Manufacturing Climate Solutions

Carbon-Reducing Technologies and U.S. Jobs

CHAPTER 8

Carbon Capture and Storage: A Post-Combustion Capture Technology

by

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Summary

Approximately 86% of all stationary sources of carbon dioxide (CO_2) emissions in North America come from electricity generation (National Energy Technology Laboratory, 2007) and U.S. coal-fired power plants account for more than 75% those emissions (Soren Anderson & Newell, 2004). If the United States intends to meet its expressed goals of reducing greenhouse gas emissions 80% by 2050, it will have to get serious about controlling CO_2 emissions from coal-fired power plants and other heavy CO_2 emitters. Carbon capture and storage would enable the United States to reduce the release of CO_2 into the atmosphere on the scale required to meet those goals.

Carbon dioxide capture and storage, or sequestration, is the process of extracting CO_2 from a combustion process and storing it in geological formations for very long periods. The process of CO_2 capture can be done in a variety of ways, including pre-combustion, oxy-fuel, and post-combustion processes. This report will focus on one promising post-combustion process that captures CO_2 from flue gas emissions and can be retrofitted to existing coal-fired power plants. After providing background information on CO_2 emissions from coal-fired energy production in the U.S. and briefly reviewing available carbon capture technologies, the report focuses on the chilled ammonia process being developed by Alstom Power. It presents the value chain of the chilled ammonia process, illustrating the U.S. job potential of this technology in research and development, manufacturing, construction, transportation and maintenance and monitoring jobs.

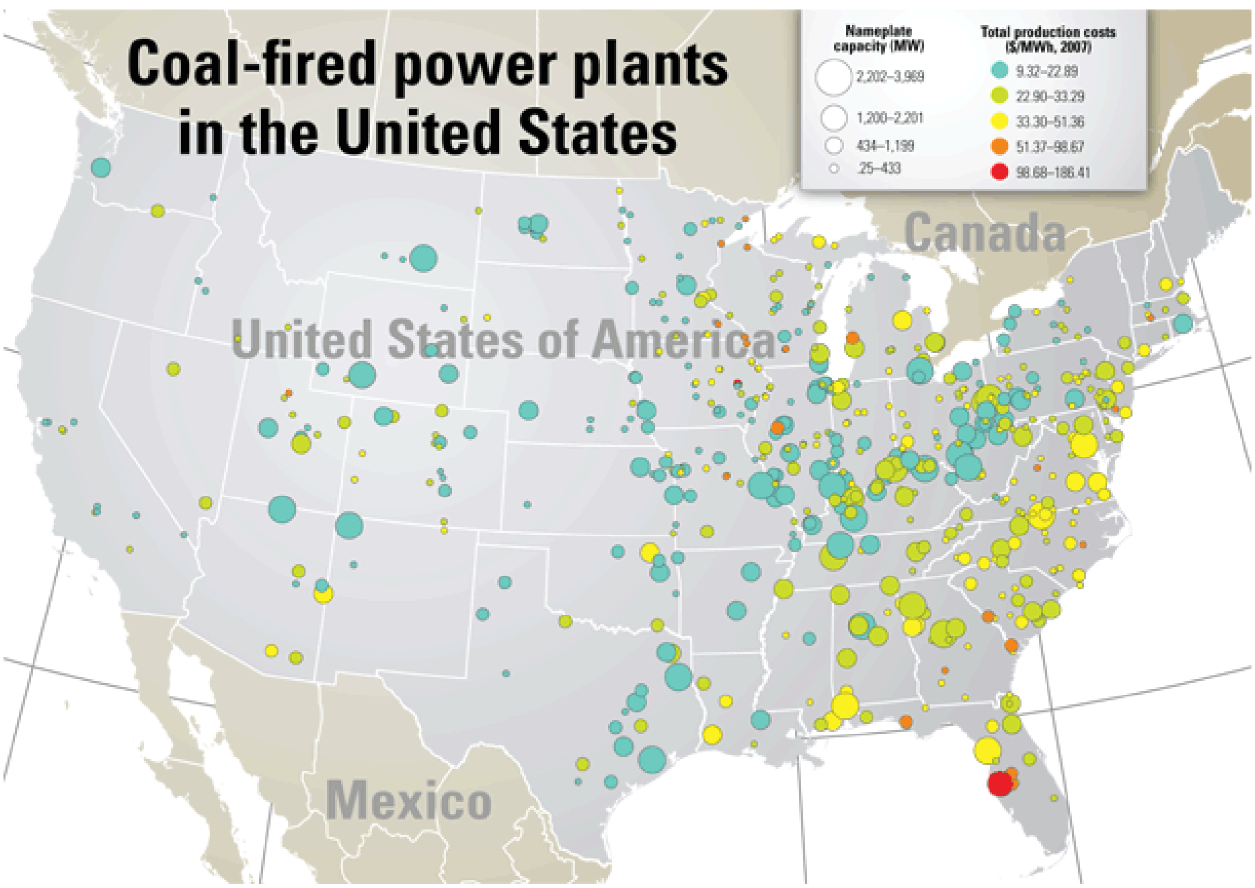
Background

The greatest U.S. source of carbon dioxide emissions is power generation. According to the U.S. Environmental Protection Agency (EPA), in 2007 fuel combustion for electricity generation accounted for 39% of total CO_2 emissions in the United States (U.S. Environmental Protection Agency, 2009). The second largest sources of CO_2 from fossil fuel combustion were transportation (31%) and industrial uses (14%). Power plants used for electricity generation account for 86% of all stationary sources of CO_2 (National Energy Technology Laboratory, 2007). Large, stationary sources of CO_2 are prime candidates for CO_2 capture and storage technologies (Soren Anderson & Newell, 2004) because the capture systems themselves are extremely large and complex. In addition to power plants, other likely applications of CO_2 capture technologies include energy-intensive industries such as iron, steel, and cement production and natural gas systems. These industries produce more concentrated CO_2 streams than utilities and other industrial processes, thus reducing the per ton costs of capture for these applications (Soren Anderson & Newell, 2004; U.S. Environmental Protection Agency, 2009).

In 1999 U.S. coal-fired power plants accounted for more than 75% of CO_2 emissions from power generation facilities (Soren Anderson & Newell, 2004). Coal-fired power plants produced almost half of all U.S. electricity generation, or 2 billion megawatt hours (MW hours) (Energy Information Administration, 2007a, 2007b) and generate twice as much CO_2 as gas combined cycle power plants (Gray, 2008). In 2007, there were 1,470 U.S. coal fired-power plants which emitted over 1.5 billion tons of CO_2 into the atmosphere (Deutch et al., 2007; Energy Information Administration, 2007b).

Coal-fired power plants are the most common source of power generation in the United States. Map 1 illustrates the locations of U.S. coal-fired power plants by size and power production costs. U.S. electricity demands are expected to increase to more than 4.6 billion MW hours by 2025 (Energy Information Administration, 2009). Coal will continue to be used for power generation well into the future. In fact, 30% of the U.S. electricity production increase is expected to be produced from new coal-fired power plants (Bohm, Herzog, Parsons, & Sekar, 2007). Thus, investing in ways to deal with the CO_2 emissions from these facilities is an important part of national CO_2 reduction strategies. Post-combustion capture technologies offer the potential to extract CO_2 from the flue gases of existing power plants. Due to the greater CO_2 emissions of coal-fired power plants, they are the most likely early adopters of CO_2 capture technologies.

Map 1: U. S. Coal-Fired Power Plants



Source: (Power Magazine, 2008)

The U.S. federal government recognizes the need for carbon capture and storage systems to curb CO_2 emissions. For many years it has supported research and development around this topic through the National Energy Technology Laboratory (NETL). In 2009 NETL's budget for post-combustion CO_2 capture research is $40 million (Parkinson, 2008). Furthermore, the stimulus package passed in January 2009 included $3.5 billion for the Fossil Energy Research and Development Program, which includes funding for carbon capture and storage research (St. John, 2009). This funding will assist with developing new capture technologies and supporting demonstration projects to ensure the feasibility of new technologies.

