University of Wyoming | School of Energy Resources

PREFEASIBILITY STUDY ON THE USE OF CARBON DIOXIDE IN CONCRETE PUBLIC WORKS PROJECTS IN WYOMING

Prepared in Fulfillment of the Requirements of Enrolled Act No. 12, Senate, 66th Legislature of the State of Wyoming, 2022 Budget Session

By

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SER collaborates with stakeholders at the state, national and international levels to advance energy technologies and policies to grow and support Wyoming's robust energy sector. SER's mission is to promote energy-driven economic development for the state, and it leads the University of Wyoming's talent and resources for interdisciplinary research and outreach, fulfilling Wyoming's promise to be a global leader in a thriving and sustainable energy future.

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GLOSSARY OF ACRONYMS

AB - Assembly Bill

A-SCM - Alternative Supplementary Cementitious Materials

BHE - Black Hills Energy

BLM - Bureau of Land Management

CARB - California Air Resources Board

CarbonSAFE - Carbon Storage Assurance Facility Enterprise

CCS - Carbon Capture and Storage

CCUS - Carbon Capture, Utilization, and/or Storage

CO_2 - Carbon Dioxide

CO_2-EOR - CO_2 Enhanced Oil Recovery

C-S-H - Calcium Silicates Hydrates

DFS - Dry Fork Station

DOE - U.S. Department of Energy

EGU - Electric Generating Units

EORI - Enhanced Oil Recovery Institute

EPA - Environmental Protection Agency

EPD - Environmental Product Declaration

FEMA - Federal Emergency Management Agency

GCCA - Global Cement and Concrete Association

GHG - Greenhouse Gas Emissions

GSA - General Services Administration

GSP - Gross State Product

HB - House Bill

IRA - Inflation Reduction Act

ISO - International Organization for Standardization

ITC - Integrated Test Center

LCA - Life-Cycle Assessment

NAPA - National Asphalt Pavement Association

NETL - National Energy Technology Laboratory

NRMCA - National Ready Mixed Concrete Association

ODOT - Oregon Department of Transportation

OPC - Ordinary Portland Cement

PCA - Portland Cement Association

PCOR - Plains CO_2 Reduction Partnership

PCR - Product Category Rule

PLC - Portland-Limestone Cement

PSC - Public Service Commission

RCF - Recycled Concrete Fines

RFP - Requests for Proposals

RMP - Rocky Mountain Power

RSU - Rock Springs Uplift

SB - Senate Bill

SCM - Supplementary Cementitious Materials

SER - School of Energy Resources

UIC - Underground Injection Control

USGS- United States Geological Survey

UW - University of Wyoming

WPCI - Wyoming Pipeline Corridor Initiative

WY-CUSP - Wyoming Carbon Underground Storage Project

WYDOT - Wyoming Department of Transportation

EXECUTIVE SUMMARY

This prefeasibility study examines the potential use of carbon dioxide (CO_2) in concrete for public works projects in Wyoming, focusing on coal-fired electric generating units (EGU) as the CO_2 source(s). The use of CO_2 in concrete is technically and commercially complicated. Historically, CO_2 is not a constituent additive to concrete, and as such, there are limited options for requiring its direct incorporation. The cement/concrete industry in Wyoming is relatively small in comparison to the quantity of CO_2 produced in the state, and public works projects are a fraction of the industry's size. Thus, the volume of CO_2 that could be used directly in concrete is relatively small (a conservative estimate is 0.15 million metric tons per year) compared to that produced by coal-fired EGUs in Wyoming (approximately 36 million metric tons per year). A large portion of this study assumes that CO_2 from one or more coal-fired EGUs in the state is available to be utilized commercially. At the time this study was written, no coal-EGU was commercially equipped with such a technology in Wyoming, but work in this field continues to advance in the state.

While it would be theoretically possible to establish a requirement to use CO_2 in concrete, Wyoming would need to weigh carefully the costs and benefits of such an approach. In lieu of a CO_2 use requirement, another option Wyoming could consider would be requiring an Environmental Product Declaration (EPD) for cement and concrete producers and eventually developing a life-cycle assessment (LCA) approach. EPDs and LCAs benchmark the embodied carbon content of building materials such as cement and concrete. EPDs and LCAs, in turn, may incentivize carbon capture, utilization, and/or storage (CCUS) approaches for concrete. This approach is consistent with comparable efforts being taken by many of the states leading in this field.

It also may be appropriate for Wyoming to continue examining various ways in which CO_2 can be deferred, sequestered, and/or used in construction materials as there are some larger-scale opportunities that would require further research to come to fruition. Alternative CO_2 use technologies include: (1) carbonation of hardened concrete; (2) injection of CO_2 in fresh concrete; (3) injection of CO_2 into reclaimed return water; (4) use of CO_2 for aggregate manufacture; (5) use of carbon to carbonate recycled concrete fines; (6) use of CO_2 in the production of value-added products such as alternative supplementary cementitious materials (A-SCM), alternative cements, aggregates, and filler materials; and (7) concrete solidification through carbonation.

Wyoming has significant potential to utilize CO_2 to produce value-added construction products for the concrete industry (e.g., A-SCM, alternative cements, concrete aggregates, and filler materials like powdered limestone) through: (1) liquid brine mineralization; (2) treatment of ponded coal ash or coal-ash that is destined for impoundment; (3) treatment of natural rock feedstocks; and/or (4) treatment of bentonite as a feedstock material. These value-added construction products could be exported to other states, thereby expanding the market for Wyoming CO_2 used in public works.

Based on decades of work, Wyoming should continue to focus on being a hub for CO_2 storage in deep saline aquifers as well as CO_2 enhanced oil recovery (CO_2-EOR). Importantly, there may be an intersection between produced water from CO_2 storage to form cementing compounds that can be used in construction. This may be an area to continue research.

Specifically concerning the questions set forth in House Bill (HB) 61 ("Carbon dioxide in public works—feasibility study"):[1]

i. Advantages and Disadvantages of a Requirement for a Specified Percentage of Concrete Used in Public Works Projects to be Made using CO_2 Emissions from Coal-Fired or Natural Gas-Fired Electric Generation Facilities

For various technical and commercial reasons, it is premature for the State of Wyoming to establish as a requirement that a specified percentage of concrete used in public works projects in Wyoming be made using CO_2 emissions from coal-fired or natural gas-fired EGUs.

[1] https://wyoleg.gov/2022/Introduced/HB0061.pdf

First, there may be technical challenges to address before widespread adoption can occur because CO_2 is not a typical ingredient in concrete. Technical challenges include, for example, CO_2 availability, product cost-effectiveness, and product long-term performance. These challenges must be overcome before CO_2 can be so utilized, yet alone be required, in infrastructure projects.

Second, and perhaps more importantly, the cement/concrete industry in Wyoming is relatively small in comparison to the quantity of CO_2 produced in the state (by at least a factor of 100) and public works projects are a fraction of the industry's size. As such, the volume of CO_2 that could be used directly in concrete is small compared to that produced by coal-fired and natural gas-fired EGUs in Wyoming.

Third, further research and investment in Wyoming are needed to develop value-added products that can be used in concrete. These value-added products include brine, ponded coal-ash, bentonite, and rock feedstock resources. Once these value-added products are commercially produced in Wyoming, it might become feasible for the State of Wyoming to establish a requirement that they be used in concrete for public works projects. Further, these value-added products could generate revenue for Wyoming. Therefore, it is prudent for Wyoming policymakers and industry to continue to monitor technological and policy developments related to decarbonizing building materials – an activity that is underway in surrounding states and within the industry.

ii. Whether any Requirement for CO_2 Use in Public Works Projects Should be Phased in as a Requirement

For various technical and commercial reasons, it is likely premature for the State of Wyoming to phase in a requirement that a specified percentage of concrete used in public works projects in Wyoming be made using CO_2 emissions from coal-fired or natural gas-fired EGUs. A different option for the state to consider is requiring an EPD – and potentially eventually an LCA – approach for cement and concrete used in public works projects in the state. This could help "set the stage" for increased use of materials that embody carbon when they are available in the future. However, the extra effort needed by entities carrying out public works projects should be considered as part of the evaluation process. The study's authors recommend research and investment in Wyoming to develop value-added products that can be used in concrete from brine, ponded coal-ash, bentonite, and rock feedstock resources.

iii. Whether There Would Be Additional Costs or Savings for Public Works Projects as a Result of a CO_2 Use Requirement

Although it varies by project, in many cases, there would be additional costs for public works projects due to a CO_2 use requirement for concrete. There may also be mechanisms or incentives to offset these costs. These costs include: providing technical support to the Wyoming concrete industry; providing solutions to creating durable concrete with CO_2 as a new ingredient in concrete; adding the required infrastructure to implement CO_2 utilization technologies; and providing a study regarding how much CO_2 capture could be completed using this methodology.

If it can be shown that Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources can be used in CO_2 mineralization technologies, value-added products could be produced for the concrete industry. Wyoming could become an exporter of such value-added products to other states. This will require additional investments in research and infrastructure; however, when successful, it could provide significant future value streams and uses for CO_2 emissions from coal-fired or natural gas-fired EGUs.

iv. What Types of Public Works Projects in the State Could Utilize CO_2 as Part of the Project

Subject to the limitations outlined in this study, the following types of public works projects in the state could, in theory, make use of concrete that utilizes CO_2: (1) highway construction, (2) school construction, and (3) projects involving the construction or renovation of state buildings.

However, the state would be best served to create value-added products that utilize large volumes of CO_2 (e.g., A-SCM, alternative cements, concrete aggregates, and filler materials like powdered limestone).

v. How Much CO_2 Could Be Captured in Wyoming to be Used for Public Works Projects

Because the concrete industry in Wyoming is relatively small, as is the demand for concrete generally, only a relatively small amount of captured CO_2 could potentially be utilized by the concrete industry. As an extreme example, if all concrete produced annually in Wyoming (approximately two million metric tons) is assumed to be available for CO_2 utilization, and all carbonatable portion of concrete (approximately 15% of the total volume of concrete) is carbonated (this is approximately five times the typical carbonation process), the maximum amount of CO_2 that can be incorporated in concrete would be around 0.15 million metric tons. Given that only a fraction of this concrete is produced for public work projects, and CO_2 would not be utilized in all concrete produced in Wyoming, the captured CO_2 would exceed the amount of CO_2 that can be used in public works projects by at least a factor of 100.

However, as mentioned, substantially more CO_2 could be utilized in the development of value-added products than that used by the conventional Wyoming concrete industry. The exact amounts depend on the application; however, Section 3.2 outlines several CO_2 utilization approaches: (1) carbonation of hardened concrete (~50 kg CO_2 per m^3 concrete); (2) injection in fresh concrete (~0.6 kg CO_2 per m^3 concrete);
(3) injection into reclaimed return water (~0.65 kg CO_2 per m^3 concrete); (4) aggregate manufacture (~600 kg CO_2 per m^3 concrete); (5) recycled concrete fines (~50-150 kg CO_2 per m^3 concrete); (6) concrete solidification through carbonation (~200-600 kg CO_2 per m^3 concrete); and (7) production of A-SCM, alternative cements, and fillers like ground limestone (CO_2 utilization depends on the details of what is produced). The numbers provided above are estimates. However, a more detailed analysis requires a follow-up study with specific materials and processes identified.

vi. Possible Infrastructure and Transportation Needs for Which CO_2 Could be Used in Public Works Projects Throughout the State

To utilize CO_2 in public works throughout the state, infrastructure and transportation needs – for delivering CO_2 to pipelines and concrete-specific utilization equipment – would have to be separately permitted, financed, constructed, and operated to enable the utilization of CO_2 in concrete in Wyoming. However, in some cases, construction materials production could be co-located with power plants to avoid additional infrastructure needs. Value-added products may need transportation to carry large volumes of material out of the state; however, this is believed possible on existing rail transportation used to transport coal.

vii. Any Disruptions or Disadvantages to Other Industries and Wyoming Businesses if a CO_2 Use Requirement is Imposed

The immediate imposition of a CO_2 use requirement would likely disrupt and/or disadvantage Wyoming's: (1) concrete industry; (2) building materials industry; and (3) construction industry. State and local government agencies and departments that rely upon the private sector to produce, deliver, and install concrete – including but not limited to the Wyoming Department of Transportation (WYDOT) – also could be disrupted and/or disadvantaged.

If it can be shown that Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources can be used in CO_2 mineralization technologies, Wyoming could become an exporter of such value-added products to other states. This could provide significant future value streams and uses for CO_2 emissions from coal-fired or natural gas-fired EGUs.

viii. Whether the Use of CO_2 in Public Works Projects May Extend or Prolong the Operation of Coal-Fired and Natural Gas Electric Generation Facilities in Wyoming

The use of CO_2 in public works projects theoretically could extend the operation of coal-fired or natural gas-fired EGUs in Wyoming by providing a potential economic return related to the utilization of CO_2. However, because the volume of CO_2 produced by EGUs greatly exceeds the potential market demand for CO_2 by the concrete industry, this issue is complicated and subject to a mix of EGU-specific considerations. Legal issues also are relevant because an EGU's sale of captured CO_2 for utilization in a product such as cement or alternative cements would also have to be recognized under the federal Clean Air Act.

If it can be shown that Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources can be used in CO_2 mineralization technologies, Wyoming could become an exporter of such value-added products to other states. This could provide significant future value streams and uses for CO_2 emissions from coal-fired or natural gas-fired EGUs. As such, this would prolong the potential operations of coal-fired and natural gas-fired EGU's in Wyoming.

ix. Whether Proposed or Enacted, Federal Legislation or Regulation May Impact the Use of, and the Advantages and Disadvantages of Using, CO_2 in Public Works Projects

This study has identified several proposed and enacted federal legislation and regulation that could impact the use, and the advantages and disadvantages, of CO_2 in public works projects. These include policies in various states to require lower-carbon footprint construction materials. In addition, there are several provisions in the Inflation Reduction Act (IRA) that may provide financial support for such products, including:

- $2.15B to install low-carbon materials in General Services Administration (GSA)-owned buildings. The GSA owns about 1,500 buildings around the country, including office buildings, land ports of entry, courthouses, laboratories, post offices and data processing centers.
- $2B for Low-Carbon Transportation Grants to reimburse and incentivize the use of low-carbon materials for Federal Highway Administration projects.
- $250M to develop and standardize EPDs for construction materials, with grants and technical assistance for manufacturers.
- $100M to identify and label low-carbon materials and products for federally funded transportation and building projects.
- $4B to improve resiliency in affordable housing, including funds for low-carbon materials, and allows the Federal Emergy Management Agency's (FEMA) Building Materials program to offer financial assistance for low-carbon materials and net-zero energy projects.

Finally, the 45Q tax credit, which was enhanced under the IRA, also now can support CO_2-utilization opportunities in the amount of $60/metric ton.

x. Advantages and Disadvantages of Using CO_2 in Public Works Projects

Advantages of using CO_2 in public works projects include: (1) opening new markets for an EGU's CO_2; (2) keeping Wyoming abreast of the latest in CCUS developments, specifically including the emerging trend in some jurisdictions regarding regulating concrete usage from a carbon footprint perspective; (3) potentially attracting new industries including, but not limited to, the Carbon XPrize activities at the Wyoming Integrated Test Center,[2] Carbon Built,[3] Solidia,[4] Carbon Upcycling,[5] Blue Planet,[6] Calera,[7] Holcim/Lafarge,[8] and Carbicrete;[9] and (4) potentially producing value-added products for the concrete industry through CO_2 mineralization technologies from Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources. If successful, the items produced by these companies and potentially others could be exported out of state as value-added products.

Disadvantages of using CO_2 in public works projects include: (1) CO_2 utilization in concrete may not qualify under forthcoming federal Greenhouse Gas (GHG) emission standards for coal-fired EGUs, depending on the specific project size; (2) in many cases, especially those where CO_2 must be transported, projects will be uneconomic or noncompetitive in the marketplace, meaning state requests for proposals (RFP's) may go under bid or, if bid, costs could be higher; (3) other CO_2 abatement options (e.g., geologic storage) will also be required given the relatively low CO_2 consumption level; (4) the CO_2-containing concrete may not qualify under existing codes and standards for materials in public works, and it would take a time and resources to work towards obtaining such qualifications; and (5) relationships with Wyoming CCUS's laws would have to be addressed – e.g., HB 200.

xi. Finally, significant potential exists for the establishment of one or more geologic CO_2 storage hubs in Wyoming.

Regardless of whether Wyoming decides to require or incentivize CO_2 in concrete public works, and even if these new public works materials are successfully deployed, geologic CO_2 storage (including CO_2-EOR) is likely necessary to address the majority of emissions from Wyoming's coal-fired and natural gas-fired EGUs.

[2] https://www.wyomingitc.org/
[3] https://www.carbonbuilt.com/
[4] https://www.solidiatech.com/
[5] https://carbonupcycling.com/
[6] https://www.blueplanetsystems.com/
[7] https://newatlas.com/novacem-calera-caron-capturing-concrete/14039/
[8] https://holcimmaqer.com/success-cases/holcim-uses-captured-co2-to-reinforce-recycled-concrete-with-neustark/
[9] https://carbicrete.com/

1. OBJECTIVES OF THE STUDY

This prefeasibility study examines the potential use of CO_2 in concrete for public works projects in Wyoming with a focus on coal-fired EGUs as the CO_2 source(s). The study begins with background information on the cement and concrete industry, including an assessment of its size and economic role and how it seeks to reduce the embodied carbon content of its activities and products. The study next discusses potential approaches to utilizing captured CO_2 emissions in concrete, focusing on the pros and cons. Infrastructure and transportation needs are also discussed. The study provides insights regarding the phasing of requirements for CO_2 utilization in concrete. The study concludes with an analysis of the potential for establishing CO_2 utilization strategies for producing value-added products intended to be used for the cement industry, concrete industry, and Wyoming public works projects and the need to pair this industry with CO_2 geologic storage in Wyoming.

2. INTRODUCTION

Enrolled Act No. 12, Senate, 66th Legislature of the State of Wyoming, 2022 Budget Session appropriated $300,000 to the School of Energy Resources (SER) at the University of Wyoming[10] for a feasibility study using carbon dioxide in public works projects. The feasibility study shall include an analysis of the economic feasibility of requiring that a specified percentage of concrete used in public works projects be made using carbon dioxide emissions from coal-fired or natural gas-fired electric generation facilities and shall also include the feasibility of establishing a potential carbon dioxide storage hub in Wyoming. The feasibility study report shall be completed and submitted by December 1, 2022, to the joint minerals, business and economic development committee and joint appropriations committee.

The referenced study was the subject of and thus is informed by separate legislation – HB 61, "Carbon dioxide in public works—feasibility study"[11] – introduced in the same legislative session. HB 61 provided as follows:

> "Section 1.
>
> "(a) The University of Wyoming school of energy resources shall conduct a study examining the feasibility of using carbon dioxide in public works projects. The study shall examine:
>
> > "(i) The advantages and disadvantages of a requirement for a specified percentage of concrete used in public works projects to be made using carbon dioxide emissions from coal-fired or natural gas-fired electric generation facilities;
> >
> > "(ii) Whether any requirement for carbon dioxide use in public works projects should be phased in as a requirement;
> >
> > "(iii) Whether there would be additional costs or savings for public works projects as a result of a carbon dioxide use requirement;
> >
> > "(iv) What types of public works projects in the state could utilize carbon dioxide as part of the project;
> >
> > "(v) How much carbon dioxide could be captured in Wyoming to be used for public works projects;
> >
> > "(vi) Possible infrastructure and transportation needs for which carbon dioxide could be used in public works projects throughout the state;
> >
> > "(vii) Any disruptions or disadvantages to other industries and Wyoming businesses if a carbon dioxide use requirement is imposed;
> >
> > "(viii) Whether the use of carbon dioxide in public works projects may extend or prolong the operation of coal-fired and natural gas electric generation facilities in Wyoming;

[10] Enrolled Act No. 12, Senate, 66th Legislature of the State of Wyoming, 2022 Budget Session, p. 38, n. 8
[11] https://wyoleg.gov/2022/Introduced/HB0061.pdf

"(ix) Whether proposed or enacted federal legislation or regulation may impact the use of, and the advantages and disadvantages of using, carbon dioxide in public works projects;

"(x) The feasibility of establishing a potential carbon dioxide storage hub;

"(xi) Any other item or issue that the school of energy resources believes may impact the feasibility of using carbon dioxide in public works projects.

"(b) Upon request of the school of energy resources, the department of transportation, the state construction department, the Wyoming energy authority, the public service commission and any other state agency shall assist the school of energy resources on the study required in subsection (a) of this section.

"(c) The school of energy resources may engage the services of consultants on a contract basis for rendering professional and technical assistance in completing the study required by subsection (a) of this section.

"(d) Not later than December 1, 2022, the school of energy resources shall report to the joint appropriations committee and the joint minerals, business and economic development interim committee on the results of the study required by subsection (a) of this section. The report shall state whether it would be feasible to require the use of carbon dioxide in public works projects, including school construction projects, projects involving the construction or renovation of state buildings and projects involving highway construction.

