



An Assessment of Carbon Capture Technology and Research Opportunities

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Abstract

One approach to limiting CO₂ emissions from oxidation of carbon-based fuels is to capture the CO₂ and store it, possibly in subsurface geologic formations. A critical component of that approach is the creation of a concentrated CO₂ stream. This assessment provides an overview of carbon capture technologies, organized by the physical process driving the separation. Chemical solvents and to a lesser extent physical absorbents are widely used in small-scale carbon capture applications, but may have difficulties processing the large volumes of CO₂ from fossil fuel combustion. Alternative techniques under consideration involve materials such as adsorbents, membranes, and chemisorbents. Current technologies require several times the theoretical energy requirement to separate CO₂ from fossil fuel conversion effluent. This low efficiency and associated high cost suggests significant opportunities for fundamental research to improve current technologies or develop entirely new approaches.

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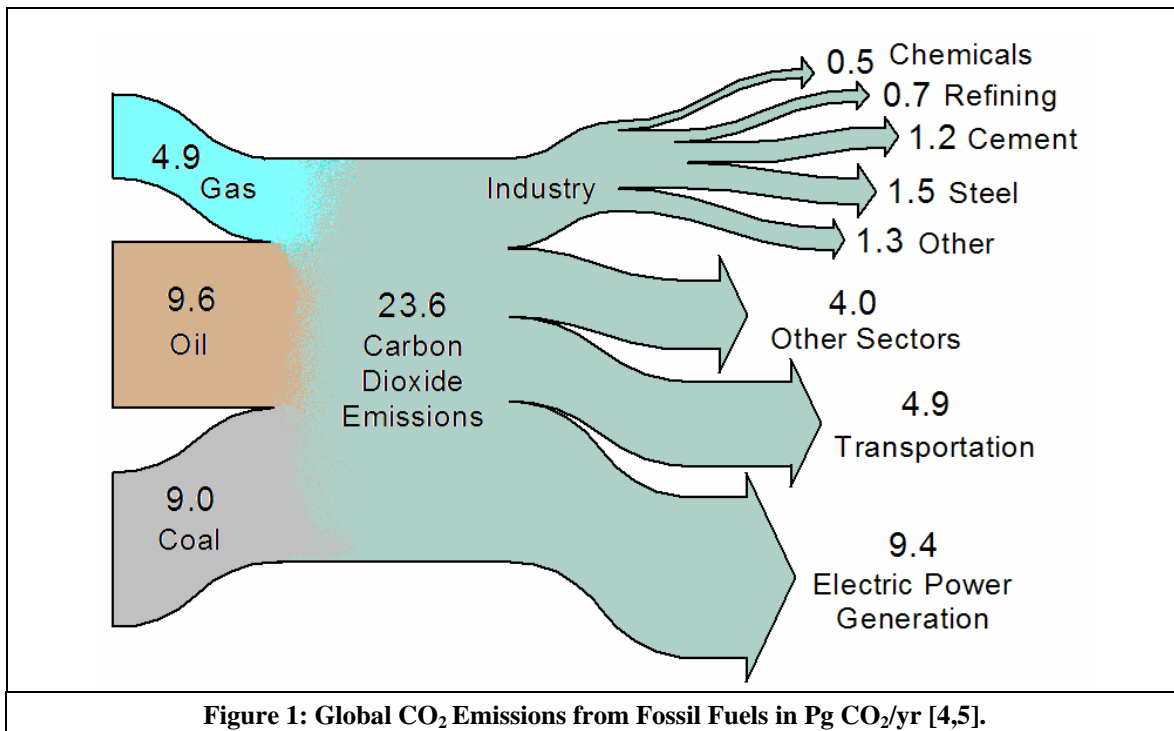
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Foreword

This report is one of a series of assessments on various areas of the energy landscape prepared by GCEP staff. The assessments are intended to provide an introduction to the energy area as well as context for future fundamental research activity towards reducing greenhouse gas emissions. By examining the goals and potential of the energy transformations in question as well as the current progress and research towards these ends, the assessments take a step toward elucidating the most promising areas for future research. This report, produced by GCEP Energy Analysis staff, was written by Wes Hermann with contributions from Paolo Bosshard, Emilie Hung, Rebecca Hunt, and AJ Simon. Please address all correspondence to gcep@stanford.edu.

