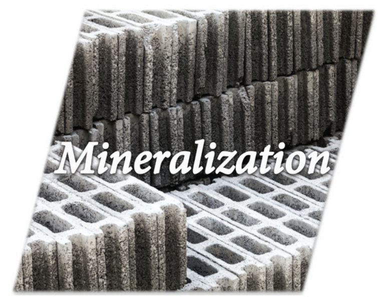
Consensus Study Report
October 2018
HIGHLIGHTS

Gaseous Carbon Waste Streams Utilization: Status and Research Needs

Carbon utilization technologies convert gaseous forms of carbon into useful products. These technologies have the potential to transform waste streams—primarily carbon dioxide and methane— into products, reduce greenhouse gas emissions, and generate positive economic returns. However, realizing this potential will require a variety of technological advances. This report outlines priority research needs that would enable the advancement of carbon utilization technologies and improve their commercial viability.



In the quest to mitigate the buildup of greenhouse gases in Earth's atmosphere, researchers and policymakers have increasingly turned their attention to techniques for capturing greenhouse gases such as carbon dioxide and methane, either from the locations where they are emitted or directly from the atmosphere. Once captured, these gases can be stored or put to use. While both carbon storage and carbon utilization have costs, utilization offers the opportunity to recover some of the cost and even generate economic value. While current carbon utilization projects operate at a relatively small scale, some estimates suggest the market for waste carbon-derived products could grow to hundreds of billions of dollars within a few decades, utilizing several thousand teragrams of waste carbon gases per year.

Produced at the request of the U.S. Department of Energy and Shell, this report assesses research and development needs relevant to understanding and improving the commercial viability of waste carbon utilization technologies and defines a research agenda to address key challenges. The report is intended to help inform decision making surrounding the development and deployment of waste carbon utilization technologies under a variety of circumstances, whether motivated by a goal to improve processes for making carbon-based products, to generate revenue, or to achieve environmental goals.

TAKING STOCK OF WASTE STREAMS

On an annual basis human activities globally emit about 35,000 teragrams of carbon dioxide, primarily from fossil fuel combustion in cars, buildings, factories, and power plants, and 320 teragrams of methane, primarily from oil and gas production, landfills, livestock, and manure (Figure 1).

Gaseous carbon waste streams are widely distributed. Some sources release waste gases constantly, while others emit only sporadically. Some contain high, relatively pure concentrations of carbon dioxide or methane while others contain lower concentrations of these gases along with a variety of other components or contaminants.

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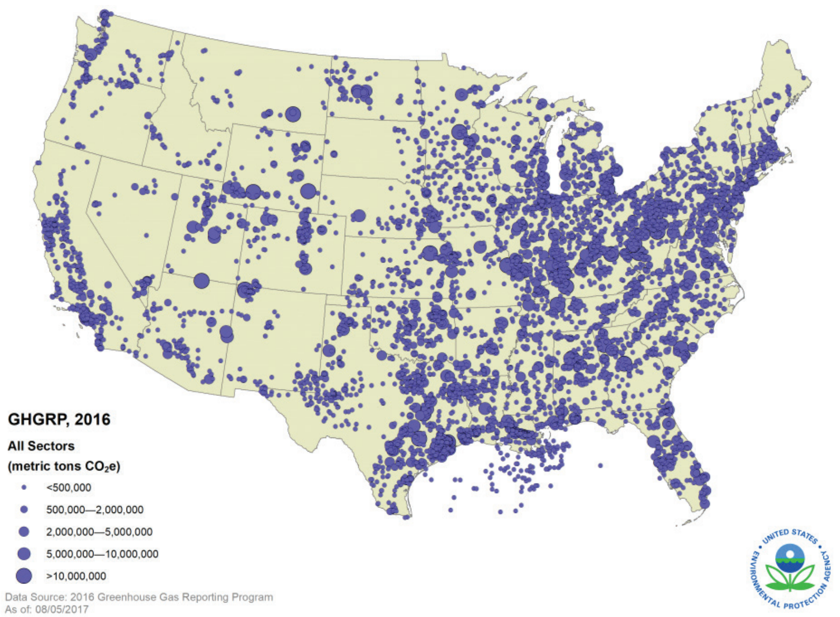

Figure 1. *2016 U.S. greenhouse gas emissions in terms of carbon dioxide equivalent (which includes both carbon dioxide and methane). Carbon utilization processes can turn some of these emission sources into feedstocks for producing fuels, building materials, chemicals, and other valuable products. SOURCE: Greenhouse Gas Reporting Program Data Sets (EPA, 2016)*

To efficiently capture and utilize carbon waste on commercial scales, it will be important to better characterize waste streams, understand which utilization technologies require separation and purification of gases, and strategically locate utilization operations to minimize the costs and environmental impacts associated with transporting and processing the inputs and products.