"(e) There is appropriated three hundred thousand dollars ($300,000.00) from the general fund to the University of Wyoming school of energy resources for the purposes of conducting the feasibility study and retaining consultants for the study required in this section. This appropriation shall be for the period beginning with the effective date of this act and ending June 30, 2023. This appropriation shall not be transferred or expended for any other purpose, and this appropriation shall not be used or expended for any indirect or overhead costs or charges for or imposed by the University of Wyoming associated with this appropriation. Any unexpended, unobligated funds remaining from this appropriation shall revert as provided by law on June 30, 2023. It is the intent of the legislature that this appropriation not be included in the standard budget of the school of energy resources for the immediately succeeding fiscal biennium."

Although neither Enrolled Act No. 12 nor HB 61 defines "public works projects," section 1(d) of HB 61 indicates that the term includes "school construction projects, projects involving the construction or renovation of state buildings and projects involving highway construction." The term "[p]ublic work" separately is defined under existing Wyoming law as including the "alteration, construction, demolition, enlargement, major maintenance, reconstruction, renovation and repair of any highway, public building, public facility, public monument, public structure or public system." Wyo. Stat. § 16-6-101(a)(ix) (2021). This study uses that existing statutory definition of "public work" as informed by section 1(d) of HB 61.

This study focuses on CO_2 utilization in concrete which, in turn, could be used in "public works projects" because concrete holds the greatest CO_2 utilization opportunity, compared to other publics works materials, for the foreseeable future. The potential utilization of CO_2 in non-concrete products was not studied in depth.

Potential uses and markets for CO_2 were considered for value-added products, such as those that use CO_2 to harden some materials or to enhance alternative cement products. These value-added products could be exported to other states, and Wyoming is well-positioned to do so.

SER will continue to fund students to make progress on select recommendations in this report through the end of the fiscal year (June 30, 2023).

3. BACKGROUND ON CONCRETE AS A MATERIAL

3.1. Concrete – An Introduction

Concrete is the most widely used material in the world. It is a primary structural material used to build civil infrastructure, including commercial and residential buildings,[12] pavements, bridges, dams, marine structures, industrial plants, pipelines, and water/wastewater infrastructure. The Global Cement and Concrete Association (GCCA) reports that over 18 billion cubic yards of concrete are produced globally every year, consuming approximately 4.4 billion tons of cement.[13] The United States is the world's third largest cement producer after China and India,[14] manufacturing approximately 87 million tons of cement annually as of 2020. An additional 20 million tons of cement are typically imported to meet demand. The GCCA estimates that the global cement and concrete products market value in 2020 was approximately $440 billion. Global cement production is expected to exceed 5.5 billion tons by 2050, when about 70% of the world's 9.8 billion people will live in urban areas.[13]

The extensive use of concrete is not by chance. First, concrete is the most economical structural material by volume.[15] Second, all constituent materials needed to produce concrete come from and are abundant in the Earth's crust. Third, concrete can produce structures in almost any shape and form. Fourth, concrete can be used in various aggressive exposure environments (e.g., wastewater, seawater, soil) that more rapidly deteriorate other materials (Figure 1). No other material in the world satisfies or has the potential to satisfy all of these features, thus making concrete indispensable and irreplaceable in many cases.

Figure 1: An example of the use of concrete in a dam (Grand Teton Park, Wyoming)

Photo 13516057 / Wyoming Concrete © Jeffrey Banke | Dreamstime.com

Concrete consists of rocks of various shapes and sizes (aggregate) held together by a glue. The word concrete comes from the Latin word "concretus" which is an amalgamation of "con" (meaning "together") and "crescre" (meaning "to grow"). Concrete can be considered a larger rock manufactured (grown) by bringing together smaller rocks. In fact, approximately 75% of the volume of concrete is composed of aggregates of different shapes and sizes that are extracted from the Earth's crust. These aggregates have formed over millions of years and have been exposed to extreme loading and environmental conditions; therefore, they tend to be strong, durable, and stable. When they are packed tightly, which can be achieved by using various aggregate sizes and held together by glue, they have the potential to carry large compressive loads, even when they are exposed to extreme environments.

The so-called glue usually is in the form of a hardened paste that is typically produced with a cementitious material (e.g., ordinary portland cement ("OPC"[16]) and water). Water and cementitious materials undergo chemical reactions that lead to the hardening of the mixture. When aggregates, cement, and water are mixed, the mixture can be placed in any shape or form. After a short period, hardening reactions between cement and water produce the structural and nonstructural elements used in buildings, roads, dams, and other structures.

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[12] About 40% of produced concrete is used in residential construction.

[13] GCCA. *The GCCA 2050 cement and concrete industry roadmap*. 2022; Available from: https://gccassociation.org/concretefuture/.

[14] China and India produced about 1.6 billion tons and 300 million tons of cement in 2021, respectively.

[15] The cost of concrete has been increasing about 2.5% annually in the last decade, and currently averages around $125 per cubic yard.

[16] Recently OPC has begun to be replaced in the United States by Portland Limestone Cement (PLC) conforming to ASTM C595. PLC is similar in composition; however, up to 15% of the OPC clinker is replaced with finely ground limestone.

After the main constituent materials (i.e., aggregate, cement, and water) are mixed together (Figure 2), concrete is a flowable material that can be transported and placed in a formwork. As it is placed in this formwork, concrete is in the fresh state (i.e., fresh concrete), which implies that it is flowable. Reactions occur between cementitious materials and water start soon after mixing, and within hours, concrete typically begins to solidify (i.e., set) and become a hardened material (i.e., hardened concrete). These reactions continue during the hardened state over a long period, most of them taking place within the first month, but may extend to many months, even years, improving strength and durability.

Figure 2: Concrete batch plant where aggregate, cement, water, and admixtures are mixed together and then transported to the construction site for placement in forms

Photo 103958440 / Concrete Batch Plant © Benjamin Gelman | Dreamstime.com

Hardened concrete is a relatively strong material in compression. However, since its tensile strength is about 10% of its compressive strength, it cannot be used as structural elements that carry tensile or flexural loads without reinforcement that can resist the tensile stresses. While some concrete products, like pavers and concrete blocks, are unreinforced, most concrete structures are reinforced (Figure 3). Reinforced concrete is a structural material that relies on the compressive strength of concrete for resisting compressive forces and the tensile strength of other materials (such as reinforcing steel bars) to resist the forces that concrete structures are required to withstand. In a typical reinforced concrete structural element, reinforcing steel is placed to form a strong bond with the concrete to carry the tensile stresses after the structure starts carrying loads. In some cases, the load-carrying capacity of structures might need to be increased further, for instance, to build longer-spanning bridges or leaner structural elements. This can be achieved by another structural type – prestressed or post-tensioned concrete – in which internal compressive stresses are introduced using tensioned high-strength steel tendons to reduce potential tensile stresses in concrete resulting from loads. Prestressed concrete structures can be pre-tensioned (i.e., tendons are stressed before concrete is cast) or post-tensioned (i.e., tendons are stressed against hardened concrete).

Concrete structures are typically classified as cast-in-place (Figure 3) or precast (Figure 4) depending on how and where the structural elements are produced.

Figure 3: Concrete placement with reinforcing steel

Photo 102577289 / Construction © Bubu-tu | Dreamstime.com

Cast-in-place concrete is made with ready-mix concrete (i.e., mixed and carried in its fresh state to the site) and placed into removable forms on site (typically within ~60 minutes of the plant). Ready-mix concrete is typically manufactured according to a recipe and delivered to the work site by truck-mounted in-transit mixers. The National Ready Mixed Concrete Association (NRMCA) estimates that about 394 million cubic yards of ready-mixed concrete were shipped to construction sites in 2021 in the United States.

In contrast, precast concrete is produced in precast plants using reusable molds or forms and cured in a controlled environment. The manufactured structural elements (e.g., beams, walls, columns, pipes, girders, etc.) are then transported to the construction site and lifted in place. Precast plants tend to have the ability to have more stringent quality control and may be better positioned to use CO_2 for curing.

Figure 4: An example of a precast concrete plant

Photo 165107999 / Construction © Konstantin Malkov | Dreamstime.com

3.2. Constituent Materials

As noted above, concrete is a mixture of a few primary materials: cement, aggregate (fine aggregate or sand and coarse aggregate or rock), water, and admixtures. Chemical admixtures are frequently used to aid by serving as a dispersing agent. In addition to these materials, concrete producers frequently use supplementary cementitious materials (SCM), powders that can provide a supplementary reaction that replaces a portion of the cement. These constituents are described in more detail below.

3.2.1. Cement

The amount of concrete used annually requires the production of large amounts of ordinary portland cement (OPC) every year. In 2020, about 87 million tons of cement were produced in the United States – specifically at 96 plants in 34 states and at 2 plants in Puerto Rico. An additional ~20 million tons of cement were imported into the United States during the same year. In descending order of production, the main cement-producing states in 2020 were Texas, Missouri, California, and Florida. These four states accounted for nearly 45% of U.S. cement production. When a material is needed and produced in such large quantities, the resource implications must be considered. Fortunately, almost all constituents of cement are abundant in the Earth's crust.

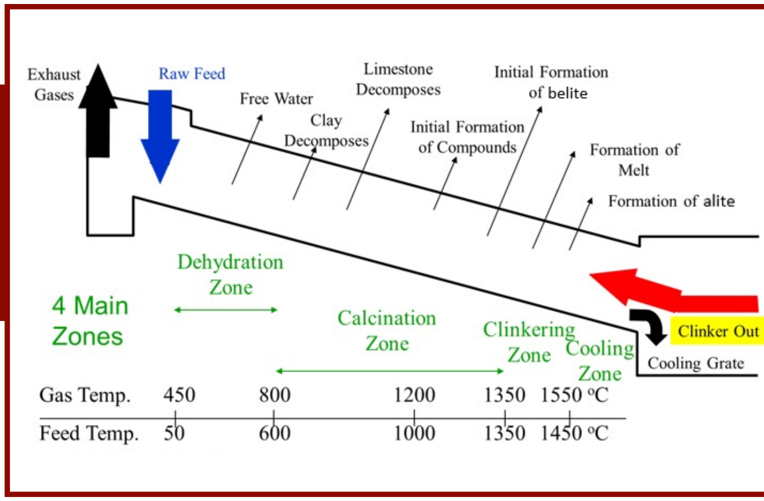
OPC is produced through a well-established and optimized manufacturing process that includes extracting calcium (Ca), aluminum (Al), and silica (Si) containing mineral rocks from the Earth's crust; crushing them into smaller pieces; mixing them in pre-determined proportions; driving off excess water from the system through pre-heating; pre-calcining; heating the mixture in a kiln (typically around 1500°C); rapidly cooling to produce clinker, and grinding them to produce a reactive powder (Figure 5). This clinker powder is highly reactive with water; therefore, the hardening reactions can take place very quickly, making concrete placement challenging in the field. To slow these reactions, the clinker is typically interground with a small amount of a sulfate source like gypsum (~<5% by mass), which results in the powder called OPC. In the United States, several types of OPC are produced depending on how the constituent materials (calcium, aluminum, and silica-containing minerals) are proportioned and how fine the clinker is ground into a powder. Some OPC types are used for general-purpose construction, while others are designed to be used in rapid construction (e.g., repair applications) when additional chemical resistance is needed or when it is desired to slow the chemical reactions between the clinker and water.

Figure 5: An illustration of a cement plant (Durkee, Oregon)

Photo 81444207 / Construction © Victoria Ditkovsky | Dreamstime.com

As the raw materials are heated in the preheater, precalciner, and/or kiln, a series of reactions occur, as illustrated in Figure 6. First, the heat dehydrates the materials, driving off water. Second, the clay and limestone are decomposed in a process known as calcination; the transformation of the limestone is responsible for a large portion of the CO_2 emitted in the manufacturing process. Third, the clinker begins to form a solid (undergoing solid and liquid reactions), creating the dicalcium silicate (alite), tricalcium silicate (belite), and tricalcium aluminate phases. There are other phases formed; however, those noted above are the primary reactive phases in cement. The reacted product (i.e., clinker) is then rapidly cooled to make the reactive phases that are eventually ground and used to make cement. As noted above, nearly 50-60% of the CO_2 produced occurs during the calcination phase, with 40–50% of the CO_2 produced by the energy required to heat the kiln and the remaining CO_2 associated with transportation and finishing. To provide a frame of reference, approximately 90% of the CO_2 emissions associated with concrete production are associated with cement manufacture.[17]

Figure 6: The schematic of a cement kiln and the process of making cement clinker[18]



The cement manufacturing process is highly optimized for efficiency, sustainability, and economy.[19] Over the years, the cement industry has reduced the energy needed in manufacturing by shifting from the wet-kiln process to the dry-kiln process. This has reduced emissions by reducing the fuel used in heating the raw materials (primarily by reducing the energy needed in the dehydration phase). The dry-kiln process uses waste heat from pre-heaters and pre-calciners to enable dehydration and a portion of the calcination to occur before the materials reach the kiln. This has reduced the amount of conventional fuels required to make clinker in cement kilns. The industry has also been exploring alternative fuels to reduce costs and emissions further.

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[17] Lippiatt, N., T.-C. Ling, and S.-Y. Pan, *Towards carbon-neutral construction materials: Carbonation of cement-based materials and the future perspective.* Journal of Building Engineering, 2020. 28.

[18] Mindess, S. and J.F. Young, Concrete. Civil engineering and engineering mechanics series. 1981, Englewood Cliffs, N.J.: Prentice-Hall. xvi, 671 p.

[19] From Jason Weiss course notes after Mindess and Young (1981).

Cement clinker is a highly reactive material when mixed with water, and this reaction produces the glue that holds the aggregate together in hardened concrete, as discussed above. Some of the phases in clinker are so reactive that they might result in concrete solidifying (setting) very quickly, which is a problem for most construction because some time (e.g., hours) might be needed between mixing and setting so that concrete can be transported to the construction site and poured into the formworks while it is in fresh state. Therefore, the clinker is ground with a source of sulfate (often gypsum) up to approximately 5% by mass, which helps slow the reactions between clinker phases and water. The product that is a mixture of ground clinker and gypsum is called OPC, and the reactions of OPC and water are called hydration reactions.

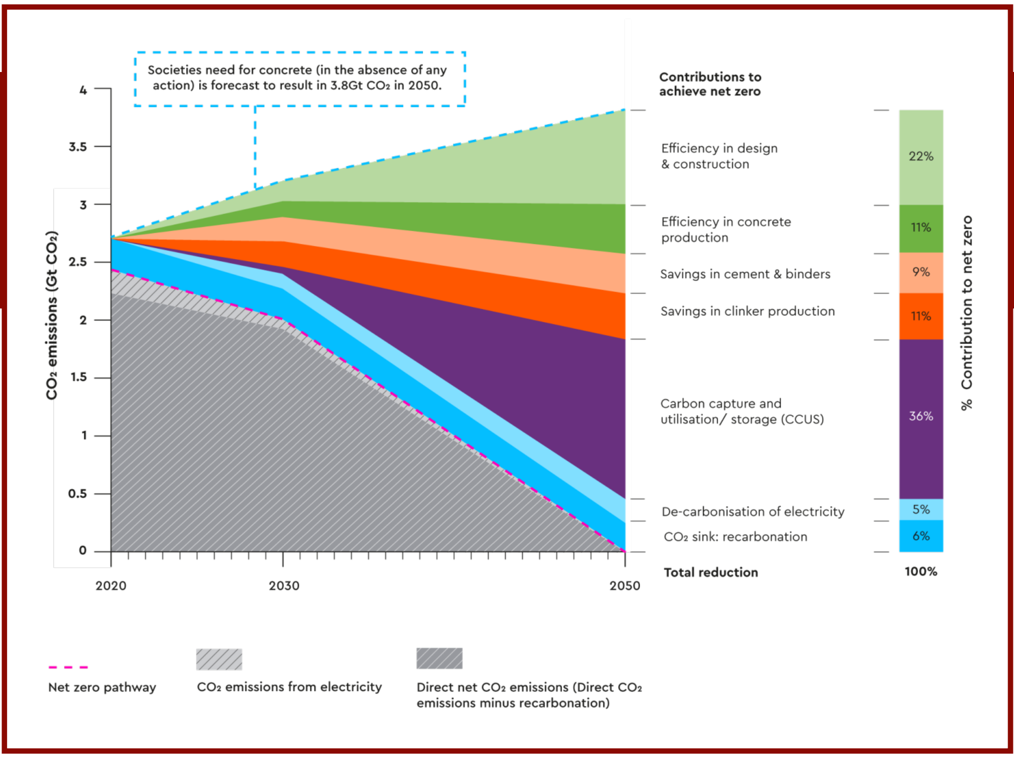
These reactions take place between the calcium silicate phases in the clinker and water to produce a very dense, strong, and stable material called calcium-silicate-hydrate (xCaO–ySiO2–zH20 is often referred to in cement chemistry notation as C-S-H) and calcium hydroxide ($Ca(OH)_2$ often referred to in cement chemistry notation as CH).[20] The primary role of C-S-H is to glue the aggregates together strongly and to resist the penetration of hazardous chemicals and moisture into concrete. The other main phase that forms during hydration reactions, calcium hydroxide, is not a strong material but helps the concrete to have a high pH (typically greater than 13). This high pH makes concrete highly stable chemically and helps prevent corrosion of steel reinforcement embedded in reinforced concrete structures. In fact, when the pH of concrete decreases, concrete structures might experience durability problems, such as the corrosion of steel reinforcement. One of the reasons behind pH reduction is a process called carbonation, in which CO_2 (in the air or artificially introduced to concrete) reacts with calcium hydroxide in a neutralizing reaction to reduce the pH of concrete, which might lead to reinforcement corrosion.[21] Corrosion-resistant steel (e.g., stainless steels) and non-metallic materials (e.g., fiber-reinforced polymeric bars) are available for use in concrete; however, their use is rather limited compared to conventional (carbon) steel, though such use is increasing.[22]

Despite these efforts to optimize the manufacturing process, there are still environmental implications associated with cement production. The extraction, transportation, and crushing of mineral rocks consume energy, as does the heating of the kiln and the grinding of clinker. Most importantly, reactions that take place in the kiln to convert the constituent materials into clinker release a significant amount of CO_2. Cement production is responsible for 5-8% of CO_2 emissions in the world[23] (~1% in the US[24]), mainly because of the calcination process that takes place inside the kiln during the formation of clinker. Numerous approaches have been investigated to minimize the carbon footprint of concrete, including using: (1) less cement; (2) materials to supplement/partially replace cement; (3) powder extenders like limestone; and/or (4) alternative cementing technologies.

The GCCA has published a roadmap (Figure 7) to reduce carbon emissions for both cement and concrete. It shows that CO_2 can be reduced through seven main areas. The first two areas deal with concrete use. First, the concrete industry proposes efficiencies from moving from small site production to more industrialized production with less waste. Second, reductions are proposed through more efficient concrete design in practice. Third, the amount of clinker can be reduced through the increased use of SCM, A-SCM, and/or limestone, as described in the following sections. Fourth, clinker production has the potential to reduce CO_2 emissions by using alternative fuels, electrification, or hydrogen. Fifth, the waste CO_2 streams could be reused in manufacturing concrete constituents and elements, as described in the following sections. Sixth, the industry proposes to reuse CO_2 by using concrete as a carbon sink. The seventh and largest strategy relies on CCUS to capture and store CO_2 emissions associated with concrete production.

[20] More information on cement chemistry notation can be found at https://en.wikipedia.org/wiki/Cement_chemist_notation.
[21] Reinforcement corrosion can also initiate due to ingress of chloride-containing salts (e.g., deicing chemicals, seawater, etc.) in concrete.
[22] ACI-440, ACI 440.1R: Guide for the design and construction of structural concrete reinforced with fiber-reinforced polymer (FRP) bars. 2015, American Concrete Institute: Farmington Hills, MI.
[23] GCCA. The GCCA 2050 cement and concrete industry roadmap. 2022; Available from: https://gccassociation.org/concretefuture/.
[24] PCA, Roadmap to carbon neutrality. 2022, Portland Cement Association: Washington, DC.

Figure 7: Proposed roadmap to net-zero carbon by the cement and concrete industry[25]



3.2.2. Aggregate

Concrete aggregates are classified based on their size. Aggregates typically consist of two sizes: coarse (such as gravel or crushed rock) and fine (such as sand). Various sizes of both types need to be used in different proportions to obtain an optimum packing for the desired concrete application. Concrete aggregates can be obtained directly from nature (such as riverbed gravel or sand) or crushed from large rock formations (such as crushed rock or sand) (Figure 8).

Concrete aggregates can also be recycled from demolished concrete to produce recycled concrete aggregate, which also can be both coarse and fine.[26] Recycled concrete aggregates typically have two parts: original virgin aggregate, which had been used to produce concrete for the demolished structure, and the attached residual cement paste. Due to the presence of the residual paste, recycled concrete aggregate materials show different fresh, mechanical, and durability properties compared to natural aggregates.