Carbon Capture Technologies

Carbon dioxide capture and storage (henceforth, carbon capture and storage) technologies would enable the continued use of fossil fuel combustion for power generation and industry use while limiting the release of CO_2 into the atmosphere. There are three general processes for CO_2 capture: pre-combustion, post-combustion, and oxy-fuel capture. These processes separate and condense CO_2 so that it can be transferred in supercritical form to a long-term storage location.

Pre-combustion capture removes CO_2 from the fossil fuel before it is burned for power. This technology is most likely to be applied to integrated coal gasification combined cycle power plants, of which there are only two in the United States (Ciferno, 2009). Therefore, it offers little opportunity to impact CO_2 emissions from existing coal-fired power plants. Oxy-fuel combustion is a process of burning fossil fuel in oxygen resulting in a flue gas largely made of CO_2 and water that requires less energy to separate (H. Herzog & Golomb, 2004). This process is still in development and offers the potential to retrofit existing coal-fired power plants.

Post-combustion technologies capture CO_2 from the flue gas released after fuel combustion by using a chemical solvent to bond the CO_2 gas with a liquid (H. Herzog & Golomb, 2004; Rubin, 2008). Some post-combustion technologies are used with industrial plants for commercial purposes, such as urea production or food-processing (Soren Anderson & Newell, 2004; Mitsubishi Heavy Industries, 2005). All the commercial CO_2 capture plants use a post-combustion capture process based on chemical absorption with a monoethanolamine (MEA) solvent (H. J. Herzog, 2001). However, this process is energy intensive and may be very costly if used to retrofit existing power plants that are much larger than current commercial applications. Thus, a number of alternatives for post-combustion technology are under development to reduce energy input (Anonymous, 2006). Table 1 lists the companies focused on post-combustion CO_2 capture technologies for CO_2 capture and storage applications.

Table 1: Post-Combustion Carbon Capture Technology Developers

Company	Location	Product / Solvent
Aker Clean Carbon	Norway	Just Catch™ Technology (amine solvent); SOLVit™ (amine solvent)
Alstom	Knoxville, TN	Chilled ammonia process; advanced amine solvent (with Dow Corporation)
Babcock & Wilcox	Barberton, Ohio	Regenerable Solvent Absorption Technology
Cansolv Technologies, Inc.	Canada	Cansolv CO_2 capture system (aqueous amine solution)
Commonwealth Scientific and Industrial Research Organization	Australia	Amine solvent
Dong Energy	Denmark	Testing various new solvents (MEA-1, MEA-2, CASTOR-1, CASTOR-2)
E.ON UK	United Kingdom	Amine solvent
Fluor Corporation and E.ON Energie AG	Irving, TX and Germany	Econamine FG+ (monoethanolamine solvent)
Ion Engineering	Boulder, CO	Ionic liquids (molten salts)
Mitsubishi Heavy Industries	Japan	Kansai Mitsubishi Carbon Dioxide Recovery Process (amine solvent)
Powerspan	Portsmouth, NH	ECO_2® (aqueous ammonia solvent)
RTI International	Durham, NC	sodium bicarbonate solvent
RWE npower	UK	Post combustion product
Sargas	Norway	Ultra Low Emissions technology
SIEMENS	Germany	POSTCAP technology (solvent: amino acid salt formulations)
Toshiba	Japan	Amine-based process

Source: CGGC, based on company websites, interviews, and industry sources.

Development of a post-combustion carbon capture market is necessary if the United States hopes to meet its greenhouse gas emission reduction goals. Carbon capture technologies will be used with utility and industrial plants that are large emitters of CO_2. Capture technologies will be largely applied to both existing and new pulverized coal or other boiler power plants (Hilton, 2009a). Initial commercial applications will likely be with smaller plants of approximately 200MW to 300MW power production and, as the market develops, larger power plants of 600MW will offer greater investment opportunities (Ciferno, 2009).

Carbon capture and storage can also be applied to oil and gas power plants, and curbing their CO_2 emissions may be necessary to reach U.S. emissions goals. Other energy-intensive industries with high CO_2 emissions that are likely candidates for carbon capture and storage include the cement industry, aluminum and steel industries, ethanol industry, petroleum refining and pulp and paper industries (Soren Anderson & Newell, 2004; Hilton, 2009a).

Based on conversations with industry representatives, capital costs involved in retrofitting a pulverized coal power plant for carbon capture and storage would be approximately $1.5 billion (Scott Anderson, 2009). Ten U.S. coal-fired plants are anticipated to be retrofitted by 2025. Thus, an estimated value of the carbon capture and storage retrofit market in the United States between now and 2025 is $15 billion.

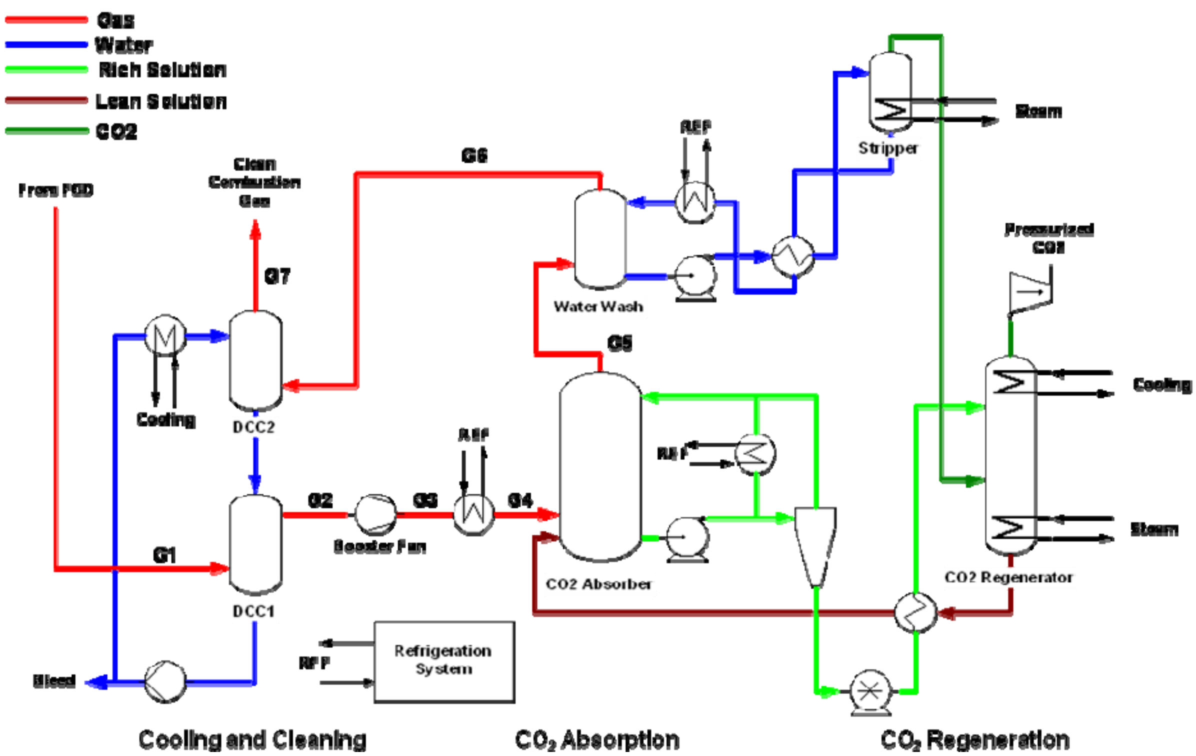
The U.S. market for capture technologies is expected to emerge once legislation related to a cap-and-trade program or a carbon tax is passed. It is unclear which specific technology will emerge as the leading candidate for commercialization and it is possible more than one technology will be adopted. For example, first adopters of CO_2 post-combustion capture technology may adopt an amine system because it is the most extensively developed for a commercial market. However, the high energy costs of the well-established amine capture technologies could prevent extensive market adoption. Many adopters may wait to employ a more efficient and less costly capture technology, and more than one process may be adopted at the same time. U.S. contenders include the Alstom chilled ammonia, Powerspan ECO_2, and RTI sodium bicarbonate processes. We will use the chilled ammonia case to illustrate how value chain analysis can be applied to post-combustion CO_2 capture processes within the carbon capture and storage field.

