Research Roadmap of Technologies for Carbon Sequestration Alternatives

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Renewable Energy Technologies
- Transportation

Research Roadmap of Technologies for Carbon Sequestration Alternatives is the final report for the Roadmap on Innovative Technologies and Concepts for Beneficial CO_2 Use project (Contract Number 500-02-004, Work Authorization Number 1014) conducted by the California Institute for Energy and Environment, University of California. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

This research roadmap reviews existing and developing technologies for the use of carbon dioxide to provide recommendations to the California Energy Commission on the further development and implementation of such technologies. The roadmap reviews and categorizes the known usage technologies currently in use or under development. Uses of carbon dioxide range from well-developed applications, such as enhanced oil recovery, to much less mature technologies, such as the use of carbon dioxide to produce fine chemicals, chemical feedstocks, working fluids for energy-related technologies, and building materials. This roadmap outlines various attributes of technologies such as technology maturity and readiness, the amount of carbon dioxide that would be consumed or used if fully deployed, technology gaps and barriers to full deployment, and the companies or organizations pursuing development of the technologies. This information is then used to highlight technological advances that are needed to overcome existing barriers to deployment. The report also reviews funding from federal sources and examines the potential for California to leverage synergistic federal funding to promote investment in and deployment of usage technologies within the state. This report also discusses the relevance of carbon dioxide usage technologies to California's greenhouse gas reduction goals.

Keywords: Beneficial uses of carbon dioxide, carbon management, carbon capture and storage, carbon dioxide utilization

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EXECUTIVE SUMMARY

This research roadmap is designed to guide the California Energy Commission in defining future funding priorities for carbon dioxide use or carbon dioxide beneficial use technology research and development. The primary focus is on technologies that can potentially help California meet its greenhouse gas emissions reductions goals as defined by the Governor's Executive Order S-3-05 in 2005 and Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006). In-state industrial sources include refineries, cement plants, and natural gas power generators; out-of-state sources are large coal-fired power plants importing power into the state and high-carbon fuelstocks for refineries. Recommended technologies are those that are both expected to reach commercialization commensurate with the time frames set for California's emissions goals in 2020 and 2050 and that also have the potential to make significant contributions to greenhouse gas reductions.

For this roadmap, beneficial use or carbon dioxide usage is defined to include technologies that produce a useful product directly from captured anthropogenic, or man-made, carbon dioxide or in connection with the processes of capture or sequestration of carbon dioxide. By this definition, capture technologies are out-of-scope unless they produce a product as part of the capture process. Geologic sequestration, likewise, is not included except in cases where something of value, such as additional oil, gas, geothermal heat, or water, is a by-product.

A Roadmap Working Group was created to establish the assessment methods and knowledge base necessary to advise the roadmap. The members consist of experts in energy technology commercialization, in beneficial use technology research and development, and in carbon capture and sequestration technology development and deployment. From the information base, an impartial committee of reviewers helped the Roadmap Working Group rank the technologies.

To evaluate the range of beneficial use technologies, the Roadmap Working Group established a set of parameters to define the current status for each technology. To assemble the knowledge base to advise the roadmap, the Roadmap Working Group searched the published literature using science and technology search tools available through the national laboratories and the University of California libraries, performing Web searches, interviewing technology developers and vendors, and performing patent searches. In addition, program managers of previous and existing beneficial use research and development programs were contacted to establish lessons learned and opportunities for leveraging any future California investments.

To make evaluating each technology easier, inputs to the process (carbon dioxide and other components including water), process attributes, and outputs from the process (product and other components, including waste products) were identified. Attributes of the process included identifying existing suppliers/developers and opportunities to deploy the process within California. These factors were then supplemented with additional parameters specific to each technology and used to rate technology readiness, barriers to deployment, knowledge gaps, maturity, and availability of lifecycle analyses, environmental impact, water use, and economic benefits.

Table E-1: Categories of Beneficial Use Technologies

CATEGORIES	TECHNOLOGY DESCRIPTION
CO_2 as a working fluid	Enhanced oil recovery (EOR) Enhanced gas recovery (EGR) Enhanced coal bed methane recovery (ECBM) Enhanced geothermal systems (EGS)
CO_2 for Building Materials Manufacture	Carbonates and other construction materials
Biochar	Pyrolysis of biomass
Fuel and Chemical Production	Chemical Conversion Biological Conversion
Power Generation Applications	Supercritical CO_2 for Brayton Cycle Turbines Working fluid / cushion gas for energy storage
CO_2 as a Solvent	Supercritical fluid extraction and other food processing applications Dry cleaning
CO_2 in Agriculture and Biomedical Applications	Greenhouse atmosphere additive Grain silo fumigant Sterilization for biomedical applications
Miscellaneous Industrial Applications	Fire extinguishers Shielding gas for welding Refrigeration and heat pump working fluid Propellant
	Rubber and plastics processing - blowing agent Cleaning during semiconductor fabrication
Water From Displaced Aquifer Fluids	Water purification Extraction of value-added solids from Water

The first finding in the research team's analysis is that there is currently no systematic set of data or existing method to enable comparison of various technologies. Each technology has key advantages and disadvantages, but its relative importance can only be qualitatively inferred. This is particularly problematic when comparing direct uses, such as working fluids, with indirect uses such as fresh water production from saline aquifer fluids. A lifecycle analysis laying out the relative merits in a quantified way is needed for each technology.

CHAPTER 1:
Summary of the State of Research and Development in Beneficial CO2 Use Technologies

1.1 Introduction

1.1.1 Definition of "Beneficial Use" used for this Roadmap

For the purposes of this roadmap, beneficial use is defined to include CO_2 utilization technologies that produce a useful product directly from anthropogenic CO_2 or indirectly in connection with the processes of capture or sequestration of CO_2. By this definition, capture technologies are out-of-scope unless they produce a product as part of the capture process. Geologic sequestration likewise is not included except in cases where something of value, such as additional oil, gas, geothermal heat, or water, is a byproduct. The terms "beneficial use" and "CO_2 utilization" are used synonymously within this report.

1.1.2 Objectives of the Roadmap

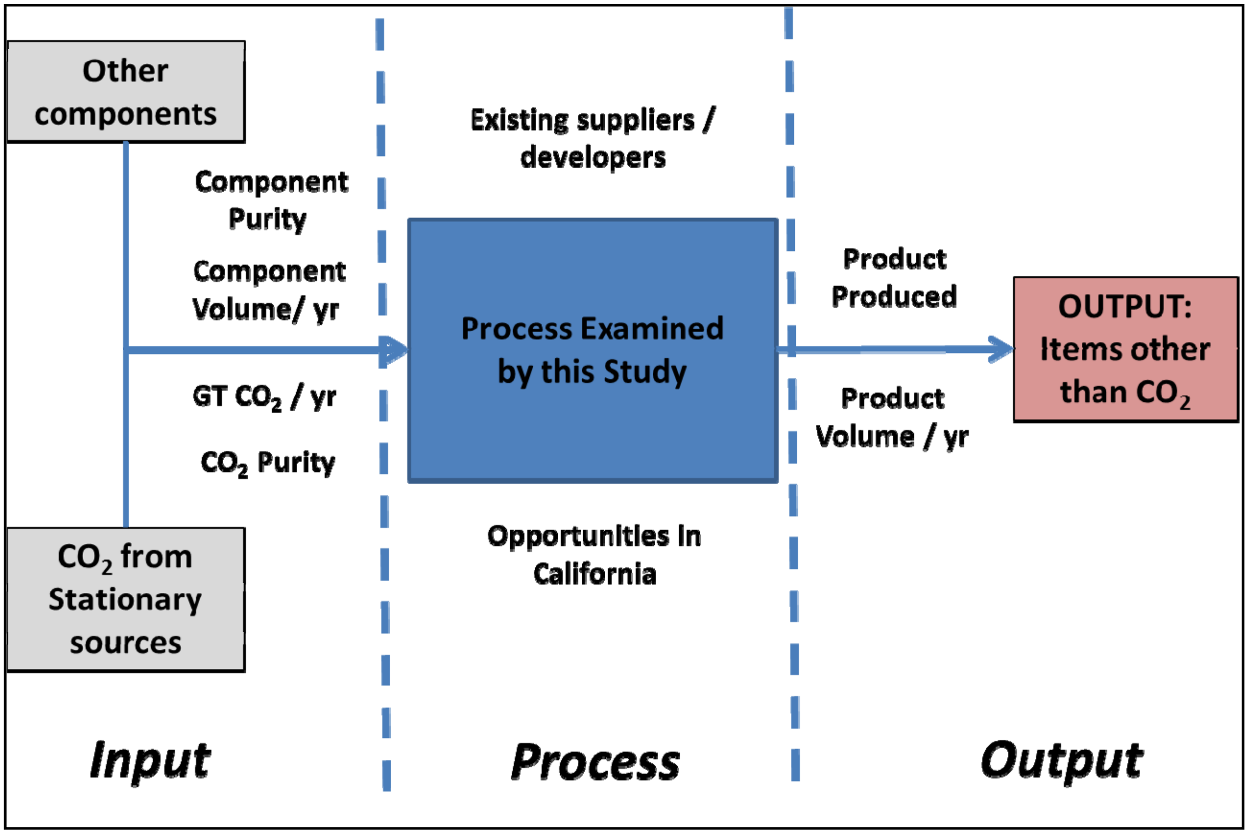
This roadmap is designed to provide guidance to the Energy Commission to define future funding opportunities in the area of beneficial use of CO_2. It is important to note that the roadmap is not comprehensive of all technologies. It is designed to focus on technologies that have the potential to assist California in meeting its greenhouse gas emissions reductions goals as defined by the Governor's Executive Order S-3-05 in 2005 and Assembly Bill 32 (AB 32). Technologies must be suitable to the California context, including the types of industrial sources that contribute to the state's greenhouse gas emissions. In-state industrial sources include refineries, cement plants and natural gas power generators; out-of-state sources are large coal-fired power plants importing power into the state and high-carbon fuel stocks for refineries. Technologies must also be expected to reach commercialization commensurate with the time frames set for California's emissions goals (2020 and 2050) and to be able to make significant contributions to greenhouse gas reductions. Technologies may contribute to reductions directly by permanently sequestering significant quantities of anthropogenic CO_2, indirectly by displacing the use of fossil fuels, or by creating local economic benefits that might offset any economic burden associated with hosting a geologic sequestration site.

1.1.3 Methods for Assessing State-of-the-Art

A Roadmap Working Group (RWG) was created to establish the assessment methods and knowledge base necessary to inform the roadmap. The members consisted of experts in energy technology commercialization, in beneficial use technology research and development, and in carbon capture and sequestration technology development and deployment. From the information base, an impartial committee of reviewers assisted the RWG in ranking of the technologies.

To evaluate the range of beneficial use technologies, a set of parameters was established by the Roadmap Working Group to define the state-of-the-art for each technology. The rationale behind these parameters can best be described by the schematic shown in Figure 1. Inputs to the use process are CO_2 from stationary sources along with other feedstocks or components, such as water. Key metrics for the input components are factors such as the level of impurities, annual volumes of the CO_2 and other components required for the process. The CO_2 purity level and annual volume of CO_2 are especially important parameters since they indicate the impact the process can make on achieving legislated reduction goals in CO_2 levels.

Figure 1: Methodology Used to Analyze Beneficial Use Technologies



For evaluating each technology, inputs to the process (CO_2 and other components), process attributes, and outputs from the process (product and other components, including waste products) were identified.

Attributes of the process that were considered include whether there are existing suppliers/developers and if there are opportunities to deploy the process within California. These factors are especially important in considering the potential impact of the technology in California.

It was also important to examine the outputs from the process, including saleable products and waste product streams. These factors provide additional insights into how these technologies might impact California’s resources, economy, and environment.

These factors were then supplemented with additional parameters to be able to rate technology readiness, time to commercialize, barriers to deployment, knowledge gaps, maturity, availability of lifecycle analyses, environmental impact, water use, and economic benefits. The full set of parameters used to define the state-of-the-art of CO_2 utilization technologies is shown in Table 1.

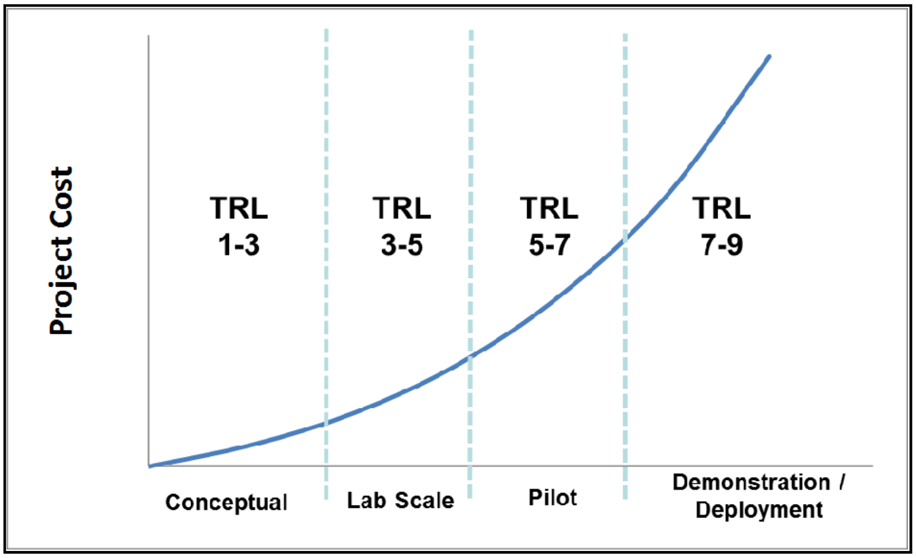
Table 1: Parameters for Defining Beneficial Use Technologies

Parameter	Factors
Technology Maturity	Technology Readiness Level (TRL)
Input to Process	Attributes of CO_2 required, especially amount of CO_2 utilized by process
	Attributes of additional components, especially indicating any water usage
Output from Process	Attributes of Product Produced
Time Frame for Commercial Viability	Less than 10 years
	Greater than 10 years
Environmental impacts	Potential impact on air emissions, disposal of used components, etc.
Economic Benefit	Job creation / growth of new or existing industries in California
Federal Investment	Status of previous and existing federal investment in RD&D of technology
Barriers to deployment	Example: Technology / Regulatory / Economic based factors that limit deployment of technology
Knowledge gaps	Knowledge or know-how hindering the removal of barriers
Suppliers	Existing developers / suppliers for the technology

The Technology Maturity scale used in this analysis is the Technology Readiness Level (TRL) scale developed by NASA, now widely used by the Department of Defense (DoD) and other agencies to assess the relative maturity of a particular technology. It is viewed as one component of a risk-reduction measure and creates a "common language" that facilitates the integration and comparison of technologies from various universities or research labs (for example NRL, ARL)[1] . The definition for each TRL is shown in Appendix A[2].

The TRL scale also is related to the relative time to commercialize the technology. New energy technologies typically mature as they are transitioned from a conceptual, to lab scale, to pilot scale, and finally to demonstration and deployment. The transition from lab to pilot scale is particularly critical since this indicates evaluation in the field, for example at a power generation site. It is not uncommon for energy technologies to perform acceptably in a laboratory environment, yet only to fail when tested at a pilot scale level. Project costs and manpower requirements commonly increase significantly during this transition out of the controlled laboratory environment. The relationship between TRL, scale, and relative project cost is illustrated in Figure 2.

Figure 2: Relationship for Energy Projects between TRL and Project Scale and Costs



Source Energy Commercialization, LLC

Project costs are shown by the blue curve, increasing significantly as technologies move through TRL stages from conceptual to demonstration. Each TRL is associated with a range of three numbers within each stage, collectively ranging from 1 to 9.

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[1] Graettinger, C; S. Garcia, J. Siviy; R. Schenk; P. Syckle, Using the "Technology Readiness Levels" Scale to Support Technology Management in the DoD's ATD/STO Environments", conducted for Army CECOM, CMU/SEI-2002-SR-027, August 2002.

[2] http://esto.nasa.gov/files/TRL_definitions.pdf

Technology risk and the time to commercialize (for example full deployment) are reduced as projects move from the left side of the horizontal axis to the right side. The TRL ranking is a means to determine the relative time scale to commercialize the technology (for example <3 years, 3-10 years, or greater than 10 years). For the purpose of this roadmap, considering the time scales of relevance to California's greenhouse gas emissions reduction goals, this ranking was simplified to two categories: less than 10 years and more than 10 years.

Technology risk is just one of the barriers to commercialization of new energy technologies. Groups have previously discussed the "three-legged stool" of barriers to the deployment of new energy technologies: technology, regulatory, and economics[3]. All three factors must be aligned to successfully launch new products into the energy marketplace. For example, if a technology meets technical performance, meets regulatory requirements, but has unacceptable process economics, it will not be commercialized. Typical technology, regulatory, and economic barriers include:

- Technology: unable to scale process to meet feed stream volumes or unable to achieve acceptable performance, for example product purities
- Regulatory: regulations that either impede the deployment of the technology or favor the deployment of competing technologies
- Economics: process economics are unacceptable for the market place

It was also important to indicate "gaps in knowledge that would be required to improve process economics or enable the process to meet regulatory requirements. These gaps could be "direct" or "indirect". Direct gaps would require R&D specifically targeted at a given process. In comparison, indirect gaps reflect R&D that could be performed for other processes or even other applications and still enable the process to achieve process economics or regulatory goals.

Environmental impacts, water usage, and economic benefits are critical to assess the overall benefits to California if these technologies are deployed. Assessments of these parameters are derived from factors previously examined. This provides a holistic look at the impact of these processes on California and Californians.

1.1.4 Methods for Researching

To assemble the knowledge base to inform the roadmap, the RWG undertook a search of the published literature using science and technology search tools available through the national laboratories and University of California libraries, performed web searches, interviewed technology developers and vendors, and performed patent searches. In addition, program managers of previous and existing beneficial use R&D programs were contacted to establish lessons learned and opportunities for leveraging any future California investments.