Another way to classify aggregates for concrete is based on their unit weight. Lightweight aggregates have a porous structure and a lower bulk density than common normal-weight construction aggregates.[27] Some of these materials can be found naturally, such as pumice, volcanic cinder, and light sand – but others are manufactured (such as expanded slate, expanded clay, expanded shale, and expanded perlite.

Figure 8: Typical example of an aggregate quarry

Photo 28969675 / Construction © Chris Van Lennep | Dreamstime.com

[25] GCCA. *The GCCA 2050 cement and concrete industry roadmap*. 2022; Available from: https://gccassociation.org/concretefuture/.

[26] Volz, J.S., et al., Recycled concrete aggregate (RCA) for infrastructure elements 2014, Center for Transportation Infrastructure and Safety/NUTC Program, Missouri University of Science and Technology Rolla, MO.

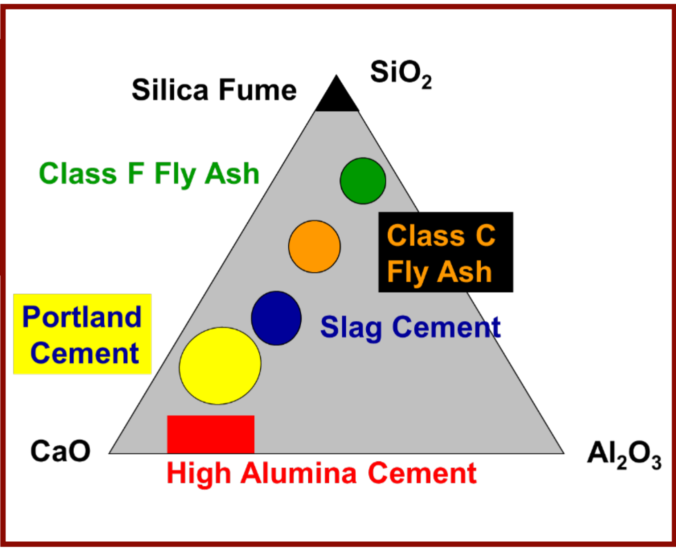
[27] ACI-213, ACI 213R: Guide for structural lightweight-aggregate concrete. 2014, American Concrete Institute: Farmington Hills, MI.

3.2.3. Supplementary Cementitious Materials

SCM are materials that have the potential to help OPC in creating the glue that holds aggregates together. These materials also contain Ca, Si, and Al oxides, typically in different proportions and phases from OPC; therefore, they can help the cementitious processes in concrete if they are used to partially replace a portion of the OPC in the concrete mixture. Figure 9 is a phase diagram illustrating how silica fume is very high in silica (silica dioxide, SiO_2) while OPC is high in calcium content (calcium oxide, CaO). The partial replacement of OPC with SCM results in reduce cement usage that can affect the carbon footprint of concrete directly (i.e., using less cement requires less clinker production). Considering the fact that most of the SCM are waste products of industrial manufacturing processes and would have to be disposed of if they are not used in concrete, it is clear that SCM use in concrete is highly advantageous.

Typical SCMs that are used in concrete include (1) fly ash, which is a byproduct of coal-fired EGUs; (2) ground granulated blast furnace slag (slag), which is a byproduct of iron production; and (3) silica fume, which is a byproduct of the silicon industry. Ground glass is also actively being explored for use. There are also natural SCM that are not the byproduct of industrial processes, including volcanic ash and pumice. Additionally, calcined clay can be used, a natural material extracted from the Earth's crust and heat treated. Due to increased demand for SCM in concrete production, a decrease in the production of these resources (e.g., fly ash), and local supply limitations, a significant amount of research is ongoing regarding identifying A-SCM sources such as agricultural and forestry ashes, and biochars. In Section 5.1.2, it is shown that Wyoming has significant opportunities to produce A-SCM using a number of CO_2 mineralization technologies from Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources.

Figure 9: A phase diagram of supplementary cementitious material chemistry



Because SCM reduces the amount of OPC in concrete, SCM use can also help produce concrete with enhanced performance characteristics. Most SCMs are classified as pozzolanic materials, which are silica or alumina sources that have the potential to react with calcium hydroxide to produce additional C-S-H, which, again, is the main glue used in concrete. This property of SCM makes it an ideal material to use with OPC because hydration reactions of OPC with water produce calcium hydroxide. When there SCMs are in the mixture, pozzolanic reactions between SCM and calcium hydroxide can produce more C-S-H with a more stable chemistry.

Despite the advantages of SCM usage, it is not trivial to proportion concrete mixtures with SCM because they exhibit a high degree of variability in chemical composition and reactivity. The use of SCM affects the chemical composition of concrete as SCM consumes calcium hydroxide in the pozzolanic reactions, which becomes important when concrete (cementitious matrix) interacts with CO_2 in the environment. However, significant advances have been made in: (1) quantifying the reactivity of these; and (2) improving SCM mixture proportioning methods in concrete to enhanced performance while reducing the carbon footprint.

3.2.4. Fillers, Inert Materials, Powder Extenders

Another approach that industry uses to reduce the carbon footprint of concrete is utilizing fillers, inert materials, and/or powder extenders to reduce the amount of OPC used in the cement powder mixture. The most commonly used powder extender is limestone. ASTM C150 (AASHTO M 85) currently allows up to 5% limestone in hydraulic cement. ASTM C595 (AASHTO M 240) allows up to 15% interground limestone to produce portland-limestone cement (PLC). PLC is engineered to perform similarly to OPC but with an approximately 10% reduction in carbon footprint.

As the use of limestone in cement in larger quantities becomes a mainstream application (either as PLC or even at replacement levels exceeding 15%), it is possible to envision the benefits of the artificial production of limestone using alternative pathways that include sequestering CO_2 during the process. Additional discussion of mineralization technologies is presented in Section 5.1.2, showing that Wyoming has significant opportunities to produce filler materials like ground limestone using a number of CO_2 mineralization technologies from Wyoming's brine, ponded coal ash, bentonite, or rock feedstock resources.

3.2.5. Chemical Admixtures

Chemical admixtures are added to the concrete immediately before or during mixing to (1) reduce the cost of concrete construction; (2) modify the properties of hardened concrete; (3) ensure the quality of concrete during mixing, transporting, placing, and curing; and (4) overcome certain emergencies during concrete operations.

There are five distinct classes of chemical admixtures: air-entraining, water-reducing, retarding, accelerating, and plasticizers (superplasticizers).

Air-entraining admixtures are intended to increase the freeze-and-thaw resistance of concrete. Water-reducing admixtures usually reduce the required water content for a concrete mixture by about 5 to 10% to increase the strength of concrete without adding additional cement. High-range water-reducing admixtures (superplasticizers) can reduce the water content by as much as 30% to make the fresh concrete more workable at the construction site. Retarding admixtures, which slow the setting rate of concrete, are used to counteract the accelerating effect of hot weather on the concrete setting. Accelerating admixtures increase the rate of early strength development, reduce the time required for proper curing and protection, and speed up the start of finishing operations. Accelerating admixtures are especially useful for modifying the properties of concrete in cold weather. In addition to these five categories, there are also corrosion-inhibiting admixtures to slow reinforcement corrosion.

Although chemical admixtures are not directly used when CO_2 is considered for incorporation in concrete, they play a significant role in concrete that is produced through some of these technologies. Depending on the technology, CO_2 incorporation in concrete could affect the workability, water demand and setting time of fresh concrete; chemical, electrical, mechanical and durability properties of hardened concrete, and how embedded steel reinforcement behaves in reinforced concrete, particularly in terms of resisting corrosive processes. Therefore, customization of chemical admixtures becomes important when CO_2 utilization in concrete is being considered.

3.2.6. Alternative Cements

Alternative cement is a general category used to describe cements that are not OPC.[28] It includes a variety of cements including calcium aluminate cements, calcium sulfoaluminate cements, alkali-activated binders (also called "inorganic polymers" or "geopolymers"), supersulfated cements, and magnesium-based cements. The use of alternative cements instead of OPC serves as an opportunity to reduce the carbon footprint of conventional concrete; however, these technologies vary substantially from the current concrete manufacturing practice and are, therefore, challenging to implement widely in practice to sequester CO_2.

[28] ACI-ITG, ITG-10.1R-18: Report on alternative cements. 2018, American Concrete Institute: Farmington Hills, MI.

As will be discussed in Section 5.1.2., it is possible to use CO_2 to help produce some of these alternative cements using mineralization technologies[29] and Wyoming has several opportunities to pursue these technologies due to its vast geological brine, ponded coal ash resources; however, the economic feasibility of these technologies highly depends on factors such as the feedstock (e.g., natural or artificial brines) availability, location, and distance to the CO_2 source (e.g., cement plants). Further, these materials are produced and used in substantially smaller quantities than OPC. As such, while they may play some role in reducing CO_2 emissions, OPC will be a dominate material for the foreseeable future.

4. CONCRETE INDUSTRY IN WYOMING

Wyoming currently has one cement plant with an annual clinker capacity of about 0.6 million metric tons, almost half of which is exported to other states. The Portland Cement Association (PCA) reports that cement consumption in Wyoming was about 0.3 million metric tons in 2015[30, 31] which implies that approximately 1.5–2 million metric tons of concrete is produced annually. NRMCA records show four certified ready-mix concrete plants in Wyoming; however, there is a significant number of additional concrete producers that are members of the Concrete Association of Wyoming.[32] PCA records further indicate that, as of 2015, the cement and concrete industry in Wyoming employed about 1,418 people with a payroll of $66 million, and generated $185 million in revenue for the state.

Based on an industry survey, the average cost of placed concrete on construction projects in typical Wyoming municipalities was approximately $170 per cubic yard. Most concrete produced in Wyoming is in the 3,000 to 4,500 psi compressive strength range and contains some form of SCM.[33] Approximately 10–15% of Wyoming's concrete is recycled.

Wyoming aggregate mining operations include granite, limestone, sand and gravel, and scoria; all of these collectively are classified as "construction aggregate." Figure 10 provides the distribution of construction aggregates in Wyoming. According to the United States Geological Survey (USGS), Wyoming produced more than 21 million metric tons of construction aggregate in 2014, with a value of approximately $142 million.[34] Tax revenues from aggregate operators amounted to more than $3.3 million in 2013, according to the Wyoming Department of Revenue.[35] That same year there were 65 mining operations in 21 of the state's 23 counties.[36] Also beneficial for Wyoming's workforce, the construction aggregate industry employed more than 1,000 workers in 2013 according to the Wyoming State Inspector of Mines.[37]

Wyoming has 218 bridges and over 380 miles of highway in poor condition.[38] The Infrastructure Investment and Jobs Act will invest $1.2 trillion nationally with nearly $2 billion for the construction of highway and bridges in Wyoming. A large number of WYDOT projects are planned, with some already in process.[39]

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[29] Morrison, J., et al., Magnesium-based cements for CO_2 capture and utilisation. Cement and Concrete Research, 2016. 85: p. 183-191.
[30] This amount is lower than the peak consumption of about 0.45 million tons in 2008.
[31] Luhr, S., Wyoming's Construction Aggregate Resource 2015, Wyoming State Geological Survey: Laramie, WY.
[32] WCA. WCA members 2022; Available from: http://wyomingconcrete.org/Members.aspx.
[33] It is estimated that 80-90% of concrete produced in Wyoming contain SCM, mainly in the form of fly ash, slag, or natural pozzolan.
[34] USGS, Mineral Commodity Summaries 2022. 2022, U.S. Geological Survey: Washington, DC.
[35] https://revenue.wyo.gov/tax-distribution-reports/aggregate-distributions.
[36] https://www.wsgs.wyo.gov/energy/coal-production-mining.aspx.
[37] Luhr, S., Wyoming's Construction Aggregate Resource 2015, Wyoming State Geological Survey: Laramie, WY.
[38] WHPS, WYOMING Infrastructure Investment and Jobs Act State Fact Sheet. 2021, White House Press Release: Washington, DC.
[39] Wyoming RoadWork Guide. 2022, Wyoming Department of Transportation: Cheyenne, WY.

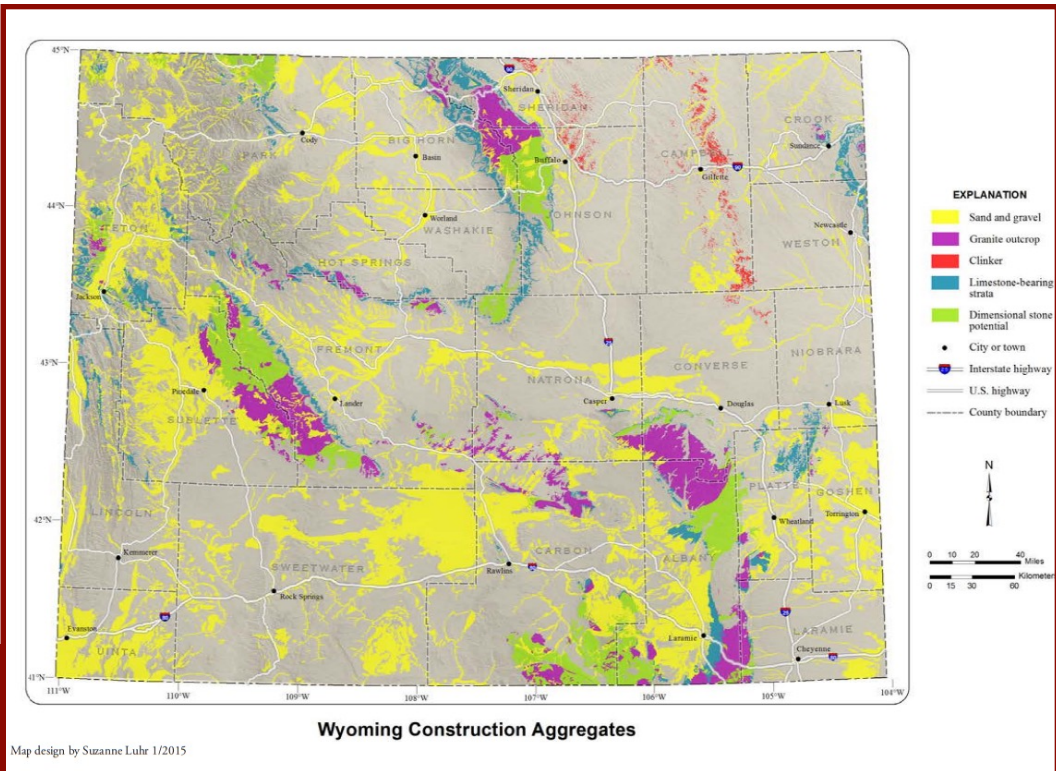

Figure 10: Wyoming construction aggregate deposits[40]

5. OVERVIEW OF CO_2 UTILIZATION IN THE CEMENT/CONCRETE INDUSTRY

The cement/concrete production lifecycle must be explained to understand the potential for CO_2 utilization in concrete, as well as carbonation and mineralization. Carbon dioxide utilization approaches include: (1) carbonation of hardened concrete; (2) injection in fresh concrete; (3) injection into reclaimed return water; (4) aggregate manufacture; (5) recycled concrete fines; (6) concrete solidification through carbonation; and (7) production of A-SCM, alternative cements, and fillers like ground limestone. While the first five technologies refer to the impact of CO_2 usage on raw materials, the sixth approach refers to the use in the solidification (i.e., hardening or strength development) process; and the seventh focuses on producing value-added products that can be used in concrete. This study does not rank these technologies nor provides an assessment of claims being made about them. Different utilization technologies require different CO_2 purity levels. Generally, the technologies intended to stabilize CO_2 within concrete (technologies 1-6 above) are less dependent on CO_2 purity. In contrast, the technologies intended to produce value-added products (e.g., A-SCM, alternative cements, and limestone) with specific chemical compositions and reactivitites generally rely on higher purity/quality CO_2. This study assumes that CO_2 from a coal-fired EGU is acceptable for use in these applications.[41]

Finally, although other potential CO_2 utilization technologies of relevance to concrete are under development, some of which might be technically and economically feasible in the future, they are not examined in this study due to numerous uncertainties associated with their development, impact, and current and near-term feasibility.

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[40] Luhr, S., *Wyoming's Construction Aggregate Resource* 2015, Wyoming State Geological Survey: Laramie, WY.

[41] Ostovari, H., et al., From Unavoidable CO_2 Source to CO_2 Sink? A Cement Industry Based on CO_2 Mineralization. Environmental Science & Technology, 2021. 55(8): p. 5212-5223.

5.1. Carbonation and Mineralization

There are many opportunities to directly utilize CO_2 in concrete ("carbonation"). Figure 11 outlines different technologies based on the carbonation of concrete and its by-products. These include carbonation of hardened concrete, CO_2 injection into reclaimed return water from concrete production, carbonation of recycled concrete fines, CO_2 injection in fresh concrete mixtures, and carbonation of recycled concrete fines.

Figure 11: Technologies based on the carbonation of concrete and its by-products

Source: B.Isgor and J. Weiss

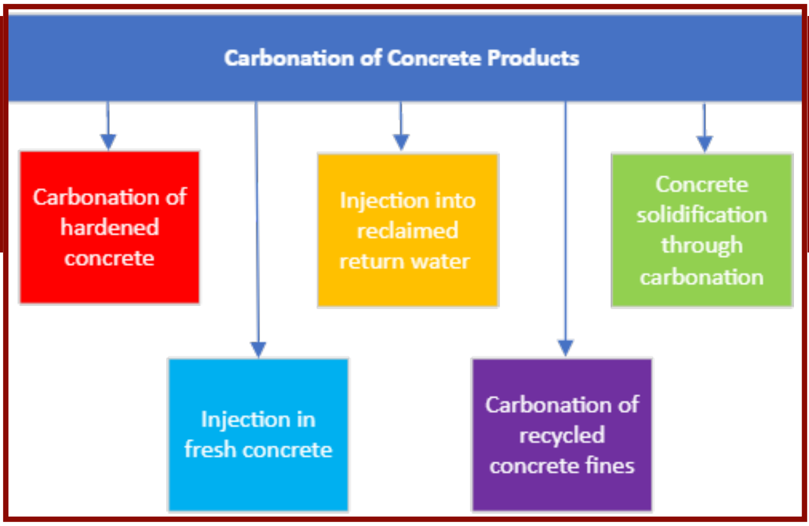

Figure 12 shows the pathways to use CO_2 mineralization technologies that use feedstock materials other than concrete to produce value-added products for the cement and construction industry, such as A-SCMs, alternative cements, concrete aggregates, and fillers/powder extenders. These mineralization technologies have multiple pathways with respect to feedstock materials. In the first pathway, the feedstock materials are in the form of natural rock minerals (metal silicate oxides) such as olivine, serpentine, and wollastonite. In the second pathway, the feedstock materials are solid industrial waste streams such as industrial slags and the ashes of fuel burning and industrial/agricultural incineration processes. The third feedstock pathway is liquid brines, such as geological reservoirs or desalination brines.

Further discussion on these technologies as they apply to the cement and concrete industry is provided in the following sections.