Chilled Ammonia Process

The chilled ammonia process, engineered by Eli Gal and adopted as a lead technology by Alstom Power, is a promising new post-combustion capture process that is more efficient at isolating CO_2 from flue gas than many existing technologies. In 2009, Alstom will complete its first demonstration of the chilled ammonia process at We Energies' Pleasant Prairie Power plant in Wisconsin. Data indicate the process has the potential to capture 90% of the CO_2 in the flue gas at a lower parasitic load, or energy penalty, than other capture processes (EPRI, 2006). The parasitic load is the amount of the power plant's energy consumed by the CO_2 capture facility and thus it will not be available for use on the grid. Research indicates the chilled ammonia process will be able to run at less than 16% parasitic load (Li & Fan, 2008), which is at the low end of the spectrum of capture technologies that range from 15% to 30% parasitic load. The chilled ammonia process absorbs CO_2 at a low temperature, between 0 and 20°C. The low temperature reduces the equipment size needed for the absorber system and the amount of energy required to reverse the absorption reaction, thus reducing the energy penalty. Furthermore, the ammonia carbonate solution used in the process is a more concentrated CO_2 carrier and the process has the added benefit of lower chemical costs (Ciferno, 2008).

The chilled ammonia process, illustrated in Figure 1, has three major stages: flue gas cooling, CO_2 absorption, and regeneration. In the first stage, the flue gas emitted from the power plant is cooled using a cooling and cleaning subsystem. The flue gas is cooled to between 0 and 10°C through a process of direct contact coolers, cooling towers and chillers. A positive byproduct of the cooling process is that it removes contaminants such as sulfur oxides, particulate matter, and hydrogen chloride from the flue gas before it enters the absorber (Black, 2008; Darde, Thomsen, Well, & Stenby, 2008). Unlike other capture technologies, the chilled ammonia process does not require additional flue gas desulfurization at this stage. Another advantage of the cooling process is that lowering the temperature of the flue gas decreases the vapor pressure and condenses the residual water, thus, reducing the flue gas volume by 30% (Black, 2008; Dailey & Shattuck, 2008; Darde et al., 2008).

Figure 1. Schematic of the Chilled Ammonia Process



Source: (Black, 2009)

The second stage of the chilled ammonia process consists of absorbing CO_2 from the flue gas. The reduced volume of flue gas allows the absorber system equipment in the chilled ammonia process to be much smaller than in other capture technologies (Dailey & Shattuck, 2008). The cold flue gas enters the bottom of the absorber column and flows up in a counter current flow. It reacts with a highly concentrated ammonia carbonate slurry, which increases the CO_2 loading capacity (Black, 2008; Dailey & Shattuck, 2008). Approximately 90% of the CO_2 is captured through this absorption process. The clean flue gas, which mainly contains nitrogen, oxygen and a low concentration of CO_2, then flows through a water wash to absorb any remaining ammonia and is released into the atmosphere. The ammonia is returned to the absorber. The captured CO_2 solution leaves the bottom of the absorber and is pumped to a heat exchanger where it is warmed (Black, 2008; Darde et al., 2008).

The third stage of the chilled ammonia process is the regeneration stage that separates the CO_2 and condenses it for transport to a storage location. The CO_2-rich solution from the absorption process is pumped to a high pressure vessel, or desorber (Black, 2008). At both high temperature and pressure, the CO_2 separates from the solution, resulting in a 99% CO_2 stream. This stream leaves the top of the desorber and runs through a cold wash to remove any remaining ammonia or water (Black, 2008; Darde et al., 2008). The CO_2 liquid is then stored in large tanks and pumped through a pipeline to the final storage destination.

Alstom's demonstration project in Pleasant Prairie, Wisconsin is a "proof of concept" project and will be complete in 2009. The company will begin production of a larger demonstration project at the American Electric Power Mountaineer Plant in New Haven, West Virginia in September 2009. The goal of this project is to optimize power consumption and validate the CO_2 injection and storage process. This demonstration will capture and store approximately 100,000 metric tons of CO_2 annually (Sherrick et al., 2008). Alstom Power is also conducting a chilled ammonia demonstration project on an oil and gas power plant in Sweden and has plans for several other demonstration projects (see Table 2).

Table 2: Alstom Power Chilled Ammonia Process Demonstration Projects

Host Energy Company	**Plant Name, Location**	**Fuel Source**	**Project Size** (tons/year)	**Expected Start Date**
We Energies	Pleasant Prairie Power Plant, Pleasant Prairie, WI	Sub-bituminous coal	15,000	July 2008
E.ON Thermal Power	Karlshamn, Sweden	High sulfur oil	15,000	April 2009
TCM Mongstad	Mongstad, Norway	Gas	80,000	August 2011
American Electric Power	Mountaineer Plant, New Haven, WV	Bituminous coal	100,000	September 2009
American Electric Power	Commercial scale plant, TBD	TBD	1.0 MM	2013
TransAlta	Wabamun, Alberta, Canada	Sub-bituminous coal	1.0 MM	December 2013
Note: An average 500 MW power plant burning a high quality bituminous coal emits roughly 2.5 million tons per year of CO_2.				

Source: (Black, 2009)

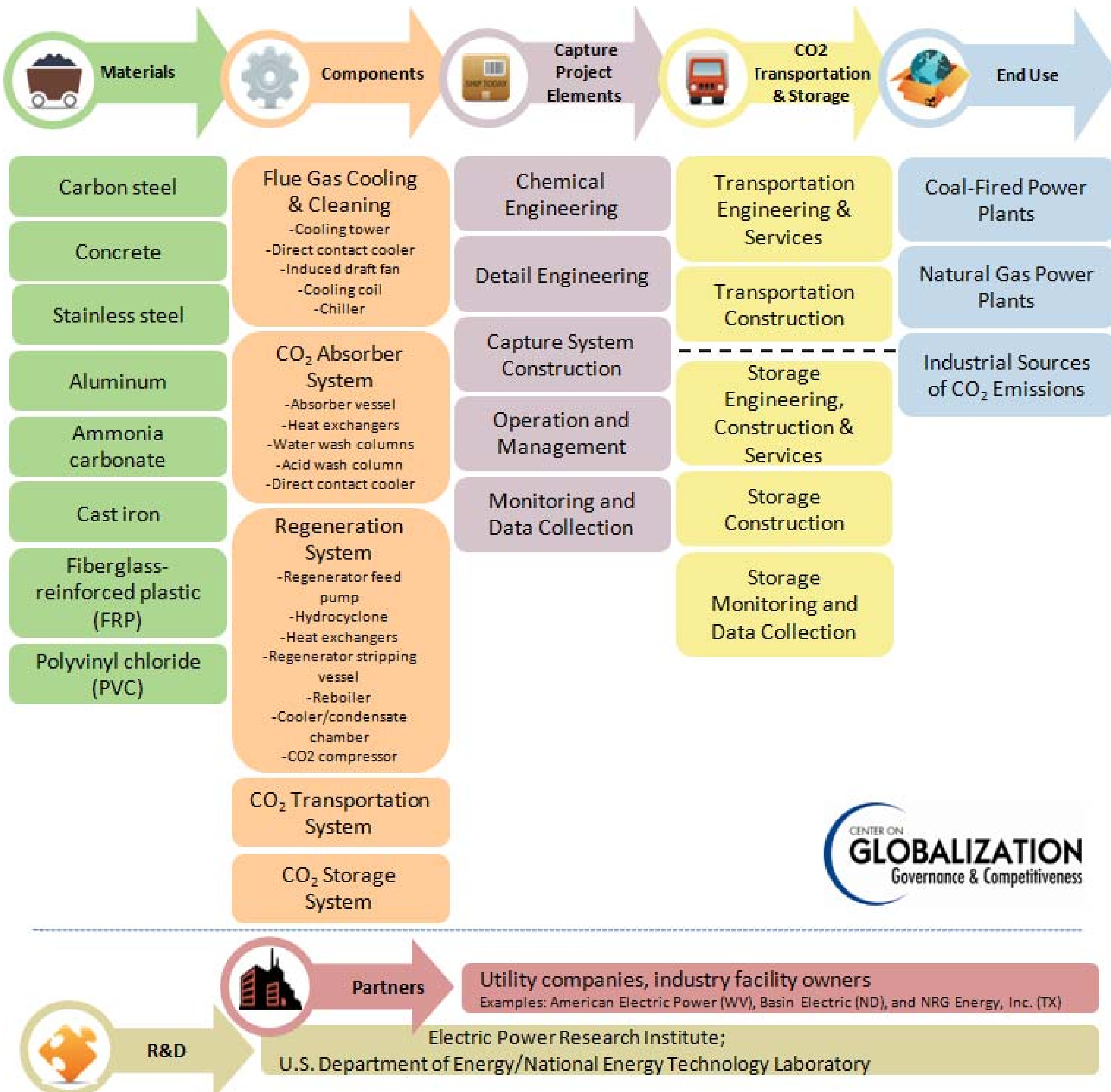
The Carbon Capture Technologies Value Chain