Introduction

Carbon-based fossil fuel resources comprise about 80% of global primary energy [1]. Electricity generation, transportation, and industry converts this fuel into approximately 24 Pg[†] carbon dioxide (CO₂) per year and releases it into the atmosphere. CO₂ is accumulating in the atmosphere at an increasing rate [2]. Future concentrations are likely to be substantially higher unless significant changes to energy systems are made. It has been proposed that a pure stream of CO₂ can be safely and successfully stored in a variety of carbon sinks on time scales long enough to reduce or eliminate its contribution to the accumulation of CO₂ in the atmosphere [3]. Since it is unlikely that this entire stream can be subject to diversion and storage, breaking down the emissions from fossil fuels into sectors of our energy system will facilitate identification of CO₂ sources most readily addressed by technological advancements. Figure 1 illustrates the flow of carbon through the energy system from fossil fuels to its eventual release into the atmosphere.



Large point sources of CO₂ would allow economies of scale in carbon separation and simplify transportation to a storage site. Electricity generation and some large fossil fuel burning industrial sources are therefore good candidates for carbon capture. Coal-fired power plants have a flue gas stream with 9-14% mole fraction CO₂, while natural gas combined-cycle plant flue gases typically have a 4% CO₂ content [5]. Many large industrial processes involve large-scale combustion similar to that used for electricity generation and could adopt similar carbon capture techniques. About two-thirds of the CO₂ emissions from oil refineries come from fossil fuel fired heaters and about 60% of the CO₂ emitted by the iron and steel industry is from blast furnaces [5]. Flue gases

[†] 1 Pg = 10¹⁵ g = 1 Gt = 10⁹ metric tonnes = 10¹² kg

emitted from cement production contain 14-33% mole fraction CO₂ due to the combustion of fossil fuels for heat and CO₂ production from calcination [6].

Any technique that prevents or reverses the release of CO₂ to the atmosphere and diverts the carbon to a viable carbon sink can be considered carbon capture. While some proposed technological methods involve capturing CO₂ directly from the air to offset emissions elsewhere [7], or putting carbon containing compounds into a material sink, the majority of carbon capture work focuses on separating CO₂ from the exhaust gas of fossil fuel conversion facilities for potential geologic storage.

In order to divert CO₂ from large, point sources in industry and electricity generation to storage in a geologic sink, it must be isolated from other gases. Air combustion effluent from these sources typically contains CO₂ in dilute concentrations (3-15% mol). It is likely to be impractical to store effluent with all its constituents because of costs associated with transportation and compression in addition to storage space considerations. The theoretical minimum energy cost for compressing the entire flue gas stream from a coal fired plant to 100 atm is about 18% of the energy released from combustion per unit of flue gas¹. With a theoretical separation energy of 110 kJ/kg CO₂ for a 14% mole fraction CO₂ stream at atmospheric pressure² and 200 kJ/kg CO₂ for compression³, the minimum energy requirement for reversible separation and compression of only the CO₂ is about 4% of the energy released. For these reasons, an efficient method of capturing CO₂ as a pure stream would greatly enhance the potential for carbon storage to make an impact on global CO₂ emissions.

Separation of CO₂ is commonly practiced, although it is currently done at a relatively small scale compared to that required for significant impact on global CO₂ emissions. Pure CO₂ streams are produced from combustion gases for products such as beverages, urea, and soda ash. During natural gas processing, CO₂ is removed to increase the energy density of the fuel and to decrease corrosion and catalyst poisoning in processes that use natural gas as a feedstock [8]. However, the energy penalties and costs associated with these processes in their present form make them unattractive for large-scale carbon capture.

Separation of CO₂ from other gases in a fossil fuel or biomass conversion process can occur through a variety of means, and may involve several separation steps. Assuming the fuel is largely composed of carbon, hydrogen and oxygen, and air is an input, there are several paths for separating a concentrated stream of CO₂:

- *Post-combustion*: Separation of CO₂ from combustion products (nitrogen, oxygen, water). Capture can occur anywhere along the product processing stream

¹ Isothermal, reversible compression of 14% CO₂, 5% O₂, 81% N₂ (mole) flue gas stream at 300 K from combustion of 30 MJ/kg coal (graphite) with 36% excess air.