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[3] Concept originally introduced by Stu Dalton, EPRI, Director of Generation Sector, at the Western States Commission in May 2006.

1.1.5 Other Issues for Evaluating Technologies

Our investigations revealed that there currently are no systematic data or methodologies for comparing the various beneficial use technologies. Each technology has key advantages and disadvantages, but their relative importance can only be qualitatively inferred. This is particularly problematic when comparing direct uses such as working fluids with indirect uses such as fresh water production from saline aquifer fluids. A life-cycle analysis is needed for each technology that lays out its merits in a quantified way. Such analyses for beneficial use technologies are either undeveloped or poorly developed for most of the technologies.

The life-cycle analysis for energy and carbon for some technologies can be particularly complex (for example the actual carbon footprint of ethanol biofuel production remains a contentious topic after years of study). Some beneficial use technologies claim sustainability because their energy needs can be supplied by renewable power sources. But in these claims, the question that often remains unanswered is the relative advantage of using the energy to power the beneficial use technology versus putting the renewable power directly on the grid to reduce fossil fuel use elsewhere. In other cases, technologies convert captured carbon dioxide back to fuels or feed-stocks but through processes that are inherently inefficient thermodynamically both with respect to energy production and CO_2 capture. These inefficiencies must be overcome to make these types of technologies net-negative for carbon. Special circumstances would be needed to justify their development. The exceptions to this are technologies that use solar-powered biological processes to carry out the conversion, such as growth of algae in CO_2-enriched water. In these methods, the energy source is renewable and not otherwise convertible to a form that can be put on the transmission grid.

While life-cycle analyses are difficult and potentially contentious, they provide some of the most important data needed to identify the best directions for technology development. To address this gap, such an analysis should perhaps be required prior to funding further development of a technology or as a key deliverable of any proposal requesting funding for a specific beneficial use technology.

Many technologies may provide potential beneficial use of CO_2, but they can be dismissed for further research and development based on low impact on mitigating California's CO_2 emissions. Unless a technology can be expected to utilize and sequester on the order of millions of tons of carbon dioxide per year, it will not have an impact in reducing the state's CO_2 emissions and public investment in its development cannot be justified unless there are extenuating benefits. However, one exception is any technology that uses CO_2 to displace a more potent greenhouse gas such as a hydrofluorocarbon, in which case an estimate should be included of the impact of the displaced greenhouse emissions. Another is a technology such as biofuels that utilizes CO_2 in a way that replaces fossil fuel use but which does not sequester utilized CO_2.

We also included technologies that, if implemented, could displace fossil fuel-generated energy. For example, the use of carbon dioxide as a working fluid in geothermal systems has the advantages of sequestering CO_2 and creating renewable power. California has the largest geothermal power potential of any state, so development of this technology would preferentially benefit California.

CO_2 use in enhanced oil recovery (CO_2-EOR) is a mature technology but is rarely used in California due to a lack of available CO_2 supply. Use of CO_2-EOR could provide substantial new oil revenue to the state but would also boost the state's production of fossil fuels and any associated fugitive greenhouse gas emissions. The relative benefits of facilitating adoption of this technology should be studied carefully in the context of California's energy and carbon emissions reduction planning. The barriers to deployment of CO_2-EOR in California are economic and logistical. Widespread adoption would require construction of a robust pipeline network connecting California's oil fields with its CO_2 sources. Similar issues apply to use of CO_2 for enhanced natural gas recovery or as a cushion gas for natural gas storage, although these two technologies also might benefit from more extensive field pilot demonstrations within the state. For all of these technologies, research should be directed at determining options for facilitating deployment infrastructure rather than on technology development.

1.2 Categorizing Beneficial CO2 Use Technologies

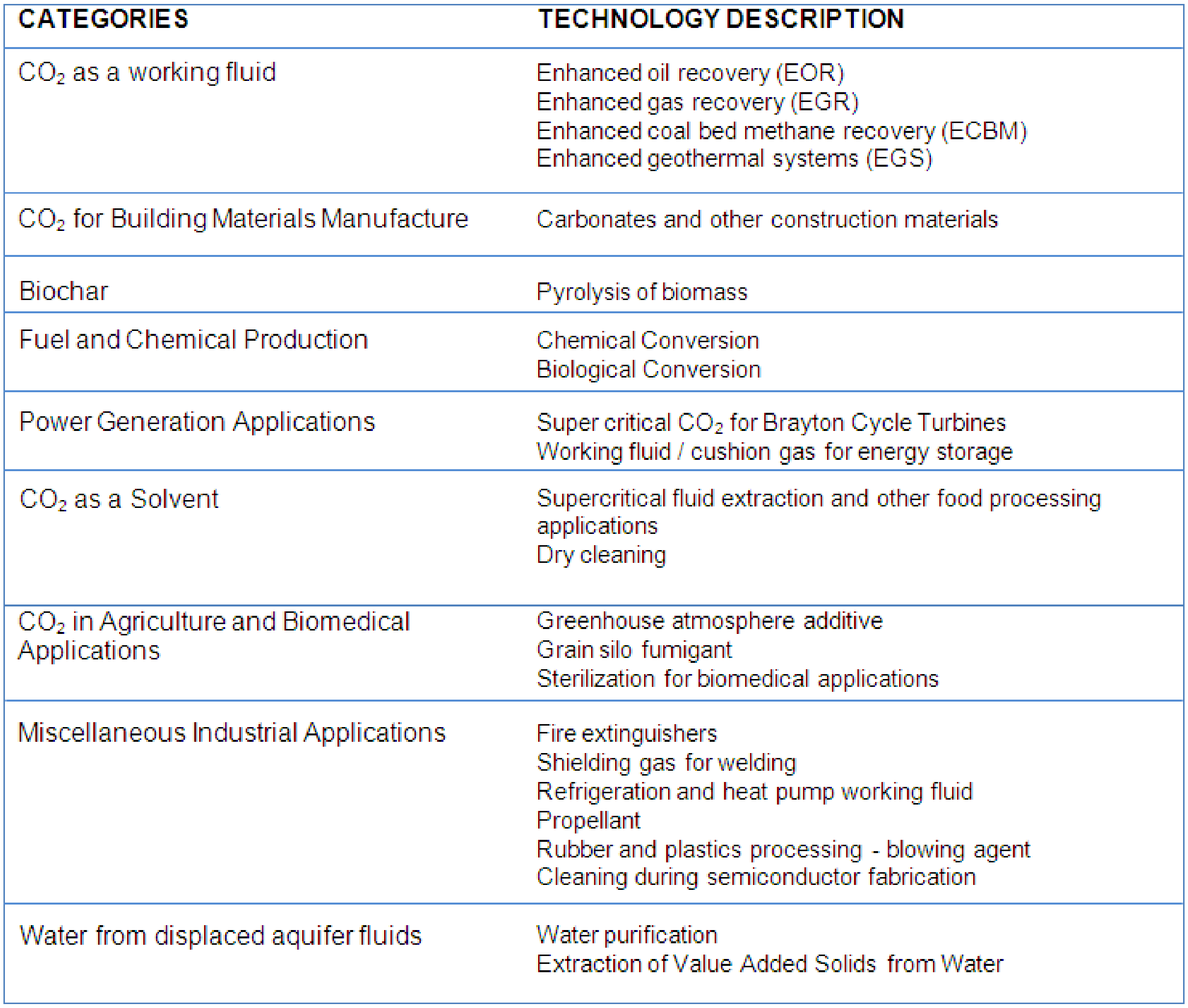
There has been a variety of definitions of beneficial CO_2 use technologies. The RWG found a wide variation in how these technologies were characterized by other funding agencies or organizations (for example, the definition of beneficial CO_2 use by the Department of Energy as described in Chapter 2 of this document). Due to the unique needs of the state of California, the RWG desired to examine a broad variety of use applications for CO_2, some not traditionally considered under the beneficial use category.

The categories established by the RWG are listed in Table 2. These categories are significantly broader than the traditional lists of beneficial use areas. The RWG included many traditional and long-standing industrial applications of CO_2, such as use of CO_2 as a solvent, as well as more recent applications considered as beneficial use (for example fuel and chemical production). Within each category, each technology was characterized using the parameters outlined in Table 1. Tables 3 through 8 show the characteristics for the categories listed in Table 2 using the parameters set forth in Table 1. Only public information (for example journal articles, patents, news releases, web sites, and so forth.) was used in this study.

One of the first parameters to be considered was the level of technology maturity using the scale discussed above. The technology maturity level varied widely across all the categories and even within categories. For example, when examining applications that use CO_2 as a working fluid in Table 3, CO_2-EOR technology is commercialized while all the other technologies are only at a pilot stage or less. Many of the technologies commonly categorized as beneficial use that are shown in Table 4 range in development from early demonstration to concept stage. The power generation applications in Table 5 are also very early stage.

As expected, many of the traditional applications for CO_2, shown in Table 6 and Table 7 are nearly or completely commercialized and are not typically included in beneficial use. The treatment of displaced water from aquifers, outlined in Table 8, is also very early in its development.

Table 2: Categories of Beneficial Use Technologies



CATEGORIES	TECHNOLOGY DESCRIPTION
CO_2 as a working fluid	Enhanced oil recovery (EOR) Enhanced gas recovery (EGR) Enhanced coal bed methane recovery (ECBM) Enhanced geothermal systems (EGS)
CO_2 for Building Materials Manufacture	Carbonates and other construction materials
Biochar	Pyrolysis of biomass
Fuel and Chemical Production	Chemical Conversion Biological Conversion
Power Generation Applications	Super critical CO_2 for Brayton Cycle Turbines Working fluid / cushion gas for energy storage
CO_2 as a Solvent	Supercritical fluid extraction and other food processing applications Dry cleaning
CO_2 in Agriculture and Biomedical Applications	Greenhouse atmosphere additive Grain silo fumigant Sterilization for biomedical applications
Miscellaneous Industrial Applications	Fire extinguishers Shielding gas for welding Refrigeration and heat pump working fluid Propellant Rubber and plastics processing - blowing agent Cleaning during semiconductor fabrication
Water from displaced aquifer fluids	Water purification Extraction of Value Added Solids from Water

One of the next parameters considered was the estimated amount of CO_2 utilized by the process when fully commercialized. For a single beneficial use project, a scale was developed using the following ranges:

- **S** denotes estimated to be less than 0.5 million metric tons/year
- **M** denotes estimated to be between 0.5 and 5 million metric tons/year
- **L** denotes estimated to be greater than 5 million metric tons/year

Technologies with **L** ratings have demand for CO_2 in the range of the individual annual emissions from California's largest point sources. This is a very important parameter since it gives an estimate of the potential impact of the technology at commercial-scale; coupling of this parameter with estimates of how many use facilities might be supported in California gives a measure of a technology's potential in contributing to California's ability to achieve its GHG reductions goals for 2020 and 2050. Clearly, technologies with an **M** or **L** value will have a larger impact on the attainment of these goals.

The attributes of the CO_2 indicate factors such as purity of the feed stream and other input components. Special emphasis was made in investigating whether residual levels of sulfur or other compounds would be deleterious since stationary sources of CO_2 often have residuals such as SOx, NOx, and so forth. Some of the technologies, especially for the food and biomedical applications listed in Table 6 and many of the traditional miscellaneous industrial applications shown in Table 7 are sensitive to residuals that could be present in the captured CO_2. These technologies would require additional purification steps for the feed stream which could negatively impact the overall economics of the process. Of particular note among other input components is water. Special focus was placed on determining the water impacts due to the general difficulties presented due to permitting and regulations to protect California's scarce water resources. High water usages would make a technology unattractive for applications in California unless reclaimed water utilization would be possible.

It was also important to consider whether other components necessary for a technology application are available in the state. An obvious example is the limited amount of coal within California, which naturally limits any application of CO_2 for enhanced coal bed methane recovery within the state, and the availability of cheaper CO_2 supplies makes it highly unlikely that California will export its CO_2 out-of-state for this application. Another example is utilization of CO_2 in nuclear power cooling applications given that current law prohibits building any new nuclear power facilities in the state.

The product produced from the CO_2 is based on the concept shown in Figure 1. Typically, beneficial use focuses on technologies that produce chemicals or fuels, but the expanded definition used here includes production of products such as electricity (see Table 5). Many of the well-developed miscellaneous industrial uses of CO_2, shown in Table 7 neither use other components nor produce a product. The wide range of products resulted in some potential challenges in comparing technologies, an aspect discussed in Chapters 3 and 5.

The time to commercialization was estimated as either being less than 10 years or greater than 10 years. Some of the technologies that can be commercialized in less than 10 years may have an impact on California achieving its 2020 targets and have a high probability of enabling the state to meet 2050 targets. Commercialization times greater than 10 years would prevent the technology from impacting 2020 goals and may or may not be commercialized in time to have an impact by 2050. This timing consideration is reflected in the rankings.

The anticipated environmental impact and economic benefit to the state are critical factors when using public funds to aid in technology development. For example, it is important to identify any concerns in terms of the generation of secondary waste streams. In addition, benefits to California's economy through new job creation and support of existing industries were considered although in most all cases, supporting data for such an analysis are lacking.

The importance of energy and carbon life cycle analyses is also a component of the environmental impact. It is important to systematically ascertain that a technology reduces CO_2

levels. This overall CO_2 life cycle concern was especially relevant with the technologies listed in Table 6 and Table 7. Accounting for the final disposition of the CO_2 after its use was not immediately evident for many technologies. Many of the processes in Table 4 consume or incorporate CO_2 into the product. In addition the technologies like those listed in Table 5 utilize a closed loop system specifically designed to minimize CO_2 leakage. While many of the technologies listed in Table 6 and Table 7 could have a specially designed closed loop system, it was not evident that such a system was either being deployed or would be feasible from an economic perspective. Additional analysis is recommended to further explore this concern, particularly as it relates to the ability of these utilization technologies to qualify under AB 32 or other regulations as a CO_2 sequestration option.

The final parameter considered was whether the technology has recently received or is currently receiving federal funding. Many of these technologies have been and are being funded by the Department of Energy. This was an important factor to consider since it would provide an opportunity to leverage state funds with federal funds. It also provided a means to reduce risk by examining lessons learned by other funding agencies. This consideration is discussed further in Chapter 2.

The RWG also developed a list of industrial and university groups active in the development of the technologies considered. This compilation is intended to be representative but is not comprehensive. This information is shown in Tables 9 through 14.

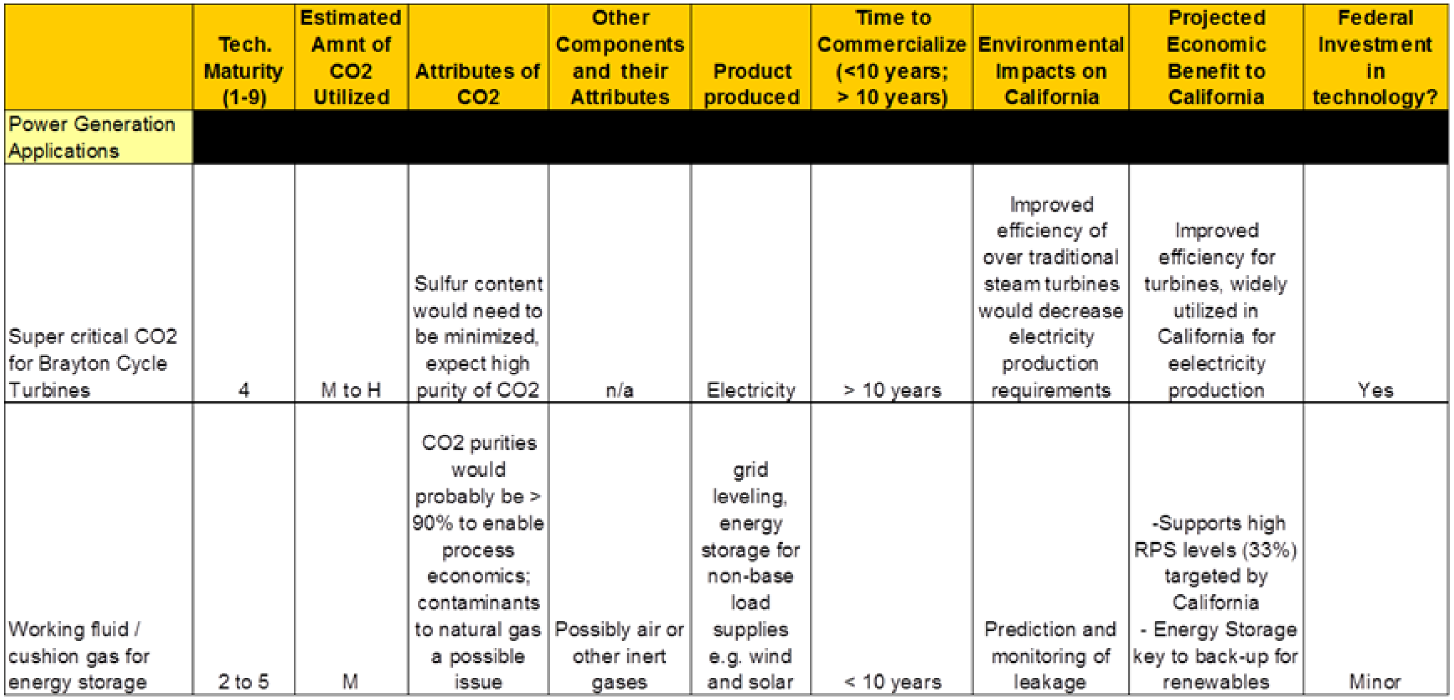
Table 3: Characterization of Technologies that Use CO_2 as a Working Fluid.