Carbon capture and storage technologies used for the sole purpose of emissions mitigation constitute a developing market in the United States. Until a cap-and-trade program or a carbon tax is introduced, it is unlikely the technology will be cost effective for commercial use.

Nonetheless, CO_2 regulations are expected and thus a number of large companies are at the forefront of developing technologies for this future market (see Figure 4).

This value chain will illustrate the potential market for the chilled ammonia process. The companies and actors included have the capacity to play a role within the value chain but may not necessarily be involved with the chilled ammonia process specifically. A simplified version of the value chain is depicted in Figure 2. A more detailed value chain with illustrative company information appears at the end of the chapter.

Figure 2: Simplified Value Chain for a CO_2 Capture Technology: The Chilled Ammonia Process



Source: CGGC, based on company websites, interviews, and industry sources.

Materials and Components

Carbon capture processes are huge, complex chemical plants built at the emission source. Stainless steel is the most predominant material used in the chilled ammonia process components because of the need to protect against corrosion over the lifetime of a system. When adapted to a power plant these capture systems may be in use for 30 to 50 years. Carbon steel and concrete are required in large amounts for construction of the entire system. To remain cost effective, carbon steel is the main material used in the CO_2 transportation pipeline. The United States is the world's leading importer of steel and is the third largest steel-producing country. Thus, the steel used in the value chain may be sourced within the United States or abroad. The most significant U.S. job potential with respect to steel will be processing and manufacturing the components using this metal.

Other materials that will be used in construction include concrete for the foundation, carbon steel for the access and structural steel (Black, 2009). Materials in the more standard components that are not in contact with the flue gas, like pumps and chillers, will be designed to meet site specific conditions and will use materials such as carbon steel with paint or other protective coatings, galvanized steel or mild grain stainless steel. For the majority of components in a post-combustion capture system, multiple materials can be used for each component. The materials chosen will be dependent upon customer requirements and design specifications for each unique system. Thus, material lists for CO_2 capture technologies and components within them will vary and not all materials are presented in this report.

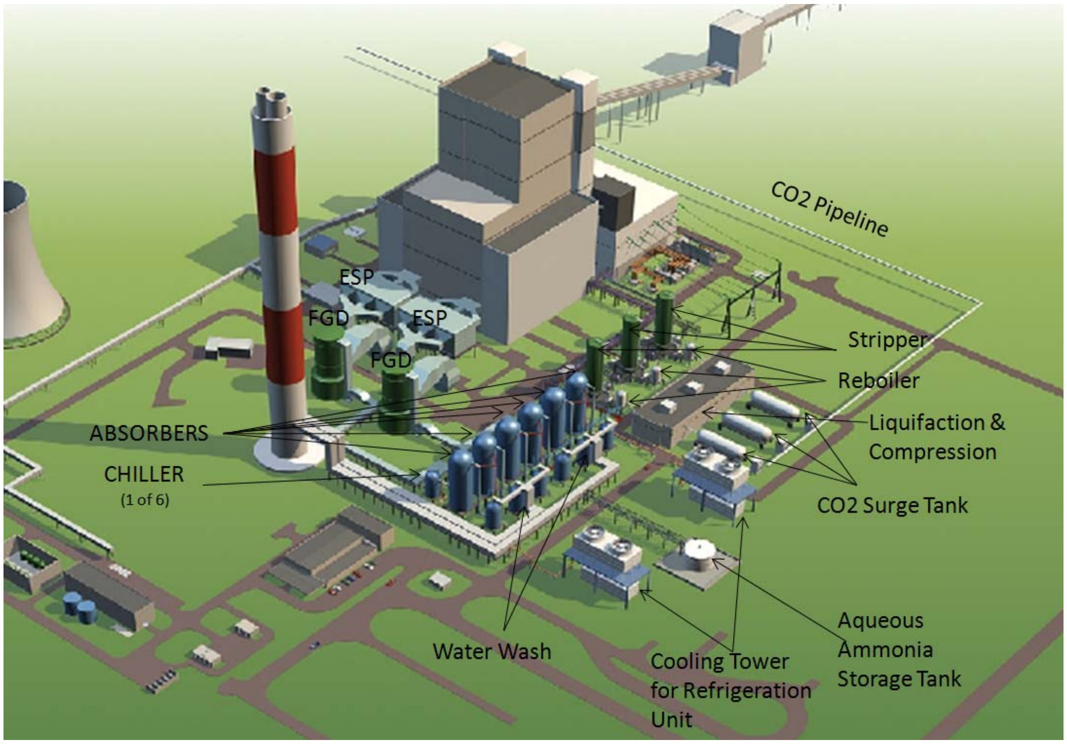
Similarly, the solvent used to capture CO_2 will vary based on the type of capture system employed. In the case of the chilled ammonia process, ammonia carbonate reacts with CO_2 to form ammonia bicarbonate. This slurry is then heated in the regenerator, which dissolves the solid into ammonia, water, and CO_2 gas (Sherrick et al., 2008). Ammonia is the feedstock for the ammonia carbonate reagent and the ammonia can be supplied in different forms including: aqueous ammonia, anhydrous ammonia or even ammonia on demand (Black, 2009). The form of ammonia supplied will depend on the client specifications.

Components

The chilled ammonia process is unique among carbon dioxide capture technologies because of its system for cooling the flue gas prior to entry into the absorber system. Therefore, key components of a chilled ammonia system that may not be integral to other CO_2 capture technologies include chillers and direct contact coolers. These components cool the flue gas and result in smaller equipment size requirements for the absorber and regeneration systems compared to other CO_2 capture technology systems.

Within the absorber system, key components include the absorber vessel, heat exchangers, water wash column, acid wash column and another direct contact cooler. The regeneration system is made up of pumps, stripping vessels, heat exchangers, hydrocyclones, reboilers, cooler and condensation chambers, and compressors. The compressors and pumps are key components of the regeneration systems and also some of the most expensive components of the entire system. For example, capital costs to compress CO_2 to supercritical conditions are approximately $1000 to $1400 per horsepower or about $60 million to treat 90% of CO_2 from a 500 MW electric power plant (Ciferno, 2009; Lawlor, 2009). Once the CO_2 is compressed, it is transported via steel pipeline to the storage location. CO_2 surge tanks are kept onsite, as well.

Figure 3: Illustration of an 800MW Power Station with a Chilled Ammonia Capture System



Source: (Morris, 2007)

Capture technology components are designed to meet the unique specifications of the technology system. Therefore, most of the components are built to suit, rather than available as prefabricated components from existing manufactures. It may be possible that as the CO_2 capture market develops and it becomes more evident which technologies will be the commercial leaders, some of the necessary components will be available from specific suppliers. Table 3 identifies some potential suppliers with the capacity to produce components needed in the chilled ammonia process. Many of them make similar types of component products; however, they are not actual suppliers. A number of the companies listed are also learning more about the CO_2 capture market in order to position themselves to serve a niche area. It is notable that many of the largest components, such as the absorbers and regenerators, are field assembled rather than shipped to the capture site.