² Ideal gas mixing exergy between 14% and 100% mole fraction CO₂ at 300 K. The separation energy rises to 180 kJ/kg for a 4% mole fraction CO₂ stream typical of a natural gas combined cycle plant.

³ Isothermal reversible compression of pure CO₂ from 1 to 100 bar at 300 K.

from combustor to effluent exhaust. The concentration of CO₂ is rarely above 15% mole fraction.

- *Oxy-fuel combustion*: Separation of oxygen from nitrogen in the air to produce a nitrogen-free oxidizer stream. Reaction with fuel produces a stream composed primarily of CO₂, oxygen, and water. The water can then be removed through phase separation.
- *Pre-combustion*: Separation of carbon in the form of CO₂ from a resource after the energy content of the resource is transferred to a carbon-free energy carrier. The most common configuration involves gasification with air or oxygen. The products undergo a water-gas shift to a high-concentration stream of CO₂ and H₂. The CO₂ is then captured and the H₂ is reacted with air.

The driving force behind all carbon capture techniques examined in this paper is the difference in chemical potential between states. At some point in the cycle, the conditions and materials present are such that gas separation is thermodynamically favored. This can be accomplished through cyclical reaction and regeneration or steady-state transformation. In general, transport driven by a difference in chemical potential produces irreversibilities proportional to the magnitude of the difference. The rate of transformation is also coupled with the difference in chemical potential. For many techniques, this introduces a trade-off between the size and associated costs of a gas separation mechanism and the energy required to provide the difference in chemical potential, which is related to the efficiency. Though this trade-off will always be present, new materials, catalysts, or compounds may be able to increase reaction rates and efficiencies above those of present carbon capture technologies.

There exists an array of technologies that help accomplish carbon separation, taking advantage of many physical processes. These technologies are often combined in proposed large-scale power or industrial systems with carbon capture. For carbon capture and storage to contribute significantly to a portfolio of energy technologies with lower emissions of greenhouse gases, a wide array of technologies should be considered. Fundamental research may be able to improve the efficiency and cost of these current technologies or enable entirely new approaches. The following sections, organized by the underlying physical processes, present the current state, efficiency, and research directions of carbon capture technologies.

Chemical Solvents

The most commonly used technology today for low concentration CO₂ capture is absorption with chemical solvents. This chemical absorption process is adapted from the gas processing industry where amine-based processes have been used commercially for the removal of acid gas impurities from process gas streams. However, problems of scale, efficiency, and stability become barriers when chemical solvents are used for high-volume gas flows with a relatively smaller fraction of valuable product. The processes require large amounts of material undergoing significant changes in conditions, leading to high investment costs and energy consumption. In addition, degradation and oxidation of

the solvents over time produces products that are corrosive and may require hazardous material handling procedures [8].

Amine Solvents

The currently preferred chemical solvent technology for carbon capture is amine-based chemical absorbent. CO₂ in the gas phase dissolves into a solution of water and amine compounds. The amines react with CO₂ in solution to form protonated amine (AH⁺), bicarbonate (HCO₃⁻), and carbamate (ACO₂⁻) [9]. As these reactions occur, more CO₂ is driven from the gas phase into the solution due to the lower chemical potential of the liquid phase compounds at this temperature. When the solution has reached the intended CO₂ loading, it is removed from contact with the gas stream and heated to reverse the chemical reaction and release high-purity CO₂. The CO₂-lean amine solvent is then recycled to contact additional gas. The flue gas must first be cooled and treated to remove reactive impurities such as sulfur, nitrogen oxides, and particulate matter. Otherwise, these impurities may react preferentially with the amines, reducing the capacity for CO₂, or irreversibly poisoning the solvent. The resulting pure CO₂ stream is recovered at pressures near atmospheric pressure. Compression, and the associated energy costs, would be required for geologic storage.