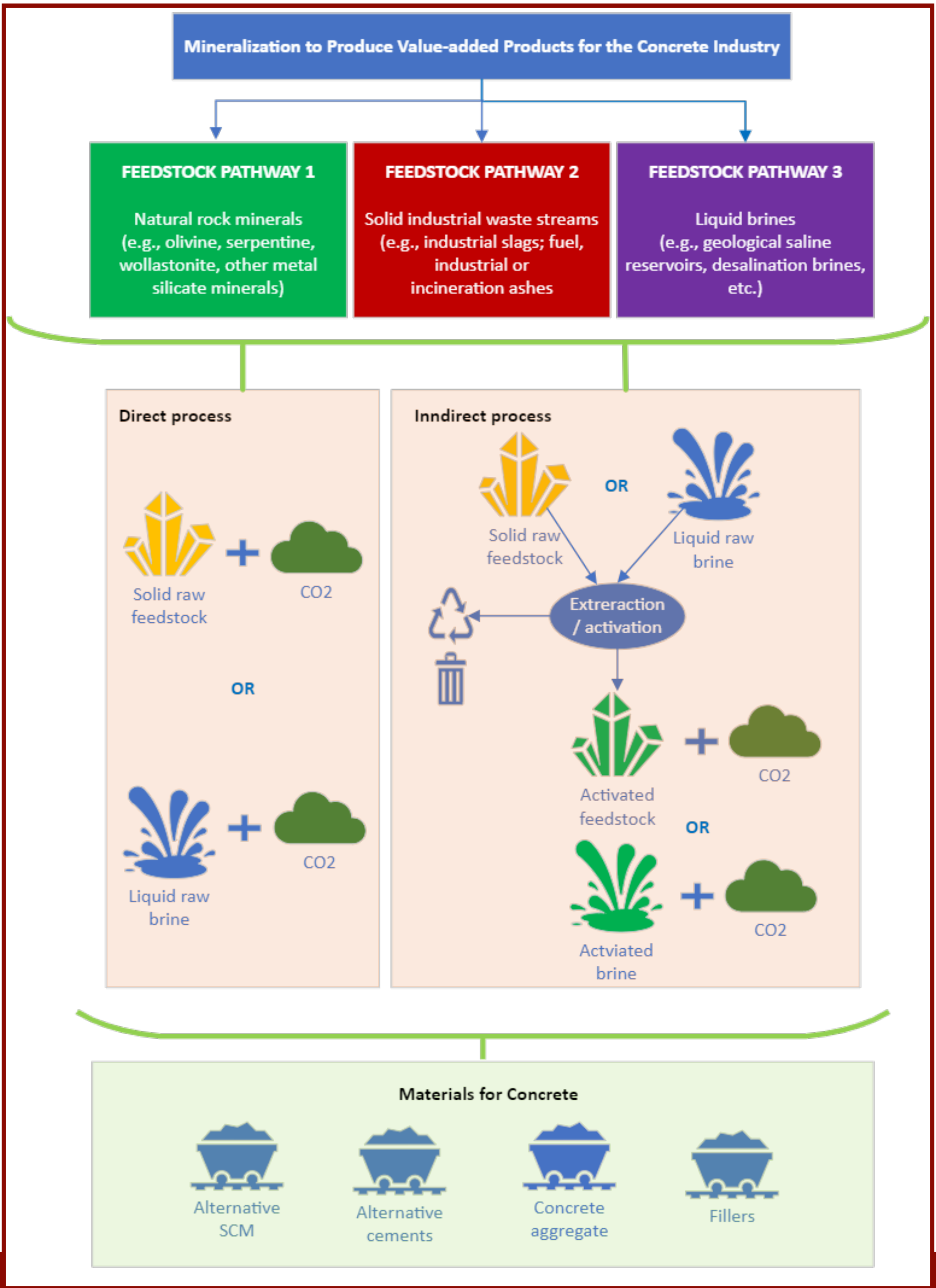

Figure 12: Pathways to use CO_2 mineralization technologies that use feedstock materials other than concrete to produce value-added products for the cement and concrete industry

Source: B.Isgor and J. Weiss

5.1.1. Carbonation of Concrete and its By-Products

Chemical reactions between OPC and water make concrete a highly alkaline material, with a pH typically greater than 13. Hardened concrete usually is rich in calcium hydroxide and other bases (e.g., NaOH, KOH, $Mg(OH)_2$); therefore, it has a large potential to react with CO_2 when exposed to the atmosphere or a stream of high-concentration CO_2. This reaction process is often referred to as carbonation.

Carbon dioxide in the air can penetrate the concrete to dissolve in concrete pore solution, where it converts to carbonic acid (Equation 1).

$$CO_2 + H_2O \rightarrow H_2CO_3 \qquad \text{Equation 1}$$

Alkaline compounds (e.g., calcium hydroxide, $Ca(OH)_2$) then react with the carbonic acid (via a carbonation reaction) to produce stable compounds such as calcium carbonate (calcite; $Ca(CO)_3$) (Equation 2).

$$Ca(OH)_2 + H_2CO_3 \rightarrow Ca(CO)_3 + H_2O \qquad \text{Equation 2}$$

Calcite in concrete is typically stable and serves as a permanent sequestration pathway for CO_2. In addition to the carbonation of calcium hydroxide, the C-S-H phase in concrete also has the potential to carbonate because it has a similar structure to some of the carbonatable natural calcium silicate hydrate compounds such as tobermorite and jennite.[42]

Water is essential for carbonation, but concrete with a high degree of water saturation does not allow CO_2 to penetrate easily. Therefore, relative humidity between 50–70% creates ideal conditions for the carbonation of hardened concrete. Carbonation reactions can also produce an additional challenge for reinforced concrete structures due to corrosion. Steel reinforcement in concrete is typically protected from corrosion due to the high pH of concrete. However, the carbonation reaction reduces this pH which can cause or contribute to the corrosion of steel reinforcement.

Carbonation of hardened concrete leads to additional opportunities, such as: (1) carbonization of reclaimed return water, which is rich in alkali hydroxides; and (2) recycled concrete fines (RCF), which are further discussed in Section 5.2.5.

5.1.2. Mineralization

Similar to carbonation, CO_2 can also be converted with little to no energy input to stable carbonate mineral phases when it reacts with Al-, Si-, or Mg-rich rock masses through a process called mineralization.[43] Mineralization is not a new concept and has been shown to be a feasible reaction for natural materials such as (1) forsterite (Mg_2SiO_4) found in olivine-bearing rocks; (2) lizardite ($Mg_3Si_2O_5(OH)_4$) found in serpentine-bearing rocks; (3) anorthite ($CaAl_2Si_2O_8$) found in igneous rocks; and (4) wollastonite ($CaSiO_3$), which is considered to be one of the fastest reacting silicates.[44, 45]

Many other rocks can serve as mineralization feedstocks, and a more comprehensive list of these common minerals and their reactivity with CO_2 are provided by Hills et al.[46] Examples of reactions of some of these rocks with CO_2 to produce carbonate minerals are provided in the following equations:

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[42] Hills, C.D., N. Tripathi, and P.J. Carey, Mineralization Technology for Carbon Capture, Utilization, and Storage. Frontiers in Energy Research, 2020. 8.
[43] Sandalow, D., et al., Carbon mineralization roadmap. 2021, Innovation for Cool Earth Forum (ICEF): Japan.
[44] Ostovari, H., A. Sternberg, and A. Bardow, Rock 'n' use of CO_2: carbon footprint of carbon capture and utilization by mineralization. Sustainable Energy & Fuels, 2020. 4(9): p. 4482-4496.
[45] Strunge, T., P. Renforth, and M. Van der Spek, Towards a business case for CO_2 mineralisation in the cement industry. Communications Earth & Environment, 2022. 3(1).
[46] Hills, C.D., N. Tripathi, and P.J. Carey, Mineralization Technology for Carbon Capture, Utilization, and Storage. Frontiers in Energy Research, 2020. 8.

$Mg_2SiO_4 + 2CO_2 \rightarrow 2Mg(CO)_3 + SiO_2$	Equation 3

$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3Mg(CO)_3 + 2SiO_2$	Equation 4

$CaSiO_3 + CO_2 \rightarrow Ca(CO)_3 + SiO_2$	Equation 5

$CaAl_2Si_2O_8 + CO_2 + 2H_2O \rightarrow CaCO_3 + Al_2Si_2O_5(OH)_4$	Equation 6

Some of these carbonate minerals have the potential to be used in concrete as fillers or powder extenders (e.g., limestone, $Ca(CO)_3$), aggregates, A-SCM, and alternative cements such as magnesium-based cements); therefore, there is also valorization potential in the process. However, the extraction of the feedstock source compounds (e.g., forsterite, lizardite, and wollastonite) comes with additional costs and environmental effects; therefore, natural mineralization technologies require careful analysis for their feasibility.

Other mineralization pathways use different feedstock materials instead of rocks, such as forsterite, lizardite, and wollastonite. For example, it has been shown that some waste streams such as coal ash (from coal-fired EGUs), slag (from steel production), and mining waste (from waste tailings of metal and mineral mining operations) can be used as feedstock for mineralization. Some of these materials (e.g., fly ash, slag) are already utilized beneficially in concrete as SCM to reduce the carbon footprint of concrete without the need for any modification or CO_2 mineralization. Therefore, SCMs that satisfy the requirements to be used in concrete directly (e.g., fly ash that meets ASTM C618[47]) are not good candidates for CO_2 mineralization feedstock as they already have a path for industrial use. However, waste materials not currently allowed to be used in concrete directly as SCM, such as coal ash that does not satisfy ASTM C618, and is destined for impoundment, are potential candidates for feedstock material to be used to produce value-added products like A-SCM. Thus, there is a pathway to use waste streams that can be valorized using CO_2, particularly those rich in Ca or Mg, to produce value-added products (A-SCM, fillers, or alternative cements) that can be utilized in concrete.

Technologies based on natural and artificial brines mineralization also serve as CO_2 sequestration opportunities. As discussed in this study, Wyoming is a leader in the storage of CO_2 in subsurface reservoirs, including saline aquifers.[48] Some of the technologies that use the mineralization of natural and artificial brines with CO_2 have been shown to have the potential to be able to produce alternative cements (e.g., Mg-based cements[49]) and A-SCM that are directly related to the concrete industry. Despite the technical feasibility, the mineralization technologies used for natural or artificial brines as feedstock are not always easy to apply in the concrete industry, primarily if either the transportation of the CO_2 to the brine reservoirs is too costly, if the chemistry of the brine is not appropriate, or if it is too costly to produce the materials from a subsurface brine. Wyoming has a significant advantage on this front because of its existing initiatives on transporting CO_2 to geological brine reservoirs.

Notwithstanding these challenges, there are many alternative pathways to mineralization in the cement and concrete production process, the most promising of which are discussed further below.

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[47] International, A., ASTM C618-17a: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. 2017: West Conshohocken, Pennsylvania. p. 5.

[48] EORI. Wyoming is CCUS Ready! 2021; Available from: https://storymaps.arcgis.com/stories/635fa72880ae4d898157b27bd1995ad0.

[49] Juenger, M.C.G., et al., Advances in alternative cementitious binders. Cement and Concrete Research, 2011. 41(12): p. 1232-1243.

5.2. CO_2 Sequestration Technologies in Concrete-Related Processes

5.2.1. Carbonation of Hardened Concrete

Hardened concrete has a considerable chemical potential for sequestering CO_2 because of its high pH, buffer calcium hydroxide content, and the presence of other hydroxide bases (e.g., NaOH, KOH, $Mg(OH)_2$) in its chemical structure. The carbonation mechanism of concrete is relatively slow for typical concrete because atmospheric CO_2 cannot penetrate hardened concrete easily. In most cases, carbonization layers remain limited to the surface layers. It can take years to decades to achieve deeper layers of carbonation under typical atmospheric conditions. Furthermore, the penetration of CO_2 is slowed when concrete is highly saturated with moisture or CO_2 cannot dissolve to produce carbonic acid if the concrete is dry. In fact, the ability of concrete to carbonate is related to several factors, including its gas and fluid transport properties, the moisture content of concrete, and the pH buffer capacity (i.e., the amount of calcium hydroxide available in the system). However, it is possible to carbonate concrete in specialized pressurized carbonation chambers where CO_2 concentration is high, and temperature and relative humidity conditions are optimized and pressurized. This approach might be feasible in precast plants, especially when producing smaller precast elements. Reinforcement corrosion is not an issue for unreinforced (plain) concrete but could become a problem for steel reinforcement in reinforced concrete elements. This issue can be resolved when fiber-reinforced polymer bars or textile-based reinforcement is used in the precast elements. Approximately 10–25 kg of CO_2 can be consumed in the complete carbonation of a cubic meter of concrete, assuming 10–20% of the system carbonates.

5.2.2. Injection in Fresh Concrete

As noted above, CO_2 can be injected[50] into fresh concrete during mixing. Injected CO_2 undergoes a reaction that converts it to calcium carbonate or limestone. CarbonCure Technologies[51] has noted that this process results in a "4 to 6% reduction in cement content with no compromise in quality and performance." Approximately 0.6 kg of CO_2 is injected into a cubic meter of concrete, with 40% being released into the atmosphere and 60% being mineralized (i.e., this is an open system).[52] This approach typically has been applied to ready-mix concrete; however, it would also be possible to use this approach for precast concrete products.

5.2.3. Injection into Reclaimed Return Water

During the production and placement of concrete, a small portion becomes waste material due to the cleaning up/washing down of trucks and pumps and/or returning unused concrete materials to the plant. These waste materials are increasingly being reclaimed. Concrete reclamation is a process that enables unused concrete to be separated back into its original aggregates and gray water. The separated aggregates can often be reused in future mixing operations. Gray water slurry also can be reclaimed or separated. Carbon dioxide may be injected into gray water slurry,[53] which can resolve potential environmental impacts by enabling the water to be reused with a potential for cement powder reduction. The manufacture of concrete has been reported to result in 114 L of wash water with 4.1 kg of solid waste per cubic meter of concrete. Assuming the 20–22% solid waste is 80–90% cement with 70–80% mineralization efficiency results in 0.65 kg of CO_2 per cubic meter of concrete.[54]

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[50] CarbonCure. Carbon mineralization in concrete. 2022; Available from: https://www.carboncure.com/carbon-mineralization-in-concrete/.

[51] CarbonCure. Carbon mineralization in concrete. 2022; Available from: https://www.carboncure.com/carbon-mineralization-in-concrete/.

[52] Rissman, J., Cement's role in a carbon neutral future. 2018, Energy Innovation: San Francisco, CA.

[53] CarbonCure. TRIO ready-mix case study. 2022; Available from: https://go.carboncure.com/rs/328-NGP-286/images/CC_CaseStudy-Trio-3pg.pdf.

[54] Monkman, S., T. Janke, and A. Hanmore, Corrigendum to: NRG COSIA Carbon XPRIZE: carbon-dioxide mineralization in recycled concrete wash water. Clean Energy, 2022. 6(1): p. 15-15.

5.2.4. Aggregate Manufacture

CO_2 utilization has been discussed in the development of synthetic aggregate. This technology is based on the fact that limestone is a sedimentary rock called calcium carbonate ($CaCO_3$) or dolomite ($CaMg(CO_3)$, which is composed primarily of calcite or argonite. Limestone forms when minerals precipitate in water containing dissolved calcium – and historically, this has come from biological processes such as corals and shells. Among many applications in other industries, limestone is used as the precursor for OPC and lime and as a potential aggregate in concrete and other construction materials. Limestone forms when calcite or aragonite precipitates out of water containing dissolved calcium.[55] The feedstock for this process is generally from calcium sources, returned concrete, cement kiln dust, steel slags, fly ash, bauxite, silicates or and/or magnesium-containing saline water (brines) from natural geological reservoirs or desalination processes.[56, 57] CO_2-containing gases are used with a slurry to store the CO_2 permanently. Increases in temperature or decreases in pressure tend to reduce the amount of dissolved CO_2 and precipitate $CaCO_3$. It has been claimed that the production of a ton of aggregate permanently sequesters 440 kg of CO_2.[58, 59]

5.2.5. Recycled Concrete Fines

It has been suggested that RCF mineralization is a viable technology to sequester CO_2.[60] Using various mineralization conditions, the ability to carbonate recycled fines has been experimentally demonstrated for laboratory and industrial materials. Recycled paste material may be re-carbonated quickly to form a product composed primarily of reactive calcite, alumina, and silica gels. These materials may be used as A-SCM to replace a portion of cement clinker. Li et al. reviewed the use of CO_2 mineralization technology to improve the quality of recycled cement-based materials.[61]

Zajac et al. discussed the impact of RCF on the supply chain of materials in the concrete industry and identified the need to redesign existing sites to accommodate the carbonation infrastructure and business model.[62] Wu et al. examined the effect of temperature (20–140°C) on the carbonation of RCF.[63] A carbonation temperature of 100°C was optimal, and the morphology of the precipitated $CaCO_3$ depended on temperature. Carbonation at a higher temperature increased the specific surface area of RCF and increased water demand. Rough approximations suggest that approximately 50–130 kg of CO_2 can be consumed in the complete carbonation of a cubic meter of concrete, assuming 40–100% of the binder can carbonate. This does not account for any carbonation emitted during crushing, transportation, or processing.

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[55] Boggs, S., Principles of sedimentology and stratigraphy 4th Edition ed. 2006, Upper Saddle River, N.J.: Pearson Prentice Hall.
[56] La Plante, E.C., et al., Saline Water-Based Mineralization Pathway for Gigatonne-Scale CO_2 Management. ACS Sustainable Chemistry & Engineering, 2021. 9(3): p. 1073-1089.
[57] Bang, J.-H., et al., CO_2 Mineralization Using Brine Discharged from a Seawater Desalination Plant. Minerals, 2017. 7(11).
[58] CarbonCure. Carbon mineralization in concrete. 2022; Available from: https://www.carboncure.com/carbon-mineralization-in-concrete/.
[59] Blue-Planet. Permanent carbon capture. 2022; Available from: https://www.blueplanetsystems.com/.
[60] Skocek, J., M. Zajac, and M. Ben Haha, Carbon Capture and Utilization by mineralization of cement pastes derived from recycled concrete. Scientific Reports, 2020. 10(1).
[61] Li, L., et al., Mineralization and utilization of CO_2 in construction and demolition wastes recycling for building materials: A systematic review of recycled concrete aggregate and recycled hardened cement powder. Separation and Purification Technology, 2022. 298.
[62] Zajac, M., et al., CO_2 mineralization of demolished concrete wastes into a supplementary cementitious material – a new CCU approach for the cement industry. RILEM Technical Letters, 2021. 6: p. 53-60.
[63] Wu, Y.Q., et al., High-temperature CO_2 for accelerating the carbonation of recycled concrete fines. Journal of Building Engineering, 2022. 52.

5.2.6. Production of A-SCM and Cements

Carbon-sequestering A-SCM is also being developed. Some industrial byproducts or natural minerals can be combined with CO_2 in a reactor to improve their reactivity. These A-SCMs can potentially be used as cement replacements, and claims have been made regarding to improved reactivity.[64] Several studies have shown that Mg-based solid or liquid feedstock materials can produce Mg-based alternative cement.[65] The mineralization technologies to produce A-SCM and alternative cements have multiple pathways with respect to feedstock materials. In the first pathway, the feedstock materials are in the form of natural rock minerals (metal silicate oxides) such as olivine, serpentine, and wollastonite. In the second pathway, the feedstock materials are solid industrial waste teams such as industrial slags and the ashes of fuel burning and industrial/agricultural incineration processes. The third feedstock pathway is liquid brines, such as geological reservoirs or desalination brines.

5.2.7. Concrete Solidification Through Carbonation

In conventional concrete (OPC-based systems), strength comes from a hydration reaction where the cement (primarily calcium silicates) reacts with water to form hydration products (calcium silicate hydrate and calcium hydroxide), as discussed above. Some producers have pursued alternative approaches to develop strength in these systems. These technologies for concrete-like products use a carbonation reaction. Several different materials have been proposed to be the reaction product for CO_2. For example, it is possible to use calcium silicate products (e.g., wollastonite) to react with cement and water to form a solid.[66, 67] Calcium silicate cements are produced at lower heats than conventional cements. Carbon dioxide can also be produced with hydrated lime (calcium hydroxide or portlandite) to manufacture concrete products.[68] Lime production and slaking are often manufactured in a kiln process;[69] however, alternative approaches based on electrochemistry have been discussed.[70] An alternative has used slag materials from the steel and stainless-steel industries.[71] Similarly, coal ash can potentially be used.

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64 Carbon-Upcycling. Carbon upcycling web site. 2022; Available from: https://carbonupcycling.com/.
65 Morrison, J., et al., Magnesium-based cements for CO_2 capture and utilisation. Cement and Concrete Research, 2016. 85: p. 183-191.
66 Villani, C., et al., Characterizing the Pore Structure of Carbonated Natural Wollastonite, in Proceedings of the 4th International Conference on the Durability of Concrete Structures. 2014. p. 262-269.
67 Svensson, K., et al., The Conversion of Wollastonite to $CaCO_3$ Considering Its Use for CCS Application as Cementitious Material. Applied Sciences, 2018. 8(2).
68 Carbon-Built. Carbon Built website. 2022; Available from: https://www.carbonbuilt.com/.
69 EPA, Mineral Products Industry, in AP 42, Volume I, Chapter 11. 2022, Environmental Protection Agency: Research Triangle Park, NC.
70 Lower-Carbon-Capital. Sublime Systems. 2022; Available from: https://lowercarboncapital.com/company/sublime-systems/.
71 Kamyab, H.K., et al., Carbstone Pavers: A Sustainable Solution for the Urban Environment. Applied Sciences-Basel, 2021. 11(14).

6. ANALYSIS OF CO_2 UTILIZATION BY THE CONCRETE INDUSTRY IN WYOMING

6.1. Overview

Wyoming has been actively pursuing using geological reservoirs to store CO_2. In this section, we consider carbonation and mineralization technologies for captured CO_2 from coal-fired EGUs that might be suitable for the cement/concrete industries. Although this report focuses on CO_2 from coal-fired EGUs, the number of studies investigating the feasibility of CCUS, regardless of the CO_2 source through mineralization and carbonation technologies for the concrete industry, has been increasing. In a recent study, Ostovari et al.[72] analyzed seven mineralization pathways, considering serpentine, olivine, and steel slag as feedstock. The mineralization products are assumed to be used as SCM to replace a portion of OPC in concrete. The researchers investigated the additional reductions in equivalent CO_2 through mineralization compared to geologically storing CO_2 alone, both from a financial perspective and a permanent carbon fixation perspective. A lifecycle analysis showed that all considered mineralization technologies could result in 0.44 to 1.17 equivalent CO_2 *additional* reductions per ton of CO_2 (in addition to the CO_2 directly stored through mineralization) compared to corresponding cases where CO_2 is only stored. These benefits (compared to the technologies that only focus on storing CO_2) were mainly due to the permanent storage of CO_2 and the credit for substituting OPC. However, the study also emphasized the need for further research to improve mineralization technologies.