Table 3: Chilled Ammonia Process Technologies with Potential Component Suppliers

Component	Company	Location	Sales (USD mil)	Employees
Chiller	Berg Chilling Systems Inc.	Ontario, Canada	$13.4	95
	General Air Products	Exton, PA	$16.3	30
Cooling Tower	Amcot Cooling Tower Corp.	Ontario, Canada	$3.4	10
	Baltimore Aircoil Co.	Baltimore, MD	$17.5	200
	Delta Cooling Towers, Inc.	Rockaway, NJ	$3.9	41
	EvapCo, Inc.	Taneytown, MD	$102.4	4
	GEA Power Cooling, Inc.	Lakewood, CO	$26.6	60
	SPX Cooling Technologies	Shawnee Mission, KS	$187.9	325
Direct Contact Cooler	Belco Technologies Corp.	Parsippany, NJ	$6.1	63
	Bionomic Industries	Mahwah, NJ	$5.9	13
	Lodge-Cottrell, Inc.	The Woodlands, TX	$1.0	5
	Alfa Laval, APV	Richmond, VA	$323.2	250
	General Air Products	West Chester, PA	$3.5	40
Fan	Lodge-Cottrell, Inc.	The Woodlands, TX	$1.0	5
	The New York Blower Co.	Willowbrook, IL	$27.7	200
	Twin City Fan & Blower Co.	Brookings, SD	$75.6	300
Absorber	Alstom Power, Inc.	Chattanooga, TN	$90.4	600
	Babcock Power Environmental	Worcester, MA	$2.2	25
	Bionomic Industries	Mahwah, NJ	$5.9	13
	Branch Environmental Corp.	Somerville, NJ	NA	NA
	Croll-Reynolds Co., Inc.	Parsippany, NJ	$2.7	28
	GE Energy & Environmental Research	Irvine, CA	$16.0	30
	Lodge-Cottrell, Inc.	The Woodlands, TX	$1.0	5
Heat Exchangers	Alfa Laval, APV	Richmond, VA	$323.2	250
	Babcock Power, Inc. Environment Division	Worcester, MA	$2.2	25
	Des Champs Technologies (Munters Corp.)	Buena Vista, VA	$30.1	235
	Luvata Grenada, LLC	Grenada, MS	$278.8	2,800
	Tranter Inc.	Wichita Falls, TX	$19.3	204
	The Alstrom Corp.	Bronx, NY	$1.6	20
Water Wash	Belco Technologies Corp.	Parsippany, NJ	$6.1	63
	Croll-Reynolds Co., Inc.	Parsippany, NJ	$2.7	28
	Lodge-Cottrell, Inc.	The Woodlands, TX	$1.0	5
Hydrocyclone	ChemIndustrial Systems, Inc.	Cedarburg, WI	NA	NA
	FLSmidth Krebs (Krebs Engineers)	Tucson, AZ	$160.0	300

Table 3: Chilled Ammonia Process Technologies with Potential Component Suppliers

Component	Company	Location	Sales (USD mil)	Employees
Pump	Croll-Reynolds Co., Inc.	Parsippany, NJ	$2.7	28
	FLSmidth Krebs	Tucson, AZ	$160.0	300
	Gould Pumps, ITT Corp.	Seneca Falls, NY	$501.8	1100
Acid Wash	Belco Technologies Corp.	Parsippany, NJ	$6.1	63
	Croll-Reynolds Co., Inc.	Parsippany, NJ	$2.7	28
	Lodge-Cottrell, Inc.	The Woodlands, TX	$1.0	5
Regenerator	Alstom Power, Inc.	Chattanooga, TN	$90.4	600
	Croll-Reynolds Co., Inc.	Parsippany, NJ	$2.7	28
	Enerfab, Inc.	Cincinnati, OH	$206.7	330
Compressor	Atlas Copco North America, Inc.	Pinebrook, NJ	$565.4	100
	Ingersoll-Rand Co.	Montvale, NJ	$932.2	290
	J-W Power	Dallas, TX	$10.4	120
	MAN Turbo Inc., USA	Houston, TX	$93.3	24
	Ramgen Power Systems, LLC	Bellevue, WA	$1.6	6
NH_3 Tank	Croll-Reynolds Co., Inc.	Parsippany, NJ	$2.7	28
	National Tank Outlet	Olive Branch, MS	$1.7	2
	Vector Systems	McKinney, TX	$1.3	18
	Wahlco Inc.	Santa Ana, CA	$27.3	106
Pipeline	Baker Hughes, Inc.	Houston, TX	$10,428.2	35,877
	Denbury Resources	Plano, TX	$972.0	686
	El Paso Corp.	Houston, TX	$4,648.0	4,992
	Exxon Mobil Pipeline Co.	Baytown, TX	$539.1	1,000
	Kinder Morgan Energy Partners	Houston, TX	$9,217.7	7,600
	Schlumberger Technology Corp.	Sugar Land, TX	$2,011.5	1,957

Source: CGGC, based on company websites, interviews, and industry sources.

Project Elements

Development of a carbon capture and storage system requires partnerships among many different entities. It is complex to coordinate the power plant (or other emitting facility) and the CO_2 capture, transportation, and storage systems. The major partner types generally include the utility company (or industry) owner, the capture technology company (e.g., technology developer) and consulting, engineering and construction firms for the capture, transportation and sequestration systems. Also involved are labor unions whose skilled workers complete the hands-on work, such as welding and pipefitting, and monitoring and evaluation firms to ensure system safety and proper functioning. The number and types of firms involved will vary depending on the type of capture technology, the distance CO_2 is to be transported, and the CO_2's final use (e.g., for enhanced oil recovery or solely long-term storage).

As an example, the chilled ammonia demonstration project at American Electric Power's (AEP) Mountaineer Plant in West Virginia will store the captured CO_2 in geologic reservoirs at the site of the plant. Thus, the two major partners are Alstom and AEP. American Electric Power is responsible for the capture system's utility power as well as for the CO_2 transportation and storage systems. Alstom is responsible for the capture system itself. In other applications where onsite sequestration is not available, additional partnerships with firms spearheading the transportation and storage systems will be necessary.

Beyond the larger partnerships between the utility company and capture, transportation and sequestration firms, there are many other subcontractors who play important engineering and construction roles within each system. For example, capture system development will be built onsite and may involve a chemical engineering firm hired to design component specifications, a detail engineering firm contracted to complete the civil, mechanical, and structural engineering, and a construction firm designated to build the system. In the case of the Mountaineer Plant, Alstom is subcontracting plant engineering to Zachry Engineering Corporation, steel work to APCom Power, and foundation construction to Bowen Engineering Corporation (Sherrick et al., 2008). American Electric Power hired Enerteq Engineering Company to conduct the engineering and procurement services for the transportation system and Battelle to complete the engineering, procurement and construction services for the storage system (Sherrick et al., 2008).

Types of firms offering elements of the capture and storage systems include, but are not limited to, those listed below. Table 4 identifies some firms with these competencies.

- *Industrial firms and utilities* – The emitting facility with which the capture system will be connected. The utility/firm is responsible for the capture system's power and power to pump the CO_2 into the transportation system. In some cases it is also the contracting entity for the transportation and storage systems. U.S.-based utilities developing capture demonstration projects include American Electric Power (WV), Basin Electric (ND), and NRG Energy, Inc. (TX).
- *Technology developers* – Firms involved in research and development and eventually the commercialization of capture and sequestration technologies. Major U.S.-based developers include Alstom Power, Babcock & Wilcox, Ion Engineering, Powerspan, and RTI International (see Table 1).
- *Consulting, engineering, and construction firms* – Feasibility studies are required for a number of purposes within a capture and storage system including determining space needs for an onsite capture facility, possible sequestration sites for a given capture location, and transportation routes to storage sites. Consulting firms can help evaluate these opportunities. Once plans are made, detail, civil, mechanical and structural engineering are all required to complete the various systems within the capture and

storage processes and skilled laborers are needed to carry out the work. Illustrative firms with these capabilities are included in Table 4.

