supply technologies as they will all imply roughly equal amounts of these key resources to build. Returning to the IEA Blue Map scenario, an increase in prices for these resources would merely decrease the amount of the global solutions based on new construction as opposed to efficiency. Currently the IEA predicts that 46 percent of the solution lies in new construction
with 19 percent of that coming from CCS. However, it resources become more expensive this amount will decrease and efficiency gains will be discovered, not only due to the financial incentives that are in place from a global climate agreement, but also from the high costs of materials.

Therefore, the final assessment for CCGS is that it will need to be deployed. The scale of this deployment cannot be known at this point but evidence suggests that it will be less than the IEA estimate implies. This nevertheless implies a significant outlay of capital for the projects that will be built, which will be numerous even if it is not exactly 3,400 as suggested by the IEA.
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## Appendix I: Global EOR Projects from Oil and Gas Journal (2008)

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## Appendix II: Global Projects from GCCSI List (Nov 2009)

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