	Tech. Maturity (1-9)	Estimated Amnt of CO2 Utilized	Attributes of CO2	Other Components and their Attributes	Product produced	Time to Commercialize (<10 years; > 10 years)	Environmental Impacts on California	Projected Economic Benefit to California	Federal Investment in technology?
Working fluids									
Enhanced oil recovery (EOR)	9	L	- Sulfur content may enhance EOR, but must maintain pipeline specs for CO2 transport - CO_2 Purity	Water, surfactants	oil / natural gas	already commercial	Minor (relative to impact of existing oil field)	Jobs & economic stimulus in vicinity of well field, locally generated fuels, royalties to state	Yes
Enhanced Gas Recovery (EGR)	3-5	M	Pipeline specs	water	natural gas	<10 years	Minor (relative to impact of existing gas fields)	Jobs & economic stimulus in vicinity of well field, locally generated fuels, royalties to	Yes
Coal bed methane recovery (ECBM)	6	negligible in CA	- CO2 Purity > 90%	Water removed from seam to enable methane to more readily	natural gas	< 10 years	Coal beds not common in California	Not much direct benefit since coal not a significant resource in California	Yes
Geothermal working fluid (Enhanced Geothermal Systems)	4	M	- CO2 Purity > 90%	Water	electricity	< 10 years	Moderate - similar to new geothermal field development	Electrical power that displaces fossil fuel use; stimulates local economy	Yes

Table 4: Characterization of Technologies Using CO$_2$ for Building, Biochar, Fuel and Chemical Production

	Tech. Maturity (1-9)	Estimated Amnt of CO2 Utilized	Attributes of CO2	Other Components and their Attributes	Product produced	Time to Commercialize (<10 years; > 10 years)	Environmental Impacts on California	Projected Economic Benefit to California	Federal Investment in technology?
Building Matrl									
Carbonates and other construction materials	3 to 6	M	- CO2 Purity > 90%	Water	cement, plaster, insulation, sheetrock	< 10 years	minor	Stimulates local economy, provides locally available building materials	Yes
Biochar									
Pyrolysis of biomass	2 to 4	L	CO2 not an input to process	Biomass	Solids that can be implanted into soils or used for fuel	> 10 years	Needs further long term studies	Potentially large positive impact of CA agricultural market	Minimal
Fuel & Chemical									
Chemical Conversion	5 to 7	M	May not require CO2 purification, may be able to directly accept exhaust gas	- Traditional chemical feedstock - biomass - catalysts	plastics or fuels	< 10 years	- Management of emissions from fuel produced - Management of the eventual disposal of plastics produced	Leverages existing biotech capabilities within California	Yes
Biological Conversion	3 to 5	M	May not require CO2 purification, may be able to directly accept exhaust gas	Algae, micro organisms, or catalysts	fuels, chemicals, or plastics	< 10 years	- Requires deployment of solar plants - Concerns regarding the use of genetically modified organisms	- Leverages biotech capability - Stimulates local economy - Reduces dependance on foreign oil	Yes

Table 5: Characterization of Technologies Using CO_2 for Power Generation Applications



	Tech. Maturity (1-9)	Estimated Amnt of CO2 Utilized	Attributes of CO2	Other Components and their Attributes	Product produced	Time to Commercialize (<10 years; > 10 years)	Environmental Impacts on California	Projected Economic Benefit to California	Federal Investment in technology?
Power Generation Applications									
Super critical CO2 for Brayton Cycle Turbines	4	M to H	Sulfur content would need to be minimized, expect high purity of CO2	n/a	Electricity	> 10 years	Improved efficiency of over traditional steam turbines would decrease electricity production requirements	Improved efficiency for turbines, widely utilized in California for eelectricity production	Yes
Working fluid / cushion gas for energy storage	2 to 5	M	CO2 purities would probably be > 90% to enable process economics; contaminants to natural gas a possible issue	Possibly air or other inert gases	grid leveling, energy storage for non-base load supplies e.g. wind and solar	< 10 years	Prediction and monitoring of leakage	-Supports high RPS levels (33%) targeted by California - Energy Storage key to back-up for renewables	Minor

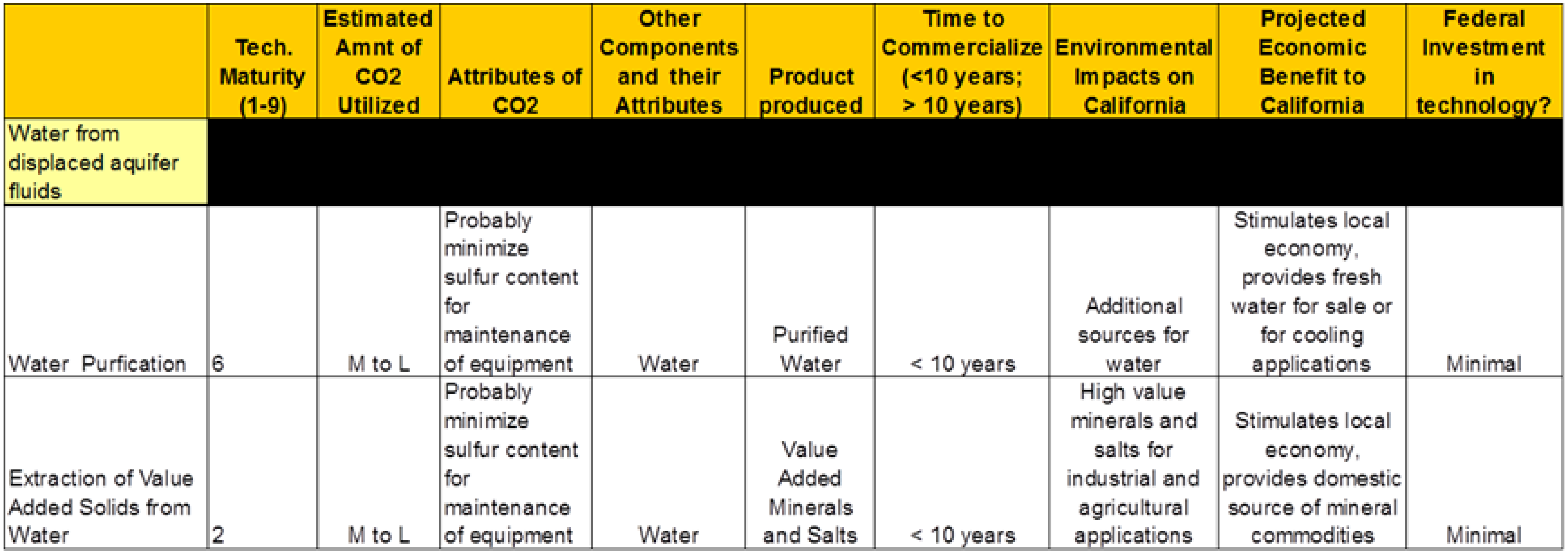
Table 6: Characterization of Technologies Where CO2 is Used as a Solvent and for Agricultural and Biomedical Applications.

	Tech. Maturity (1-9)	Estimated Amnt of CO2 Utilized	Attributes of CO2	Other Components and their Attributes	Product produced	Time to Commercialize (<10 years; > 10 years)	Environmental Impacts on California	Projected Economic Benefit to California	Federal Investment in technology?
CO_2 as solvent									
Supercritical fluid extraction and other food processing applications	9	S	High grade CO2, sulfur levels needed to be especially low	food goods	purified food	< 10 years	Final disposition of CO2 after usage	- ISSUE: transport of CO2 to food processing facilities, many outside California	Minor
Dry cleaning	8 to 9	S	High grade CO2, sulfur levels needed to be especially low	apparel	cleaned apparel	< 10 years	Final disposition of CO2 and life cycle	- Growth of new CA based business - Reduction in water demands for California	None
CO_2 in ag & biomed									
Greenhouse atmosphere additive	9	S	High grade CO2, sulfur levels needed to be especially low	crops	crops	< 10 years	Final disposition of CO2?	Needs additional analysis	None
Grain silo fumigant	9	S	High grade CO2, sulfur levels needed to be especially low	grain	grain	< 10 years	Final disposition of CO2?	Needs additional analysis	None
Sterilization for biomedical applications	9	S	Medical grade requirements for CO2, sulfur levels needed to be extremely low	medical implants	sterilized surface	> 10 years	Final disposition of CO2?	Needs additional analysis	None

Table 7: Characterization of Technologies for Miscellaneous Industrial Applications for CO2

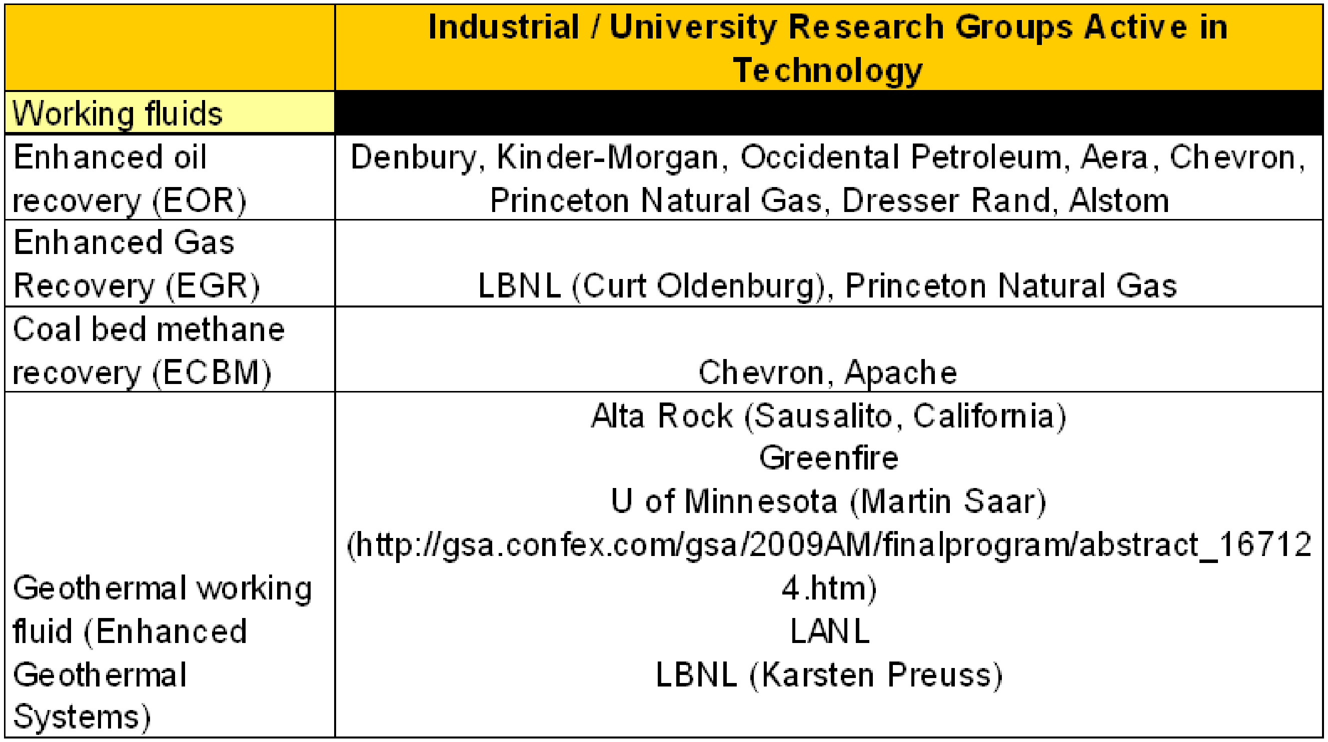
	Tech. Maturity (1-9)	Estimated Amnt of CO2 Utilized	Attributes of CO2	Other Components and their Attributes	Product produced	Time to Commercialize (<10 years; > 10 years)	Environmental Impacts on California	Projected Economic Benefit to California	Federal Investment in technology?
Misc. Industrial Appl									
Fire extinguishers	9	S	High grade CO2, sulfur levels especially low	n/a	n/a	< 10 years	Final disposition of CO2?	Needs additional analysis	None
Shielding gas for welding	9	S	High grade CO2, sulfur levels especially low	n/a	n/a	< 10 years	Final disposition of CO2?	Needs additional analysis	None
Refrigeration and heat pump working fluid	9	S	High grade CO2, sulfur levels especially low	n/a	n/a	< 10 years	Final disposition of CO2?	Needs additional analysis	None
Propellant	9	S	High grade CO2, sulfur levels especially low	n/a	n/a	< 10 years	Final disposition of CO2?	Needs additional analysis	None
Rubber and plastics processing - blowing agent	8 to 9	S	High grade CO2, sulfur levels especially low	n/a	n/a	< 10 years	Final disposition of CO2?	Needs additional analysis	None
Waste water treatment	8 to 9	S to M	High grade CO2, sulfur levels especially low	n/a	n/a	< 10 years	Improved and more cost effective water treatment	Potential to impact waste water treatment industry in California	None
Cleaning during semiconductor fabrication	9	S	High grade CO2, sulfur levels especially low	n/a	n/a	< 10 years	Final disposition of CO2?	Needs additional analysis	None

Table 8: Characterization of Technologies that Use CO_2 in the Management of Displaced Aquifer Fluids



	Tech. Maturity (1-9)	Estimated Amnt of CO2 Utilized	Attributes of CO2	Other Components and their Attributes	Product produced	Time to Commercialize (<10 years; > 10 years)	Environmental Impacts on California	Projected Economic Benefit to California	Federal Investment in technology?
Water from displaced aquifer fluids									
Water Purfication	6	M to L	Probably minimize sulfur content for maintenance of equipment	Water	Purified Water	< 10 years	Additional sources for water	Stimulates local economy, provides fresh water for sale or for cooling applications	Minimal
Extraction of Value Added Solids from Water	2	M to L	Probably minimize sulfur content for maintenance of equipment	Water	Value Added Minerals and Salts	< 10 years	High value minerals and salts for industrial and agricultural applications	Stimulates local economy, provides domestic source of mineral commodities	Minimal

Table 9: Groups Active in Working Fluid Uses of CO_2



	Industrial / University Research Groups Active in Technology
Working fluids	
Enhanced oil recovery (EOR)	Denbury, Kinder-Morgan, Occidental Petroleum, Aera, Chevron, Princeton Natural Gas, Dresser Rand, Alstom
Enhanced Gas Recovery (EGR)	LBNL (Curt Oldenburg), Princeton Natural Gas
Coal bed methane recovery (ECBM)	Chevron, Apache
Geothermal working fluid (Enhanced Geothermal Systems)	Alta Rock (Sausalito, California) Greenfire U of Minnesota (Martin Saar) (http://gsa.confex.com/gsa/2009AM/finalprogram/abstract_167124.htm) LANL LBNL (Karsten Preuss)

Table 10: Industrial and University Research Activity in Building Materials, Biochar, Fuel and Chemical Production

	Industrial / University Research Groups Active in Technology
CO_2 for building materials manufacture	
Carbonates and other construction materials	Calera, Skyonics, Searles Valley Minerals, Alcoa, CCS Materials, Indian National Environmental Engineering and Research Institute (Nagpur) enzymatic transformation of CO2->CaCO3
Biochar	
Pyrolysis of biomass	Eprida, International Biochar Initiative
Fuel and Chemical Production	
Chemical Conversion	Pacific Renewables Fuels, Novomer, Huntsman Performance Products, Mantra Energy Alternatives, Research Triangle Institute, UOP LLC (Honeywell Company), RCO2
Biological Conversion	Algenol, Sapphire energy, Synthetic Genomics, Joule Unlimited, Sunrise Ridge Algae, Phycal, LLC (Ohio), Columbia Energy Partners LLC (CEP, Washington), Carbon Recycling International, Phosphortech Corp. (GA), Singapore's Institute of Bioengineering and Nanotechnology (CO2->methanol)

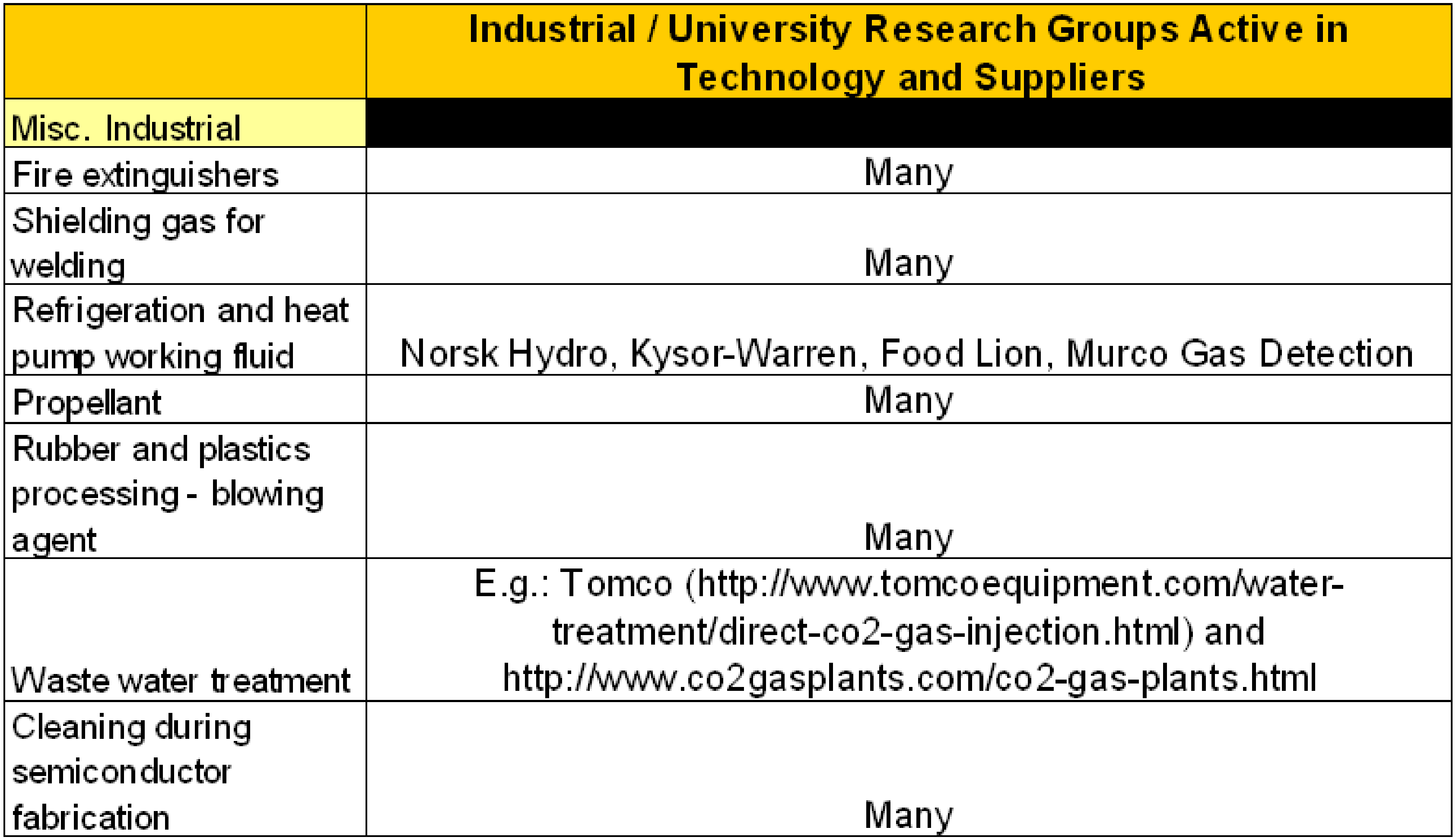
Table 11: Industrial and University Research Activities in Power Generation Applications