- *Monitoring and evaluation firms* – Monitoring and evaluation firms have distinct roles in capture and storage systems. During CO_2 capture demonstration projects, they are needed to determine how much CO_2 is captured from the flue gas and whether or not the system is working properly. This also will be needed during the testing phases of commercial systems. Monitoring and evaluation firms are also needed long-term at the storage location to ensure CO_2 is not leaking from its below-ground storage location. Electric Power Research Institute is an energy industry non-profit organization partnering with capture technology developers to monitor and evaluate demonstration projects. Schlumberger is an example of a firm with capability to provide monitoring and evaluation of storage sites.

Table 4: Construction, Engineering and Monitoring Firms with Capture and Storage System Competencies

Project Element	Company	Headquarters Location
Chemical Engineering	Burns & McDonnell	Kansas City, MO
	Linde North America, Inc.	Murray Hill, NJ
	Process Engineering Associates	Oak Ridge, TN
	Reaction Engineering International	Salt Lake City, UT
Detail Engineering	Dunbar Mechanical	Toledo, OH
	Mustang Engineering	Houston, TX
	Siemens Energy & Automation	Alpharetta, GA
	URS Washington Div.	Bellevue, WA
	Zachry Engineering Corp.	Houston, TX
Capture System Construction	APCom Power	Counce, TN
	Bowen Engineering	Fishers, IN
	Kiewet Energy	Houston, TX
	Patent Construction Systems	Paramus, NJ
Transportation Engineering and Services	Baker Hughes, Inc.	Houston, TX
	Battelle	West Jefferson, OH
	Denbury Resources	Plano, TX
	El Paso Corp.	Houston, TX
	Exxon Mobil Pipeline Co.	Baytown, TX
	Kinder Morgan Energy Partners	Houston, TX
Transportation Construction	Babcock Eagleton, Inc.	Houston, TX
	Enerteq Engineering Co.	Stafford, TX
Storage Engineering, Construction and Services	Advanced Resources International Inc.	Houston, TX
	Baker Hughes, Inc.	Houston, TX
	Battelle	West Jefferson, OH
	Halliburton Co.	Houston, TX
	Schlumberger	Houston, TX

Table 4: Construction, Engineering and Monitoring Firms with Capture and Storage System Competencies

Storage Monitoring and Data Collection	Arcadis	Highlands Ranch, CO
	Schlumberger	Canada

Source: CGGC, based on company websites, interviews, and industry sources.

Carbon Transportation Scenarios

In most cases, captured carbon dioxide will be stored long-term in geologic reservoirs underground. The compressed CO_2 will be transported to these storage locations using pipelines and developing the infrastructure for these pipelines may offer significant job potential. It will require both manufacturing the pipes used in the transportation and laying the pipe in the ground. Although the opportunities here are vast, there are several transportation scenarios possible given the varying distances from the CO_2 capture location to the point of storage.

In the United States, there already exists a 3,600-mile pipeline network transporting CO_2 for enhanced oil recovery (EOR) (Fernando, Venezia, Rigdon, & Verma, 2008). It is possible that some early adopters of CO_2 capture systems will do so as part of the EOR market. Map 2 illustrates the existing U.S. CO_2 pipelines. Firms serving the transportation market for EOR also have the expertise and experience to provide transportation services within the carbon capture and storage value chain. Some of these companies include Denbury Resources, Inc. (Jackson Dome pipeline), Exxon Mobil (Oklahoma pipeline), and Kinder Morgan (Bravo pipeline; TX-NM-CO pipelines) (Strömberg, 2005)

Map 2: U.S. Carbon Dioxide Pipelines

Source: (Strömberg, 2005)

Carbon dioxide transportation pipelines will need to meet specifications for transporting supercritical CO_2 (>72.9 atm). The size of the pipeline will vary depending on the plant type and resulting CO_2 flow rate (measured in million tons per year). The size could range from 4 inches in diameter to 36 inches in diameter (H. Herzog et al., 2007). According to industry sources and interviews, the most likely scenario is that CO_2 pipelines from coal-fired power plants will require 24- to 26-inch diameter steel pipes with ½-inch wall thickness (Dooley et al., 2006; Evans, 2009).

Early carbon capture and storage projects may be chosen in part for their proximity to a suitable geological storage location, as is the case for the Alstom chilled ammonia demonstration project at the American Electric Power plant in West Virginia. Furthermore, a recent analysis cited by Parfomak & Folger, 2008 indicates that more than 75% of potential carbon capture sources are located in regions of the country that are thought to contain candidate storage sites, while another 18% are located within 100 miles of such areas.

However, there will be significant regional variation. For example, research conducted by Massachusetts Institute of Technology for the West Coast Regional Carbon Sequestration Partnership found that 80% of the major stationary sources of CO_2 emissions in that region are within 31 miles of geologic formations that are thought to contain candidate storage sites (H. Herzog et al., 2007). By contrast, research by the University of Texas at Austin found very limited to no storage space in the Southeastern states of Virginia, North Carolina, South Carolina, and Georgia (Hovorka et al., 2006). Therefore, a network of CO_2 transportation pipelines may need to be developed in particular regions of the United States in the long term. However, CGGC interviews and review of industry materials suggest that future pipelines are likely to range in length from less than 50 miles to no more than a few hundred miles (National Energy Technology Laboratory, 2008) and there will be a limited need for additional long-distance CO_2 pipelines (Parfomak & Folger, 2008).

The demand for steel and labor required to produce the steel for the CO_2 transportation pipelines will depend on the size and length of the pipe and the productivity of the mill producing the steel. Assuming 26-inch diameter (½ inch thick) steel pipes, the estimated steel requirements per mile of pipeline would be 315 tons. This would require 630 man-hours to produce, assuming the average productivity for U.S. steel mills at two man-hours/ton of steel (Wagman, 2008). The United Association of Journeymen and Apprentices of the Plumbing and Pipe Fitting Industry estimates the cost of 1 mile of 26 inch long, ½ inch thick steel pipe manufacturing at $400,000 to $1.2 million (Hendrix, 2009). The anticipated costs of pipeline manufacturing and construction based on our research estimates are approximately $1.5 million, which falls between the frequently referenced estimates of $1 million to $2 million per mile (Dooley et al., 2006; Evans, 2009). Table 5 presents the steel and labor requirements estimated for five CO_2 pipeline distance scenarios and their projected costs.

Table 5: Five Scenarios of Estimated Steel Needs for Carbon Dioxide Capture Pipelines, Per Project

Scenario (pipeline length)	**Steel** (tons)	**Estimated Cost**	**Estimated Man-Hours**
1 mile	315	$1,495,000	630
50 miles	15,750	$74,750,000	31,500
100 miles	31,500	$149,500,000	63,000
200 miles	63,000	$299,000,000	126,000
300 miles	94,500	$448,500,000	189,000
Notes: Estimates are based on 26-inch long, ½ inch thick steel pipes; Costs based on $57,500 per mile per inch pipeline diameter; Total man hours based on 2.0 man-hours per ton.			

Source: Calculated by CGGC from industry sources and interviews

Carbon Capture and Storage Job Potential

Regardless of the technology chosen for carbon capture and storage, this developing market offers immense opportunities for large-scale infrastructure projects with significant demands for U.S. labor in both component production and infrastructure installation. Furthermore, there will be an increased demand for materials, steel in particular, which are often produced in the United States. It is notable that the market for carbon capture and storage is still in development; thus, these job opportunities are not currently available with the exception of the few demonstration projects being built with lower labor needs. Labor demands are anticipated to grow in 2015 and increase rapidly through 2020 as the market expands. For example, Alstom will complete chilled ammonia process demonstrations in 2014 and the company will begin quoting commercial plant guarantees in 2014-2015. Full scale deployment is expected to begin sometime in 2018 or 2019 (Hilton, 2009c).

Once carbon capture and storage commercial applications begin, a wide range of job types and a large number of workers will be needed for this industry.