Strunge et al.[73] studied the production and use of CO_2 mineralization products such as A-SCM to partially replace cement. The investigation made several assumptions, such as CO_2 was captured directly from a cement kiln, while feedstock minerals were assumed to be brought from a distance. Two mineralization techniques were investigated, and the produced A-SCM was assumed to replace 25% of OPC. The study concluded that it was possible to create additional profits for each ton of cement sold, which varied depending on the technology used between €29 and €32 at the time of the article's publication (at which the US dollar was about at parity with the Euro). The proposed process showed a potential decrease in equivalent CO_2 emissions from the plant by 8–33%.

The study by Strunge et al. draws a promising picture for using CO_2 in mineralization. Wyoming has only one cement plant; however, it is highly possible that a case can be made for CO_2 mineralization. The impact of this initiative would remain small compared to the amount of CO_2 that could be captured from a coal-fired power plant in Wyoming.[74] The amount of CO_2 produced from coal-fired power plants in Wyoming is significant and easily outstrips any demand by the Wyoming cement/concrete industry to utilize it.

"The amount of CO_2 produced from coal-fired power plants in Wyoming is significant and easily outstrips any demand by the Wyoming cement/concrete industry to utilize it."

[72] Ostovari, H., A. Sternberg, and A. Bardow, Rock 'n' use of CO_2: carbon footprint of carbon capture and utilization by mineralization. Sustainable Energy & Fuels, 2020. 4(9): p. 4482-4496.

[73] Strunge, T., P. Renforth, and M. Van der Spek, Towards a business case for CO_2 mineralisation in the cement industry. Communications Earth & Environment, 2022. 3(1).

[74] EIA, State Energy Data System, Production, Table P3, Total Primary Energy Production and Total Energy Consumption Estimates in Trillion Btu. 2019, US Energy Information Administration: Washington, DC.

6.2. Wyoming Electric Generating Units as Potential CO_2 Sources for Utilization

Enrolled Act No. 12 directed SER to focus on CO_2 emissions from coal-fired or natural gas-fired EGUs as a potential source for producing low-CO_2 concrete, which, in turn, could be utilized in public works projects in the state.

Wyoming is generally a leader in CCUS technologies, including potentially retrofitting one or more coal-fired EGUs in the state with CO_2 capture technology. The bulk of Wyoming's CCUS efforts have focused on geologic storage and geologic utilization (i.e., CO_2-EOR). For example, Wyoming's CCUS laws and regulations address the entire lifecycle of geologic CO_2 storage projects, from Underground Injection Control Class VI permitting CO_2 injection wells to the long-term stewardship of geologic storage sites.[75]

6.2.1. Coal-Fired EGUs

Implementing CCUS at Wyoming's fleet of coal-fired EGUs has been, and remains, a focus of intense research and policy efforts for many years.

Specifically concerning coal-fired EGUs and CCUS, in 2020, the Wyoming Legislature enacted HB 200[1][1]76 regarding "reliable and dispatchable low-carbon energy standards" for electricity utilities that are regulated by the Wyoming Public Service Commission (PSC). HB 200:

> Require[s] the [PSC] to enact rules that require a certain percentage of electricity in the power grid to be dispatchable, reliable, low-carbon electricity by 2030, with intermediate standards for generation set for the years until 2030. The law encourages the use of [CCUS] technology for coal-fired generation …."

HB 200's definition of "CCUS" encompasses "reusing, storing, sequestering or using" CO_2 emissions and thus would include the utilization of CO_2 in concrete and concrete making materials.

Under the PSC's regulations implementing HB 200, electric utilities subject to the law were required to file an initial application by March 31, 2022 that included, at minimum, an "analysis of [CCUS] suitability of a utility's Coal Fired Electric Generation Facilities … that shall include: (A) [a] description of the potential suitability of each Coal-Fired Electric Generation Facility for [CCUS] technologies; [and] (B) [t]he proximity of each Coal-Fired Electric Generation Facility to known sequestration locations, carbon dioxide transport pipelines, and oil fields potentially suitable for enhanced oil recovery or **any other possible uses of carbon dioxide ….**"[77]

As required by the PSC regulations, utilities such as Rocky Mountain Power (RMP) and Black Hills Energy (BHE) made their initial applications by March 31, 2022.

Meanwhile, Basin Electric Power Cooperative's coal-fired Dry Fork Station (DFS) remains the location of two applied CCUS research projects that are separately funded by the U.S. Department of Energy (DOE): (1) the Wyoming Carbon Storage Assurance Facility Enterprise (CarbonSAFE) project[5], which is focused on characterizing geologic saline storage formations in the vicinity of DFS; and (2) Membrane Technology & Research, Inc.'s large-scale CO_2 capture demonstration project at the Integrated Test Center (ITC), which is located at DFS. Under the DOE grant that is funding Wyoming CarbonSAFE, that project is required to store a minimum volume of CO_2 in saline reservoirs geologically. Still, other utilizations – potentially including the use of CO_2 for concrete – are not prohibited as long as those minimum geologic storage volumes are met.

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[75] Summary of Wyoming's CCS/CCUS Legal Regime & Opportunities for Geological Sequestration of Carbon Dioxide, Kipp Coddington, Senior Advisor, UW/SER (June 1, 2022) (available at https://wyoleg.gov/InterimCommittee/2022/09-202206276-01ResponsetoJMEDCLetter-Murrell.pdf.

[76] Wy. Stat. § 37-18-101 et. seq. (2022).

[77] Wyoming Administrative Rules, PSC Rules, Chapter 3 (Electric, Gas, Water and Pipeline Utilities), § 38(a)(i) (2022) (emphasis added).

Separately, the ITC recently hosted the NRG COSIA Carbon XPrize Competition. One of the tenants and a winner of the competition was UCLA-based CarbonBUILT, which demonstrated a technology (CO_2Concrete™) to convert CO_2 emissions into construction materials and products.[6]

In some cases, CO_2 use in concrete will require purification (i.e., capture) other than coal-EGU flue gas. Retrofitting CO_2 capture on one or more coal-fired EGUs in Wyoming was the subject of a recent study by the University of Wyoming.[78] While outlining numerous technology, economic and related challenges to retrofitting CO_2 capture technology, the study concluded that increasing the value of the section 45Q tax credit to $85/ton for geologic storage in saline formations – which was subsequently enacted into law as part of the Inflation Reduction Act (IRA) – would offset the added cost for carbon capture and geologic saline storage deployment for a total capacity of 3.4 GW in Wyoming. The corresponding amount of CO_2 captured is estimated to be approximately 21 million metric tons per year.

The combination of CO_2 utilization with the section 45Q tax incentive could further improve the economic viability of CCUS retrofits, which depends on the carbon capture and utilization project size and how it affects the eligibility for tax credits. As discussed earlier, however, just about 1.5-2 million metric tons of concrete are produced annually in Wyoming today, so only a small amount of CO_2 could be utilized and geologic CO_2 storage would remain necessary.

The CO_2 demand for concrete production in the state may be much less than that potentially captured by CCUS. As such, legislation to require CO_2 utilization in conventional concrete would not have a sizable effect in mitigating emissions from the Wyoming electric sector. For perspective, approximately 2 million metric tons of concrete is produced annually in the state, and if the complete carbonation of the cement in this concrete is assumed, less than 0.15 million metric tons of CO_2 would be utilized. This estimate is an upper bound, and the realistic value is likely 10 to 20% of that number resulting in 0.02 million metric tons of CO_2 as compared to the 50 million metric tons produced (and 36 million metric tons from coal-fired EGUs) in the state. As such, it is clear that additional CO_2-consuming value-added products would need to be developed to utilize the CO_2.

6.2.2. Natural Gas-Fired EGUs

Although enrolled Act No. 12 directed SER to focus on CO_2 emissions from coal-fired or natural gas-fired EGUs as a potential source for producing low-CO_2 concrete, this study does not consider natural gas-fired EGUs for several reasons. As discussed above, Wyoming's coal fleet remains the subject of ongoing CCUS assessments, which this study could reference, thereby facilitating the research team's ability to meet the legislatively mandated deadline for the study's completion. Coal units dominate electricity production in Wyoming. It is almost certain that the CO_2 captured from a single coal-fired EGU would supply substantially more CO_2 than the entire cement industry in Wyoming could ever make productive use of – and assuming the many technical, economic, and related challenges identified in this study could be overcome. On a case-by-case basis, however, it is conceivable that a specific natural gas-fired EGU in Wyoming might serve as a suitable CO_2 source for concrete production in the state.

[78] Dindi, A., Coddington, K., Garofalo, J., Wu, W., Zhai, H. "Policy-Driven Potential for Deploying Carbon Capture and Sequestration in a Fossil-Rich Power Sector," Environ. Sci. Technol. 2022, 56, 9872-9881 (available at https://pubs.acs.org/doi/pdf/10.1021/acs.est.1c08837).

6.3. Critical Review of CO_2 Utilization Technologies in Relation to the Realities of Wyoming

6.3.1. Direct Utilization of CO_2 by the Cement/Concrete Industry in Public Works Projects

As discussed above, in some cases, CO_2 can be used directly in concrete production, as summarized in Figure 11. These technologies are based on the carbonation of concrete and its by-products. They include carbonation of hardened concrete, CO_2 injection into reclaimed return water from concrete production, carbonation of recycled concrete fines, CO_2 injection in fresh concrete mixtures, and carbonation of recycled concrete fines. Several studies and currently active private companies have been active in implementing these technologies all over the world. These technologies can potentially provide significant value for concrete producers in reducing their carbon footprint and making additional income through carbon credits. Therefore, if implemented, the concrete producers, precast plants, and public works sector in Wyoming could also benefit from some of these technologies.

However, also as discussed above, the concrete market in Wyoming is small compared to the amount of CO_2 that can be captured in the state. It is estimated that the capturable equivalent CO_2 volume from various sources in Wyoming was over 50 million metric tons, as shown in Table 1 below. Increasing the 45Q tax credit to $85 per metric ton for geologic storage would offset the added cost for CCS deployment for a total coal-fired capacity of 3.4 GW, with about 21 million metric tons of CO_2 that could be captured economically annually in Wyoming. As an extreme example, if all concrete produced in Wyoming (approximately two million metric tons) is assumed to be available for CO_2 utilization, and all carbonatable portion of concrete (approximately 15% of the total volume of concrete is cement) is utilized, the maximum CO_2 that can be incorporated in concrete would be around 0.15 million metric tons. Given that only a fraction of this concrete is produced for public work projects (only 10 to 20% carbonation appears practical) and CO_2 would not be utilized in all concrete produced in Wyoming, the captured CO_2 would exceed the amount of CO_2 that can be used in public works projects by a factor of at least 100.

Therefore, efforts to increase the capacity of CO_2 utilized directly by the concrete industry in the form of the carbonation of concrete would not likely make a significant impact in reducing the available CO_2. As a result, it is difficult to make a compelling case for mandating the industry to use CO_2 directly in concrete. Instead, encouraging the concrete industry to produce concrete with a low carbon footprint though existing and well-established cement and clinker-reducing approaches would likely be more impactful. These approaches include the increased use of SCM, incorporation of larger amounts of limestone filler in mixtures, reducing past content through increased aggregate packing, and optimized mixture proportioning procedures.

However, there is a potentially compelling case for CO_2 mineralization technologies to produce value-added products for the concrete and construction industry, as shown in Figure 12. These technologies are designed to produce A-SCM, alternative cements, construction aggregates, and fillers used in making concrete throughout the United States and potentially other countries. This increases the volume of materials used substantially compared to what may be used in Wyoming alone. There is an existing market for these products in the concrete industry, which is only expected to increase over time. Therefore, if Wyoming could find pathways to utilize these CO_2 mineralization technologies, it would be possible to convert a sizable portion of the captured CO_2 to marketable construction materials. These products have the potential to be exported from Wyoming due to its rail distribution to surrounding states as value-added products. Colorado, Texas, California, Missouri, Iowa, and Illinois are examples of states that use high volumes of concrete and have established rail lines to Wyoming.

Valorized fly ash, for instance, could be one such material. Currently, fly ash is widely used in concrete. The global fly ash market was valued at $4.13 billion in 2018 and is expected to reach $6.86 billion by 2026,[79] a trend that is expected to increase in the upcoming years due to pressures on the cement/concrete industry to reduce the impact of CO_2 emissions by producing concrete with low carbon footprint via reduced cement and clinker use. The price of high-quality fly ash ranges from $15 to $60 per ton. The retirement of coal-fired EGUs has led to concerns by some producers that fly ash supplies could decrease in the future. Therefore, if CO_2 mineralization technologies can produce high-quality A-SCM (e.g., valorized fly ash) to compensate for the dwindling supply of fly ash that can be supplied consistently with consistent properties, it is likely that there will be a significant national market for these products. These materials can permanently bind the CO_2 as well.

6.3.2. CO_2 Availability and Transportation Within the State

As of 2021, it is estimated that the capturable equivalent CO_2 volume from various sources in Wyoming was over 50 million metric tons as shown in Table 1.[80] Most of this CO_2 was from power plants (13 reporting facilities), totaling 36 million metric tons,[81] followed by the oil and natural gas sector, including refineries (35 reporting facilities), totaling 7.5 million metric tons, and the minerals sector, totaling 6.3 million metric tons. A detailed breakdown of emissions from each plant or site can be found in the EPA's FLIGHT tool.

Sector	Number of reporting facilities	Equivalent CO_2 emissions (million metric tons)
Power plants	13	36
Oil and gas	30	6.2
Refineries	5	1.3
Chemicals	4	1.2
Other	3	0.1
Minerals	10	6.3
Waste	3	0.1
Total	**66**	**51**

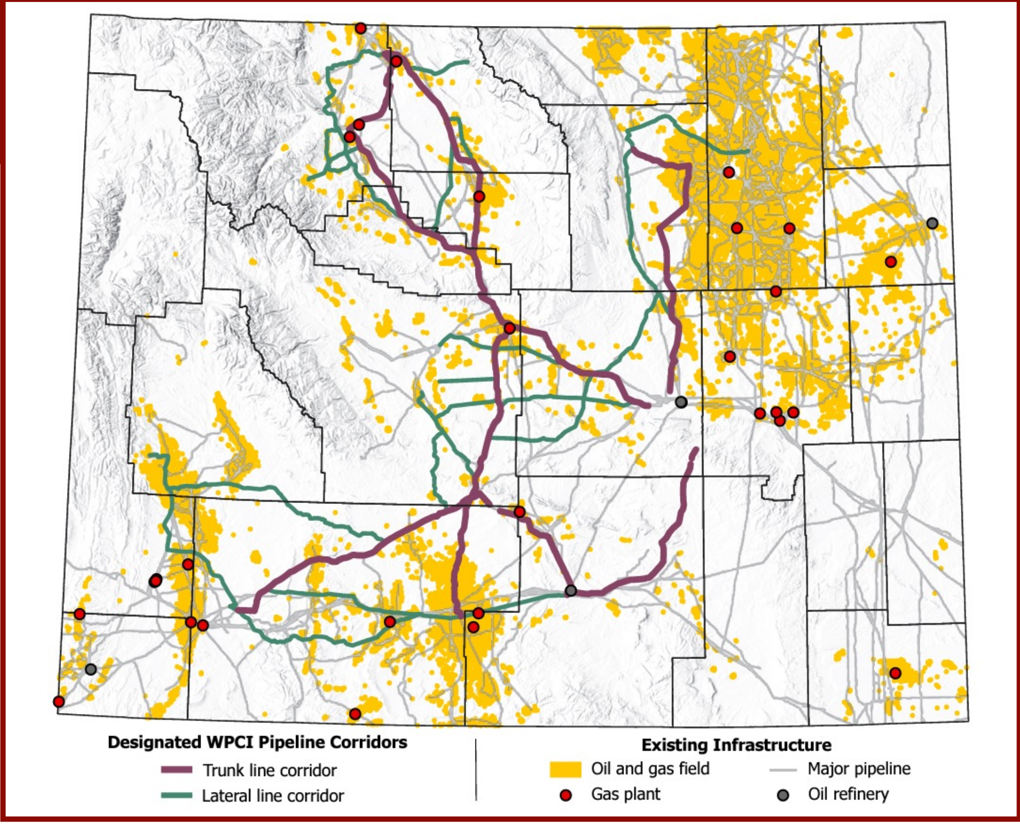
Table 1: 2021 Equivalent CO_2 emissions of different sectors in Wyoming[82]

Because the power plants are distributed throughout the state, opportunities exist to establish infrastructure (e.g., A-SCM or alternative cement manufacturing plants) close to the impoundments so that captured CO_2 can be used without substantial transportation. However, in some cases, the transport of CO_2 is needed, and the infrastructure needs are further discussed in Section 4.2.4. Fortunately, Wyoming has a well-established and distributed CO_2 pipeline infrastructure. Figure 13 illustrates the extent of this pipeline network.

In addition to the existing pipeline network, the Wyoming Pipeline Corridor Initiative (WPCI) designates an additional almost 2,000 miles of corridors on public lands for dedicated CO_2 pipelines to help connect CO_2 sources with oil fields suitable for CO_2-EOR and/or locations of dedicated geologic storage. About 1,111 miles of this expansion is on public lands managed by the US Department of the Interior Bureau of Land Management (BLM), and others are on private, state, and BLM-managed lands.[83]

[79] Reports-and-Data. Fly Ash Market To Reach USD 6.86 Billion By 2026. 2019; Available from: https://www.reportsanddata.com/report-detail/fly-ash-market.
[80] U.S. EPA's Facility Level Information on Greenhouse Gases Tool (FLIGHT) tool.
[81] In 2021, about 73% of Wyoming's electricity was produced by coal-fired power plants.
[82] U.S. EPA's Facility Level Information on Greenhouse Gases Tool (FLIGHT) tool.
[83] BLM, BLM Wyoming releases decision on corridor initiative. 2022, US Department of the Interior Bureau of Land Management (BLM).

Figure 13: The CO_2 pipeline network and the Wyoming Pipeline Corridor Initiative[84]



The expansion initiative is important because only two coal-powered power plants are within a reasonably short distance from the existing pipeline (specifically, PacifiCorp's coal-fired Jim Bridger Power Plant and Basin Electric Power Cooperative's coal-fired Dry Fork Station). All other power plants would require a co-located use plant or the pipeline expansion to be in a position to supply CO_2 into the network. Expanding the pipeline to reach coal-powered plants would also require future considerations of these plants because some of the plants in Wyoming are expected to close in the future. Although Wyoming still produces about 73% of its energy from coal-burning power plants, this figure is significantly lower than the peak 2003 values, when coal-powered plants supplied about 97% of Wyoming energy demand. For example, wind power provided 19% of Wyoming's power generation in 2021, which is more than double the 2019 amount.[85]

The availability of the existing CO_2 pipeline network and the potential to expand it in the future provide opportunities for growing the diversity of CO_2 utilization technologies in Wyoming. Expansion of the pipeline network could allow captured CO_2 to be transported where it can be utilized. This unique advantage can potentially beneficially affect the economic feasibility of several CO_2 utilization technologies and even make some of the less feasible options economically feasible.

One challenge in this process, however, is the fact that Wyoming's existing pipeline network is privately owned. Therefore, a compelling financial case needs to be made to show that utilizing CO_2 through mineralization and carbonation technologies to produce value-added products that can be used in the cement/concrete industry. The option of storing the CO_2 in geological saline reservoirs without utilization approaches would generate direct income ($85 per metric ton CO_2) through the newly amended section 45Q tax credit. However, utilizing some of the captured CO_2 will also provide an additional $60 per metric ton CO_2 tax credit. The value-added products produced through these utilization technologies would be expected to sell at the market prices for typical SCM. Therefore, initiatives to utilize captured CO_2 to produce value-added products might become more profitable than the gains the tax credits provide for capturing and storing CO_2. However, since the investment in the utilization technologies and infrastructure (e.g., A-SCM or alternative cement manufacturing plants.) would involve other public and private parties, there are uncertainties about the feasibility of using the CO_2 pipeline network for CO_2 utilization in the concrete industry in Wyoming.

[84] Campbell, E.A., Oil & natural gas resources in Wyoming. 2022, Wyoming State Geological Survey: Laramie, WY.
[85] EIA, Wyoming Electricity Profile, Table 10, Supply and disposition of electricity, 1990-2020. 2020, U.S. Energy Information Administration (EIA): Washington, D.C.

6.3.3. Feedstock Availability and Composition of Mineralization Technologies

Our preliminary investigation indicated that Wyoming does not have rich deposits of natural rock feedstock that can be used in the CO_2 mineralization process, such as olivine, serpentine, wollastonite, etc., to produce value-added products like A-SCM, alternative cements, fillers like ground limestone, and carbonated aggregates. However, it is not clear if the availability of these rock minerals has been investigated in a systematic study. Therefore, it is necessary to perform a more comprehensive investigation to conclude that Wyoming does not have feasible feedstock rock deposits that can be used in CO_2 mineralization operations. If this is the case, the other options for this pathway are: (1) importing these mineral rocks to Wyoming, where they will be used in direct and indirect CO_2 mineralization operations, or (2) exporting the captured CO_2 to neighboring states through pipelines where the mineralization can be done where feedstock rocks are locally available. Both options assume that neighboring states have some of the rock feedstock needed for CO_2 mineralization, which needs to be confirmed. For example, wollastonite deposits have been found in Arizona, California, Idaho, Nevada, New Mexico, New York, and Utah.[86] However, a feasibility assessment would be needed considering the cost of transportation of raw materials and the lack of an adequate CO_2 pipeline network connecting Wyoming's CO_2 pipeline network to other states.