	Industrial / University Research Groups Active in Technology
Power Generation Applications	
Super critical CO2 for Brayton Cycle Turbines	Sandia National Laboratories, Idaho National Laboratories
Working fluid / cushion gas for energy storage	NETL, LBL

Table 12: Industrial & University Research Groups and Suppliers for CO_2 as Solvent and in Agricultural and Biomedical Technologies

	Industrial / University Research Groups Active in Technology and Suppliers
CO_2 as solvent	
Supercritical fluid extraction and other food processing applications	Many, e.g. JASCO (http://www.jascoinc.com/products/Chromatography/SFC-SFE/Supercritical-Fluid-Extraction.aspx), Eden Labs
Dry cleaning	CO2Nexus, Hermosa Beach, CA
CO_2 in ag & biomed	
Greenhouse atmosphere additive	http://www.omafra.gov.on.ca/english/crops/facts/00-077.htm
Grain silo fumigant	
Sterilization for biomedical applications	Many: e.g. NuAire (http://www.nuaire.com/autoflow/5510/sterilization-cycle-co2-incubator.htm)

Table 13: Industrial and University Research Groups and Suppliers for Miscellaneous Industrial Applications



	Industrial / University Research Groups Active in Technology and Suppliers
Misc. Industrial	
Fire extinguishers	Many
Shielding gas for welding	Many
Refrigeration and heat pump working fluid	Norsk Hydro, Kysor-Warren, Food Lion, Murco Gas Detection
Propellant	Many
Rubber and plastics processing - blowing agent	Many
Waste water treatment	E.g.: Tomco (http://www.tomcoequipment.com/water-treatment/direct-co2-gas-injection.html) and http://www.co2gasplants.com/co2-gas-plants.html
Cleaning during semiconductor fabrication	Many

Table 14: Industrial and Research Groups and Suppliers for Water from Displaced Aquifer Fluids

	Industrial / University Research Groups Active in Technology and Suppliers
Water from displaced aquifer fluids	
Water Purfication	seawater desalination companies
Extraction of Value Added Solids from Water	brine/salt mining companies

CHAPTER 2: Lessons Learned and Synergies from Other Efforts and Research Programs in Beneficial CO2 Use

The objective of this chapter is to summarize the results of other programs and funding opportunities that have advanced technologies for the beneficial use of CO_2, especially at the U.S. federal level. Understanding past and future federal funding trends should enable the formation of strategies to maximize the flow of federal funds into California. Analyzing the types of projects and rationale for funding these projects also provides lessons-learned for future state funding efforts. Leveraging and lessons learned should accelerate the deployment in the state of beneficial use technologies. Information was also gathered as to which California-based beneficial use technology developers were recipients of federal funding.

2.1 Summary of Domestic Activities

Federal funding for beneficial use of CO_2 has been managed through the U.S. Department of Energy (DOE), mainly by the National Energy Technology Laboratory (NETL), one of the DOE national laboratories. The American Recovery and Relief Act (ARRA) expanded the amount of funds available for the capture, sequestration, and beneficial use of CO_2. ARRA funding has accelerated RD&D (Research, Development, and Deployment) efforts ranging from early stage development to large scale demonstration projects.

DOE funded projects require cost share. The cost share is typically cash or in-kind contributions. In-kind efforts can include contributions such as labor and equipment. Cost share can also consist of matching funding from other non-federal funding sources. For example, state funds can provide the required match for DOE projects. California state funding could be used to provide part or all of the matching funds required by the DOE.

2.2 Definition of Beneficial Use at a Federal Level

The Department of Energy/NETL indicated that re-use efforts for CO_2 focus on developing beneficial uses for CO_2, such as the conversion of CO_2 to useable products and fuels, and other concepts that will mitigate CO_2 emissions in areas where geologic storage may not be an optimal solution[4].

Typical beneficial uses of CO_2 are defined by NETL as:

Conversion of CO_2 – Using CO_2 as one of the feedstocks to produce chemicals (including fuels and polymers) and identifying applications for the end products.

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[4] NETL, "Carbon Sequestration: CO_2 Use/Reuse", http://www.netl.doe.gov/technologies/carbon_seq/core_rd/use-reuse.html / 4 February, 2011.

Non-Geologic Storage of CO_2 –immobilize CO_2 permanently by producing stable solid materials that are either useful products with economic value or a low-cost produced material. This approach could be viewed as an effective carbon storage method.

Indirect Storage – Promoting indirect carbon storage by removing CO_2 from the air (such as enhanced photosynthesis) or by enhancing carbon uptake by terrestrial vegetation and soils where the biomass could be used to produce power, liquid fuels, or synthetic natural gas.

Beneficial Use of Produced Water – Develop methods to extract useful solid materials and purified water from formation fluids displaced at carbon capture and storage sites.

Breakthrough Concepts Novel approaches that produce useful products or fuels from CO_2.

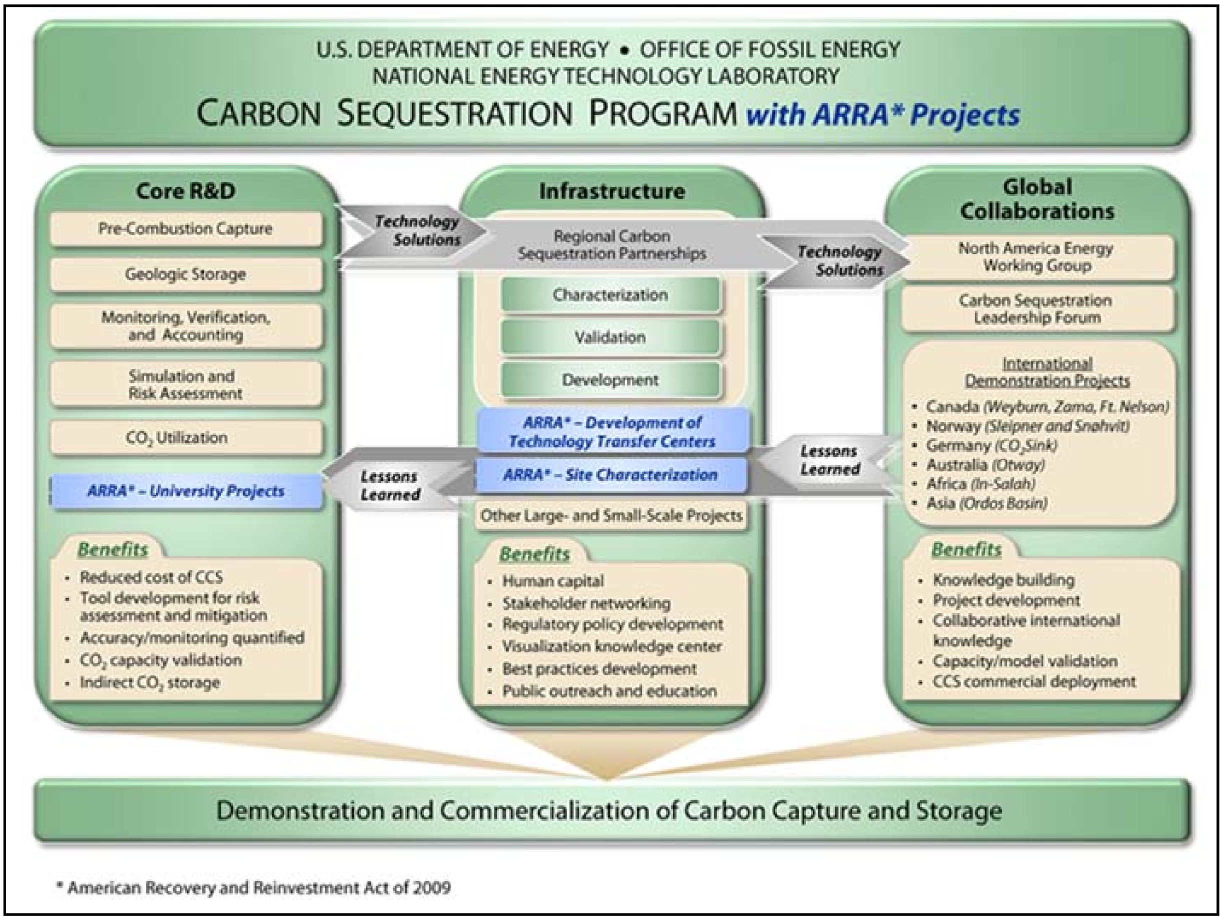
In addition to the definitions above, NETL indicates that processes or concepts that undertake this CO_2 reduction must take into account the life cycle of the process to ensure that additional CO_2 is not produced beyond what is already being removed from or is going into the atmosphere.

Based on its compilation of funded research including non-DOE projects, NETL documents research and development progress by a variety of groups on a wide range of technologies. The examples listed include:

- CO_2 derived from flue gas to grow algae that can later be used as a fuel or feedstock for other materials
- using CO_2 injection for enhancing methanol production in which CO_2 is used as one of the reactants
- using CO_2 to make polycarbonates or other polymers
- enhancing the rate of photosynthesis to increase the net fixation of atmospheric carbon dioxide
- CO_2 as a working medium for enhanced geothermal systems that would facilitate CO_2 storage in underground formations.
- genetic studies conducted on microbes that use CO_2 to generate methane.

An overview of DOE's / NETL's carbon sequestration program, which demonstrates the context for funding CO_2 utilization, is shown in Figure 3. It is important to note that CO_2 utilization funding is categorized as a core R&D program, indicating that NETL tends to view these technologies as relatively immature, generally at the stage of fundamental technology development rather than at the stage of pilot or large-scale demonstrations.

Figure 3: Overview of NETL's Carbon Sequestration Program



Source: NETL

2.3 Specific Federal Funding Programs and Activities

The following is a list of programs that have been funded by NETL and have beneficial use aspects to them. The objective of each program is discussed, along with the release date for the request for proposals (RFP), total funding that was available, and the organizations that were funded. All of the programs are currently active (since they were typically initiated in the 2008-2010 time-frame). Due to the early stage of the programs, there are no final results currently available.

Unconventional Fossil Energy Funding Opportunity, DE-FOA0000312; Topic Area 2 – Next-Generation CO_2-EOR[5]

Date released 06/04/2010

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[5] NETL, "Unconventional Fossil Energy Funding Opportunity", http://www.netl.doe.gov/business/solicitations/archive/main-FY10.html#00312 / 9 February, 2011.

Date closed 07/29/2010

Cost share minimum of 20 percent

The objective of Topic Area 2 research is to advance "next-generation" CO_2-EOR technology to the point where it is ready for pilot-scale testing. Next-generation technologies include but are not limited to:

- Methods for improving the mobility ratio through applications such as: CO_2 thickeners, CO_2 foams, improved water soluble polymers, and innovative water-alternating-gas (WAG) injection schemes.
- Methods for improving sweep efficiency by using nanoparticles for long term stabilization of foams and emulsions that can selectively control CO_2 mobility.
- Methods to allow miscible flooding of additional target reservoirs by extending crude oil-CO_2 miscibility [lowering the minimum miscibility pressure (MMP)].
- New approaches to the optimization of flood design through application of improved measures such as targeted horizontal wells, new well alignment and infill drilling.
- Real time data acquisition/diagnostics tools to monitor and control flood performance.
- Methods for increasing recovery of oil from the residual oil zone through improved flood design or other technologies or techniques.

Total Funding for Program Topic Area 2: $4.1 Million

Awards Area 2: Next-Generation Carbon Dioxide Enhanced Oil Recovery

- Impact Technologies LLC (Tulsa, Okla.)—Improved Mobility Control in CO_2 Enhanced Recovery Using SPI Gels. Impact Technologies in partnership with CTI, Talee R., and Redcorn, will demonstrate, in a set of injectivity tests in both "Huff & Puff" and conventional pattern flood applications, the ease of use and potential of CO_2 injection/ production profile modifications using SPI-CO2 gel systems. (DOE Share: $1,200,000; Recipient: $300,000; Duration: 36 months)
- The University of Texas (Austin, Texas)—Use of Engineered Nanoparticle-Stabilized CO_2 Foams To Improve Volumetric Sweep of CO_2-EOR Processes. The UT Austin research will develop a new CO_2 injection enhanced oil recovery process using engineered nanoparticles with optimized surface coatings that has better volumetric sweep efficiency and a wider application range than the conventional CO_2 process. (DOE Share: $1,198,717; Recipient: $299,679; Duration: 36 months)
- The University of Texas of the Permian Basin (Midland, Texas)—Next Generation CO_2-EOR Technologies To Optimize the Residual Oil Zone CO_2 Flood at the Goldsmith Landreth Unit, Ector County, Texas. The UT of the Permian Basin will team up with Legado Resources, Meltzer Consulting, and Advanced Research International to develop a new CO_2 injection enhanced oil recovery process using engineered nanoparticles with optimized surface coatings that has better volumetric sweep efficiency and a wider application range than the conventional CO_2 process. (DOE Share: $1,198,547; Recipient: $654,563; Duration: 36 months)
- Sky Research, Inc. (Ashland, Ore.)—Development of Real Time Semi Autonomous Geophysical Data Acquisition and Processing System to Monitor Flood Performance. Sky Research in

partnership with PNNL will work on the design, development, and validation of a real time, semi-autonomous geophysical data acquisition and processing system using electromagnetic technology to monitor CO_2 flood performance (DOE Share: $496,847; Recipient: $180,425; Duration: 36 months)

- The University of Texas (Austin, Texas)—Novel CO_2 Foam Concepts and Injection Schemes for Improving CO_2 Sweep Efficiency in Sandstone and Carbonate Hydrocarbon Formations. The UT Austin team will work in partnership with Rice University to develop mobility control agents using surfactants injected with CO_2 (rather than in water) for CO_2 enhanced oil recovery in heterogeneous carbonate and sandstone reservoirs (DOE Share: $1,134,984; Recipient: $283,746; Duration: 36 months)
- New Mexico Institute of Mining and Technology/Petroleum Recovery Research Center (Socorro, N.M.)—Nanoparticle-Stabilized CO_2 Foam for CO_2-EOR Application. The Petroleum Recovery Research Center team will develop and evaluate, through coreflood tests at reservoir conditions, a nanoparticle-stabilized CO_2 foam system that can improve CO_2 sweep efficiency in CO_2 EOR and minimize particle retention in the reservoir (DOE Share: $772,934; Recipient: $385,888; Duration: 36 months).

Analysis of Impact on California: No California companies were funded. Texas received the largest amount of funding ($3.5 Million). However, it is likely that the benefits would be transferrable to CO_2-EOR projects within California.

DE-FOA-0000015 Technology Area 2 --Carbon Capture and Sequestration from Industrial Sources and Innovative Concepts for Beneficial CO_2 Use[6]

Date released 06/08/2009

Date closed 08/07/2009

Demonstrate innovative concepts for beneficial CO_2 use, which include, but are not limited to, CO_2 mineralization to carbonates directly through conversion of CO_2 in flue gas; use of CO_2 from power plants or industrial applications to grow algae/biomass; or, conversion of the CO_2 to fuels and chemicals. The carbonates produced from the mineralization processes must have the ability to result in permanent storage of the CO_2 through end uses such as cement additives or long term underground storage. "Use" of CO_2 is defined as the permanent conversion of CO_2 from flue gas into another form such as solid carbonates (for example, mineralization), plastics, and fuels.

CO_2 use efforts focus on pathways and novel approaches for reducing CO_2 emissions by developing beneficial uses for the CO_2, such as the conversion of CO_2 to useable products and

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[6] NETL, "DE-FOA-0000015 Phase 2 Down Select Carbon Capture & Sequestration from Industrial Sources Technology Area 2 --Innovative Concepts for Beneficial CO2 Use", http://www.netl.doe.gov/publications/proceedings/10/gfe/Elaine%20Everitt_ICCS2.pdf) / 12 February, 2011.

fuels and other breakthrough concepts that will mitigate CO_2 emissions in areas where geologic storage may not be an optimal solution. Examples of CO_2 use include the use of algae or another medium to convert CO_2 to biomass (which in turn can be used for fuel, chemicals, or plastics production), direct conversion to fuels or chemicals, or direct or indirect mineralization of CO_2 to solid carbonates.

