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Carbon Utilization to Meet California's Climate Change Goals

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Abstract

We have developed a roadmap of CO_2 utilization technologies for the California Energy Commission, a state government energy research, policy and permitting agency. The objective of the roadmap is to identify technologies that can make significant contributions to the state's 2020 and 2050 greenhouse gas (GHG) reduction goals. The state of California, under Assembly Bill 32, is committed to achieving reductions to 1990 GHG inventory levels by 2020 and, under Governor's Executive Order S-3-05, to 80 percent below those levels by 2050. The roadmap will guide future R&D investment and policy development for enabling carbon utilization technologies in California.

For the purposes of the roadmap, we defined utilization as including technologies that produce a useful product from anthropogenic CO_2, or through the processes of capture or sequestration of CO_2. Technologies may contribute to reductions directly by permanently sequestering CO_2, or indirectly by displacing the use of fossil fuels or more potent GHGs, such as CFCs. Technologies considered include: CO_2 as a working fluid (including enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced geothermal systems (EGS)), chemical feedstocks, biofuels, building materials, compressed gas energy storage, cushion gas for natural gas storage, and water and marketable minerals produced from displaced sequestration reservoir fluids.

Evaluation criteria include technological maturity, potential market size, purity of CO_2 required, commercialization time frame, environmental impacts, water use, data on energy-carbon life cycle analysis, and potential local economic benefits such as job creation. In addition, we evaluated the potential impact of non-technical barriers to commercial-scale adoption, such as the need for clear accounting protocols to provide incentives for CO_2 producers to adopt these technologies to meet carbon standards.

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It may be possible to integrate different utilization approaches. For example, CO_2 can be reduced to produce methanol or formic acid, which can be converted into fuels. Other processes to functionalize the carbon atom produce saleable chemicals, such as urea. By combining these two approaches, synthesis of even more chemicals directly from CO_2 could be achieved.

Widespread deployment of CO_2 utilization technologies also depends on integration into planning of a future carbon-energy infrastructure. While single projects for some technologies, such as EOR, may create a demand comparable to the CO_2 volumes generated by large sources, other technologies may have to be aggregated and/or combined with geologic sequestration to provide the volume of sequestration required. Deployment networks provide opportunities for cost optimization of pipeline infrastructure and for focusing public or private investment to facilitate commercialization.

Currently in California, utilization projects are in the research, pilot, or permitting stages, including projects to combine urea production and EOR, produce high carbon-content building materials, and develop chemical and biological CO_2 recycling technologies. None of these projects have yet reached the development stage necessary to demonstrate whether the technologies can contribute effectively to reducing California's GHG emissions.

Keywords: carbon utilization; beneficial use; California; carbon policy

Nomenclature

EGR	Enhanced gas recovery
EGS	Enhanced geothermal systems
EOR	Enhanced oil recovery
RWG	Roadmap Working Group
TRL	Technology Readiness Level

1. Introduction

California policy makers are interested in determining which CO_2 utilization or CO_2 beneficial use technologies have the potential to assist the state in meeting its greenhouse gas emissions reduction goals as defined by the Governor's Executive Order S-3-05 in 2005 and Assembly Bill 32 in 2006. In-state industrial sources of CO_2 in need of emissions mitigation technologies include refineries, cement plants and natural gas power generators; out-of-state sources include large coal-fired power plants exporting power to the state and high-carbon fuel stocks for refineries. To serve the needs of the state, technologies should reach commercialization commensurate with the time frames set for California's emissions goals in 2020 and 2050 and have the potential to make significant contributions to greenhouse gas reductions.

To meet policy makers' needs, we completed a roadmap. For the purposes of the roadmap, beneficial use or CO_2 utilization is defined to include technologies that produce a useful product directly from captured anthropogenic CO_2, or 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. Consequently, geologic sequestration is not included except in cases where something of value, such as additional oil, gas, geothermal heat, or usable water or brine, is a byproduct. Table 1 summarizes the categories and descriptions of CO_2 utilization technologies considered.