Without a state rock feedstock pathway, the other options are waste feedstock or liquid brine feedstock pathways, as shown in Figure 12. As discussed above, Wyoming produces a significant amount of coal ash. Some of this ash (i.e., fly ash) can be used directly as an SCM in concrete. Therefore, it is difficult to justify using these materials as feedstock for CO_2 mineralization to produce other concrete materials such as A-SCM. Considering that there is already a strong market for fly ash as SCM in the concrete industry, it seems more feasible to use other forms of coal ash (e.g., bottom ash) from coal-burning processes that are not typically used in concrete. Wyoming generates over two million tons of coal ash each year. There is potential to utilize the ash destined for surface impoundments and reclaim the ash already in these impoundments for CO_2 mineralization to produce value-added concrete materials. From a chemical perspective, ponded fly and bottom ash are similar to wollasonite, a known feedstock mineral for CO_2 mineralization (Figure 14). If realized, this approach could have multiple benefits by reducing the coal ash sent to ponds, reducing the existing pond volumes through reclaiming ponded ashes, producing value-added products (e.g., A-SCM) to be used in concrete, and utilizing captured CO_2. As this appears a viable source to convert captured CO_2 to a value-added product, additional studies are highly recommended to explore this option.

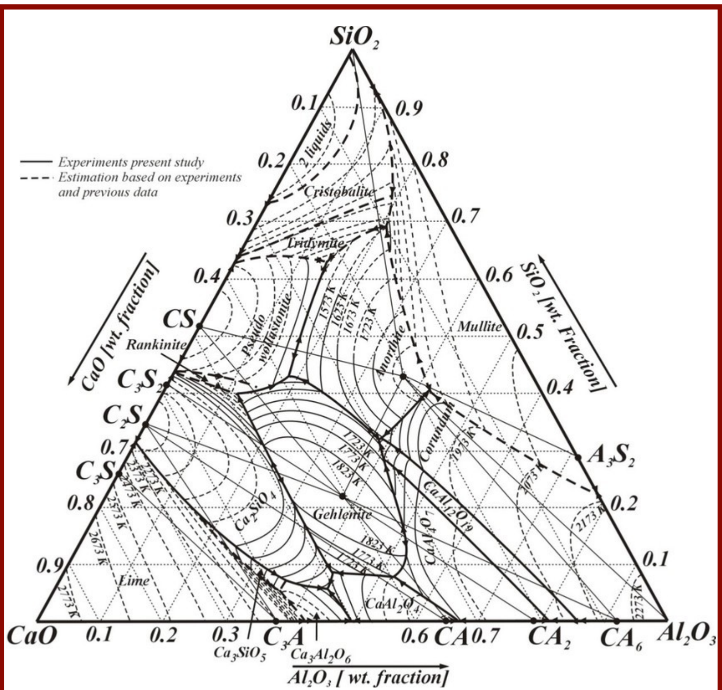


Figure 14: A classic CaO-SiO2-Al2O3 Phase diagram illustrating wollastonite and typical waste ash[87]

[86] USGS, Mineral Commodity Summaries 2022. 2022, U.S. Geological Survey: Washington, DC.

[87] Shu, Q., et al., Effect of Na_2O on Dissolution Rate of Alumina in $CaO–Al_2O_3–MgO–SiO_2$ Slag. ISIJ International, 2015. 55(11): p. 2297-2303.

Wyoming is also home to sizeable geological saline reservoirs, which might be able to serve as CO_2 mineralization feedstock to produce value-added products for the concrete industry. However, the feasibility of this pathway depends on the chemical composition and reactivity of the feedstock brines; therefore, additional studies are needed to quantify the economic feasibility of this potential. The type of infrastructure required to activate the brines for CO_2 mineralization depends on the brine composition and reactivity. However, suppose it can be shown that value-added concrete products can be mineralized using the existing subsurface brines in Wyoming. In that case, this pathway could be highly attractive, given that there are ongoing efforts to transport the CO_2 to the saline reservoirs. Therefore, with some investments in additional liquid-to-solid mineralization infrastructure, it is possible to produce these value-added products at the sites where CO_2 is captured in geological brines. Further studies to explore this option are highly recommended.

Wyoming is also home to the world's largest bentonite deposits (Figure 15), constituting approximately 70% of the international supply.[88] Some natural clays, such as metakaolin, have been widely used in concrete as pozzolanic SCM.[89] Bentonite clays have a chemical composition similar to some of the pozzolanic SCMs commonly used in concrete; however, they have a low-grade reactivity. Hence, they need to be activated to become effective in concrete. Using low-grade clays as SCM in concrete is an active field of research,[90] and it might be possible to activate bentonite clays with additional research. This activation process might also involve CO_2 mineralization technologies, which could open the large bentonite deposits to be used as feedstock material. Additional studies to explore this option are highly recommended.

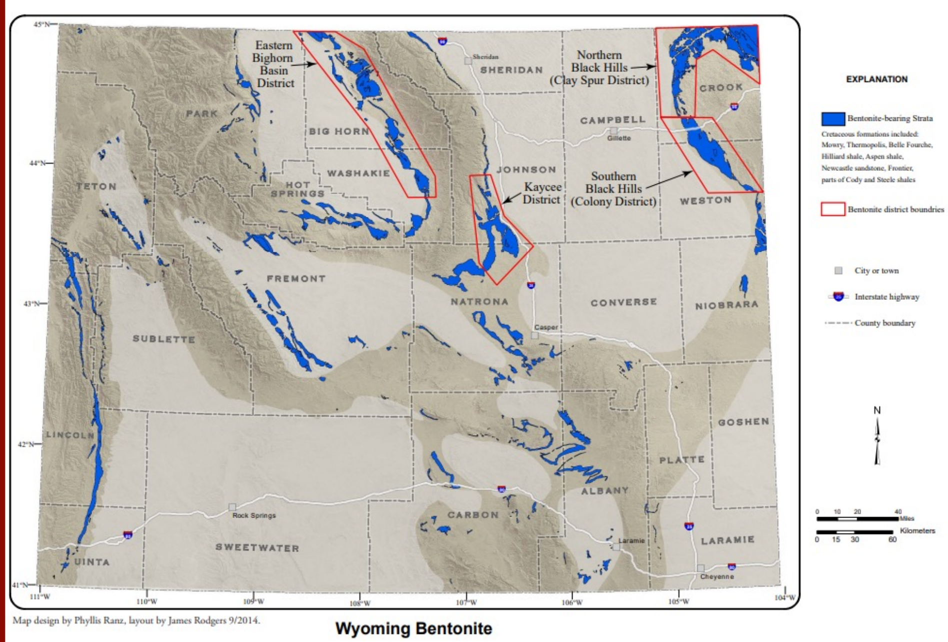


Figure 15: A Map of Wyoming bentonite deposits[91]

[88] In 2019, Wyoming bentonite developers mined more than five million tons of bentonite.
[89] Thomas, M., Supplementary Cementing Materials in Concrete, 2013, CRC Press, 210 pp.
[90] Ayati, B., et al., Low-carbon cements: Potential for low-grade calcined clays to form supplementary cementitious materials. Cleaner Materials, 2022. 5.
[91] Sutherland, W.M., Wyoming bentonite. 2014, Wyoming State Geological Survey: Laramie, WY.

6.3.4. Infrastructure Needs

New infrastructure would be needed to implement the technologies described in this study. For technologies designed to carbonate concrete and concrete by-products directly, as shown in Figure 11, new infrastructure would be needed at precast and ready-mix concrete plants where CO_2 is readily available for carbonation. However, not all precast and ready-mix concrete plants in Wyoming are located near the source of the CO_2 or the CO_2 pipeline network; therefore, it is expected that some of these plants would not be able to adopt these technologies.

For CO_2 mineralization technologies, infrastructure is also needed to convert feedstock materials to value-added products for the concrete industry. For liquid-to-solid technologies that use brines as feedstock material, as shown in Figure 12, this can be done at the locations where currently infrastructure is developed for sequestering the CO_2 in the geological reservoirs. The CO_2 is delivered to these points already, and the brine is locally available at these locations. For CO_2 mineralization technologies that utilize the coal ash that is destined for surface impoundments and reclaimed ponded ash to produce value-added concrete materials, the new infrastructure would be needed near the coal-burning power plants.[92]

[92] "The U.S. Enhanced Oil Recovery Survey 2021 Update" (ARI, 2021) (available at https://www.eoriwyoming.org/library/eori-library/co2-eor-survey-update-2021).

7. LOW-CARBON POLICY DRIVERS INFLUENCING THE CONCRETE INDUSTRY

The concrete industry faces pressure to reduce its carbon impact on numerous fronts, including: (1) the Paris Agreement and industry low-carbon roadmaps issued thereunder; (2) state and municipal construction-related requirements; and (3) environmental product declarations. Relevant developments on these three fronts are discussed separately below. Thus, the industry is actively pursuing options to reduce net emissions and is motivated to identify solutions, including those identified in this report.

7.1. Paris Agreement and Cement Industry Low-Carbon Roadmaps

Internationally, and thus in the United States and Wyoming, the low-carbon policy drivers influencing the concrete industry are based upon the 2015 Paris Agreement, to which the United States is a party. The objective of the Paris Agreement is "[h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change …."[93]

The Paris Agreement has led governments and industries, including the cement industry, to establish various net-zero, carbon-neutral, and related mid-century decarbonization goals and objectives. The United States' current commitment under the Paris Agreement, for example, is an economy-wide target of reducing its net greenhouse gas (GHG) emissions by 50-52% below 2005 levels in 2030;[94] by executive order dated January 27, 2021, the Biden Administration declared that the United States will endeavor to "achieve net-zero emissions, economy-wide, by no later than 2050."[95] Given the relatively high carbon footprint of the concrete industry, as discussed elsewhere in this study, these and related policy developments at the federal level almost certainly mean that the cement industry will continue to face unrelenting pressure to reduce its carbon profile moving forward.

Like many industries, the cement industry is currently establishing a variety of mid-century decarbonization goals. For example, in 2021, the US-based PCA published a Roadmap to Carbon Neutrality under which PCA's members committed to the goal of reaching carbon neutrality throughout the cement-concrete-construction value chain by 2050.[96] The PCA's roadmap includes several pathways – specifically including CCUS and carbonation – to achieve carbon neutrality (see Figure 16 below). Currently, the CCUS project are associated with emissions from cement plants and largely overseas.

"Like many industries, the cement industry is currently establishing a variety of mid-century decarbonization goals."

[93] Paris Agreement, Art. 2, Para. 1(a) (available at https://unfccc.int/sites/default/files/english_paris_agreement.pdf).
[94] https://unfccc.int/sites/default/files/NDC/2022-06/United%20States%20NDC%20April%2021%202021%20Final.pdf.
[95] Executive Order on Tackling the Climate Crisis at Home and Abroad, E.O. 14008, § 201 (Jan. 27, 2021) (available at https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/).
[96] Roadmap to Carbon Neutrality: A More Sustainable World is Shaped by Concrete (PCA, 2021) (available at https://www.cement.org/sustainability/roadmap-to-carbon-neutrality).

PRODUCTION: AT THE CEMENT PLANT	
Replace raw materials with decarbonated materials	Using decarbonated materials eliminates CO_2 emissions from processing traditional raw materials, like limestone.
Use alternative fuels	Replacing traditional fossil fuels with biomass and waste-derived fuels lowers greenhouse gas (GHG) emissions and keeps materials out of landfills.
Continue efficiency improvements	Increasing energy efficiency reduces the amount of CO_2 emitted for each ton of product.
Implement carbon capture, utilization, and storage (CCUS) technology	CCUS directly avoids a significant portion of cement manufacturing emissions.
Promote new cement mixes	Creating new cements using existing and even alternative materials reduces emissions from mining for new materials, while optimizing the amount of clinker used ensures emissions correspond to necessary production.
Increase use of portland-limestone cement (PLC)	As an existing lower-carbon blend, universal acceptance of PLC will reduce clinker consumption and decrease emissions.
CONSTRUCTION: DESIGNING AND BUILDING	
Optimize concrete mixes	Considering the specific needs of the construction project and using only the materials necessary, avoiding excess emissions.
Use renewable fuels	Switching to solar, wind and other renewable sources of energy directly reduces emissions from other energy sources.
Increase the use of recycled materials	Diverting these materials from landfills.
Avoid overdesign and leverage construction technologies	Designing for the specific needs of the construction project reduces unnecessary overproduction and emissions; incorporating just-in-time deliveries.
Educate design and construction community	Improve design and specifications to be more performance oriented which will permit innovation in cement and concrete manufacturing. Encourage the use of advanced technologies to improve structural performance, energy efficiency, resiliency, and carbon sequestration.
EVERYDAY: CONCRETE INFRASTRUCTURE IN USE	
Incentivize energy efficient buildings	Increasing buildings' energy efficiency can cut energy use and resulting emissions from heating and cooling.
Reduce vehicle emissions by improving fuel efficiency	Because of its rigidity, concrete pavements enhance the fuel efficiency of vehicles driving over them, reducing vehicle emissions.
Decreased maintenance	Due to their durability, concrete structures (buildings, pavements, bridges, dams, etc.) last longer and require less frequent maintenance.
Recycling	Concrete in place can be 100% recycled, limiting the use of raw materials and production emissions.
Carbonation	Every exposed concrete surface absorbs CO_2 and over the course of its service life, a building can reabsorb 10% of cement and concrete production emissions.

Figure 16: PCA's Pathways to Achieve Carbon Neutrality[97]

[97] Roadmap to Carbon Neutrality: A More Sustainable World is Shaped by Concrete, Executive Summary, p. 4 (PCA, 2021) (available at https://www.cement.org/docs/default-source/cement-concrete-applications/executive-summary_pca-roadmap-to-carbon-neutrality_jan-2022.pdf?sfvrsn=37d8fcbf_2).

7.2. State & Municipal Construction-Related Requirements

A growing number of state and local jurisdictions in the United States are adopting policies regarding the environmental performance of construction materials, including carbon content of materials such as concrete (see Figure 17 below). In the western United States, three jurisdictions – California, Colorado and Oregon – have specifically taken action with respect to reducing the carbon intensity of concrete in the years ahead.

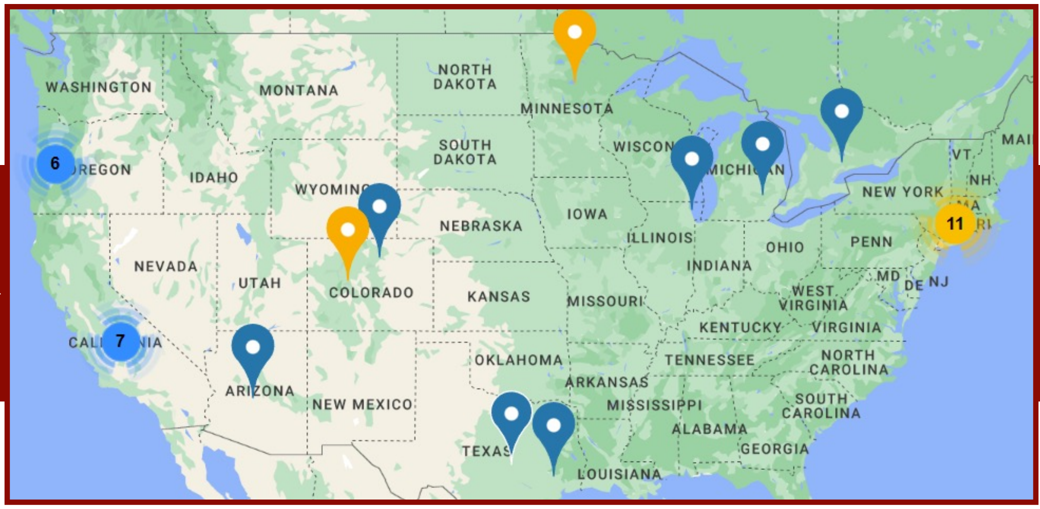


Figure 17: State and Local Carbon Content Requirements for Products and/or Materials (yellow = state policy; blue = local policy)[98]

7.2.1. California

California recently enacted legislation specifically for lowering the carbon intensity of concrete. Thus, there may be potential for Wyoming to export some CO_2-containing value-added products for concrete if it ultimately were to stand up an industry in this area.

Enacted in 2021, Senate Bill (SB) 596 directs the California Air Resources Board (CARB) to prepare by July 1, 2023 a "comprehensive strategy for the state's cement sector to achieve net-zero emissions of greenhouse gases associated with cement used within the state as soon as possible, but not later than December 31, 2045." CA Health & Safety Code, § 38561.2(a)(1) (2022).[99] In developing this comprehensive strategy, CARB must, in part –

> "Define a metric for greenhouse gas intensity and evaluate the data submitted by cement manufacturing plants … and other relevant data about emissions of greenhouse gases for cement that was imported into the state to establish a baseline from which to measure greenhouse gas intensity reductions." Id. § 38561.2(b)(1).
>
> "Assess the effectiveness of existing measures, identify any modifications to existing measures, and evaluate new measures to overcome the market, statutory, and regulatory barriers inhibiting achievement" of the law's objectives. Id. § 38561.2(b)(2).
>
> "Include provisions to minimize and mitigate potential leakage and account for embedded emissions of greenhouse gases in imported cement in a similar manner to emissions of greenhouse gases for cement produced in the state, such as through a border carbon adjustment mechanism." Id. § 38561.2(b)(4).
>
> "Prioritize actions that leverage state and federal incentives, where applicable, to reduce costs of implementing greenhouse gas emissions reduction technologies and processes and to increase economic value for the state." Id. § 38561.2(b)(6).
>
> "Evaluate measures to support market demand and financial incentives to encourage the production and use of cement with low greenhouse gas intensity, including, but not limited to, consideration of the following measures" –

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[98] https://carbonleadershipforum.org/clf-carbon-policy-toolkit/#map.

[99] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB596; https://www.canarymedia.com/articles/carbon-free-buildings/cement-is-terrible-for-the-climate-california-just-passed-a-law-to-fix-that.

"Measures to expedite the adoption for use in projects undertaken by state agencies, including the Department of Transportation, of Portland limestone cement and other blended cements";

"Measures to provide financial support and incentives for research, development, and demonstration of technologies to mitigate emissions of greenhouse gases from the production of cement with the objective of accelerating industry deployment of those technologies";

SB 596 further stipulates that –

CARB must establish "interim targets for reductions in the greenhouse gas intensity of cement used within the state relative to the average greenhouse gas intensity of cement used within the state during the 2019 calendar year, with the goal of reducing the greenhouse gas intensity of cement used within the state to 40% below the 2019 average levels by December 31, 2023." Id. § 38561.2(a)(2).

In setting these targets, CARB must focus on "raw materials, fuels [and] other energy sources, processes, [and] transportation involved in making or using cement or its inputs." Id. § 38561.2(a)(3).

In 2022, similar legislation (AB 2446) was enacted that imposed similar requirements with respect to the average carbon intensity of materials used in the construction of new buildings in California. CA Health & Safety Code, § 38561.3 (2022).[100] Assembly Bill (AB) 2446 requires CARB, by July 1, 2025, to develop, in consultation with specified stakeholders, a framework for measuring and then reducing the average carbon intensity of the materials used in the construction of new buildings, including those for residential uses. The law requires the framework to include a comprehensive strategy for the state's building sector to achieve a 40% net reduction in GHG emissions of building materials, as determined from a specified baseline. The law requires the strategy to achieve this target as soon as possible, but no later than December 31, 2035, with an interim target of 20% net reduction by December 31, 2030.

The Caltrans EPD Implementation Project collects EPDs for each eligible material in a Caltrans project to quantify total global warming potential.[101]

The City of Los Angeles' 2019 Green New Deal Sustainable City "pLAn" incorporates embodied carbon.[102]

In 2020 the mayors of Low Angeles and San Francisco signed the "C40 Clean Construction Declaration."[103] The goals of the declaration are to (1) reduce embodied emissions by at least 50% for all new buildings and significant retrofits by 2030; (2) reduce embodied emissions by at least 50% for all infrastructure projects by 2030; and (3) require zero emission construction sites city-wide by 2030 where technology is available.

