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Synthesis of Carbon Capture and Repurposing By-Products

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16. Abstract

Project 0-7231 evaluated the feasibility and readiness of Carbon Capture, Utilization, and Storage (CCUS) technologies for integration into Texas transportation infrastructure. The study provided a comprehensive review of CCUS methods, assessed material-based applications such as CO_2-injected concrete and bio-based alternatives, and developed a life cycle assessment (LCA) framework tailored to TxDOT projects. While not necessarily intended for immediate implementation, the research equips TxDOT with the knowledge, tools, and policy guidance needed to respond rapidly if future legislation, funding programs, or sustainability policies prioritize CCUS deployment.

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Patent Disclaimer: There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Engineering Disclaimer

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Products

P1 "Guidelines for Implementing Carbon Capture, Utilization and Storage (CCUS) Technologies on TxDOT Projects" (*this is provided as Chapter 6 in this report*).

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Chapter 1. Introduction

A common topic among researchers and companies across various industries and sectors is how to mitigate the environmental impact of various processes and activities. One focus of environmental protection involves the concentration of carbon dioxide within Earth's atmosphere. Carbon Capture, Utilization, and Storage (CCUS) technologies can be used by industrial players to reduce carbon dioxide emissions. CCUS is an umbrella term for a range of processes with the common goal of reducing the concentration of carbon dioxide in Earth's atmosphere through the capture, use, or storage of CO2 (Tapia et al., 2018). There are three main categories within CCUS: carbon capture, carbon utilization, and carbon storage.

With the advancement of CCUS technologies, TxDOT requested a review of technologies that can be considered to decrease the energy consumption and/or carbon footprint of TxDOT construction and transportation projects. Therefore, the objective of this research project is to conduct a review of current technologies and to investigate possible technologies that can be implemented within TxDOT procedures and infrastructure.

1.1 Report Organization

An overview of the report organization is depicted in Figure 1.

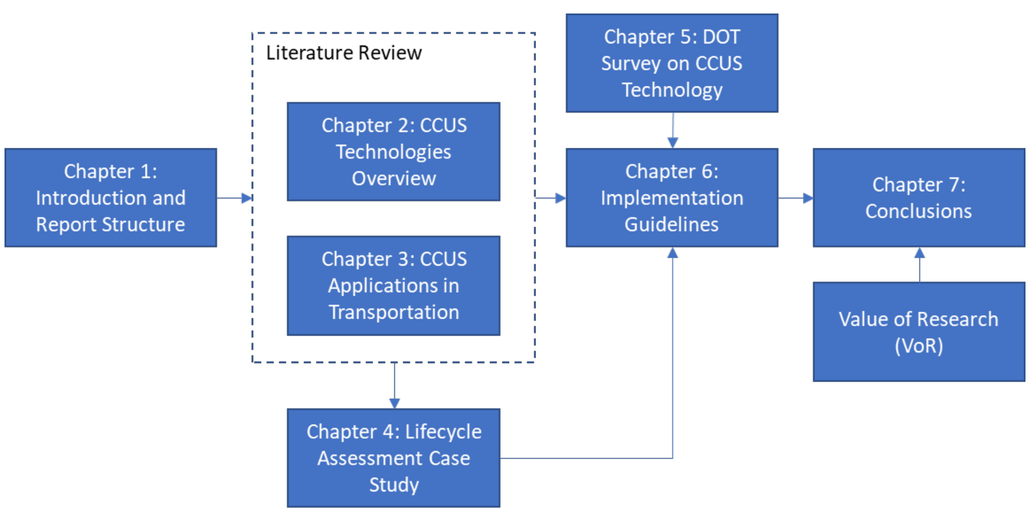


Figure 1: Report Organization for CCUS Synthesis

Chapter 1 presents a brief introduction to the research report, including background, report structure, and a disclaimer on the approach taken for the research.

Chapter 2 presents a literature review of existing CCUS technologies, especially those with high Technology Readiness Levels (TRL) and for which there are existing case studies. In this task, the team reviewed different processes related to carbon capture, carbon utilization, carbon storage, and by-products from CCUS processes. The team also reviewed the by-products produced from carbon capture processes and investigated how these by-products can be utilized in existing processes. The focus of this review is across industries and sectors.