Alkanolamines, simple combinations of alcohols and ammonia, are the most commonly used category of amine chemical solvents for CO₂ capture. Reaction rates with specific acid gases differ among the various amines. In addition, amines vary in their equilibrium absorption characteristics and have different sensitivities with respect to solvent stability and corrosion. Alkanolamines can be divided into three groups [10]:

- Primary amines, including monoethanol amine (MEA) and diglycolamine (DGA)
- Secondary amines, including diethanol amine (DEA) and diisopropyl amine (DIPA)
- Tertiary amines, including triethanol amine (TEA) and methyldiethanol amine (MDEA)

MEA, relatively inexpensive and the lowest molecular weight, is the amine that has been used extensively for the purpose of removing CO₂ from natural gas streams. MEA has a high enthalpy of solution with CO₂, which tends to drive the dissolution process at high rates. However, this also means that a significant amount of energy must be used for regeneration. In addition, a high vapor pressure and irreversible reactions with minor impurities such as COS and CS₂ result in solvent loss [8].

Research on improved chemical solvents seeks a high absorption capacity for CO₂ without a corresponding large energy requirement for regeneration. Other desirable properties include high chemical stability, low vapor pressure, and low corrosiveness. It has been shown that solvents based on piperazine-promoted K₂CO₃ can have reaction rates approaching that of MEA, but currently have lower capacity [11]. Sterically-hindered amines have been developed with similar capacity and possibly less regeneration energy requirement than conventional MEA absorbents [9]. These modified

amines attempt to balance good absorption and regeneration characteristics under some conditions due to the reduced chemical stability of the amine-CO₂ anion [9]. Controlled species selectivity is also possible with these compounds.

Physical Absorption

Absorbents allow a gas to permeate a solid or liquid under one set of conditions, and desorb under others. The rate of absorption or desorption is temperature and pressure dependent. Smaller differences in conditions require less energy, but require more absorbent to capture CO₂ at an equivalent rate.

Physical Solvents

Absorption in most current physical solvent systems occurs at high partial pressure of CO₂ and low temperatures. The solvents are then regenerated by either heating, pressure reduction, or a combination of both. The interaction between CO₂ and the absorbent is weak relative to chemical solvents, decreasing the energy requirement for regeneration. Capacity can be higher than chemical solvents, since it is not limited by the stoichiometry of the chemical system.

Physical solvent scrubbing of CO₂ is well established. Selexol, a liquid glycol-based solvent, has been used for decades to process natural gas, both for bulk CO₂ removal and H₂S removal [5]. Glycol is effective for capturing both CO₂ and H₂S at higher concentration. However, the CO₂ is released at near atmospheric pressure, requiring re-compression for transportation and geologic storage. The Rectisol process, based on low-temperature methanol, is another physical solvent process that has been used for removing CO₂. Glycerol carbonate is interesting because of its high selectivity for CO₂, but it has a relatively low capacity [12].

Mixed Chemical-Physical Solvents

Some CO₂ capture applications benefit from a mixture of physical and chemical solvents. The most commonly used examples are Sulfinol, a mixture of the physical solvent sulfolane and the amines DIPA or MDEA, and Amisol, a mixture of methanol and secondary amines. These hybrid solvents attempt to exploit the positive qualities of each constituent under special conditions.

Physical Adsorption

Physical adsorption relies on the affinity of CO₂ to the surface of a material under certain conditions without forming a chemical bond. Adsorbents can separate CO₂ from a stream by preferentially attracting it to the material surface at high pressures through weak interactions such as van der Waals forces. During capture, the chemical potential of the adsorbed CO₂ is lower than the chemical potential of CO₂ in the gas mixture.

Regenerable Physical Adsorbents

Regenerable adsorbents must have the ability to reverse the chemical potential of the adsorbed phase upon changing the conditions to remove the CO₂. This is done primarily through changes in pressure or stripping with an easily separable gas such as steam. Limited temperature changes can improve efficiency, but take time cycle due to the heat capacity of the adsorbent material. Since adsorption is a surface phenomenon, a successful adsorbent will have a high surface area to volume ratio. The central advantage of physical adsorption methods is the possibility for low energy requirement to regenerate the sorbent material and the quick regeneration time associated with changing the pressure.

Proposed adsorbents include activated carbon [13], zeolites (molecular sieves) [14,15,16], and promoted hydrotalcites. Current zeolite systems can produce nearly pure streams of CO₂, but have high energy penalties due to vacuum pumps and dehumidification equipment [17]. Hydrotalcites are most effective at high temperatures (450-600 K), enabling capture inside or near combustion or gasification chambers [18,19]. Research is required to decrease the pressure difference requirement and increase the capacity of current adsorbents.