Table 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	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

2. Methods

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. Using the knowledge base created by the RWG, 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 RWG to define the current status for each technology. To assemble the knowledge base to inform the roadmap, the RWG searched 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.

For evaluating each technology, inputs to the process (CO_2 and other components, including water), process attributes and outputs from the process (product and other components, including waste products) were identified (Figure 1). These factors provide insights into how these technologies might impact California's resources, economy, and environment. Attributes of the process included identifying existing suppliers/developers and opportunities to deploy the process within California. These factors are especially important in considering the potential impact of a technology in 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, availability of lifecycle analyses, environmental impact, water use, and economic benefits. The Technology Maturity scale used in this analysis is the Technology Readiness Level (TRL) scale developed by and widely used by U.S. government agencies to assess the relative maturity of a particular technology. 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 concept, 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, e.g., at a power generation site. It is not uncommon for energy technologies to perform acceptably in a laboratory environment, yet fail when tested at pilot scale. Project costs and manpower requirements commonly increase significantly during this transition and up-scaling out of the controlled laboratory environment.

The relationship between TRL, scale, and relative project cost is illustrated conceptually in Figure 2. 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.

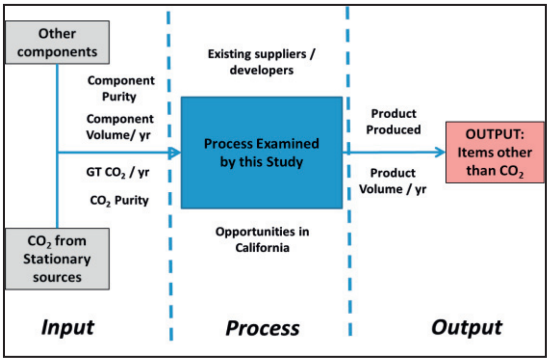

Figure 1. Methodology Used to Analyze Beneficial Use Technologies

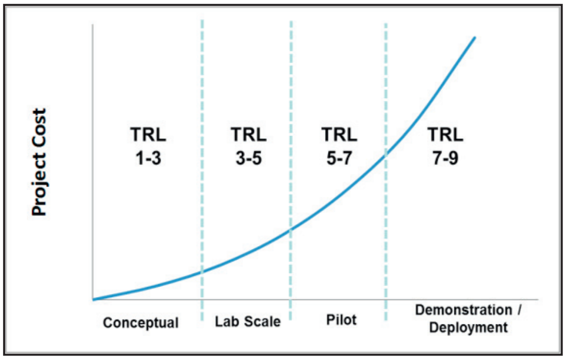

Figure 2. Relationship for Energy Projects Between TRL and Project Scale and Costs

Technology risk and the time to commercialize (i.e., 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 (i.e., <3 years, 3-10 years, or greater than 10 years). For the purpose of this roadmap, considering the time scales of relevance to the timeline for 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 economic. All three factors must be aligned in order 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, e.g. product purities
- Regulatory: regulations that either impede the deployment of the technology or favor the deployment of competing technologies
- Economic: process economics are unacceptable for the market place

The full set of parameters used to define the state-of-the-art of CO_2 utilization technologies is shown in Table 2.

Table 2: 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

3. Results

The first finding in our analysis is that currently there is no systematic set of data or methodology to enable comparison of the various 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 lifecycle analysis is needed for each technology that lays out the relative 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 (e.g., 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 insignificant reduction of 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.

Despite the wide range of categories and technologies examined (for a complete listing of the technologies assessed, see [1]), 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 paper.

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. Table 3 provides a summary of rankings. Technologies that we ranked as "A" are those that we consider to have a high potential for application in California, and that R&D investment would likely lead to commercially deployable technology in California to meet 2020 emission reduction goals. The technologies that we rank as "B" have a moderate potential in California and for which R&D investment could lead to commercially viable products with an impact on the 2020 or 2050 goals. Within rank "A", we gave highest marks for biological conversions, treatment of displaced aquifer fluids, and EOR/EGR applications.

Table 3. 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

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