Chapter 3 provides a review of CCUS technologies implemented in transportation infrastructure projects to assess their potential feasibility for future TxDOT projects. The aim of this review is to identify potential CCUS technologies that TxDOT can use to lower the embodied energy or carbon footprint of its projects.

Chapter 4 presents a case study to explore select CCUS alternatives for an ongoing highway project (I-35 CapEx South Project in Austin, TX). A high-level lifecycle assessment is used to compare baseline carbon emissions against 5 different CCUS alternatives (e.g., concrete-based CCUS technologies and right-of-way-based CCUS technologies).

Chapter 5 provides a summary of a national survey conducted by the project team to solicit feedback from DOT stakeholders on the current state of CCUS and adoption for project implementation.

Chapter 6 presents implementation guidelines that stem from major conclusions found in the literature review (Chapters 2 and 3) and the lifecycle assessment (Chapter 4). This chapter is also the direct output of Product 1 "Guidelines for Implementing Carbon Capture, Utilization and Storage (CCUS) Technologies on TxDOT Projects"

Chapter 7 provides a brief set of conclusions from the report, including a Value of Research (VoR) statement.

1.2 Disclaimer

It is important to highlight the following items with respect to this review:

- No federal law requires state DOTs to mitigate CO_2 for transportation projects.
- Limits exist on how federal and state transportation dollars can be used.
- Federal policy and funding may change.

Chapter 2. Overview of CCUS Technologies

Carbon capture is the process of capturing ambient or industrially produced carbon dioxide to decrease the emissions and concentration of carbon dioxide in Earth's atmosphere. Current technologies that accomplish this goal are based on five different methods: absorption, adsorption, chemical looping, membrane separation, and cryogenic processes. From these methods, different processes were developed to capture carbon in various industries and applications.

There are two main approaches for capturing carbon: direct carbon capture and indirect carbon capture. Direct carbon capture techniques directly remove carbon dioxide from the atmosphere or from point sources, such as exhaust gas. The most common direct carbon capture methods are pre-combustion capture, post-combustion capture, oxy-fuel combustion capture, direct air capture. Common indirect carbon capture methods are soil and farming practices, afforestation-reforestation, enhanced weathering, and bioenergy with carbon capture.

2.1 Direct Carbon Capture

2.1.1 Pre-Combustion Capture

Pre-combustion capture is the process of intercepting carbon dioxide emissions prior to the combustion of fossil fuels. This process involves converting the solid or liquid fossil fuel into a synthesis gas, comprised of carbon monoxide and hydrogen gas, through gasification. This "syngas" is then exposed to steam and a catalyst that turns carbon monoxide into carbon dioxide and hydrogen gas. From this, the carbon dioxide is separated from the gas mixture, where it is processed and compressed for storage.

The typical technologies used to separate the carbon dioxide from the gas mixture are physical absorption, chemical absorption, and pressure swing adsorption. Physical and chemical absorption employ physical solvents and amine-based solvents, respectively, to selectively absorb carbon dioxide from the syngas. These technologies are mature and commercially available; however, they have a high energy requirement for solvent regeneration, have a large equipment size and space requirement, and are susceptible to solvent degradation and impurities. Pressure swing adsorption uses solid adsorbents to capture carbon dioxide at high pressures. This process has a lower selectivity than previous methods, but it has moderate energy consumption for adsorbent regeneration and has compact equipment compared to physical or chemical absorption.

New technologies are under development, including ionic liquids, membrane-based separation, and metal-organic frameworks. Ionic liquids are solvents that have a low vapor pressure and a high carbon absorption capacity, so they have the potential to improve the efficiency of the capture process with a reduced energy requirement for solvent regeneration. Ionic liquids have reduced equipment size and space requirements and are less susceptible to degradation and impurities. Membranes, based on advanced materials such as polymers, ceramics, or metal composites, can selectively separate carbon dioxide from syngas with low energy consumption and compact equipment size. However, there are potential challenges with membrane stability and durability. Metal-organic frameworks are a class of porous materials that can be designed to selectively adsorb carbon dioxide. Since metal-organic frameworks have the properties of high surface area and tunable pore size, these materials have the potential to perform better than traditional adsorbents, but there are challenges with scalability, stability and cost-effectiveness.

Pre-combustion carbon capture technologies are versatile and can be applied to various industries, including chemical production, energy-intensive industries such as steel production, and fuel production plants. When integrated into production processes, this technology can capture up to 90% of emitted carbon dioxide in a relatively concentrated carbon dioxide stream (C2ES, n.d.). This will lead to industries producing less carbon emissions and more sustainable production.