Membrane Separation Processes

Membrane systems include thin barriers that allow selective permeation of certain gases, allowing one component in a gas stream to pass through faster than the others. Membrane separation can be considered a steady-state combination of adsorption and absorption. A successful membrane allows the desired gas molecule to adsorb to the surface on one side, often at higher pressure. The molecule then absorbs into the membrane interior, eventually reaching the other side of the membrane where it can desorb under different conditions, such as low pressure.

Membrane gas separation processes have been widely used for hydrogen recovery in ammonia synthesis, removal of CO₂ from natural gas, and nitrogen separation from air. Each of the membranes used in these capacities could be applied to carbon capture. Commonly used membrane types for CO₂ and H₂ separation include polymeric membranes, inorganic microporous membranes, and palladium membranes [5]. Polymeric membranes, including cellulose acetate, polysulfone, and polyimide are the most commonly used for separation of CO₂ from nitrogen, but have relatively low selectivity to other separation methods [20]. Inorganic membranes, able to withstand high temperatures, are capable of operating inside combustion or gasification chambers [21]. Membrane reactors based on inorganic membranes with palladium catalyst can reform hydrocarbon fuels to mixture of H₂ and CO₂ and at the same time separating the high-value H₂ [22]. Combining membranes with chemical solvents has also been proposed [23]. Despite an extra energy requirement, this arrangement may eliminate problems associated with direct contact between the liquid solvent and gas mixture.

Most membranes have inherent difficulty achieving high degrees of gas separation due to varying rates of gas transport. Stream recycling or multiple stages of membranes may be necessary to achieve CO₂ streams amenable to geologic storage, increasing energy consumption [24]. However, the potential for high surface area could reduce the chemical potential difference required to drive gas separation.

Chemisorption

Gas molecules can chemically bond to the surface of some materials. The process is called associative if the molecule bonds in whole to the surface and dissociative if the gas molecule breaks up in order to form a bond. Chemisorbents are often composed of an active surface layer supported by an inert substrate. Proposed systems use small particles as substrates in order to provide large surface area. Regeneration drives the chemical reaction in reverse, often at elevated temperature.

Metal Oxide Air Separation

Air separation allows a pure stream of oxygen to react with the fuel, creating an effluent of only CO₂ and water or other useful products such as hydrogen. It is often easier with current technology to separate CO₂ from water or hydrogen than from nitrogen. Reactive metal exposed to air will oxidize rapidly. The metal oxidation reaction is highly exothermic ($\Delta H_{OX} \sim -950$ kJ/mol). The oxides can then be endothermically ($\Delta H_{RED} \sim -150$ kJ/mol) [25] regenerated by exposing them to a high temperature reducing environment. The oxygen combines with the fossil fuel to form carbon oxides and varying amounts of hydrogen-containing species depending on the type of fuel. The chemistry and geometry of this separation has allowed recent small-scale studies to obtain a nearly 100% pure stream of oxygen to react with the fuel [6]. Phase separation of water from the resulting effluent could produce a pure stream of CO₂. This complete process is commonly called chemical looping separation.

Research in metal oxide air separation is focused on cost and the physical and chemical stability of the oxygen carriers over many cycles. The particles usually consist of a reactive oxide and a supporting inert oxide. While various oxygen carrier particles are under consideration, copper, iron, manganese, and nickel are the most promising reactive metals [6].

No large-scale demonstration has been performed, but models predict that a power system utilizing metal oxide air separation has significant advantages. The lower irreversibilities associated with the regeneration step relative to conventional combustion add to the already low energy requirement of the inherent separation of CO₂ from nitrogen. Exergy analyses show the resulting overall energy penalty could be as low as 400 kJ/kg CO₂ for a natural gas combined cycle plant, assuming idealized chemical stability of the oxygen carrier [25].

Dry Chemical Absorbents

Under some conditions, CO₂ can undergo a reversible chemical reaction with a dry absorbent material. The chemical reaction can be reversed by changing the conditions, resulting in the release of pure CO₂. Sodium carbonate supported on an inert particle has been proposed as such an absorbent. An exothermic reaction of sodium carbonate with CO₂ and water held at 60 to 70°C forms primarily sodium bicarbonate and Wegscheiderite [26]. The products must be heated to 120 to 200°C to reverse the reaction. Lithium zirconate is also being investigated for its high capacity chemisorption separation of CO₂ at high temperatures [27,28].