San Francisco's 2021 Climate Action Plan includes requirements related to embodied carbon; under that plan, for example, the city intends to: (1) phase in policies between 2024-2026 to reduce embodied carbon by more than 10% per project by addressing at least three product categories or building assembly types; and (2) maximize replacing concrete to create more biodiverse green space on public land by 2030.[104]

The City of Albany's Climate Action and Adaption Plan similarly addresses embodied carbon. The city also intends to utilize its Sustainable Purchasing Policy to focus on purchasing items with a smaller carbon footprint, such as low-carbon concrete.[105]

The City of Oakland's 2030 Equitable Climate Action Plan stipulates that the city, by 2023, will adopt a concrete code for new construction that limits embodied carbon emissions, and that subsequent updates to that code will "implement improved embodied carbon performance standards including additional materials and material-efficient building practices, with exemptions for cost barriers as needed to prevent these changes from directly increasing housing or rent costs."[106]

[100] https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220AB2446; see also https://www.gov.ca.gov/2022/09/16/governor-newsom-signs-sweeping-climate-measures-ushering-in-new-era-of-world-leading-climate-action/.
[101] https://dot.ca.gov/programs/engineering-services/environmental-product-declarations.
[102] https://plan.lamayor.org/sites/default/files/pLAn_2019_final.pdf.
[103] https://www.c40.org/news/clean-construction-declaration-launch/; https://www.c40.org/accelerators/clean-construction/.
[104] https://sfenvironment.org/sites/default/files/cap_fulldocument_wappendix_web_220124.pdf.
[105] https://www.albanyca.org/home/showpublisheddocument/43215/637116692863100000.
[106] https://cao-94612.s3.amazonaws.com/documents/Oakland-ECAP-07-24.pdf.

7.2.2. Colorado

Colorado has enacted similar legislation. Enacted in 2021, Colorado House Bill 21-1303 ("Buy Clean Colorado Act") provides that –

By January 1, 2024, the Office of the State Architect "shall establish by policy a maximum acceptable global warming potential for each category of eligible materials used in an eligible projects" in accordance with certain requirements. Co. Rev. Stat. § 24-92-117(3)(a) (2022). "Eligible material" means "materials used in the construction of a public project, including … [c]ement and concrete mixtures."[107] "Eligible project" means "a public project … for which an agency of government issues a solicitation on or after January 1, 2024 … [not including] any maintenance program for the upkeep of a public project or any road, highway, or bridge project."

By January 1, 2025, the Colorado Department of Transportation has to develop and thereafter impose similar requirements where "[e]ligible material" means "materials used in the construction of a public project, including but not limited to … [c]ement and concrete mixtures …" Id. § 24-92-118(2)(b)(II). Here, "[p]ublic project" means "all publicly bid construction projects, projects from within the asset management, or other projects as determined by the department." Id. § 24-92-118(2)(d). These requirements apply to bid highway and related bid invitations after July 1, 2022.

7.2.3. Oregon

Enacted in Oregon in 2022, HB 4139 requires the Oregon Department of Transportation (ODOT), by not later than December 31, 2025, to establish a program that[108]

> "Assesses the greenhouse gas emissions attributable to covered materials [ODOT] uses in [its] construction and maintenance activities for the state's transportation system";
>
> Conducts life cycle assessments of a selected set of [ODOT's] construction and maintenance activities;" and
>
> Devises strategies for reducing greenhouse gas emissions that include, but are not limited to, improving pavement and bridge conditions."

"Covered materials" included but is not limited to: (1) "[c]oncrete, including ready mix concrete, shotcrete, precast concrete and concrete masonry units"; (2) "[a]sphalt paving mixtures"; and (3) "[s]teel, including rebar, reinforcing steel and structural steel, hot-rolled sections, hollow sections, plate steel and cold-formed steel".

Under this program, ODOT must require contractors to submit "environmental product declarations" (EPD) before the contractor installs the covered materials (except with respect to asphalt paving mixtures, which are discussed next), with limited exceptions.

ODOT may not use EPDs "as a consideration in ranking or scoring a bid or proposal before January 1, 2027." After that date, ODOT may do so if it "determines that doing so is beneficial and if, after consulting with … construction contractors, material suppliers and other stakeholders, [ODOT] devises a scoring methodology that ensures fairness among bidders and proposers."

Meanwhile, the Oregon Concrete EPD program provides a free tool to create concrete EPDs and cost reimbursement incentives for Oregon concrete producers. The program is a partnership between the Oregon Concrete & Aggregate Producers Association and the Oregon Department of Environmental Quality.[109]

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[107] Id. § 24-92-117(2)(a)(II).
[108] https://olis.oregonlegislature.gov/liz/2022R1/Downloads/MeasureDocument/HB4139/Enrolled.
[109] https://www.ocapa.net/index.php?option=com_content&view=article&id=247:oregon-concrete-epds&catid=20:site-content&Itemid=201s.

7.3. Environmental Product Declarations

The cement industry is subject to low-carbon policies that directly regulate and/or otherwise influence the use of fossil fuels in the production process and product attributes such as carbon content, specifically known as "embodied carbon" in the building industry. "[E]mbodied carbon refers to the greenhouse gas emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials."[110] In contrast, "operational carbon" refers to GHG emissions due to building energy consumption.[111] Figure 18 below highlights the difference between "embodied carbon" and "operational carbon" during key lifecycle stages of a typical building, public works project or similar infrastructure.

Figure 18: Embodied versus Operational Carbon in the Lifecycle of a Typical Building, Public Works Project or Similar Infrastructure[112]

EPDs are published by product manufacturers to communicate potential environmental impacts of products or processes. The International Standardization Organization (ISO) has established processes that use LCA methods to declare the environmental impacts of on product labels.[113] Under ISO requirements, so-called Type III declarations are equivalent not EPDs. EPDs are preferred because they provide a high level of confidence as the information provided as followed a standardized and transparent scientific process.

EPDs are developed through a prescribed process that starts with what is known as a "Product Category Rule" (PCR). A PCR is a "[s]et of specific rules, requirements, and guidelines for developing [EPDs] for one or more product categories." (ISO 14025). A PCR has been established for "Portland, Blended, Masonry, Mortar, and Plastic (Stucco) Cements."[114] The resulting EPDs that are prepared under a PCR "[p]rovid[e] quantified environmental data using predetermined parameters and, where relevant, additional environmental information" as defined in a PCR which is based on a LCA (ISO 14025). EPDs can be issued on a specific product from a specific producer, but may also be issued for a generic product from a group of manufacturers (such as an association).

A commonly cited set of LCA standards specific to EPDs for building materials are those published by the European Committee for Standardization under the Technical Committee 350 "sustainability of construction works", and which include a standard for EPDs published as EN15804 (CEN 2012).[115]

Recent examples of industry involvement in this area are: (1) the PCR Task Group produced a draft PCR for Portland and blended cements in 2012 and is close to releasing a publication; (2) NRMCA is certifying EPDs for cement (Carbon Leadership Forum 2010) and concrete (Carbon Leadership Forum 2013) as a program operator; and (3) the National Asphalt Pavement Association (NAPA) has formed a task group to develop PCRs and EPDs for the asphalt pavement industry.

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[110] Embodied Carbon 101, CLF Policy Primer Series, p. 1 (Carbon Leadership Forum, 2020) (available at https://carbonleadershipforum.org/embodied-carbon-101/).
[111] Embodied Carbon 101, CLF Policy Primer Series, p. 1 (Carbon Leadership Forum, 2020) (available at https://carbonleadershipforum.org/embodied-carbon-101/).
[112] Embodied Carbon 101, CLF Policy Primer Series, p. 1 (Carbon Leadership Forum, 2020) (available at https://carbonleadershipforum.org/embodied-carbon-101/).
[113] A LCA is a "[c]ompilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. ISO 14040.
[114] https://www.cement.org/docs/default-source/pcr-2020/pcr-portland-cement-2020.pdf?sfvrsn=9acee2bf_2.
[115] https://www.fhwa.dot.gov/pavement/sustainability/articles/environmental.cfm.

Figure 19 below is a sample EPD for a concrete mix design courtesy of the Central Concrete Supply Company. The industry average EPD for ready-mix concrete is provided by NRMCA.[116, 117]

Summary of
Environmental Product Declaration

Central Concrete

Mix 340PG9Q1

San Jose Service Area

EF V2 Gen Use P4000 3" Line 50% SCM

Performance Metrics

28-day compressive strength	4,000 psi
Slump	4.0 in

Environmental Impacts

Impact name	Unit	Impact per m3	Impact per cyd
Total primary energy consumption	MJ	2,491	1,906
Concrete water use (batch)	m3	6.66E-2	5.10E-2
Concrete water use (wash)	m3	8.56E-3	6.55E-3
Global warming potential	kg CO2-eq	271	207
Ozone depletion	kg CFC-11-eq	5.40E-6	4.14E-6
Acidification	kg SO2-eq	2.26	1.73
Eutrophication	kg N-eq	1.31E-1	1.00E-1
Photochemical ozone creation	kg O3-eq	46.6	35.7

Figure 19: Sample EPD for a concrete mix design

[116] https://www.nrmca.org/association-resources/sustainability/environmental-product-declarations/
[117] https://www.nrmca.org/wp-content/uploads/2022/03/NRMCA_EPDV3-2_20220301.pdf.

8. RESPONSES TO QUESTIONS POSED THE WYOMING LEGISLATURE REGARDING CONCRETE

Specifically concerning the questions set forth in HB 61 ("Carbon dioxide in public works—feasibility study"):[118]

i. Advantages and Disadvantages of a Requirement for a Specified Percentage of Concrete Used in Public Works Projects to be Made using CO_2 Emissions from Coal-Fired or Natural Gas-Fired Electric Generation Facilities

For various technical and commercial reasons, it is premature for the State of Wyoming to establish as a requirement that a specified percentage of concrete used in public works projects in Wyoming be made using CO_2 emissions from coal-fired or natural gas-fired EGUs.

First, there may be technical challenges to address before widespread adoption can occur because CO_2 is not a typical ingredient in concrete. Technical challenges include, for example, CO_2 availability, product cost-effectiveness, and product long-term performance. These challenges must be overcome before CO_2 can be so utilized, yet alone be required, in infrastructure projects.

Second, and perhaps more importantly, the cement/concrete industry in Wyoming is relatively small in comparison to the quantity of CO_2 produced in the state (by at least a factor of 100) and public works projects are a fraction of the industry's size. As such, the volume of CO_2 that could be used directly in concrete is small compared to that produced by coal-fired and natural gas-fired EGUs in Wyoming.

Third, further research and investment in Wyoming are needed to develop value-added products that can be used in concrete. These value-added products include brine, ponded coal-ash, bentonite, and rock feedstock resources. Once these value-added products are commercially produced in Wyoming, it might become feasible for the State of Wyoming to establish a requirement that they be used in concrete for public works projects. Further, these value-added products could generate revenue for Wyoming. Therefore, it is prudent for Wyoming policymakers and industry to continue to monitor technological and policy developments related to decarbonizing building materials – an activity that is underway in surrounding states and within the industry.

ii. Whether any Requirement for CO_2 Use in Public Works Projects Should be Phased in as a Requirement

For various technical and commercial reasons, it is likely premature for the State of Wyoming to phase in a requirement that a specified percentage of concrete used in public works projects in Wyoming be made using CO_2 emissions from coal-fired or natural gas-fired EGUs. A different option for the state to consider is requiring an EPD – and potentially eventually an LCA – approach for cement and concrete used in public works projects in the state. This could help "set the stage" for increased use of materials that embody carbon when they are available in the future. However, the extra effort needed by entities carrying out public works projects should be considered as part of the evaluation process. The study's authors recommend research and investment in Wyoming to develop value-added products that can be used in concrete from brine, ponded coal-ash, bentonite, and rock feedstock resources.

[118] Wyo. Stat. §§ 37-18-101, 102 (2022).

iii. Whether There Would Be Additional Costs or Savings for Public Works Projects as a Result of a CO_2 Use Requirement

Although it varies by project, in many cases, there would be additional costs for public works projects due to a CO_2 use requirement for concrete. There may also be mechanisms or incentives to offset these costs. These costs include: providing technical support to the Wyoming concrete industry; providing solutions to creating durable concrete with CO_2 as a new ingredient in concrete; adding the required infrastructure to implement CO_2 utilization technologies; and providing a study regarding how much CO_2 capture could be completed using this methodology.

If it can be shown that Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources can be used in CO_2 mineralization technologies, value-added products could be produced for the concrete industry. Wyoming could become an exporter of such value-added products to other states. This will require additional investments in research and infrastructure; however, when successful, it could provide significant future value streams and uses for CO_2 emissions from coal-fired or natural gas-fired EGUs.

iv. What Types of Public Works Projects in the State Could Utilize CO_2 as Part of the Project

Subject to the limitations outlined in this study, the following types of public works projects in the state could, in theory, make use of concrete that utilizes CO_2: (1) highway construction, (2) school construction, and (3) projects involving the construction or renovation of state buildings.

However, the state would be best served to create value-added products that utilize large volumes of CO_2 (e.g., A-SCM, alternative cements, concrete aggregates, and filler materials like powdered limestone).

v. How Much CO_2 Could Be Captured in Wyoming to be Used for Public Works Projects

Because the concrete industry in Wyoming is relatively small, as is the demand for concrete generally, only a relatively small amount of captured CO_2 could potentially be utilized by the concrete industry. As an extreme example, if all concrete produced annually in Wyoming (approximately two million metric tons) is assumed to be available for CO_2 utilization, and all carbonatable portion of concrete (approximately 15% of the total volume of concrete) is carbonated (this is approximately five times the typical carbonation process), the maximum amount of CO_2 that can be incorporated in concrete would be around 0.15 million metric tons. Given that only a fraction of this concrete is produced for public work projects, and CO_2 would not be utilized in all concrete produced in Wyoming, the captured CO_2 would exceed the amount of CO_2 that can be used in public works projects by at least a factor of 100.

However, as mentioned, substantially more CO_2 could be utilized in the development of value-added products than that used on the conventional Wyoming concrete industry. The exact amounts depend on the application; however, Section 3.2 outlines several CO_2 utilization approaches: (1) carbonation of hardened concrete (~50 kg CO_2 per m^3 concrete); (2) injection in fresh concrete (~0.6 kg CO_2 per m^3 concrete); (3) injection into reclaimed return water (~0.65 kg CO_2 per m^3 concrete); (4) aggregate manufacture (~600 kg CO_2 per m^3 concrete); (5) recycled concrete fines (~50-150 kg CO_2 per m^3 concrete); (6) concrete solidification through carbonation (~200-600 kg CO_2 per m^3 concrete); and (7) production of A-SCM, alternative cements, and fillers like ground limestone (CO_2 utilization depends on the details of what is produced). The numbers provided above are estimates. However, a more detailed analysis requires a follow-up study with specific materials and processes identified.

vi. Possible Infrastructure and Transportation Needs for Which CO_2 Could be Used in Public Works Projects Throughout the State

To utilize CO_2 in public works throughout the state, infrastructure and transportation needs – for delivering CO_2 to pipelines and concrete-specific utilization equipment – would have to be separately permitted, financed, constructed, and operated to enable the utilization of CO_2 in concrete in Wyoming. However, in some cases, construction materials production could be co-located with power plants to avoid additional infrastructure needs. Value-added products may need transportation to carry large volumes of material out of the state; however, this is believed possible on existing rail transportation used to transport coal.

vii. Any Disruptions or Disadvantages to Other Industries and Wyoming Businesses if a CO_2 Use Requirement is Imposed

The immediate imposition of a CO_2 use requirement would likely disrupt and/or disadvantage Wyoming's: (1) concrete industry; (2) building materials industry; and (3) construction industry. State and local government agencies and departments that rely upon the private sector to produce, deliver, and install concrete – including but not limited to WYDOT – also could be disrupted and/or disadvantaged.

If it can be shown that Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources can be used in CO_2 mineralization technologies, Wyoming could become an exporter of such value-added products to other states. This could provide significant future value streams and uses for CO_2 emissions from coal-fired or natural gas-fired EGUs.

viii. Whether the Use of CO_2 in Public Works Projects May Extend or Prolong the Operation of Coal-Fired and Natural Gas Electric Generation Facilities in Wyoming

The use of CO_2 in public works projects theoretically could extend the operation of coal-fired or natural gas-fired EGUs in Wyoming by providing a potential economic return related to the utilization of CO_2. However, because the volume of CO_2 produced by EGUs greatly exceeds the potential market demand for CO_2 by the concrete industry, this issue is complicated and subject to a mix of EGU-specific considerations. Legal issues also are relevant because an EGU's sale of captured CO_2 for utilization in a product such as cement or alternative cements would also have to be recognized under the federal Clean Air Act.

If it can be shown that Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources can be used in CO_2 mineralization technologies, Wyoming could become an exporter of such value-added products to other states. This could provide significant future value streams and uses for CO_2 emissions from coal-fired or natural gas-fired EGUs. As such, this would prolong the potential operations of coal-fired and natural gas-fired EGUs in Wyoming.

"If it can be shown that Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources can be used in CO_2 mineralization technologies, Wyoming could become an exporter of such value-added products to other states. "

ix. Whether Proposed or Enacted, Federal Legislation or Regulation May Impact the Use of, and the Advantages and Disadvantages of Using, CO_2 in Public Works Projects

This study has identified several proposed and enacted federal legislation and regulation that could impact the use, and the advantages and disadvantages, of CO_2 in public works projects. These include policies in various states to require lower-carbon footprint construction materials. In addition, there are several provisions in the Inflation Reduction Act (IRA) that may provide financial support for such products, including:

- $2.15B to install low-carbon materials in General Services Administration-owned buildings. The GSA owns about 1,500 buildings around the country, including office buildings, land ports of entry, courthouses, laboratories, post offices and data processing centers.
- $2B for Low-Carbon Transportation Grants to reimburse and incentivize the use of low-carbon materials for Federal Highway Administration projects.
- $250M to develop and standardize EPDs for construction materials, with grants and technical assistance for manufacturers
- $100M to identify and label low-carbon materials and products for federally funded transportation and building projects.
- $4B to improve resiliency in affordable housing, including funds for low-carbon materials, and allows FEMA's Building Materials program to offer financial assistance for low-carbon materials and net-zero energy projects.

Subject to numerous terms and conditions, the federal section 45Q tax credit for carbon dioxide sequestration applies to the capture of CO_2 from stationary sources and subsequent: (1) storage of that CO_2 in secure geological storage; or (2) utilization in, for example, products such a cement or concrete. 26 U.S.C. § 45Q (2022). If the activity satisfies the recently enacted IRAs wage and apprentice requirements, the former and latter are eligible for incentive amounts of $85/metric ton and $60/metric ton, respectively. A coal-fired EGU would need to assess the relative economic benefits of utilizing the CO_2 in concrete versus storing the CO_2 in a saline reservoir. That analysis would be subject to numerous project-specific variables that make broad generalizations about the potential economic benefits of the former impossible to assess in the abstract.

x. Advantages and Disadvantages of Using CO_2 in Public Works Projects

Advantages of using CO_2 in public works projects include: (1) opening new markets for an EGU's CO_2; (2) keeping Wyoming abreast of the latest in CCUS developments, specifically including the emerging trend in some jurisdictions regarding regulating concrete usage from a carbon footprint perspective; (3) potentially attracting new industries including, but not limited to, the Carbon XPrize activities at the Wyoming Integrated Test Center,[119] Carbon Built,[120] Solidia,[121] Carbon Upcycling,[122] Blue Planet,[123] Calera,[124] Holcim/Lafarge,[125] and Carbicrete;[126] and (4) potentially producing value-added products for the concrete industry through CO_2 mineralization technologies from Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources. If successful, the items produced by these companies and potentially others could be exported out of state as value-added products.

[119] https://www.wyomingitc.org/
[120] https://www.carbonbuilt.com/
[121] https://www.solidiatech.com/
[122] https://carbonupcycling.com/
[123] https://www.blueplanetsystems.com/
[124] https://newatlas.com/novacem-calera-caron-capturing-concrete/14039/
[125] https://holcimmaqer.com/success-cases/holcim-uses-captured-co2-to-reinforce-recycled-concrete-with-neustark/
[126] https://carbicrete.com/

Disadvantages of using CO_2 in public works projects include: (1) CO_2 utilization in concrete may not qualify under forthcoming federal GHG emission standards for coal-fired EGUs, depending on the specific project size; (2) in many cases, especially those where CO_2 must be transported, projects will be uneconomic or noncompetitive in the marketplace, meaning state RFP's may go under bid or, if bid, costs could be higher; (3) other CO_2 abatement options (e.g., geologic storage) will also be required given the relatively low CO_2 consumption level; (4) the CO_2-containing concrete may not qualify under existing codes and standards for materials in public works, and it would take a time and resources to work towards obtaining such qualifications; and (5) relationships with Wyoming CCUS's laws would have to be addressed – e.g., HB 200.

xi. **Finally, significant potential exists for the establishment of one or more geologic CO_2 storage hubs in Wyoming.**

Regardless of whether Wyoming decides to require or incentivize CO_2 in concrete public works, and even if these new public works materials are successfully deployed, geologic CO_2 storage (including CO_2-EOR) is likely necessary to address the majority of emissions from Wyoming's coal-fired and natural gas-fired EGUs.