Two Phases:

Phase 1 – Phase 1 shall be seven months and may encompass work anywhere from project definition activities through preliminary design and permitting. Project definition activities include, but are not limited to, development of a project baseline, detailed project management plan, project schedule, project cost estimate, firm host site commitments and firm financial commitments and funding plan for the non-DOE share of the project costs. Applicants who have completed such activities need not include them in their Phase 1 scope. Also during Phase 1 information will be prepared to assist the Department in performing its obligations pursuant to the National Environmental Policy Act (NEPA).

Preliminary design activity permitted in Phase 1 includes, but is not limited to: overall design, the process concept and how it operates (including process flow diagram(s) with major equipment items and energy and material balances); process chemistry and engineering concepts; identifying the technology hardware, describing the attributes of the devices or modules or major pieces of equipment; principles and engineering or R&D analysis and process data to support the design, and the capital and operating costs for the project. Additionally, for large scale industrial sources projects, design and plan for the sequestration method including, but not limited to, well drilling, pipelining, and surface equipment including compressors, tanks, and fluid processing towers, as appropriate. Award size: $500,000 to $3,000,000

Phase 2 – Subphase 2a: Design, Subphase 2b: Construction, and Subphase 2c: Operation: to be considered for Phase 2 funding, Phase 1 Recipients will be required to submit a detailed Renewal Application in accordance with the guidance provided in the Model Cooperative Agreement and their Phase 1 Cooperative Agreement or TIA. DOE will evaluate the Renewal Application against established criteria as part of a competitive Renewal Application process. For successful Phase 2 Applications, the DOE funds will be obligated no later than September 30, 2010, and be available for reimbursement of costs until September 30, 2015. NEPA analyses will continue during Phase 2. Recipients will not be authorized to begin detailed design and site specific project work until DOE has fulfilled its NEPA obligations. During Phase 2 Recipients will be required to provide additional project and environmental information to DOE. Award size: $50,000,000 to $400,000,000.

Awards PHASE I: 50 acceptable applications received: 22 algae, 19 chemical conversion, 8 mineralization, 1 other

Table 15: Number of Phase I Awardees: 12

Mineralization (4)	Chemical Conversion (3)	Biological Conversion (5)
University of Mass.–Lowell	Research Triangle Institute	Touchstone Research Laboratory
Alcoa	Renewable Energy Institute International	Sunrise Ridge Algae
Calera Corporation	Novomer	UOP LLC
Skyonic Corporation		Phycal
		Gas Technology Inst

Originally proposed applications in Phase I:

Proposed Products

- Carbonate enhanced clay
- Plastics/resins
- SNG/Methane
- Methanol/DME
- Formic acid
- Biocrude/biofuel
- Carbonates/bicarbonates
- Gasoline/Kerosene/Diesel
- Fertilizer
- Ethanol

Phase II was initiated July 22, 2010 with the announcement of winning applicants. A selected number of awardees were continued into Phase II. ***NOTE: the required cost share of Phase II prevented some applicants from Phase I from submitting for the Phase II activity.***

Alcoa, Inc. (Alcoa Center, Pa.)—Alcoa's pilot-scale process will demonstrate the high efficiency conversion of flue gas CO_2 into soluble bicarbonate and carbonate using an in-duct scrubber system featuring an enzyme catalyst. The bicarbonate/carbonate scrubber blow down can be sequestered as solid mineral carbonates after reacting with alkaline clay, a by-product of aluminum refining. The carbonate product can be utilized as construction fill material, soil amendments, and green fertilizer. Alcoa will demonstrate and optimize the process at their Point Comfort, Texas aluminum refining plant. (DOE Share: $11,999,359)

Novomer Inc. (Ithaca, N.Y.)—Teaming with Albemarle Corporation and the Eastman Kodak Co., Novomer will develop a process for converting waste CO2 into a number of polycarbonate products (plastics) for use in the packaging industry. Novomer's novel catalyst technology enables CO_2 to react with petrochemical epoxides to create a family of thermoplastic polymers that are up to 50 percent by weight CO_2. The project has the potential to convert CO_2 from an industrial waste stream into a lasting material that can be used in the manufacture of bottles, films, laminates, coatings on food and beverage cans, and in other wood and metal surface applications. Novomer has secured site commitments in Rochester, NY, Baton Rouge, Louisiana, and Orangeburg, SC where Phase 2 work will be performed. (DOE Share: $18,417,989)

Touchstone Research Laboratory Ltd. (Triadelphia, W. Va.)—This project will pilot-test an open-pond algae production technology that can capture at least 60 percent of flue gas CO_2 from an industrial coal-fired source to produce biofuel and other high value co-products. A novel phase change material incorporated in Touchstone's technology will cover the algae pond surface to regulate daily temperature, reduce evaporation, and control the infiltration of invasive species. Lipids extracted from harvested algae will be converted to a bio-fuel, and an anaerobic digestion process will be developed and tested for converting residual biomass into methane. The host site for the pilot project is Cedar Lane Farms in Wooster, Ohio. (DOE Share: $6,239,542)

Phycal, LLC (Highland Heights, Ohio)—Phycal will complete development of an integrated system designed to produce liquid biocrude fuel from microalgae cultivated with captured CO2. The algal biocrude can be blended with other fuels for power generation or processed into a variety of renewable drop-in replacement fuels such as jet fuel and biodiesel. Phycal will design, build, and operate a CO_2-to-algae-to-biofuels facility at a nominal thirty acre site in Central Oahu (near Wahiawa and Kapolei), Hawaii. Hawaii Electric Company will qualify the biocrude for boiler use, and Tesoro will supply CO_2 and evaluate fuel products. (DOE Share: $24,243,509)

Skyonic Corporation (Austin, Texas)—Skyonic Corporation will continue the development of SkyMine® mineralization technology—a potential replacement for existing scrubber technology. The SkyMine process transforms CO_2 into solid carbonate and/or bicarbonate materials while also removing sulfur oxides, nitrogen dioxide, mercury and other heavy metals from flue gas streams of industrial processes. Solid carbonates are ideal for long-term, safe aboveground storage without pipelines, subterranean injection, or concern about CO_2 re-release to the atmosphere. The project team plans to process CO_2-laden flue gas from a Capital Aggregates, Ltd. cement manufacturing plant in San Antonio, Texas. (DOE Share: $25,000,000)

Calera Corporation (Los Gatos, California)—Calera Corporation is developing a process that directly mineralizes CO_2 in flue gas to carbonates that can be converted into useful construction materials. An existing CO_2 absorption facility for the project is operational at Moss Landing, California, for capture and mineralization. The project team will complete the detailed design, construction, and operation of a building material production system that at smaller scales has produced carbonate-containing aggregates suitable as construction fill or partial feedstock for use at cement production facilities. The building material production system will ultimately be integrated with the absorption facility to demonstrate viable process operation at a significant scale. (DOE Share: $19,895,553)

Analysis of Impact on California: One California company, Calera was funded. No one state received a large amount of funding. Funding of Calera provides a means to generate new jobs within the state of California. Should their process eventually provide a commercial-scale alternative to traditional cement production economically, it may become an opportunity for California's cement industry to reduce its carbon footprint. Skyonics capture process also holds promise for California's cement industry to achieve carbon reductions.

The Alcoa process could potentially be applied to aluminum plants in California. Similarly the Novomer process could supply California with net-negative carbon packaging materials. The Touchstone Research Laboratory and Phycal, LLC technologies have the potential to influence the biotech industry and could assist the state in achieving legislated low carbon fuel standards.

Recovery Act Funds to Advance CO_2 Reduction, Alternate Fuel Production[7]

Date of press release 9/15/2009

Arizona Public Service (APS), Phoenix, Ariz., has been awarded $70.5 million from the American Recovery and Reinvestment Act (ARRA) to expand an existing industrial and innovative reuse carbon mitigation project.

Arizona Public Service's ongoing algae-based carbon mitigation project, previously selected via competitive solicitation, will be expanded to include testing with a coal-based gasification system. The process aims to minimize production of carbon dioxide when gasifying coal. The host facility for this project is the Cholla Power Plant located in Holbrook, AZ.

Funding for the project expansion falls under the ARRA's $1.52 billion funding for carbon capture and storage from industrial sources.

Arizona Public Service will scale up a concept for coproduction of electricity and substitute natural gas via coal gasification, while scaling up an innovative reutilization technology where power plant CO_2 emissions are biologically captured by algae and processed into liquid transportation fuels. APS will focus on the engineering aspects of continuous cultivation, harvesting, and processing of algae grown from power plant emissions.

Funding will enable APS to scale up its algae cultivation concept by about two orders of magnitude and scale up its hydrogasification concept by one order of magnitude. Researchers expect that the algae farm will reuse CO_2 at a rate of 70 metric tons per acre per year.

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[7] NETL. "Department of Energy Awards $71 Million to Accelerate Innovative Carbon Capture Project http://www.netl.doe.gov/publications/press/2009/09064-APS_to_Scale_Up_CCS_Project.html / 14 February 2011.

This effort builds upon previous efforts developed by APS with algae.

Total Funding for Program $71,000,000

Single award to APS [$71 Million]

Analysis of Impact on California: No California companies were funded. This award has the potential to have indirect impact on the state of California since it involves the use of algae to produce biofuels and because APS is a member of the Western States Power Pool (WSPP), which provides a wholesale electricity market for its members to manage their power deliverability and price risk. Many California power producers as well as the California Department of Water Resources are members. This activity also may have synergy with the biotech industry and, by providing biodiesel, assist the state in achieving low carbon fuel standards.

Solar Reforming of Carbon Dioxide to Produce Diesel Fuel Technologies and Methods Employed DE-FE0002558[8]

Date of press release: 1/15/2010

Focused on the demonstration of technologies which utilize waste CO_2 as a feedstock for the production of diesel fuel using concentrating solar energy. A solar reformer system was successfully demonstrated during the first phase of this project. The next project phase will utilize CO_2 from a power plant to produce a high-quality synthetic diesel fuel. Testing will be carried out to collect essential technical, operational and financial data that will be used for the commercial-scale design, scale-up and reliable deployment of the first commercial solar CO_2 reforming systems.

Commercial Plant Configuration. The system uses a unique solar reforming reactor and catalyst that converts CO_2 rich gas streams into syngas (H_2 and CO) using concentrating solar energy at high energy conversion efficiencies. This syngas is subsequently converted to high-quality synthetic diesel fuel using next generation liquid fuel production processes. Based on a detailed commercial analysis, this technology will be ideal for use with stationary emissions sources and have the potential to sequester up to 2073 million tons of CO_2 per year in the United States. Commercial technologies are projected to be deployed in the 2013-14 time.

The alliance team members include Sandia National Laboratories, Renewable Energy Institute International (REII), Pacific Renewable Fuels, Pratt Whitney Rocketdyne (a United Technologies Division), Quanta Services, Desert Research Institute and Clean Energy Systems.

Analysis of Impact on California: Clean Energy Systems is a California company, and many of the alliance team members have offices in California. If the technology and plants were

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[8] Department of Energy, "Recovery Act Funding, RENEWABLE ENERGY INSTITUTE INTERNATIONAL", http://origins2.recovery.gov/Transparency/RecipientReportedData/pages/RecipientProjectSummary508.aspx?AwardIdSur=93082&AwardType=Grants / 11 February 2011

deployed in California, this technology could assist the state in achieving legislated low carbon fuel standards. It could also potentially be applied to many of California's stationary CO_2 sources. However, the relative efficiencies of using solar energy to produce the chemical conversion vs. producing solar power for the grid should be examined. Incorporating this process as a way to utilize excess solar capacity during times of low electricity demand might also be possible.

Research projects to Convert CO_2 into Useful Products[9]

Date of Press release 7/6/2010

Research to help find ways of converting into useful products CO_2 captured from emissions of power plants and industrial facilities will be conducted by six projects announced today by the U.S. Department of Energy (DOE).

The projects are located in North Carolina, New Jersey, Massachusetts, Rhode Island, Georgia, and Quebec, Canada (through collaboration with a company based in Lexington, Ky.) and have a total value of approximately $5.9 million over two-to-three years, with $4.4 million of DOE funding and $1.5 million of non-Federal cost sharing. The work will be managed by the Office of Fossil Energy's National Energy Technology Laboratory.

Converting captured CO_2 into products such as chemicals, fuels, building materials, and other commodities is an important aspect of carbon capture and storage technology, viewed by many experts as part of a solution for reducing CO_2 emissions and helping mitigate climate change.

It is anticipated that large volumes of CO_2 will be available as fossil fuel–based power plants and other CO_2-emitting industries are equipped with CO_2 emissions control technologies to comply with regulatory requirements. While DOE efforts are underway to demonstrate the permanent storage of captured CO_2 through geologic sequestration, there is also a potential opportunity to use CO_2 as an inexpensive raw material and convert it to beneficial use. The selected projects will develop or improve scalable processes with the potential to use significant amounts of CO_2.

Total Funding for Program was $5.9 Million. Six projects were selected:

Research Triangle Institute (Durham, N.C.)—RTI will assess the feasibility of producing valuable chemicals, such as carbon monoxide, by reducing CO_2 using abundant low-value carbon sources, such as pet coke, sub-bituminous coal, lignite, and biomass, as the reductant. The team will then evaluate whether additional processes can be added that use the carbon monoxide to produce other marketable chemicals, such as aldehydes, ketones, carboxylic acids, anhydrides, esters, amides, imides, carbonates, and ureas. (DOE share: $800,000; recipient share: $200,000; duration: 24 months).

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[9] Department of Energy, "Research Projects to Convert Captured CO2 Emissions to Useful Products", http://www.netl.doe.gov/publications/press/2010/100706-Research_Projects_To_Convert.html / 8 February 2011

CCS Materials, Inc. (Piscataway, N.J.)—Investigators will attempt to create an energy efficient, CO_2-consuming inorganic binding phase to serve as a high-performing substitute for Portland cement (PC) in concrete. The project team will use a novel near-net-shape forming process that uses a binding phase based on carbonation chemistry instead of the hydration chemistry used in PC concrete. (DOE share: $794,000; recipient share: $545,100; duration: 36 months).

Massachusetts Institute of Technology (Cambridge, Mass.)—In this project, researchers will investigate a novel electrochemical technology that uses CO_2 from dilute gas streams generated at industrial carbon emitters, including power plants, as a raw material to produce useful commodity chemicals. This integrated capture and conversion process will be used to produce a number of different chemicals that could replace petroleum-derived products. (DOE share: $1,000,000; recipient share: $250,067; duration: 24 months).

Brown University (Providence, R.I.)—Researchers will demonstrate the viability of a bench-scale reaction using CO_2 and ethylene as reactants to produce valuable acrylate compounds with low-valent molybdenum catalysts. Exploratory experiments will be conducted to identify the factors that control the current catalyst-limiting step in acrylic acid formation. (DOE share: $417,155; recipient share: $107,460; duration: 24 months).

McGill University (Quebec, Canada)—In collaboration with the 3H Company (Lexington, Ky.), researchers aim to develop a curing process for the precast concrete industry that uses CO_2 as a reactant. To make the process economically feasible, a self-concentrating absorption technology will be studied to produce low-cost CO_2 for concrete curing and to capture residual carbon after the process. (DOE share: $399,960; recipient share: $100,000; duration: 24 months).

PhosphorTech Corporation (Lithia Springs, Ga.)—Investigators will develop and demonstrate an electrochemical process using a light-harvesting CO_2 catalyst to reform CO_2 into products such as methane gas. Researchers hope to achieve a commercially feasible CO_2 reforming process that will produce useful commodities using the entire solar spectrum. (DOE share: $998,661; recipient share: $249,847; duration: 36 months).

Analysis of Impact on California: No California companies were funded. The effort at Research Triangle Institute could assist California in meeting its legislated targets for CO_2 reduction as required by AB 32 since the process uses fuel sources that are abundant in the state, for example biomass and pet coke. The CCS and McGill efforts impact the concrete industry, a major emitter of CO_2 within the state of California. As a result, these efforts could assist the state in achieving its legislated reductions in CO_2 emissions as required by AB 32. The PhosphorTech, Brown and MIT technologies could provide processes that eventually could substitute for current chemicals manufacture done using fossil fuels.

DOE Office of Science "Fuels from Sunlight" Project[10]

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[10] Department of Energy, "Research Projects to Convert Captured CO2 Emissions to Useful Products", http://www.netl.doe.gov/publications/press/2010/100706-Research_Projects_To_Convert.html / 8 February 2011

On July 22, 2010, the Department of Energy announced the selection of the Joint Center for Artificial Photosynthesis (JCAP), a team led by the California Institute of Technology (Caltech), to run the Fuels from Sunlight Energy Innovation Hub. JCAP will be located in two California-based sites, operated under a unified management structure. The Southern California site is on the Caltech campus in Pasadena, California and the Northern California site is at Lawrence Berkeley National Laboratory in Berkeley, California. JCAP partners include Caltech, Lawrence Berkeley National Laboratory, the SLAC National Accelerator Laboratory, UC Berkeley, UC Santa Barbara, UC Irvine, and UC San Diego. A one-page Fact Sheet on JCAP can be found at http://www.science.doe.gov/bes/Hubs/JCAP_Fact_Sheet.pdf and a brief technical summary at http://www.science.doe.gov/bes/Hubs/JCAP_Tech_Summary.pdf

The Fuels from Sunlight Hub will develop an effective solar energy to chemical fuel conversion system. The system should operate at an overall efficiency and produce fuel of sufficient energy content to enable transition from bench-top discovery to proof-of-concept prototyping.