PATHWAYS FOR UTILIZING CARBON WASTE

The report defines waste carbon utilization as the manufacture of valuable products from a gaseous carbon waste feedstock (carbon dioxide or methane) that results in a net reduction of greenhouse gases emitted to the atmosphere. Broadly, carbon dioxide utilization can be categorized into three main pathways: (1) mineral carbonation to produce construction materials; (2) chemical conversion to produce chemicals and fuels; and (3) biological conversion to produce chemicals and fuels (Figure 2a). Methane utilization pathways include chemical and biological conversion to produce chemicals and fuels (Figure 2b).

The report describes the current status of each of these pathways, key barriers to commercialization, and research and development needed to advance the technologies involved.

Mineral Carbonation

Mineral carbonation processes transform carbon dioxide into mineral carbonates, which can be used to make concrete and cement. The chemical reactions involved in these processes can typically be performed at room temperature, and require little, if any, energy. Because concrete and cement are used at enormous scale and have product lifetimes that span decades, mineral carbonation represents a significant opportunity for long-term carbon storage in addition to being an opportunity for waste carbon utilization.

Mineral carbonation is already being used to produce concrete and other building materials at limited commercial scales, suggesting this pathway is well positioned for expansion in the short to medium term. Further research is needed to optimize the processes involved, identify which waste streams are best suited as inputs, and characterize the chemical and physical properties of the resulting products. In addition, it will be important to address logistical and regulatory factors that affect whether carbon-derived building materials can compete with conventionally produced materials on the basis of price, acceptability, and other factors.

Chemical conversion of carbon dioxide

Chemical processes can be used to transform carbon dioxide into carbon containing materials such as fuels, polymers, commodity chemicals, and fine chemicals. A few commodity chemicals are currently produced from carbon dioxide at a commercial scale, including salicylic acid (used in pharmaceutical and cosmetic products) and urea (used in agricultural, industrial, pharmaceutical, and other products). Many other applications that use carbon dioxide as a feedstock are in development at the laboratory or pilot plant scale.

However, because carbon dioxide is a relatively stable molecule, converting it into commodity chemicals or fuels is typically an energy-intensive process. Key research needs for chemical conversion of CO_2 include catalyst development, avoiding stoichiometric consumption of additives, interfacing capture with conversion, identifying new product targets, and system engineering and reactor design. The grand challenge for chemical conversion of carbon dioxide is to develop processes that require minimal amounts of non-renewable energy, are economically competitive, and provide substantial reductions in greenhouse gas emissions compared to existing technology.

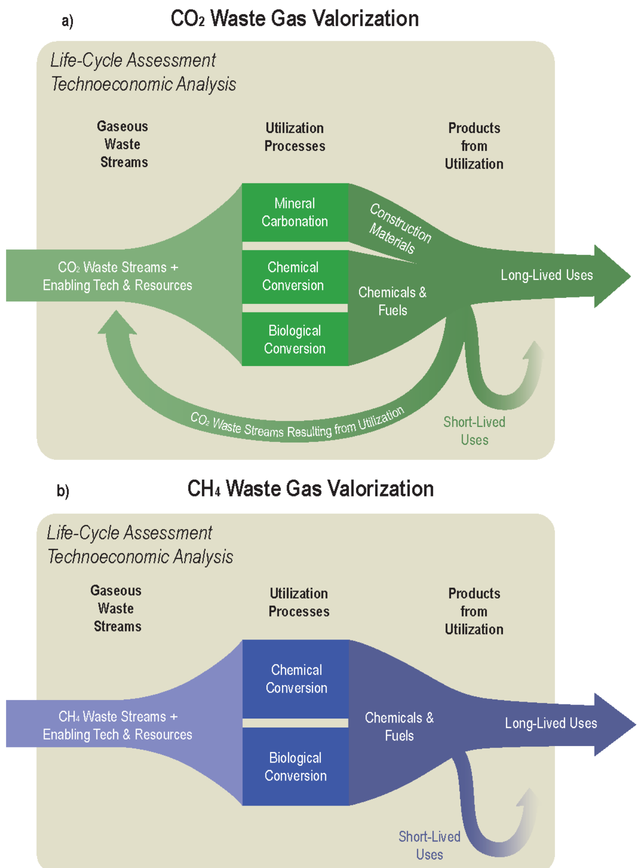

Figure 2. *Conceptual illustration of the process for valorization—the extraction of value—for carbon dioxide (a) and methane (b) waste streams. Gaseous waste streams enter each system on the left, with enabling technologies and resources implemented as needed. Utilization processes transform gases into products. As they are used and discarded or recycled, products can eventually result in carbon emission to the atmosphere or long-term carbon storage. Some waste gases from the process may be recovered and reused. The shaded box around each process represents tools for assessing the environmental impacts and economic value involved in the carbon utilization pathways.*

Biological conversion of carbon dioxide

Many microorganisms and biological processes naturally utilize carbon dioxide. For decades, people have harnessed this ability to produce chemicals and fuels. For example, photosynthetic algae can be cultivated to produce biofuels, dietary protein and food additives, commodities, and specialty chemicals. While some algae cultivation technologies are well established, there remain opportunities to improve product marketability, reduce land and water requirements, and reduce the greenhouse gas emissions of these technologies.