- *Research and development jobs* – Research and development jobs within the carbon capture and storage market currently exist. The companies developing new capture technologies employ a variety of individuals within the chemical, engineering, design, and monitoring and evaluation fields. These workers are involved in conducting research and demonstration projects to create technologies that will effectively capture and store CO_2. Research and development jobs are likely to continue as the market expands and new techniques for reducing CO_2 emissions are developed.
- *Design and engineering jobs* – The application and design of capture technologies will vary based on the facility for which it is being configured. Therefore, design consultants

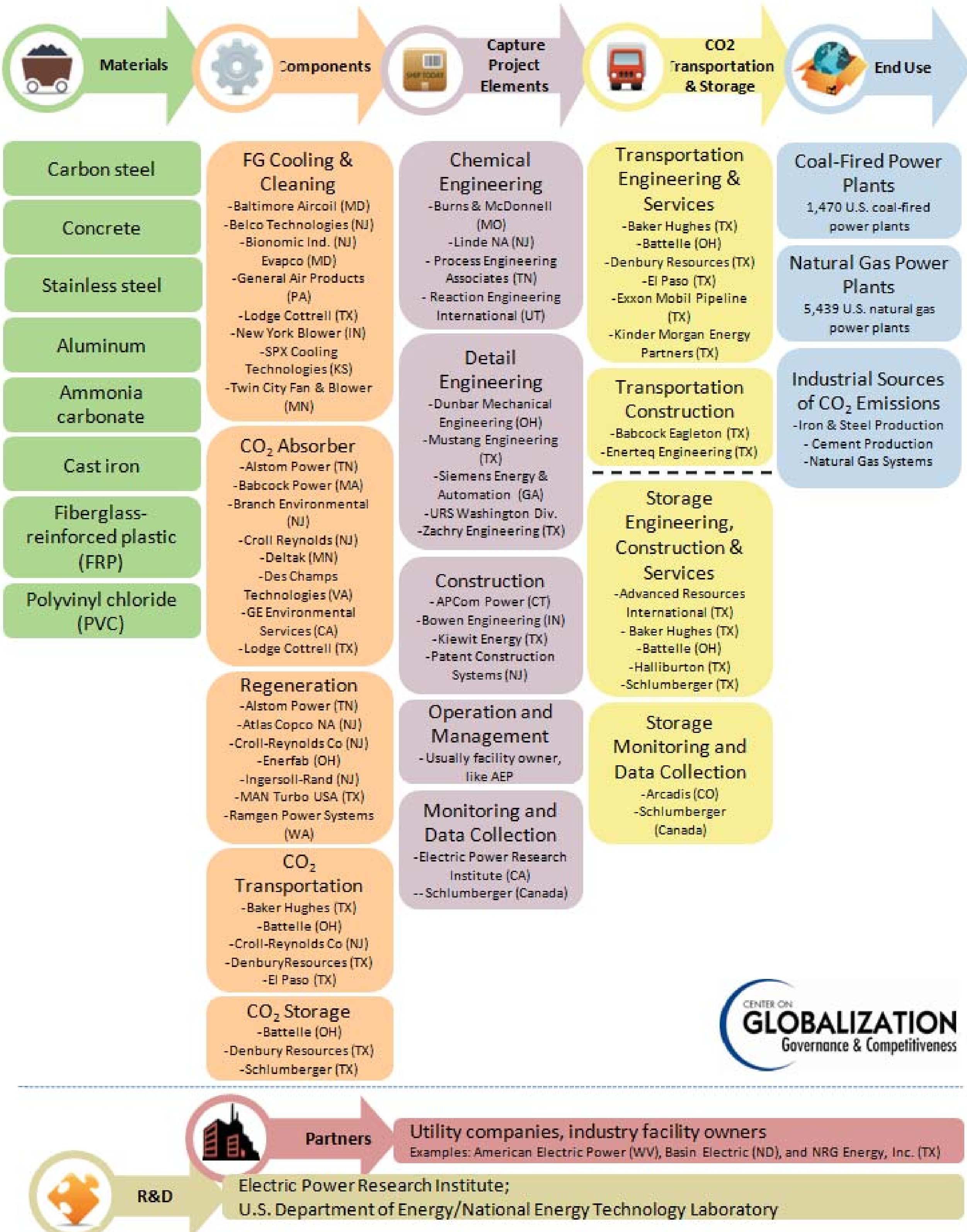
and chemical, civil, mechanical, and structural engineers will be needed to determine the capture technology specifications for each site. The number and types of consultants and engineers employed vary by project; however, many skilled workers will be needed throughout the value chain.

- *Component manufacturing jobs* – Components involved in CO_2 capture processes will range from small bolts to three-story tall stripping vessels. Most of the large components will be built on location with specifications unique to the site. Alstom Power Vice President for Technologies and Government Affairs, Robert Hilton, stated that nearly all the components for the existing chilled ammonia process demonstration projects were supplied by U.S. companies (Hilton, 2009b) and Alstom has similar expectations for commercial applications. If the same holds true for other companies, component manufacturing may have a significant footprint in the United States. One design and engineering firm noted that its suppliers are generally identified based on qualifications for working with applicable materials and proximity to the project location. The idea is to limit shipping costs. Thus, U.S. firms would mostly be used for U.S. projects of this size (Byszewski, 2009). In addition, sub-suppliers are inspected to ensure they employ qualified welders and fabricators and follow the design specifications. Alstom also identified quality craft laborers as an important need in the United States (Hilton, 2009c).
- *Capture facility construction jobs* – Demand for construction jobs will increase as the carbon capture and storage market expands. Alstom estimates building a chilled ammonia process facility for a 600 MW power plant would take three years and require 2,000 construction jobs. Powerspan representatives estimate carbon capture facilities over 100 MW in size to take between three and four years to construct and create up to 500 jobs at their peak (Procopis, 2009).
- *Pipeline construction jobs* – Captured CO_2 will be transported to the geologic storage site through steel pipelines. Regardless of the distance CO_2 pipelines extend between the capture and storage sites, it is generally agreed that there will be significant infrastructure jobs related to manufacturing and laying the pipes for CO_2 transportation.
- *Storage site characterization and monitoring* – Determining appropriate geological storage locations is integral to the safety of CO_2 capture and storage projects. Furthermore, selected sites will need to be monitored to ensure storage is working properly. These jobs will involve a wide range of services including three-dimensional seismic computer modeling, risk analysis, and engineering.
- *Operation and maintenance jobs (both capture facility and storage facility)* – Carbon capture systems also will employ a smaller number of people on a long-term basis to manage, maintain, and evaluate system functioning and safety.

Conclusion

Carbon capture and storage is necessary if the United States expects to meet its CO_2 emissions reduction goals. In addition, development of the market offers extensive U.S.-based job opportunities in research and development, infrastructure development, component manufacturing and material supply. In the near-term, job opportunities exist within research and development, engineering and construction of demonstration projects for carbon capture technologies. As these technologies become commercially available, pipeline infrastructure will also be needed. The full scope of job potential will likely be realized sometime around 2020 when commercial applications of technologies currently being tested are available. Continued financial support from government and industry sources will assist development of this market in the United States. However, its full potential will probably not be realized until a U.S. CO_2 cap-and-trade program or CO_2 emission tax is in effect.

Figure 4: Carbon Dioxide Capture and Storage Illustrative Example: The Chilled Ammonia Process Value Chain with Potential Companies



Source: CGGC, based on company websites, interviews, and industry sources.

References

Anderson, Scott. (2009). *Senior Policy Advisor, Environmental Defense Fund*. Personal communication with CGGC Staff. April 25.

Anderson, Soren and Newell, Richard. (2004). Prospects for Carbon Capture and Storage Technologies. *Annual Review of Environment and Resources, 29*(1), 109-142.

Anonymous. (2006). Chilling News for Carbon Capture. *Modern Power Systems, 26*(12), 17-18.

Black, Sean. (2008, June). Carbon Captures the Moment: A Chilled Ammonia Pilot Project. *Power Engineering International, 16*(5), 40-42.

---. (2009). *Chilled Ammonia Process Business Manager, Alstom Power*. Personal communication with CGGC Staff. April 29.

Bohm, Mark C., Herzog, Howard J., Parsons, John E., and Sekar, Ram C. (2007). Capture-Ready Coal Plants—Options, Technologies and Economics. *International Journal of Greenhouse Gas Control, 1*(1), 113-120.