Critical issues for the Fuels from Sunlight Hub[11] include the following:

1. *Understanding and designing catalytic complexes or solids that generate chemical fuel from carbon dioxide and/or water.* This research would necessarily be coordinated with complementary efforts to comprehend and design other essential elements required for the overall conversion of solar energy into chemical fuels. These include solar photon capture, energy transfer, charge separation and electron transport. A fundamental concern is the design and discovery of materials that will be cost effective and sustainable in the future economy.
2. *Integration of all essential elements from light capture to fuel formation into an effective solar fuel generation system.* This would require research and methodology that seek to understand complex issues of the system as an operating unit. Unlike natural photosynthesis, successful systems within the scope of this FOA should function efficiently at full solar flux; hence, the efficacy of system components should be evaluated in consideration of such a demanding environment.
3. *Pragmatic evaluation of the solar fuel system under development.* While a robust solar fuels industry does not presently exist for deployment of resulting technologies, the Hub should have the capacity to determine the practicality of a solar fuel system as a prototype and as a potential product in the marketplace.

Total Funding for Program was $122 million over 5 years.

<u>Analysis of Impact on California</u>: Obviously this project provides a substantial flow of federal research funding directly into California research institutions and contributes substantially to the recognition nationally and internationally of California as a leader in development of these

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[11] http://Solarfuelshub.org

types of beneficial use technologies. Applying successfully demonstrated bench scale technologies developed through this program to industrial sources through pilot or larger scale demonstrations would demonstrate the state's commitment to supporting and using high tech innovation to address its greenhouse gas emissions.

2.4 Strategies for Increasing the Flow of Federal Funding into California

The six federal programs listed above account for a total funding effort of over $300 Million. A large part of this funding was devoted to large scale demonstration projects. One of the California company recipients, Calera Corporation, received approximately $20 million; the consortia of research institutions involved in the Fuels from Sunlight Hub control $122 million. Many of the projects, especially those involving algae and biodiesel and those which provide processes for economic conversion of point-source CO_2 emissions, could be very relevant to contributing to greenhouse gas emissions reduction for California.

There are a number of strategies California could utilize to attract more federal funding:

Provide Matching Funds for Federal Projects. This type of activity would aid California-based companies and better enable them to compete for federal funds. Most federal DOE programs require a 20 percent cost share, and so California could leverage federal funds at a ratio as attractive as 5:1 (five federal funding dollars per every California funding dollar). This activity would provide a major advantage to California-based firms or research institutions. In particular, research institutions typically have difficulty with identifying sources of matching funds.

Encourage Teaming with California Based Biotech Companies. Many of the current projects that were awarded federal funds utilize algae / biodiesel technologies. California could develop programs to encourage these firms to team with California's biotech industry to accelerate the development process. This is another means to leverage federal funds and encourage the formation of more projects that engage and help to stimulate the growth of one of California's key existing industries.

Serve as a Demonstration Facility for Beneficial Use Technologies. The oil and gas industry within California could benefit from the beneficial use of CO_2 for EOR applications, however the pipeline infrastructure to facilitate widespread adoption is lacking. Activities to encourage these types of projects within California include reducing the complexity of the permitting process, establishing clear accounting protocols, and studies to plan and optimize infrastructure.

2.5 Summary of International Activities

There are a number of activities outside the United States that focus on the beneficial reuse of CO_2. The conversion of CO_2 into methanol using organic catalysts has been showcased by Singapore's Institute of Bioengineering and Nanotechnology, but the energetics of the process has yet to be demonstrated. With exemplary economy, Indian National Environmental

Engineering and Research Institute (Nagpur) has a $202,000 project that has demonstrated that the use of bacterial enzymes that can quickly convert CO_2 into $CaCO_3$ – a compound useful for building materials.

The heavily promoted use of biochar has a broad international interest and has adherents across a wide spectrum of applications. The pyrolytic combustion of biomass to create biochar is used to improve soil quality, and thereby sequestering CO_2 instead of releasing it through regular burning or decomposition, providing a double benefit. The global interest in this process is underscored by such organizations as the International Biochar Initiative (over 20 countries or regions), the UK Biochar Research Centre at the University of Edinburgh, Scotland, BiocharEurope, Swiss-Biochar, and other organizations in Japan, SE Asia, Australia and New Zealand, and Canada. These initiatives also aim to improve soil quality, and thus crop yield, in the Developing World. There is a Biochar Fund to seed biochar commercialization projects. The scope of these biochar activities extends from community-scale soil improvement schemes to large scale commercial projects.

In all the activities listed above, the chemistry is largely demonstrated, but the energetic and process economics require a more comprehensive demonstration as to the effectiveness of this technology

CHAPTER 3: Technology Barriers and Knowledge Gaps

The technologies outlined in Tables 3-8 were examined to identify any technology, regulatory, or other barriers, or key knowledge gaps. Such barriers could prevent the full scale deployment of a technology. Process performance of the scaled up system could be significantly worse than those measured at the lab scale. This reduced performance could result in unattractive process economics. Regulatory barriers will also inhibit the full scale deployment of technologies. Permitting issues could result in long delays in construction and deployment.

Knowledge gaps are technical developments that will be required to overcome these barriers (technical, regulatory, or other). It is valuable to identify knowledge gaps and in particular gaps that may be common to a variety of technologies.

The barriers and knowledge gaps for the technologies that were previously discussed in Tables 3-8 are outlined in Tables 15-20. There are a number of barriers and knowledge gaps that are common to technologies within a category. In Table 15, for example, proximity of CO_2 sources to oil and gas production is a technical barrier common to EOR, EGR, and ECBM. Permitting issues are regulatory barriers for many of these technologies. A common knowledge gap is monitoring the CO_2, especially over long periods of time.

Scalability is a common barrier that needs to be overcome for the technologies in Table 16. This reflects their lower technology readiness levels as compared to the technologies in the previous table. Consumer safety codes and regulations and consumer acceptance are especially important when products are materials for construction or involve genetically modified organisms. Issues related to the actual CO_2 life cycle are common themes for barriers and knowledge gaps. Process economics, power supply and demand cycles, and other issues related to power plant and/or storage reservoir operations are relevant to the technologies in Table 17.

The barriers and knowledge gaps for Table 18 and share many commonalities. One of the reasons is that most of these technologies would be very sensitive to residuals present in the CO_2. Public acceptance and regulatory approvals would be extremely rigorous since many of these technologies result in products that are consumed by, worn by, or implanted in humans. The economics are a concern since most of these technologies have an estimated amount of CO_2 utilized rating of "**S**" and are more than likely not in close proximity to a major stationary CO_2 source.

The barriers and knowledge gaps in Table 20 focus on the management of highly concentrated brines. Many of these barriers and knowledge gaps are shared with existing needs being addressed in the water treatment industry.

3.1 Commonalities in Barriers and Knowledge Gaps

Despite the wide range of categories and technologies examined in Tables 15-20, there are some commonalities. These provide the basis for some key RD&D efforts that would impact a range of beneficial use technologies.

- **Need for CO_2 Life Cycle**. This is a critical factor that forms the basis for a more quantitative comparison of the technologies. As a part of this analysis, the amount of energy required also needs to be quantified. It is recommended that a standard be developed and be utilized for ALL technologies. This is a critical common metric.
- **Monitoring CO_2 Levels**. In subsurface storage applications, it is critical that monitoring methods be standardized, adopted and utilized to enable acceptance of these technologies in cap-and-trade or other accounting schemes for CO_2 emissions reduction. Where technologies create products, the CO_2 life-cycle analysis should be sufficiently robust to allow assignment of a carbon mitigation value that is acceptable in meeting California's GHG emissions reductions requirements.
- **Permitting, Regulatory, and Legal Hurdles**. These are common themes that include permits and regulations related to (1) CO_2 capture retrofits on existing CO_2 sources or for new builds, (2) pipeline infrastructure, and, in some cases, (3) the subsurface. Given that networks of CO_2 suppliers and users will be necessary to support deployment of many of these technologies, the legal liability/chain of custody for the CO_2 should be clearly established. Delays in these processes could severely impede the adoption and deployment of many of the technologies discussed in this report.

These common themes are vital metrics for beneficial use technologies that could initially be addressed generically by the relevant California state agencies involved in permitting and regulation of CO_2 sources and CO_2 emissions, including the California Air Resources Board, the California Public Utilities Commission, the Department of Oil and Gas and Geothermal Resources in the Department of Conservation, and the California Energy Commission.

Table 15: Barriers and Knowledge Gaps for Technologies Using CO_2 as a Working Fluid

	Technical Barriers to Deployment	Regulatory and Other Barriers to Deployment	Knowledge gaps	Notes
Power Generation Applications				
Super critical CO2 for Brayton Cycle Turbines	- Impact of super critical CO2 on turbine components	- Process economics	- Long term performance - Impact on materials in turbines	See work by Sandia National Laboratories (http://www.sciencecodex.com/supercritical_carbon_dioxide_brayton_cycle_turbines_promise_giant_leap)
Working fluid / cushion gas for energy storage	-Turbine modifications to handle CO2 stream -Requires salt caverns, depleted gas or oil fields, or aquifers	Methods to monitor CO2 release	- Requires additional subsurface reservoirs; - Methods to characterize suitability of subsurface reservoirs - Large scale demonstration	Compressed Air plants are currently operational, but switch to CO2 not trivial. Would require major modfications and testing.

Table 16: Barriers and Knowledge Gaps for Building Materials, Biochar, Fuel and Chemical Technologies for CO_2

	Technical Barriers to Deployment	Regulatory and Other Barriers to Deployment	Knowledge gaps	Notes
CO_2 for building materials manufacture				
Carbonates and other construction materials	design of materials with adequate physical properties for anticipated service conditions	Permitting and public acceptance of new types of bulding materials	sources of alkalinity for making carbonates	Concept is to chemically transform CO2 into carbonate phases that can be engineered with favorable properties for use as building materials. In particular to replace or serve as an additive for ordinary portland cements (OPC) that are themselves a major source of CO2 during calcining of limestone.
Biochar				
Pyrolysis of biomass	Questions on scalability; also need certain soil characteristics	Implications on acceptance of food produced from resulting soil	- True CO2 balance to validate sequestration. - Economics as scale-up process.	Pyrolysis equipment exists, but key is systems analysis.
Fuel and Chemical Production				
Chemical Conversion	Scalability of technology and economics	Permitting - especially if genetically engineered microrganisms are used	- Overall CO2 life cycle for process	This concept is severely limited by energetics. Energy from photosynthesis must be added to CO2 to turn it back into a higher-energy state as an organic carbon species. Plant sizing and overall costs need to be evaluated to test concept viability.
Biological Conversion	Scalability of reactors to handle large volumes of CO2	Land-use issue as very large areas of ponds needed, regulations having to do with genetically altered organisms	- Filtration and processing of biomass into fuel - Maintaining health and vigor of microbial communities - Economic analysis and impact of impurities in CO2 stream	Significant number of companies in this space

Table 17: Barriers and Knowledge Gaps for Power Generation Technologies for the Beneficial Use of CO_2

	Technical Barriers to Deployment	**Regulatory and Other Barriers to Deployment**	**Knowledge gaps**	**Notes**
Working fluids				
Enhanced oil recovery (EOR)	- Proximity of wells to CO2 sources - Need for more large scale systems studies	-Access to oil fields and economic price for CO2 relative to oil price forecasts; - Methodology for monitoring potential CO2 escape - Permitting process in CA exists, but ambiguities storage accounting and Class II v. VI	-Monitoring of injected CO2 - Details of long term sequestration	EOR is a mature technology. The amount of CO2 that is truly sequestered is not known; barriers to deployment in California are mainly the lack of an available CO2 source. None of the existing CO2 pipelines bring CO2 into California. EOR will generate additional fossil fuel for burning, thus adding to the problem that beneficial re-use is trying to address. DOE-NETL report estimates 7.5GT CO2 could be used between now and 2020 for EOR applications in the U.S. (DOE/NETL 402 1312-02-07-08)
Enhanced Gas Recovery (EGR)	-Requires proof-of-concept field studies - Proximity of wells to CO2 sources - Need for more large scale systems studies	-Access to gas fields and economic CO2 price relative to forecast natural gas prices; - Requires methodology for monitoring potential CO2 escape - Permitting process in CA exists, but ambiguities wrt storage accounting and Class II v. VI	Effectiveness of CO2 displacement of CH4 in field studies	EGR is not a mature technology. While the displacement of CH4 by CO2 has been demonstrated as has gas drive in hydrocarbon recovery, field demonstrations are lacking to prove sweep efficiency and other economic parameters. Many gas fields in CA are natural water drive, so it is unclear what residual gas ssturations remain and wehther they could be removed by repressuring with CO2
Coal bed methane recovery (ECBM)	Need for more large scale systems studies	Permitting process	-Monitoring of injected CO2 - Details of long term sequestration	CO2 can be used to displace methane bound to coal surfaces. This technology is analogous to EOR and EGS.
Geothermal working fluid (Enhanced Geothermal Systems)	- optimized turbine technology - methods for reservoir optimization - avoiding fast path fluid flow	prediction of potential CO2 leakage	- Subsurface chemical evolution of CO2 working fluid, - CO2 capture flux	CO2 can be used instead of water as a working fluid in geothermal systems. Over long time periods, the CO2 will carbonate the rocks, using the intrinsic alkalinity of the rocks to form carbonate minerals. This enhances the rate of mineral trapping, a desirable outcome in conventional CCS systems in terms of reducing the risk of long-term CO2 confinement.

Table 18: Barriers and Knowledge Gaps for Uses of CO_2 as a Solvent, in Agricultural and Biomedical Applications

	Technical Barriers to Deployment	Regulatory and Other Barriers to Deployment	Knowledge gaps	Notes
CO_2 as solvent				
Supercritical fluid extraction and other food processing applications	- Requirements for clean up of CO2 capture streams from stationary sources - Proximity to CO2 sources drive overall CO2 life cycle and process economics	Acceptance of use for food applications and resulting permits.	- Economics after achieving required CO2 purity - Means to insure containment of CO2 after usage	Existing market
Dry cleaning	- Requirements for clean up of CO2 capture streams from stationary sources. - Proximity to CO2 source impacts economics	Acceptance of use for dry cleaning applications and resulting permits.	- Economics after achieving required CO2 purity - Means to insure containment of CO2 after usage	Perchloroethylene substitute
CO_2 in ag & biomed				
Greenhouse atmosphere additive	- Typically desire 1000 ppm CO2 - sulfur levels are a concern	Acceptance of use for food applications and resulting permits.	- Economics after achieving required CO2 purity	Use of enriched CO2 atmospheres in greenhouses and other agricultural uses to increase crop productivity
Grain silo fumigant	Mixed with Ethyl Formate (16.7%) to protect against stored-grain insects	Acceptance of use for food applications and resulting permits.	- Economics after achieving required CO2 purity	
Sterilization for biomedical applications	- Ability to sufficiently purify CO2 to levels required while still maintaining attractive economics	Acceptance of use for medical applications and resulting permits.	- Economics after achieving required CO2 purity	Major concern since used with implantables. Would probably require extensive clinical testing to insure no impact of use of CO2 from stationary sources.

Table 19: Barriers and Knowledge Gaps for Miscellaneous Industrial Applications

	Technical Barriers to Deployment	Regulatory and Other Barriers to Deployment	Knowledge gaps	Notes
Misc. Industrial				
Fire extinguishers	- Manage CO2 after discharge - Process economics and proximity to source of CO2	- Permitting and acceptance of CO2 source	- Impact of residuals on performance	Highly developed technology
Shielding gas for welding	- CO2 life cycle - Process economics and proximity to source of CO2	- Permitting and acceptance of CO2 source	- Impact of residuals on performance	Highly developed technology
Refrigeration and heat pump working fluid	- CO2 life cycle - Process economics and proximity to source of CO2	- Permitting and acceptance of CO2 source	- Impact of residuals on performance	See German Association of the Automotive Industry (VDA) archives
Propellant	- CO2 life cycle - Process economics and proximity to source of CO2	- Permitting and acceptance of CO2 source	- Impact of residuals on performance	Low end applications
Rubber and plastics processing - blowing agent	- Signficant work to replace blowing agents - Some work to reversibly complex during blowing	- Permitting and acceptance of CO2 source	- Impact of residuals on performance	Highly developed technology
Waste water treatment	- Economics	- long term studies on impact of residuals in CO2 - Overall process economics - CO2 life cycle	- Process economics - impact of residuals in CO2 stream - Overall CO2 life cycle	CO2 is the acid of choice for scale control - displacing sulfuric acid
Cleaning during semiconductor fabrication	- Economics of purifying CO2 - Proximity to source	- Permitting and acceptance of CO2 source	- Process economics - impact of residuals in CO2 stream - Overall CO2 life cycle	Highly developed

Table 20: Barriers and Knowledge Gaps for Technologies for the Use of Water to Displace Aquifer Fluids

	Technical Barriers to Deployment	Regulatory and Other Barriers to Deployment	Knowledge gaps	Notes
Water from displaced aquifer fluids				
Water Purfication	- Ability to treat of high salinity brines - Process economics need to be developed	brine disposal	Energy efficient methods for desalinating high salinity brines, scale control in high-salinity brines	Desalination of formation water that is displaced during CCS operations. The water could be used for power plant cooling, or other potable water applications. This technology would be of great value in arid regions of California.
Extraction of Value Added Solids from Water	- Economical separation technologies - process economics	waste stream permitting	Existence of marketable minerals in brines in any given area	Mineral recovery from formation water that is displaced during CCS operations. Some brines may contain salts of magnesium, manganese, lithium, zinc and other metals that could be extracted for a profit.