In addition, researchers are exploring approaches using non-photosynthetic organisms or artificial photosynthesis to convert carbon dioxide into a wide range of products. However, these approaches are at an earlier stage of development than algae cultivation, and additional research is needed to enhance organism and process engineering, improve efficiency, and explore the range of products that can be produced.

Methane utilization

Methane is already extensively used as a fuel and as a chemical feedstock. As a result, technologies to capture and use methane waste gas are already relatively mature. Additional research could further improve processes for chemical and biological conversion of methane and potentially identify new products to address unmet needs in commodity and specialty chemicals.

ENABLING TECHNOLOGIES AND RESOURCES NEEDED

To operate carbon utilization technologies at commercial scales with a net reduction in greenhouse gas emissions, certain enabling technologies, resources, and infrastructures will be needed. In particular, cost effective methods are needed to separate contaminants such as hydrogen sulfide and sulfur dioxide from the carbon dioxide or methane in waste gas streams. For carbon dioxide utilization (particularly chemical conversion), there is a need for low cost, low greenhouse gas emission sources of energy or energy carrying components such as hydrogen, heat, or electricity. Finally, because there is often a mismatch between the locations where such energy sources are available and the locations and magnitudes of emitted carbon streams, transportation or co-location infrastructures are needed to bring energy and waste gases together for processing.

TOOLS FOR EVALUATING COMMERICAL VIABILITY

The report identifies factors and criteria to compare the potential commercial viability of carbon utilization technologies. Waste carbon utilization technologies may be pursued for a variety of reasons, including economic value, process improvement and long term mitigation of greenhouse gas emissions, and different implementers will weigh factors differently. In addition to factors common to all technologies, such as economic value and market scale, some unique facets must be considered in evaluating commercial viability of waste carbon utilization technologies, such as the suitability of waste streams, risks associated with the use of waste as a feedstock, and greenhouse gas impacts.

Tools and methods such as life-cycle assessment and techno-economic analysis are useful for evaluating waste carbon utilization technologies, but existing assessments have important weaknesses. The report identifies improvements to advance these evaluation tools to provide the level of transparency, consistency, and accessibility needed to inform decisions related to waste carbon utilization.

Conclusions and Next Steps

There are reasons to be optimistic that both the environmental benefits and economic value of waste carbon utilization technologies could grow substantially in the coming decades. Already there are commercial technologies, operating at relatively small scale, that are or could be using waste gas as their raw materials. Additional fundamental research and process development could enable larger-scale implementation of more waste carbon utilization pathways.

Achieving this will require application-specific technological improvements as well as enabling technologies and conducive social, regulatory, and economic environments.

Key findings and recommendations include:

Finding: To play a meaningful role in carbon management, carbon utilization needs to be done at scale. The scale of carbon waste utilization will depend on the pace of technology development and future energy, market, and regulatory landscapes.

Recommendation 1: In order to realize potential benefits including improved energy and resource efficiency, creation of valuable industrial products, and mitigation of greenhouse gas emissions, the U.S. government and the private sector should implement a multifaceted, multiscale research agenda to create and improve technologies for waste gas utilization.

Recommendation 2: The U.S. federal science agencies should coordinate carbon utilization research and development efforts with private sector activities in the United States and with international activities in the private and public sector. Support for carbon utilization research and development should include technologies throughout different stages of maturity, from fundamental research through to commercialization, and evaluate them using a consistent framework of economic and environmental criteria.

COMMITTEE ON DEVELOPING A RESEARCH AGENDA FOR UTILIZATION OF GASEOUS CARBON WASTE STREAMS

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For More Information . . . This Consensus Study Report Highlights was prepared by the National Academies of Sciences, Engineering, and Medicine based on the Consensus Study Report *Gaseous Carbon Waste Streams Utilization: Status and Research Needs* (2018). The study was sponsored by the Department of Energy and Shell. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project. Copies of the Consensus Study Report are available from the National Academies Press, (800) 624-6242; http://www.nap.edu or via the Board on Chemical Sciences and Technology web page at http://www.nationalacademies.org/bcst.

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