Byszewski, Carolyn. (2009). *Air Pollution Control Sales Manager*. Personal communication with CGGC Staff. March 23.

Ciferno, Jared. (2008, April 23-24). *Existing Coal Power Plants: CO_2 Retrofit Possibilities and Implications.* Paper presented at the The Future of Coal in Pennsylvania: A Dialogue, Harrisburg, PA.

---. (2009). *Technology Manager, National Energy Technology Laboratory*. Personal communication with CGGC Staff. May 7.

Dailey, Ryan M. and Shattuck, Donald S. (2008). *An Introduction to CO_2 Capture and Sequestration Technology*. Denver, CO: Utility Engineering Corporation.

Darde, Victor, Thomsen, Kaj, Well, Willy van, and Stenby, Erling. (2008). Chilled Ammonia Process for CO_2 Capture. Technical University of Denmark; DONG Energy.

Deutch, John, Moniz, Ernest J., Ansolabehere, Stephen, Beer, Janos, Ellerman, A. Denny, Friedmann, Julio, Herzog, Howard, Jacoby, Henry D., Joskow, Paul L., McRae, Gregory, Lester, Richard, Steinfeld, Edward, and Katzer, James. (2007). *The Future of Coal*. Boston: Massachusetts Institute of Technology, pp. ix.

Dooley, James J., Dahowski, Robert T., Davidson, Casie L., Wise, Marshall A., Gupta, Neeraj, Kim, Son H., and Malone, Elizabeth L. (2006). *Carbon Dioxide Capture and Geologic Storage: A Core Element of a Global Energy Technology Strategy to Address Climate Change*. College Park, MD: Battelle, Joint Global Change Research Institute.

Energy Information Administration. (2007a). Electric Power Industry 2007: Year in Review. Retrieved February 16, 2009, from U.S. Department of Energy: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

---. (2007b). Table 2.2. Existing Capacity by Energy Source, 2007. Retrieved February 16, 2009, from U.S. Department of Energy: http://www.eia.doe.gov/cneaf/electricity/epa/epat2p2.html

---. (2009). Table 8. Electricity Supply, Disposition, Prices, and Emissions. Washington, DC: U.S. Department of Energy.

EPRI. (2006). *Chilled-Ammonia Post Combustion CO_2 Capture System-Laboratory and Economic Evaluation Results*. Palo Alto, CA: Electric Power Research Institute.

Evans, Tracy. (2009). *Senior Vice President, Reservoir Engineering, Denbury Resources Inc.* Personal communication with CGGC Staff. February 6.

Fernando, Hiranya, Venezia, John, Rigdon, Clay, and Verma, Preeti. (2008). *Capturing King Coal: Deploying Carbon Capture Storage Systems in the U.S. at Scale*. Washington, DC: World Resources Institute.

Gray, Mark A. (2008, June 14-18). *CO_2 Reduction Overview: AEP's Perspective on Reducing Carbon Dioxide Emissions.* Paper presented at the Mid-America Regulatory Conference, Oklahoma City, OK.

Hendrix, Dan. (2009). *Business Manager of UA Pipeline Local 798, United Association of Journeymen and Apprentices of the Plumbing and Pipe Fitting Industry of the United States and Canada*. Personal communication with CGGC Staff. April 30, 2009.

Herzog, Howard and Golomb, Dan (Eds.). (2004) Encyclopedia of Energy (Vols. 1). Elsevier.

Herzog, Howard J. (2001). What Future for Carbon Capture and Sequestration? *Environmental Science & Technology, 35*(7), 148-153.

Herzog, Howard, Li, Weifeng, Zhang, Hongliang, Diao, Mi, Singleton, Greg, and Bohm, Mark. (2007). *West Coast Regional Carbon Sequestration Partnership: Source-Sink Characterization and Geographic Information System-Based Matching*: California Climate Change Center.

Hilton, Robert. (2009a). *Vice President for Technology for Government Affairs, Alstom Power Inc.* Personal communication with CGGC Staff. March 3.

---. (2009b). *Vice President of Technologies for Government Affairs, Alstom Power*. Personal communication with CGGC Staff. January 30.

---. (2009c, February 5). *Workshop 15: The Case for Clean Coal and Carbon Capture and Sequestration.* Paper presented at the Good Jobs Green Jobs National Conference, Washington, DC.

Hovorka, Susan D., Holtz, Mark H., Smyth, Rebecca C., López, Vanessa Núñez, Kim, Eugene, Breton, Caroline L., Scanlon, Bridget R., Reedy, Reedy C., Paine, Jeffrey, Tinker, Scott, and Duncan, Ian. (2006). *Assessment of Geological Storage Capacity of the Southeastern U.S. for CO_2 in Brines and Economic Use for EOR*. Atlanta, Georgia: Gulf Coast Carbon Center, the Bureau of Economic Geology, The University of Texas at Austin.

Lawlor, Shawn. (2009). *CO_2 Compression Using Supersonic Shock Wave Technology,* Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting.

Li, Fanxing and Fan, Liang-Shih. (2008). Clean Coal Conversion Processes - Progress and Challenges. *Energy & Environmental Science, 1*(2), 248-267.

Mitsubishi Heavy Industries, Ltd. (2005). MHI's Experiences: Commercial Plant in Malaysia. Retrieved March 4, 2009, from http://www.mhi.co.jp/mcec/product/recov_co2/experience/malaysia.html

Morris, Mike. (2007, March). *Strategic Business Issues of CCS Deployment.* Paper presented at the Carbon Sequestration Leadership Forum, Paris, France.

National Energy Technology Laboratory. (2007). *Carbon Sequestration Atlas of the United States and Canada*: U.S. Department of Energy Office of Fossil Energy, pp. 11.

---. (2008). *2008 Carbon Sequestration Atlas II of the United States and Canada - Version 2*: U.S. Department of Energy.

Parfomak, Paul W. and Folger, Peter. (2008). *Carbon Dioxide (CO_2) Pipelines for Carbon Sequestration: Emerging Policy Issues*. Retrieved January 20, 2009, from http://opencrs.com/document/RL33971.

Parkinson, Gerald. (2008, December). Newsfront: Capturing CO_2. *Chemical Engineering, 115*(13), 16-20.

Power Magazine. (2008, October 15). Map of Coal-Fired Power Plants in the United States. Retrieved April 7, 2009, from http://www.powermag.com/issues/cover_stories/Map-of-Coal-fired-Power-Plants-in-the-United-States_1446.html

Procopis, Stephanie. (2009). *Vice President of Communications and Government Affairs, Powerspan Corp.* Personal communication with CGGC Staff. April 8.

Rubin, Edward S. (2008). CO_2 Capture and Transport. *Elements, 4*(5), 311-317.

Sherrick, Brian, Hammond, Mike, Spitznogle, Gary, Muraskin, David, Black, Sean, and Cage, Matt. (2008). *CCS with Alstom's Chilled Ammonia Process at AEP's Mountaineer Plant*: Alstom Power, Inc.

St. John, Jeff (2009). Carbon Capture on the Cheap? *Greentech Media*, (January 20). Retrieved from http://www.greentechmedia.com/articles/carbon-capture-on-the-cheap-5766.html

Strömberg, Lars. (2005, January 17). CO_2 Capture and Storage - Part of the Solution to the Climate Change Problem? *European Energy Forum* Retrieved March 23, 2009, from http://www.europeanenergyforum.eu/archives/european-energy-forum/environmental-matters/co2-capture-and-storage-2013-part-of-the-solution-to-the-climate-change-problem

U.S. Environmental Protection Agency. (2009). *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007*, pp. 3. Retrieved April 2, 2009, from http://www.epa.gov/climatechange/emissions/downloads09/07Trends.pdf.

Wagman, David. (2008, July, 2008). Steel Prices "Exploding" ABMA Hears. *Power Engineering*.

We Energies. (2008). Carbon Capture Project Photos. *Carbon Capture Pilot Project at the Pleasant Prairie Power Plant in Pleasant Prairie, WI* Retrieved January 5, 2009, from http://www.we-energies.com/home/co2_projphotos.pdf