CHAPTER 4:
Role of CO2 Utilization in Climate Change Mitigation in California

Governor Arnold Schwarzenegger and the California Legislature recognized the importance of reducing carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions to the atmosphere to combat climate change. On June 1, 2005, the Governor signed Executive Order S-3-05, which established three target reduction levels for GHG emissions in California: 2000 levels by 2010; 1990 levels by 2020; and 80 percent below 1990 levels by 2050.[12] Upon passage of Assembly Bill 32 (AB 32), the Global Warming Solutions Act of 2006 (Núñez, Chapter 488, Statutes of 2006), California began to identify ways to meet the second target of reducing GHG emissions to 1990 levels by 2020.[13]

Sequestration of carbon is an important component of the strategy to meet emissions targets. Sequestration options include geologic, terrestrial, and utilization of CO_2 in products which permanently sequester carbon. In this context, the definition of permanence takes on regulatory significance. In addition to consistency with climate change goals and technically achievable constraints, time scales for CCS projects must be practical and consistent with overarching energy policy goals. Timelines set for CCS projects, for example, might depend on factors such as the maximum atmospheric concentration of CO_2 that is set as a policy goal and the timing of that maximum, but also on the anticipated duration of the fossil fuel era, the availability of alternative fuels, and alternative energy and climate change mitigation strategies in the event that deeper emissions cuts are necessary in the future. The practicality of CCS may depend on economic and logistical factors that constrain activities such as monitoring and stewardship to human institutional timelines, which rarely have exceeded a few hundred years.

Although the legislature has recognized geologic sequestration as a strategy to meet California's climate change goals, as of the close of the 2010 legislative session, the role of CO_2 utilization technologies in sequestration has been largely ignored. However, for any type of sequestration by geologic, terrestrial, utilization or other means, regulations remain unclear with respect to the accounting and verification methods and requirements.

Geologic sequestration has received some recognition in the state as a greenhouse gas mitigation technology. It was the focus of Assembly Bill 1925 (AB 1925), (Blakeslee, Chapter 471, Statutes of 2006), passed unanimously, which directed the California Energy Commission, in coordination with the Department of Conservation, to prepare a report for the Legislature that contains "recommendations for how the state can develop parameters to accelerate the adoption

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[12] *Executive Order S-3-05 by the Governor of the State of California*, June 1, 2005, <http://www.climatechange.ca.gov>.

[13] Legislative Counsel, "Assembly Bill 32," *Official California Legislative Information*, n.d., <http://www.leginfo.ca.gov/pub/05-06/bill/asm/ab_0001-0050/ab_32_bill_20060927_chaptered.pdf>.

of cost-effective geologic sequestration strategies for long-term management of industrial carbon dioxide."[14] Senate Bill 1368 (Perata, Chapter 598, Statutes of 2006), mandates that new or renewed long-term contracts to purchase electricity from baseload facilities meet the GHG emission performance standard established by the California Public Utilities Commission (CPUC) and the Energy Commission, in consultation with the Air Resources Board (ARB), and allows for exclusion of emissions that are geologically sequestered.[15] ARB's carbon fuel standard also allows use of geologic sequestration for high carbon fuels. However, ambiguities in permitting, regulation, and accounting for geologic sequestration led the Energy Commission, ARB, and the CPUC in 2010 to convene an independent panel, the California CCS Review Panel, to make recommendations to the state for addressing these issues.

Beneficial use technologies have received even less recognition. Although the California CCS Review Panel examined beneficial use technologies, including a white paper and presentations from technology developers, the final recommendations report omitted it from consideration. While there is interest within California industry and research institutions in the possibilities of CO2 utilization technologies because they have the potential to turn waste into useful products, there is an overarching perception that their potential contribution to reducing the state's GHG emissions is small, except perhaps in the case of EOR.

The major point sources in California are natural gas power plants, oil refineries, and cement plants. Overall, many of these point sources are close to potential geologic sequestration sites, but capture and transportation costs suggest that carbon prices above $70/ton are necessary to make CO_2 disposal into saline formations approach viability. Most of this cost is for capture.

It is difficult to find any data documenting what value for CO_2 would pertain to CO_2 utilization technologies with the exception of CO_2-EOR. Given recent historically high oil prices and forecasts for their continuation, CO2 for EOR in 2010 is priced at about $30-40/ton. In California, oilfield operators have expressed that CO2 would need to be similarly priced to interest them in undertaking CO_2-EOR. For other utilization technologies, those which can reduce the costs of capture and transport would have significant price advantages, for example, those that include the CO_2 separation from flue gas as a part of their process or those that can co-locate near sources so that lengths of pipeline are minimized. Otherwise, it is likely that the economies of scale for capture and transport will limit one-to-one source-sink CCS projects to the largest sources in the state (Figure 4). For these sources, there are only a few beneficial use technologies that may be appropriate matches to the characteristics of the CO_2 emissions stream.

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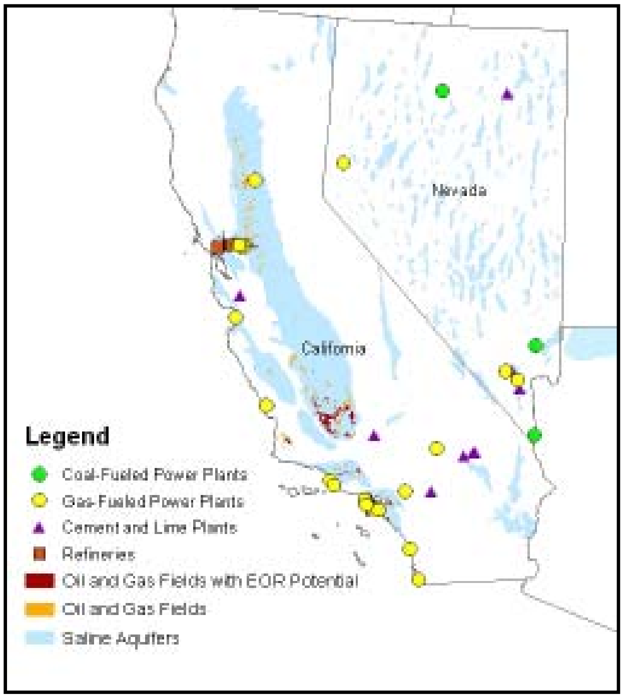
[14] Legislative Counsel, "Assembly Bill 1925," *Official California Legislative Information*, n.d., <http://www.leginfo.ca.gov/pub/05-06/bill/asm/ab_1901-1950/ab_1925_bill_20060926_chaptered.pdf>.

[15] Legislative Counsel, "Senate Bill 1368," *Official California Legislative Information*, n.d., <http://www.leginfo.ca.gov/pub/05-06/bill/sen/sb_1351-1400/sb_1368_bill_20060929_chaptered.pdf>.

Figure 4: Locations of Point Sources for CO2 Emissions, Saline Aquifers, and Oil and Gas Fields

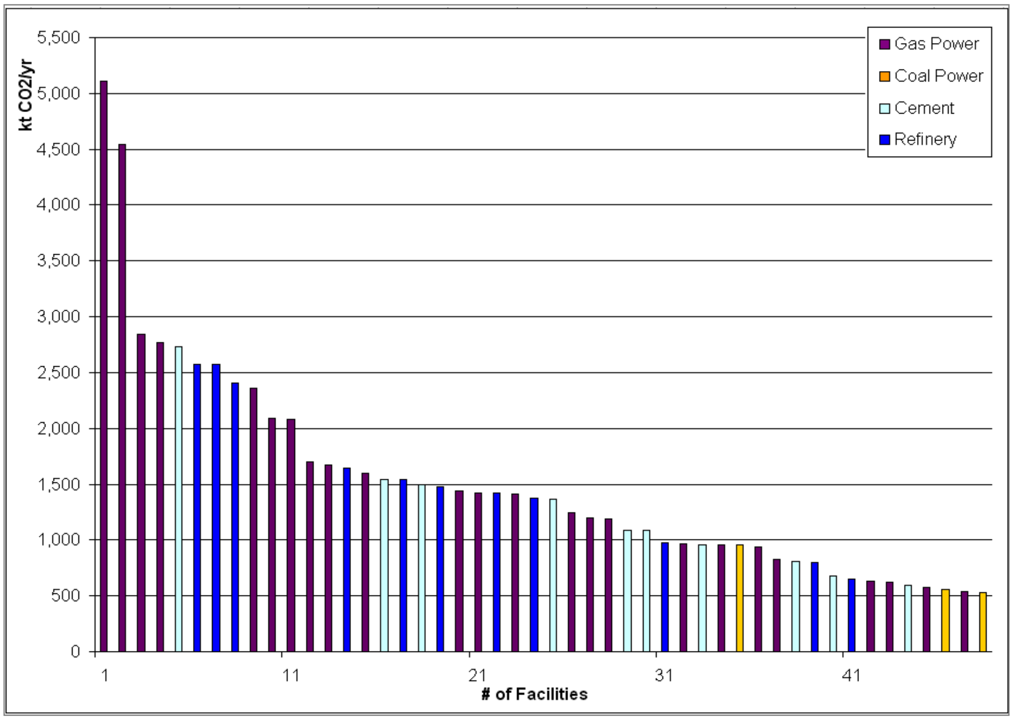


Source:Herzog, Howard, Weifeng Li, Hongliang (Henry) Zhang, Mi Diao, Greg Singleton, and MarkBohm. 2007. West Coast Regional Carbon Sequestration Partnership: Source-Sink Characterization and Geographic Information System-Based Matching. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-053.

In the context of matching technologies to sources, several factors are of importance. The ability of the technology to utilize the volume of CO_2 emissions is one such factor. For some sources, however, the supply of CO_2 will vary over time (for example for peaker power plants) or may vary in composition (for example if fuel types vary). These inconsistencies will have to be accommodated by a utilization facility.

The alternative approach to one-to-one source-sink matching is building infrastructure networks. In this approach, multiple sources would be linked through a common pipeline network connecting to a variety of CO_2 users, including beneficial use facilities and geologic sequestration sites. In this case, any fluctuations in CO_2 supply or quality could be moderated, economies of scale could be realized for smaller sources and smaller CO_2 users. A case study of how to produce such a network was done for Pennsylvania.[16]

Figure 5: Fifty Largest CO2 Point Sources in California



Source: Katzer, J. and Herzog, H., 2008, "PIER white paper on Economics of CO_2 Capture and Sequestration," *Assessment of Geologic Carbon Sequestration in California,* E. Burton and R. Myhre, Eds. PIER Energy-Related Environmental Research, CEC-500-2008-009.

Table 21: EOR Potential in California Oil Fields

Type of Reservoir	Number of Fields	Estimated Total Capacity (MMT CO_2)
Oil fields with miscible CO_2-EOR potential	121	3,186
Oil fields with immiscible CO_2-EOR potential	18	178

Sources: Herzog, H.J., 2005, *West Coast Regional Carbon Sequestration Partnership CO_2 Sequestration GIS Analysis.* Topical Report West Coast Regional Carbon Sequestration Partnership (WESTCARB), DOE Contract No.: DE-FC26-03NT41984; Downey, Cameron and John Clinkenbeard, 2006, *An Overview of Geologic Carbon Sequestration Potential in California*. California Energy Commission, PIER Energy-Related Environmental Research, CEC-500-2006-088.

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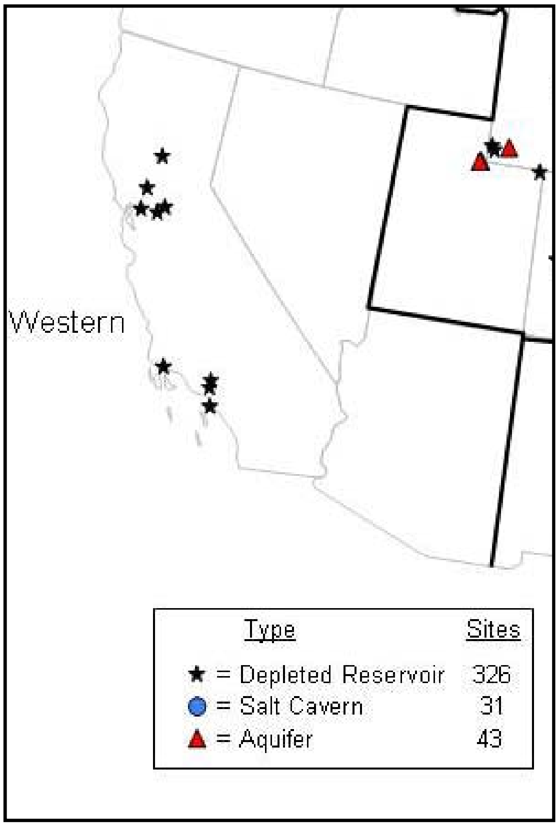
[16] Clinton Climate Initiative, 2009, Viability of a Large-scale Carbon Caputre and Sequestration Network in Pennsylvania http://www.dcnr.state.pa.us/info/carbon/viabilitylargescale-ccs.pdf. AccessedMarch 31,2011

Deployment of CO_2-EOR presents some specific additional challenges. The potential demand for CO_2 is large (Table 21) and dispersed within the southern San Joaquin Valley region and Los Angeles Basin (see distribution of oil fields in Figure 5, above). A CO_2 pipeline network connecting these oil fields with the collective sources necessary to meet the demand is lacking.

There are also significant geographic barriers separating the San Joaquin Valley oil fields from the locations of the largest point sources in the coastal areas of the state.

Figure 6: Locations of Natural Gas Storage Facilities



Source: Energy Information Administration, Office of Oil and Gas, Natural Gas division, Gas, Gas Transportation Information system, December 2008.

Similar issues arise in use of CO_2 as a cushion gas for natural gas storage. Demand for cushion gas is seasonal. California has 12 underground natural gas storage sites with a working capacity of 266 Bcf and a daily withdrawal capacity of 6875 MMcf.[17] Seven of these are owned by the two principal gas distributors in the State, Southern California Gas Company (SoCal) and Pacific Gas and Electric Company (PG&E). Most of their storage capacity is used for system

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[17] Energy Information Administration, 2008. Gas Transportation Information System, December 2008.

balancing and to maintain a steady and high-utilization of pipeline capacity directed from Canada and the Southwest.

The areas where beneficial use technologies may be of particular importance are urban areas with large point sources. Communities at such locations typically have opposed attempts at geologic sequestration. For example, the Hydrogen Energy California (HECA) experience at Carson with environmental justice groups highlights the fact that geologic sequestration is viewed as imposing waste disposal on locals already unfairly impacted by heavy concentrations of industrial development. In addition, few if any local jobs are created by such projects. Beneficial use facilities located in such areas can bring visible benefits to communities through job creation.

Thus, a larger view of the merits of CO_2 utilization technologies beyond their specific volume capacity to reduce CO_2 emissions seems warranted. Utilization technologies could provide important contributions to the state's overall strategy in ways beyond sequestration of large single source volumes of carbon, the traditional target for geologic sequestration. These include:

- Integrated projects where capture provides a CO_2 supply for CO_2 utilization facilities which provide local community benefits such as jobs, while the bulk of the captured stream may still require geologic sequestration.
- Replacement of fossil fuel use with CO_2 neutral products
- Potential to address disperse sources which in aggregate may provide significant GHG mitigation volumes
- In this context, the overarching issues which must be addressed include:
- Verification of sequestration for the products created, including a life cycle analysis of carbon and energy
- Establishing accounting protocols to verify sequestration and life cycle so technologies can be demonstrated to clearly contribute to AB32 requirements
- Studies to establish the best sites in the state for investment in integrated infrastructure that could combine multiple sources and geologic and beneficial use sequestration options to realize economies of scale, local benefits and climate change goals most effectively.

CHAPTER 5:
Research Roadmap: Recommendations on Funding Through the State of California

5.1 Objective and Methodology

As indicated in Chapter 1, the objective of this research roadmap is to assist the Energy Commission in defining future funding opportunities in the area of beneficial use of CO_2. Table 1 outlined the factors used to evaluate the list of technologies, while Table 2 lists the categories of technologies examined.

The data outlined in Tables 3-20 were reviewed by a panel consisting of the RWG and experts in the field. This combined panel reviewed the tables and developed the recommendations for the research roadmap.

5.2 Need for Common Research Metrics

One of the results from the barriers and gap analysis was the identification of some commonalities amongst the barriers and knowledge gaps of all the technologies. Two key needs were establishing:

- Standard methodology for establishing CO_2 life cycles
- Standard protocols for monitoring or verification of CO_2

The CO_2 life cycle tool is especially important. One approach would be for the Commission to produce such a tool to then provide to all applicants for research grants so that they can analyze their beneficial use technologies. This would assure that a standard means was being used to determine CO_2 life cycles, which would allow for better comparison among technologies, and it would also begin to make these critical data available.

It is also important that CO_2 levels be monitored and verified using standardized methods or protocols, since these results provide experimental feedback to validate the calculations from the CO_2 life cycle analysis and also provide a basis for establishing accounting and chain-of-custody and liability risk. Different methods may be required based on the category of the technology, and it may take some time to establish appropriate methodologies. Requiring effort to identify appropriate methods for their technologies could be a requirement for a beneficial use grant program.

5.3 Ranking of Beneficial Use Technologies

The panel reviewed the data in the tables and developed a ranking methodology to summarize the overall impact of the technology on the state of California. This methodology, outlined in Table 22, was then applied based on the analysis of the tables of data outlined in previous chapters, and the A and B rankings are shown in Table 24. A summary of the relative merits of each technology type follows.

Table 22: Ranking Categories

RANK	COMMENT
A	High potential for application in CA (either by volume of CO_2 used or based on other factors that might make the technology important for the state); investment in R&D has potential to lead to a commercially deployable technology in CA to meet 2020 goals
B	Moderate potential for CA (based on volume or other factors that would make it important to the state); investment in R&D has potential to be commercially deployable to meet 2020 or 2050 goals
C	Low potential for CA or investment in R&D is high risk with commercialization unlikely to meet 2020 or 2050 goals
D	Not significant to the state (remove from further consideration)

Table 23: Technologies with A and B Ranking

RANK	TECHNOLOGY
A	Biological Conversion Treatment of displaced aquifer fluids EOR and EGR Building materials Working fluids for energy storage
B	Geothermal working fluid Chemical conversions Working fluids for energy generation

5.4 CO2-Enhanced Oil Recovery (CO2-EOR) and Enhanced Gas Recovery (EGR)

The goal of both of these technologies is to increase the production of fossil fuel from existing sources. Both use carbon dioxide to sweep additional oil or gas from the reservoir. EOR is a well-established technology used in oil production, but is restricted in use to areas that have available sources of carbon dioxide, generally from natural sources. Although oil fields suitable for CO_2-EOR exist in California, the technology is not used due to a lack of available CO_2. EGR is a much less mature technology that aims to extract additional gas from gas reservoirs. It has been the object of several modeling studies and pilot studies, but needs to be demonstrated at a commercial size. California has gas fields appropriate for such field projects.