Chemical Bonding

Some gas separation technologies use materials that create stable, thermodynamically favored chemical bonds with a gas in a mixture or a gas in solution. These materials can either be endothermically regenerated and used in a loop much like the sorbent technologies or form stable waste materials to be stored.

CO₂ Mineralization

Some minerals will undergo thermodynamically favorable reactions with CO₂, separating it from a gas stream and forming a stable, chemically bonded product. Although most proposed cycles have problems with kinetics due to the relatively low enthalpy of reaction, separation and conversion to a stable storage medium is accomplished in one step. Open-ended cycles such as this have the advantage of not requiring regeneration. The reactant minerals can be considered a separate resource that provides the energy requirement for separation.

One proposed method involves a reaction of CO₂ with CaCO₃, or limestone, and water to form calcium and bicarbonate ions. These ions can be deposited into the ocean, short-circuiting the residence of carbon in the atmosphere [29]. Another method proposes enhancing the otherwise slow mechanism of silicate weathering. A gas stream containing CO₂ could react with magnesium silicate to form magnesium carbonate and pure silicate [30]. The large volumes of material involved present significant challenges for transportation and handling.

Phase Separation

Below certain temperatures, gas molecules are moving slow enough to succumb to weak intermolecular forces. Depending on the partial pressure of other gases in a mixture, condensing gases will form a distinct phase with a composition different from that of the vapor that is easily separated.

Cryogenics

When gases have different boiling temperatures, they can be separated by cooling them until they separate into different phases. Cryogenic processes such as these are widely used to separate gases into very pure streams [10]. CO₂ can be frozen at 195 K and atmospheric pressure, or pressurized past its critical point at about 304 K and 74 bar to form a liquid. Bringing a 10% CO₂ fossil fuel conversion effluent stream to the critical point of CO₂ has theoretical energy requirement of about 1.9 MJ/kg CO₂⁴. With real devices, this could represent a significant energy penalty, unless liquid CO₂ is already required for transport. Another difficulty is that water must be removed before cooling or it will form a solid, possibly disrupting the process.

Another option for using cryogenics for carbon capture is the separation of oxygen from nitrogen in air for oxy-fuel combustion. Combustion reactions are then performed with pure oxygen, rather than air, so that the primary combustion products are CO₂ and water. This method has the advantages of simple separation of CO₂ from water later in the process to obtain a pure CO₂ stream. The air is cooled until the nitrogen becomes a liquid. This occurs at about 77 K at atmospheric pressure, with an energy requirement of about 700 kJ/kg air⁵, corresponding to over 1 MJ/kg CO₂ for this portion of the process, not including other necessary separations.

CO₂ Clathrate

Clathrates are a phase of water in which the hydrogen-bonded structures encapsulate “guest” molecules of gas. The preferential formation of CO₂ clathrate over other fossil fuel conversion effluent gases could be used as a method to capture CO₂. The CO₂ clathrates could later be dissociated, producing a pure stream of CO₂. Formation of CO₂ hydrates occurs at about 140 atm and at temperatures near the freezing point of water. The high pressure and heat removal requirement to keep the temperature near 273 K during the phase change has been modeled using practical device efficiencies to correspond to an energy loss of about 3 MJ/kg CO₂, including an attempt to recover the compression work through a turbine [31].

Conclusions

Progress toward more efficient and lower cost carbon capture from large point sources is constrained primarily by technological progress in gas separation. Few developed energy conversion processes have efficiencies as low as current CO₂ capture technology. A comparison of published energy requirements for current capture technologies to the theoretical minimum energy requirement for separation from a flue gas stream of less than 200 kJ/kg CO₂ indicates that there is the potential for significant progress to be made in CO₂ capture technology.