9. FEASIBILITY OF ESTABLISHING A CO_2 STORAGE HUB IN WYOMING

This section responds to the separate directive in enrolled Act No. 12, Senate, 66th Legislature of the State of Wyoming, 2022 Budget Session that SER separately address the "feasibility of establishing a potential carbon dioxide storage hub in Wyoming."[127] SER interpreted "carbon dioxide storage hub" to mean a facility focused on the subsurface storage of CO_2 and that could include storage in association with CO_2-EOR operations.

While this report has identified potential areas to grow CO_2 use in public works. Potential exists to use larger volumes of CO_2 for use in construction material constituents, i.e., value-added materials which have the potential to utilize large CO_2 volumes. Current technologies can only consume about a small fraction of the CO_2 produced from Wyoming's coal-fired EGUs. Therefore, CO_2-EOR and dedicated storage remain the large-scale opportunities for Wyoming's coal fleet. Fortunately, Wyoming is in an ideal position to convert its work to date on CCUS into a robust hub. The state has many attributes that make it an ideal location to create a CO_2 storage hub.

9.1. Ideal Regulatory and Policy Framework

Wyoming elected and appointed officials have been contributing to creating a CCUS-friendly regulatory environment for decades. At a high level, the Wyoming CCUS-specific regulatory framework includes:

- Specifies who owns the pore space (Wyo. Stat. § 34-1-152)
- Establishes permitting procedures & requirements for CCS/CCUS sites (Wyo. Stat. § 35-11-313)
- Provides a mechanism for post-closure MRV via a trust fund approach (Wyo. Stat. § 35-11-318)
- Provides a mechanism for unitization of storage interests (Wyo. Stat. § 35-11-315)
- Specifies the injector, not the owner of pore space, is generally liable (Wyo. Stat. § 34-1-513)
- Clarifies that vis-à-vis storage rights, production rights are dominant but cannot interfere with storage (Wyo. Stat. § 30-5-501)
- Provides certification procedure for CO_2 incidentally stored during EOR (Wyo. Stat. § 30-5-502)
- SF159 – "Good faith effort" to evaluate CCS before closing/selling
- HB 200 CCUS – Low carbon energy standards including CCS/CCUS
- SF21 – Market for electrons beyond SF159
- Wyoming Energy Authority (WEA) with $3B bonding capacity
- State Primacy for EPA UIC Class VI

[127] Enrolled Act No. 12, Senate, 66th Legislature of the State of Wyoming, 2022 Budget Session, p. 38, n. 8.

9.2. Familiarity and Experience with CCUS Project, Including CO_2-EOR

Located near LaBarge, Wyoming, ExxonMobil's Shute Creek Gas Processing Plant is described as the world's largest CO_2 capture and storage facility.[128] The project captures approximately seven (7) million metric tons of CO_2 per year, with much of the captured CO_2 transported via pipeline for downstream CO_2-EOR projects. A $400 million expansion is under consideration that, if implemented, would increase the annual CO_2 capture volume to approximately eight million metric tons of CO_2.[129] In February 2018 EPA approved a monitoring, reporting and verification plan for the Shute Creek facility under subpart RR of EPA's Greenhouse Gas Reporting Program.[130]

According to the fifth edition of the DOE/NETL "Carbon Storage Atlas," oil and natural gas reservoirs in Wyoming represent a storage resource with low (0.23 billion metric tons), medium (0.59 billion metric tons) and high (1.41 billion metric tons) estimates.[131]

Not surprisingly then, Wyoming is already home to a robust CO_2-EOR industry which, in turn, can support the build-out of a CCUS industry in the years ahead. As of 2020, five operators own seventeen (17) active CO_2-EOR projects in the Rockies, thirteen (13) of which are in Wyoming.

A 2013 study examined the economic impact of the CO_2-EOR industry in Wyoming for the period 2010-2012. That study concluded that CO_2-EOR projects generated: (1) $1.56B in additional oil revenues; (2) $179M in government royalties; (3) $98M in private royalties; (4) $77M in severance taxes; and (5) $94M in ad valorem taxes. During the same period, the CO_2-EOR projects accounted for an average of 1,914 jobs annually, paying a total of $326M in labor income and adding $1.6B in Wyoming Gross State Product (GSP) during that time. Finally, the study found that for every direct job created from CO_2-EOR production an additional six (6) jobs are also supported throughout the economy.[132]

A 2014 study concluded that if a baseline scenario of 0.7 to 1 billion barrels of additional oil is realized, the CO_2-EOR industry in Wyoming may be able to support a 40-year average of 2,967 to 8,278 jobs annually. These jobs, in turn, translate into a gross total of $6.1–$17.5B in additional government mineral payments, and add $34.2–$100.2B to Wyoming GSP.[133]

Building upon the existing positive economics of CO_2-EOR, a CCS/CCUS industry in Wyoming could create up to 3,340 project jobs over a 15-year period and 1,964 ongoing operational jobs at ten industrial and power facilities. The retrofit of equipment at these facilities would capture thirty (30) million metric tons of CO_2 per year. Along with the development of CO_2 transport infrastructure, this would generate up to $11.2 billion in private investment.[134]

According to the Wyoming Enhanced Oil Recovery Institute (EORI), the full development of CO_2-EOR in Wyoming would result in 1.6 billion barrels of incremental oil production and a storage potential of 750 million metric tons of CO_2.[135] Critically for CCUS purposes, because the CO_2 displaces the oil from the rock pores during the EOR process, as the CO_2 sweeps through the reservoir some of the CO_2 remains securely geologically stored in the pores while the remainder remains miscibly mixed with the oil and is co-produced with the oil at the production well(s). At the surface any produced CO_2 is separated from the oil, recompressed for reinjection along with additional volumes to newly purchased CO_2 to make up for CO_2 that was previously geologically stored, then reinjected into the reservoir. That process continues, frequently for decades, with more and more CO_2 being geologically sequestered in the reservoir over time. "Cumulative injected CO_2 volumes vary, but typically range between 15 and 30 percent of the hydrocarbon pore volume of the reservoir."[136]

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[128] https://www.statista.com/statistics/1108355/largest-carbon-capture-and-storage-projects-worldwide-capacity/.
[129] https://www.naturalgasworld.com/exxonmobil-plans-400mn-wyoming-ccs-expansion-93138.
[130] https://www.epa.gov/sites/default/files/2018-06/documents/shutecreekmrvplan.pdf.
[131] https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf.
[132] Cook, B. "The Economic Contribution of CO_2 Enhanced Oil Recovery in Wyoming 2010-2012" (July 2013). USAEE Working Paper No. 14-159 (available at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2411868).
[133] Cook, B. "The Future Economic Contribution of Wyoming's CO_2-EOR Potential" (Jan. 2014).
[134] https://carboncaptureready.betterenergy.org/wp-content/uploads/2020/10/WY_Jobs.pdf.
[135] https://storymaps.arcgis.com/stories/635fa72880ae4d898157b27bd1995ad0.
[136] https://www.netl.doe.gov/sites/default/files/netl-file/CO_2_EOR_Primer.pdf.

9.3. Opportunities for Dedicated CO_2 Storage

Saline Formations. According to the fifth edition of the U.S. Department of Energy (DOE)/National Energy Technology Laboratory (NETL) "Carbon Storage Atlas," saline formations in Wyoming represent a storage resource with low (146.34 billion metric tons), medium (570.92 billion metric tons) and high (1539.56 billion metric tons) estimates.[137] With financial support from DOE, the State of Wyoming and numerous project participants, researchers at SER to date have extensively investigated two specific saline formations in Wyoming: (1) the Rock Springs Uplift (RSU) in southwestern Wyoming; and (2) a series of stacked formations just north of Gillette in northeastern Wyoming.

9.4. Creating a CO_2 Storage Hub

With an ideal regulatory framework, an existing CCUS projects, a robust CO_2-EOR industry, and CO_2 storage opportunities, Wyoming is an ideal location for a CO_2 storage hub. However, for Wyoming to become a true CCUS hub and fully leverage all the work that has been done to date, more coordination is needed. Wyoming should:

- Aggressively pursue opportunities to further develop the pipeline routes identified in the Wyoming Pipeline Corridor Initiative,
- Assess the revenue structure for CCUS projects,
- Ensure state agencies coordinate to optimize both:
  - o Pore space use for storage and;
  - o Future mineral production.

To this end, the School of Energy Resources and its partners across the state are undertaking a series of CCUS studies to collect the information necessary to optimize CO_2 storage in Wyoming. In Figure 20, the state's existing pipelines are showing in solid with the WPCI pipelines routes shown dashed. The CO_2 storage projects span much of the state, including the following:

9.4.1. Wyoming CarbonSAFE Project at Dry Fork Station

The stacked storage formations under investigation in Gillette are taking place as part of the Wyoming Carbon Storage Assurance Facility Enterprise (Wyoming CarbonSAFE) project led by the Center for Economic Geology Research at UW/SER. That project, which is still underway, already has concluded that the formations have the potential to store at least fifty (50) million metric tons of CO_2.[138]

While the DOE program requires suitable locations to store at least 50 million metric tons of CO_2, initial observations indicate that the storage must be significantly larger. Given that many point source emitters are in the region, further investigation of this location is warranted.

9.4.2. Rock Springs Uplift-Regional CCUS Hub

The RSU research was conducted in the middle of the last decade under a project known as the Wyoming Carbon Underground Storage Project (WY-CUSP). WY-CUSP consisted of CO_2 storage site characterization and evaluation, focusing on some of Wyoming's most promising CO_2 saline storage reservoirs: the Pennsylvanian Weber/Tensleep Sandstone and Mississippian Madison Limestone. Results from the WY-CUSP project suggest the two reservoirs could store up to 17,000 million tons of CO_2.[139]

[137] https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf.
[138] https://www.uwyo.edu/cegr/research-projects/wyoming-carbonsafe.html.
[139] https://www.uwyo.edu/cegr/research-projects/project-wy-cusp.html#:~:text=The%20Carbon%20Management%20Institute%20(CMI,the%20Rock%20Springs%20Uplift%20in; https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf.

9.4.3. Depleted Oil and Gas Fields

Several Wyoming oil and gas fields are nearing the end of their economic life. Many fields are not candidates for CO_2-EOR recovery and therefore without other options are soon to face remediation. However, many of these depleted fields are ideal candidates for CO_2 storage. Repurposing aging fields into permanent CO_2 storage hubs are compelling for many reasons:

- Geologically, the reservoirs and seals are well understood
- Economically, much of the infrastructure can be reused (e.g. compression, pipelines, monitoring wells, injection wells, electricity, etc.)
- Environmentally, limited new surface disturbance is required
- Lower risk, the formations are under pressured due to many years of oil and gas productions and the formations have proven to have held oil and gas for geologic time scales

9.4.4. Project Blue Bison (Blue Hydrogen)

SER is teamed with Tallgrass MLP Operations, LLC to assess hydrogen production from natural gas and incorporating CCUS at a location near Douglas, Wyoming. The facility aims to capture and sequester 1.66 million metric tons of CO_2 per year of 95% pure CO_2. Preliminary storage evaluations in the project area have identified four (4) potential injection targets, that when combined are greater than one thousand (1000) feet in total thickness. Additional site characterization work is needed however to understand the full CO_2 storage potential of this area.

9.4.5. PCOR

The Plains CO_2 Reduction (PCOR) Partnership in the Department of Energy's Regional Sequestration Partnership program is developing estimates of local sources and sinks throughout the region.

It is in Wyoming's best interest to ensure that projects are coordinated to optimize pore space. Even more importantly, Wyoming should undertake a study of the potential intersection of minerals production and dedicated CO_2 storage.

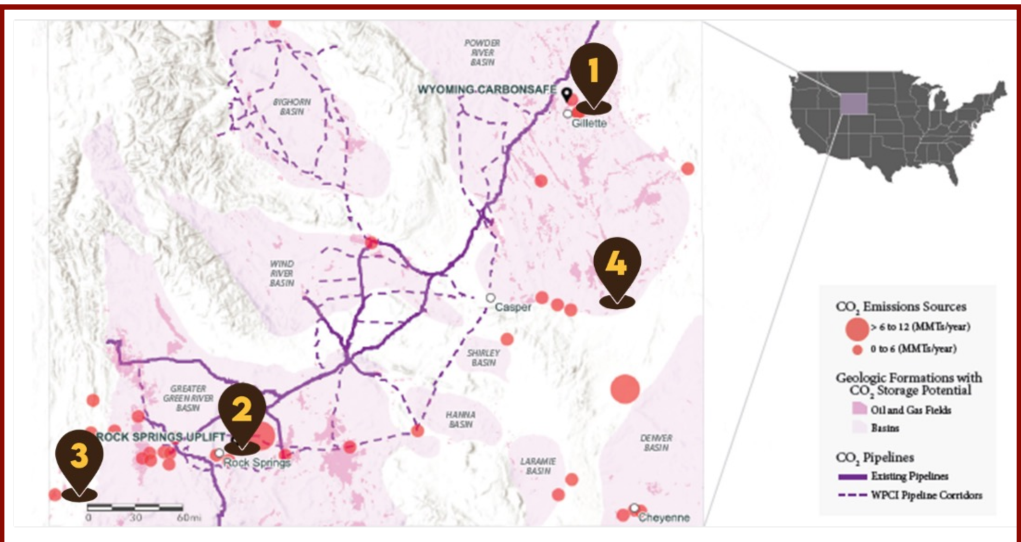

Figure 20: Large-scale dedicated CO_2 storage projects underway in Wyoming (with SER involvement).

9.5. CO_2 Pipelines

Wyoming is home to hundreds of miles of CO_2 pipelines which are used to transport CO_2 captured from facilities such as ExxonMobil's Shute Creek Gas Processing Plant, discussed above, to downstream CO_2-EOR fields through the state. The CO_2 pipeline network consists of two large-scale trunk links and several smaller scale distribution systems.

The State of Wyoming has laid the groundwork to expand this CO_2 pipeline network to accommodate a growing CCS/CCUS industry through the WPCI. WPCI is a State of Wyoming initiative to designate almost 2,000 miles of rights of ways across private, state and Bureau of Land Management ("BLM") lands in Wyoming for future CO_2 pipelines. Approximately 1,150 miles of the corridors are located on BLM managed lands. WPCI designates a statewide corridor network for future development of pipelines associated with CCS/CCUS. WPCI does not authorize any new pipelines or construction but amends BLM Resource Management Plans across the state to make analysis of future proposals more efficient. The public comment period on BLM's draft environmental impact statement closed in July 2020, and the record of decision was granted by BLM in January 2021.

10. RECOMMENDATIONS

State of Wyoming elected and appointed officials:

- Should continue to focus on CO_2 geologic storage and geologic-based utilization for CO_2 (i.e., CO_2-EOR) as they both continue to offer the greatest potential in managing the largest volumes of CO_2 at the lowest cost, particularly in light of the recent amendments to the section 45Q tax credit.
- Should consider directing UW to conduct a formal techno-economic study regarding the utilization of Wyoming-sourced CO_2 in products such as concrete making materials that includes all potential Wyoming feedstocks that can consume CO_2 and be used in public works or other large-scale projects, including a detailed economic evaluation of the role that amended section 45Q for carbon utilizations ($60/ton) could play in influencing market behavior.
- Should ensure that relevant Wyoming state agencies explore the $5B in funding that the IRA provides for low-carbon construction-related activities, and $1B in funding that the IRA provides for energy code related activities.

11. CONCLUSIONS

This study's conclusions are divided into two sections. The first section discusses potential approaches to address the embodied carbon content of concrete used in Wyoming, specifically focused on public works projects. The second sub-section discusses possible strategies to utilize CO_2 in value-added construction products.

11.1. Addressing the Embodied Carbon Content of Concrete in Public Work Projects

The concrete industry in Wyoming is relatively small, especially compared to the CO_2 emissions from coal-fired or natural gas-fired EGUs. As a result, it is difficult to have a substantial impact in reducing the capturable CO_2 supply in the state though direct utilization technologies based are based on the carbonation of concrete, such as CO_2 injection into reclaimed return water from concrete production or CO_2 injection in fresh concrete mixtures. Additionally, infrastructure does not exist for using CO_2 in concrete in Wyoming. There is no track record or experience for the commercial use of CO_2 in concrete in Wyoming. Therefore, making a strong case for mandating the industry to use CO_2 directly in concrete in public works projects is difficult. However, there are opportunities that may be of interest and worth pursuit.

An alternative approach would be to establish the use of environmental product declarations (EPDs).[140] EPDs provide a document that quantifies the environmental impact data from manufacturing a product. Over time this can encourage the industry to reduce the embodied carbon content of concrete using various approaches. Additionally, this system can be transitioned over time to a system that considers life cycle impacts.

It is anticipated that initially, encouraging the concrete industry to produce concrete with a low carbon footprint through existing and well-established cement and clinker-reducing approaches would be more impactful. These approaches include increased use of SCM, incorporation of larger amounts of limestone filler in the mixtures, reducing paste content through increased aggregate packing, and optimized mixture proportioning procedures.

Over time the industry can determine the value of utilizing alternative carbon uses in concrete as these technologies continue to emerge. This may include but is not limited to the carbonation of hardened concrete, injection of carbon dioxide in fresh concrete, injection of carbon dioxide into reclaimed return water, use of carbon dioxide for aggregate manufacture, use of carbon to carbonate recycled concrete fines, use carbon dioxide production of A-SCM, and/or concrete solidification through carbonation. Some of these technologies have the potential to develop in Wyoming.

11.2. Utilizing CO_2 in Value-added Construction Products

There is a strong case for CO_2 mineralization technologies to produce value-added products for the construction industry. The technologies are designed to produce A-SCM, alternative cements, construction aggregates, and fillers used in making concrete throughout the United States and other countries. There is a wide market for these products in the concrete industry, which is currently observing the fly ash stream decline in some markets. The need for SCM and enhanced A-SCM is only expected to increase to provide durable concrete and concrete with a lower carbon footprint. Given the potential for rail shipping, Wyoming is well-positioned to explore potential exported materials. Therefore, if Wyoming could find pathways to utilize these CO_2 mineralization technologies, it would be possible to convert a sizable portion of the captured CO_2 to marketable construction materials (either as raw feeds or finished products).

Since the majority of the CO_2 pipeline network in Wyoming is privately owned, a strong financial case is needed that shows how utilizing CO_2 through mineralization technologies that can produce a value-added product for the cement/concrete industry would be more profitable than storing the CO_2 in geological brine reservoirs. This could include the role of secondary value-added product sales, the benefit of long-term embodiment, and tax credits.

[140] NRMCA. Environmental Product Declarations. 2022; Available from: https://www.nrmca.org/association-resources/sustainability/environmental-product-declarations/.

Our preliminary investigation indicated that Wyoming does not have rich deposits of natural rock feedstock that can be used in CO_2 mineralization (such as olivine, serpentine, wollastonite, etc.). If this is confirmed to be the case, the other options for this pathway [importing the feedstock or exporting the CO_2 to the neighboring states (e.g., Colorado, Utah, Idaho)] would need to be assessed to see if they are feasible considering the cost of transportation of raw materials and the lack of adequate CO_2 pipeline network connecting Wyoming's CO_2 pipeline network to other states. Additional research is recommended if these materials could be determined to be economically brought to Wyoming.

There is a potential to utilize coal ash generated at the coal-burning power plants in Wyoming, which is currently destined for surface impoundments, to reclaim ponded ash for CO_2 mineralization to produce value-added concrete materials. If realized, this approach could have multiple benefits by reducing the coal ash sent to ponds, reducing the existing pond volumes through reclaiming ponded ashes, producing value-added products (e.g., A-SCM) to be used in concrete, and utilizing captured CO_2. Additional research is recommended to explore these pathways.

As the home of sizeable geological brine reservoirs, Wyoming might be able to use liquid brines as CO_2 mineralization feedstock to produce value-added products for the concrete industry. However, the feasibility of this pathway depends on the chemical composition and reactivity of the feedstock brines; therefore, additional studies are needed to quantify the economic feasibility of this potential.

Since Wyoming is also home to the world's largest bentonite deposits, there is a potential to use bentonite clay as a feedstock material to produce A-SCM. This, however, would require the activation of bentonite clays as it is not a reactive material in its natural state. This activation process might also involve CO_2 mineralization technologies, which could open the large bentonite deposits to be used as feedstock material. Additional research is recommended to explore these pathways.

Carbon dioxide utilization in products, including concrete, remains a topic of interest on various fronts, so Wyoming is wise to stay abreast of developments in this area. If it can be shown that Wyoming's brine, ponded coal-ash, bentonite, or rock feedstock resources can be used in CO_2 mineralization technologies, value-added products can be produced for the concrete industry. Wyoming could become an exporter of such value-added products to other states. Although this will require additional investments in research and infrastructure, it might provide significant future value streams and uses for CO_2 emissions from coal-fired or natural gas-fired EGUs.

Carbon dioxide utilization in concrete and concrete-making materials is an early-stage opportunity with many technical, economic, and related challenges, in addition to issues related to CO_2 sourcing from Wyoming's existing fleet of coal-fired EGUs. While opportunities may emerge related to CO_2 use in concrete, CO_2 utilization in CO_2-EOR and CO_2 storage (Class VI/saline) should remain a focus for volumetric, economic, and related considerations.

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