In addition, CO_2 could be used to help upgrade heavy crude oils, which are common in the state. CO_2 fluids might also be used for fracking to produce additional natural gas.

Both CO_2-EOR and CO_2-EGR benefit the state by enhancing oil and gas production and the state's revenues from those operations, but also boost the state's production of fossil fuels and any associated fugitive greenhouse gas emissions. Absent a sufficiently high price on carbon set by a carbon tax or sustained by a carbon market, the price for CO_2 obtained for EOR or EGR is likely to be an important factor in enabling a business case for many early CO_2 capture projects in California. These technologies also present a sufficiently large market to begin to justify the private or public investment in a pipeline infrastructure system in the state which might eventually enable the integration of a wide variety of small volume demand beneficial use facilities at dispersed locations.

5.5 Enhanced Geothermal Systems (EGS)

This concept is to replace the normal aqueous working fluids of geothermal systems with fluids composed primarily of carbon dioxide. The geothermal system would operate in a similar manner to current systems, except CO_2 would circulate to depths and serve as the heat transfer medium. CO_2 has some favorable properties relative to water including a reduced viscosity, greater change in density with temperature, and less reactivity with rocks. Although in the short term the CO_2 simply recirculates, over the long term, CO_2 would react with the host rocks to form carbonate minerals which provide the ultimate sink for the carbon.

The benefit of this technology is the production of electric power, which displaces an equivalent amount of fossil fuel burning. In addition, it would reduce the water use of geothermal power production, which has been an issue for expanding geothermal energy use in California. Water is lost in geothermal power plants that flash water to steam to drive turbines, currently the most efficient plant design. The flashed steam is lost and in many systems must be replaced with local water supplies.

Currently there is significant uncertainty as to the rate at which CO_2 reacts to form carbonates. Without this parameter, the amount of CO_2 that can be sequestered using this technology is uncertain also. Because California has abundant geothermal resources, CO2-EGS technology ranks highly as one technology advancement that could have significant impact on meeting the state's carbon reduction goals and increasing its ability to take advantage of its geothermal resource.

5.6 Building Materials

The goal of these technologies is to convert carbon dioxide into solid materials that can be used as building materials, such as cements, gypsum-based products, and others. A key advantage of these technologies is that the market sizes of building materials are large and commensurate with the scale of the problem. The materials can be made into forms such as carbonates that are stable under atmospheric conditions and therefore provide reliable long-term storage of CO_2 with relatively low risk. The materials have market value that can potentially offset the cost of CO_2 capture, although the prices for many of the possible products are low.

One of the barriers to deployment is the lack of a low-cost source of alkalinity needed to convert gaseous CO_2 into carbonate or other solid forms. Natural as well as man-made sources, including alkaline waste streams, have been investigated.

Further development of building materials ranks high based on the market size, favorable economic drivers, and the existence of start-up companies in California already working in this area. Like CO_2-EOR, it provides a relatively straightforward market-based entry into carbon capture.

5.7 Biochar

Biochar refers to pyrolyzed plant remains and biochar as a beneficial use refers mainly to the incorporation of biochar into soils as soil amendments. Carbon sequestration takes place because the biochar tends to be inert in the soil relative to oxidation by microbes. Thus biochar provides long-term storage for CO_2 that originally was removed from the atmosphere by plants.

Although biochar was originally included as part of this study, it was determined that because it has significant fundamental differences from the other beneficial use technologies and much in common with methods of terrestrial sequestration and changing land use practices, it deserves its own analysis. In particular, the life-cycle analysis is very complex and comparable to that of ethanol biofuel production. The biochar concept might also be extended to include new energy cycles involving coal gasification and carbon residues. We recommend biochar be the focus of a separate study by the Energy Commission to understand the potential of this technology to address the state's GHG reduction goals.

5.8 Biological Conversion

These technologies utilize CO_2 either directly from flue gas, or from concentrated streams including bicarbonate, to serve as the carbon source for microbiological activities. The organisms then are harvested to provide either fuels or carbon feedstocks that replace those traditionally sourced by fossil fuels.

There has been significant development of these technologies, and they look very promising. In California, their outputs could provide transportation fuels and thus lower the need for petroleum imports. The ultimate source of energy is solar, so that they do not need significant energy from the electrical grid. They appear to be close to commercialization and therefore have the potential to have a significant impact on meeting California's greenhouse gas reduction goals.

Major limitations include the need for large areas to capture sufficient solar energy (the efficiency of biological conversion is low), and the need for supplemental nutrients to grow a vigorous microbiological community. In addition to land resources, biological conversions will also require water. How well these technologies can be incorporated into California's complex water-energy nexus is an area that needs analysis to help identify biological-based technologies that have the greatest potential benefit.

5.9 Chemical Conversion

These technologies have similar purposes to biological conversion, but differ in that instead of using solar energy they use some other form of energy, in most cases from the grid, for their energy requirements. Their end products are either fuels or feedstocks that are produced from a feedstock of carbon dioxide. Much of the R&D to develop these technologies involves identifying effective catalysts to lower the energy barriers of converting CO_2 back into higher energy forms.

There are many R&D efforts underway on these technologies. Those that hold most promise are those that generate high value products such that the overall process has the greatest likelihood of being economically favorable.

A major disadvantage is the energy lifecycle for these technologies. They essentially convert CO_2 back into a high energy form, with an energy level comparable to that of the original fossil fuel. The inefficiencies of energy conversion, plus the energy needs of carbon separation weigh against both the energy use and the economic benefit of these technologies. The key question is the net carbon footprint of the process. Does the process, overall, actually result in a net decrease in carbon? Does the use of a technology of this type require substantial energy from the grid? An alternative to this is presented by the Fuels from Sunlight Hub approach where solar energy is used for the conversion, however again, whether it makes more sense to make electricity rather than chemical products from the solar energy should be investigated. Although we recommend that the Commission consider chemical conversion technologies because of their high payoff in high value products and ability to create replacements for products now made from fossil fuel, we suggest that a fairly detailed energy- carbon life-cycle analysis be undertaken prior to or as part of any funding for technology development in this area.

5.10 Working Fluids in Energy Generation

This concept is to replace working fluids such as steam or hydrocarbons with carbon dioxide. Laboratory studies and small-scale tests have shown improved energy efficiency for energy cycles such as supercritical carbon dioxide Brayton cycle turbines.

Significant work has already been carried out to develop this technology. A key question is whether existing energy plants can readily be retrofitted to take advantage of this improvement.

A downside is that the carbon dioxide is not sequestered in the process, it is re-cycled and only small amounts are needed. The advantage is that the improved efficiency decreases the amount of CO_2 released from the plant for an equivalent energy output compared to a plant using less efficient cycles.

5.11 Cushion Gas

It may be possible to use compressed CO_2 or air storage as a way to store energy from non-baseload power sources such as wind and solar. CO_2 can also be used as a ‘cushion gas’ for natural gas storage. In either application, most of the gas remains in the reservoir and expands or contracts as needed as the reservoir charges and discharges, providing pressure maintenance. CO_2 has favorable physical properties for this application.

This technology has merit in California both because of the existence of numerous natural gas storage reservoirs and the likely increased use of non-baseload, intermittent renewable energy sources such as wind and thermal. The technology is at a developmental stage where funding pilot or demonstration projects could provide the proof-of-concept needed for commercialization. The downside is that the potential CO_2 demand for this application probably is not significant relative to the state's inventory.

5.12 Minor Uses of CO2

There are many uses of CO_2 that have been developed. These include dry cleaning, silo fumigants, fire extinguishers, fluids for refrigeration, propellants, water supply acidification, blowing agents for plastics, and many others. However, these technologies use such minor amounts of gas that they are not recommended for further funding consideration. The only exception is for those technologies for which CO_2 replaces a much more potent greenhouse gas (so-called high greenhouse potential gases) where displacing the use of the more potent gas is the driver for technology development. For example, sulfur hexafluoride has a greenhouse gas potency 24,000 higher than CO_2. We did not identify any examples of these technologies in our review, but such technologies may be under development and they should be encouraged.

5.13 Water Resources from Displaced Saline Aquifer Fluids

Hydrologic modeling of geologic carbon capture and storage in saline aquifers indicates that for some systems it will be necessary to remove the saline brines to alleviate pressure buildup in the subsurface. To proceed with geologic CCS at these sites, it will be necessary to identify uses for these brines, or at least an economically viable means of disposal.

The technologies in this category are those that would desalinate these brines to provide useful water for industrial, agricultural, or other uses. The most likely scenario is using these produced waters for power plant cooling and avoiding the need to use local water supplies for energy production. By providing needed water, these technologies might allow power plants to be permitted in areas where the lack of water would otherwise prevent them from being located. This technology also would allow substantially greater CO_2 storage in a given saline aquifer relative to the scenario where saline brine removal is not carried out.

Given the persistent water problems in California, synergies with geologic sequestration, and the level of technical readiness, technologies of this type ranked highly in our analysis. A pilot demonstration project would provide proof-of-concept for the water and power industries in the state. A companion research program might focus on development of technologies to extract useful mineral components from produced fluids in cases where marketable components exist.

5.14 Recommended Next Phase in Analysis

The working group recommends that this roadmap be considered an initial step in the process to assess beneficial use technologies. There are a number of factors which could not be used in our ranking due to the limited data publicly available and insufficient time and resources to perform analyses to generate such data. Hence, the rankings were done based on qualitative or semi-quantitative assessments.

The group recommends that more in-depth analysis be performed on the top-ranked technologies to better evaluate their potential impact on the state of California. The next analysis should also be quantitative, likely requiring interactions with specific technology vendors and proprietary data to obtain the necessary information. Analyses needed include carbon life-cycle analyses, energy inputs, specific projections of market size and suitability for California's portfolio of CO_2 point sources.

It would also be useful to develop a more quantitative means to assess the combination of regional economic impact coupled with environmental impact. For example, a metric that examines the relative increase in the number of jobs/ ton CO_2 removed could provide an important means to further assess the selected technologies. As a precedent, the Department of Energy required applicants for ARRA funding to indicate the projected number of jobs created if technologies were deployed. Specific guidelines and standards were developed to assure consistency in this often difficult calculation.

In addition, given the rapid development of technology in this area, it seems appropriate that this roadmap be updated annually or semi-annually. This approach would assure the Commission stays current with changes in the technical and policy landscapes that would affect the applicability of these technologies as alternatives for sequestering or reducing the state's GHG emissions.

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GLOSSARY

ARB	Air Resources Board
ARRA	American Recovery and Relief Act
CPUS	California Public Utilities Commission
DOE	Department of Energy
ECBM	Enhanced Coal-Bed Methane Recovery
EGS	Enhanced Geothermal Systems
EOR	Enhanced Oil Recovery
ERG	Enhanced Gas Recovery
GHG	Greenhouse Gas
HECA	Hydrogen Energy California
JCAP	Joint Center for Artificial Photosynthesis
NETL	National Energy Technology
PC	Portland Cement
REII	Renewable Energy Institute International
RFP	Request for Proposal
RWG	Roadmap Working Group
WSPP	Western States Power Pool

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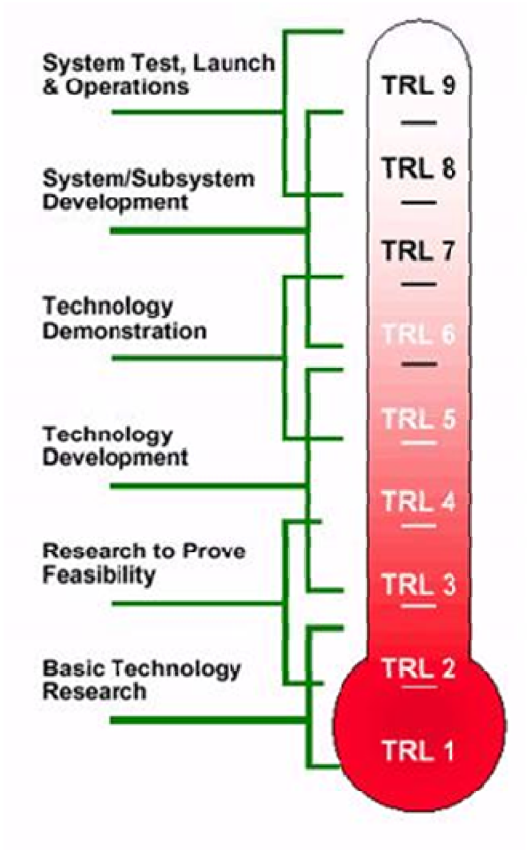
Appendix A:
Technology Readiness Level (TRL) Descriptions



- Technology Readiness Levels (TRLs) : scale for assessing the maturity of a particular technology
- Developed by NASA, now wider use in DoD and other agencies
- Viewed as one component of a risk-reduction measure*
- Creates "common language" that facilitates the integration of technologies from universities and research labs (e.g. NRL, ARL)*
- Recent versions include market related risks, e.g. COSYSMO**

Appendix B: Biographical Sketches of Roadmap Working Group Members

William Bourcier until recently was a staff research chemist in the Energy and Environment Directorate at Lawrence Livermore National Laboratory. At LLNL he led or assisted with several water treatment and water desalination projects at bench to pilot scale, including a novel electrostatic desalination technology and a carbon dioxide separation technology based on conventional desalination. Previous to this, he spent over a decade working on the development of durable glass and ceramic waste forms for radioactive waste disposal. He also worked on projects on fundamental measurements of thermodynamic properties of aqueous systems, including mineral solubilities and stabilities of aqueous species at elevated temperatures. He currently serves on technical review boards overseeing demonstration projects aimed at nitrate removal from groundwaters in Central California, and thermal desalination of water from the Salton Sea in California. William left LLNL in 2008 to co-found Simbol Mining Corporation, a company focused on developing and implementing extraction technologies to harvest marketable by-products from aqueous brines. He recently returned to LLNL part-time to work on water-related and other aspects of geologic sequestration of carbon dioxide, including carbon capture using encapsulated solvents. William received his Ph.D. in Geochemistry & Mineralogy from Penn State University in 1983.

Elizabeth Burton is the Technical Director of the West Coast Regional Carbon Sequestration Partnership (WESTCARB) and a project manager in Carbon Management at Lawrence Berkeley National Laboratory. She has worked in the field of carbon capture and storage for over 10 years, both as a researcher and as a technical consultant, in industry as well as in government. She has extensive experience at the federal and state level in providing technical consultation for energy policymakers, including as a team member in developing the Energy-Water Report to Congress and Energy-Water Roadmap, in leading the Assembly Bill 1925 effort at the Energy Commission to report to the California Legislature on recommendations as to how to facilitate commercial-scale CCS adoption in the state, and as a member of the Technical Advisory Committee to the California CCS Review Panel. She is the author or coauthor of over 100 published technical papers and a college textbook on oceanography. She received a Ph.D. in Earth and Planetary Sciences from Washington University in St. Louis, a M.S. in Marine Geology from the Rosenstiel School of Marine and Atmospheric Sciences at the University of Miami, and a B.A. in Geology from Bryn Mawr College.

James Ekmann is with Leonardo Technologies, Inc. (LTI). Prior to his current appointment he was Associate Director of Systems and Policy Support at the DOE National Energy Technology Laboratory. He has spent many years at DOE and LTI researching various Carbon Capture and Storage topics.

Dorota Keverian is the Director of the William J. Clinton Foundation Climate Initiative, and focuses on carbon capture and storage projects. She is the former Global Director of Consultant

Human Resources, Boston Consulting Group, and also served as former Arthur D. Little Director and Vice President, responsible for Global Oil Practice P&L and people development. Ms Keverian was Exxon International project manager with various downstream responsibilities. She has extensive international experience in talent management, organizational change, and strategy and performance improvement. Board member of Plan International and Plan USA. Graduate of Massachusetts Institute of Technology.

Niall Mateer is Director of the Carbon Sequestration Research Program at the University of California's California Institute for Energy and Environment, where he manages the West Coast Regional Carbon Sequestration Partnership (WESTCARB) contract awarded by the California Energy Commission (CEC). He was the founding Executive Director of the University of California Trust in the United Kingdom (UK), and before that he was Director of Research Outreach at the University of California Office of the President, where he oversaw the administration of UC's diverse system-wide research organizations. Dr Mateer is an earth scientist by training and has been active in 35 countries as a researcher, as a geoscience project leader for UNESCO, and as editor of an international geological journal. He was a founder faculty member of geology departments in Texas and in Nigeria. He received a B.Sc. (Hons) from Durham University in the UK and a Ph.D. from the University of Uppsala in Sweden.

Kevin O'Brien is a technology expert and project manager with over 20 years of experience in the management of multi-million-dollar programs related to the development and deployment of technologies and practices for the power sector. One of the keys to the success of these projects is the ability to systematically resolve conflicting needs and provide an acceptable solution for a variety of stakeholders. This encompasses resolving regulatory and environmental issues, while still maintaining attractive return on investments for projects. The multi-organization teams he has led combine OEMs, EDC firms, technology developers, regulators, regional, and federal stakeholders. His international project experience includes Europe, Middle East, and Asia. He is a recipient of R&D 100 awards as well as awards for technology transfer. Dr Obrien is CEO and President of Energy Commercialization, LLC.