⁴ Difference between results of non-flow exergy expression for mixture properties at STP and critical point of CO₂ [32]

⁵ Isobaric reversible cooling

Fundamental research taking advantage of recent advances in chemistry and materials engineering may improve one of the physical processes discussed or adapt a yet unconsidered process to carbon capture. High selectivity, separation rate, and capacity are often coupled with high energy input in current technology. Improved capture technologies could reduce this dependence, leading to smaller, more efficient systems. Opportunities for advances in materials to improve current capture technologies include higher capacity adsorbents and increased membrane selectivity. Research enabling improved compounds for chemical separation processes could decrease energy requirements and increase stability. Chemical solvent separation could benefit from compounds with high capacity and lower regeneration energy.

While several carbon capture methods are commercially mature for use in niche markets, application on a scale necessary to impact global CO₂ emissions may lead to unacceptable increases in the cost of plant operations unless the current techniques can be significantly improved or new approaches are developed. The relatively recent emphasis on improving carbon capture and the historical progress of other energy conversion processes suggests that, with intensive research, improved capture technologies can be developed to help reduce carbon dioxide emissions to the atmosphere.

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Appendix A: Ongoing Projects

The following research programs give an indication of the range of research underway in the area of CO₂ capture:

Australia: Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)

- The Australian project, CO2CRC, is a complex collaboration that involves many research participants (including a number of universities), industrial sponsors and research participants, and CSIRO (the national laboratory system for Australia). There are technical programs in “Storage R&D,” “Capture R&D,” and “Demonstration and Regional R&D.” Included in the Capture R&D area are the following projects. For details, see http://www.co2crc.com.au/RESEARCH/research_capture.html.
- Performance of Novel Equipment for Solvent Absorption Systems – University of Melbourne – solvent systems, column internals, cost evaluations.
- Innovative Membrane Systems –University of Melbourne, University of New South Wales – glassy polyimide gas-separation membranes at elevated temperature, plasticization and effect of other gas components characterizing structure and performance of 6DFA polymer systems, optimization of membrane module design.
- Innovative Pressure Swing Adsorption Systems – Monash University – laboratory and pilot-scale experiments to test adsorbents for various gas feedstocks, novel adsorbents of nanocomposite mesoporous solids with chemically modified surfaces, inorganic-organic hybrid membranes, electrically regenerable adsorbent carbons.
- Hydrate Formation and Cryogenic Distillation Systems – Curtin University of Technology – evaluate hydrate systems and cryogenic systems for cost effectiveness.
- Capture of CO₂ in Brines and Minerals – CSIRO Minerals.
- Metal Activated Conversion of CO₂ – University of Adelaide.

Canada: CO₂ Capture and Storage Activities

- An International Test Centre for CO₂ Capture has been established with two components, a pre-commercial scale chemical absorption demonstration pilot plant (at the Boundary Dam power plant) and a smaller technology development pilot plant at the University of Regina. The Boundary Dam project will investigate commercially available solvents, while the plant at the University of Regina will develop new solvent technologies. Pilot-scale O₂ combustion with

CO₂ recycle is also being investigated. For a summary of activities in this project, see <http://www2.nrcan.gc.ca/es/oerd/english/View.asp?x=649&oid=25>.

- The CANMET CO₂ Consortium is investigating oxy-fuel combustion capture for retrofit to existing pulverized coal power plants. Computer simulations of flames and burners.
- Several geologic storage projects are also underway.

Europe: Fifth and Sixth Framework Programs

- The EU funds research in carbon capture through calls for proposals in specific areas. Under the Fifth Framework Program, work was done on amine post-combustion capture and on membranes for air separation to produce O₂ for natural gas combustion. The Sixth Framework Program includes work on post-combustion and pre-combustion capture (as well as geological storage of CO₂ and chemical/mineral sequestration). Specific projects are:
 - Enhanced Capture of CO₂ (ENCAP) – work being performed by a large team of contractors led by Vattenfall. Many companies and several national labs are involved. Universities involved include Chalmers University of Technology, Norwegian University of Science and Technology, University of Stuttgart, University of Twente, University of Ulster, and Universität Paderborn – work is being done on cryogenic O₂ production for oxy-fuel applications, non-cryogenic O₂ production technologies, chemical looping combustion, and high temperature O₂ generation for power production, using applications of polymer and ceramic membranes.
 - CO₂ from Capture to Storage (CASTOR) – the Institut Francais du Petrole leads another large team of contractors, companies, national labs and universities. Universities include Norwegian University of Science and Technology, University of Stuttgart, and University of Twente. 65% of the effort is to go to development of absorption liquids, with the remainder on geologic storage sites (Casablanca field, Snohvit, and K12b, and a depleted gas reservoir in Austria).
 - Innovative In Situ CO₂ Capture Technology for Solid Fuel Gasification (ISCC) – the University of Stuttgart leads a team of company, national lab, and university contractors. The universities include National Technical University of Athens, Wroclaw University of Technology, University of Ulster, Technical University of Brandenburg-Cottbus – high temperature sorbents for application to gasification of low-rank brown coals.

Japan: Carbon Capture Research

- Research is being conducted on CO₂ separation at the Research Institute for Innovative Technologies for the Earth (RITE), including research on use of

polymer composite membranes, zeolite membranes, absorption/hybrid membranes, and amine-anchored mesoporous silica. Research on geologic storage is also being done at RITE.

US DOE Program in Carbon Capture

- CO₂ Capture Project – This is a project funded partly by DOE and partly by eight companies, with subprojects conducted at a variety of universities, companies and national labs in the US and Europe. The first phase is now complete, and a book that summarizes results is to be published soon. The work has included components that have investigated assorted separation techniques, including improved solvents, membrane separations for hydrogen, integrated hydrogen generation designs that allow CO₂ capture, and oxy-fuel combustion.
- Advanced Oxy-fuel Boilers and Process Heaters – Praxair and Alstom Power – ceramic oxide O₂ transport membranes, laboratory-scale designs.
- CO₂ Capture for Pulverized Coal Boiler Using Flue Gas Recirculation – Argonne National Laboratory – evaluate process designs for O₂ combustion with recycle of CO₂ to control operating temperatures.
- Oxygen Firing in Circulating Fluidized Bed Boilers – Alstom Power, ABB Lummus Global, Praxair, Parsons Energy and Chemicals Group – O₂ combustion in a circulating fluidized bed combustor.
- CO₂ Separations Using Hydrates – Nexant, Los Alamos National Laboratory, Simteche – use high pressure, low temperature separation of solid hydrates to capture CO₂.
- CO₂ Capture from Flue Gas Using Dry Regenerable Sorbents – Research Triangle Institute, Church and Dwight, Inc., Louisiana State University – alkali carbonates are reacted to produce bicarbonates, physically separated and then regenerated by heating.
- CO₂ Capture by Absorption with Potassium Carbonate – University of Texas – add piperazine (an amine) to K₂CO₃ to improve absorption kinetics and reduce the heat of absorption (and therefore the recovery heat requirements).
- CO₂ Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO₂ – Media and Process Technology, Inc., and the University of Southern California – deposit hydrotalcite on ceramic membranes using sol gel and chemical vapor deposition technologies. Use the CO₂ adsorption properties of the hydrotalcite to remove CO₂ in shift reaction systems at high temperature.

- CO₂ Separation using Thermally Optimized Polymer Membranes – Los Alamos National Laboratory, Idaho National Engineering and Environmental Laboratory, Pall Corporation, University of Colorado, Shell Oil Company – polymer-metal hybrid membranes for CO₂ separation at high temperature (100 to 450 C) and high pressure (10 to 150 bar).
- An Integrated Modeling Framework for Carbon Management Technologies – Carnegie Mellon University – develop a systematic framework for characterizing the
 - performance and cost of alternative carbon capture and sequestration
 - technologies applicable to a broad range of electric power systems.
- Conceptual Designs of Optimized Fossil Energy Systems with Capture and Sequestration of CO₂ – Princeton University -- develop new analytic and simulation tools to model the design and evolution of fossil energy systems with CO₂ sequestration.
- Development of Pressure Swing and Temperature Swing Adsorbents – National Energy Technology Laboratory, Carnegie Mellon University, Sud Chemie – zeolites with high sodium concentrations and an undescribed new sorbent.
- The Zero Emission Coal Alliance is a US-Canadian consortium of 18 organizations investigating a coal gasification concept that captures CO₂ with CaO, uses H₂ produced in a fuel cell, uses waste heat from the solid oxide fuel cell to regenerate CaO, and reacts with magnesium silicates to make stable minerals, which are then returned to the site where the magnesium silicates are mined. A feasibility study has been completed.