The challenges associated with this process are the high cost of initial capital and operation. The complex gasification process and carbon dioxide capture process require significant amounts of energy, which lowers the overall efficiency rate, is difficult to scale, and can produce harmful by-products such as particulate matter, sulfur compounds, and nitrogen oxides.

2.1.2 Post-Combustion Capture

Post-combustion capture is the process of removing carbon dioxide from exhaust fumes produced by combusting fossil fuels, most commonly within a power generation or industrial plant (Sahu et al., 2023). Combusting fossil fuels produces exhaust gases that contain CO_2, water vapor, and other pollutants. To capture the carbon dioxide, this flue gas is cooled to a suitable temperature, using a heat exchanger or cooling tower, and is passed through a carbon capture unit. In this unit, the CO_2 is separated from the other components of the flue gas using various methods. From this, the carbon dioxide is released through a regeneration process to produce a concentrated CO_2 stream.

Post-combustion capture uses physical and chemical absorption such as pre-combustion capture with the main difference being the gas composition before separation. Pre-combustion capture deals with a gas mixture of hydrogen and carbon dioxide, while post-combustion capture is concerned with flue gas that is comprised of carbon dioxide and nitrogen. There are also some technologies being developed or already deployed in pre-combustion capture processes. These technologies include advanced solvents, membrane-based separation, and solid sorbents.

Calcium looping is a technology being developed that is unique to post-combustion capture. The most advanced calcium looping technology makes use of CaO as a solid sorbent in a configuration consisting of a carbonator and a calciner. CO_2 captured in the carbonator (as flue gas) reacts with the CaO particles from the calciner to form carbonated solids. These carbonated solids are then heated to create a stream of CO_2 rich gas, to be captured, and CaO, to be recycled in the calcium looping process.

Although post-combustion uses similar technologies to pre-combustion carbon capture, post-combustion carbon capture tends to be more advantageous over pre-combustion since the technology can be retrofitted to existing power plants (as opposed to being integrated in the design of new industrial processes). However, significant energy is required in the carbon capture and regeneration processes (Raganati & Ammendola, 2024). This causes post-combustion to have higher operating costs and a lower overall performance (lower carbon dioxide capture efficiency) (Darabkhani et al., 2023). To achieve high levels of carbon capture, this technology may need larger-scale equipment and infrastructure as well as regular replacements of the solvents.

There is a relatively new process of capturing carbon dioxide that is similar to the process of post-combustion capture called mobile carbon capture (MCC) (Kim et al., 2024). It is performed through a capture device mounted directly on carbon-emitting vehicles. The device contains systems that can adsorb, desorb, compress, and store carbon as engine exhaust gas flows through it. When tested on a semi-truck, this device was found to capture about 40% of emitted carbon dioxide (Voice & Hamad, 2022). This process is still in the research and development stage (i.e., has a low technology readiness level), so there are some limitations to the existing technology. These limitations include equipment weight, energy use, and installation space of the equipment. The main research focuses for the development of MCC devices are minimizing and optimizing energy consumption, simplifying the equipment, and making the system lighter.

2.1.3 Oxy-Fuel Combustion Capture

Oxy-fuel combustion is the process of burning fossil fuels in oxygen gas instead of ambient/non-treated air, resulting in a flue gas comprised primarily of carbon dioxide. Since carbon dioxide is produced directly from the combustion process, the need for carbon dioxide separation processes is eliminated, simplifying the carbon capture process and allowing for more efficient and cost-effective separation.

To generate the supply of oxygen in which to combust fossil fuels, air separation units are used to separate oxygen from other gases in ambient air (e.g., nitrogen), typically using cryogenic distillation or membrane separation. When combusted in oxygen, the resulting flue gas is primarily composed of carbon dioxide, water vapor, and small amounts of pollutants. This flue gas is then cooled and treated to remove the water vapor and pollutants, respectively.

The main components of the oxy-fuel combustion carbon capture process (the air separation unit, flue gas treatment, water vapor separation, and oxy-fuel combustion) are in the research and development phase to discover new techniques to make the process more efficient with less energy consumption. Air separation techniques are being tested to find a way to produce oxygen with lower energy requirements. Ion transport membranes (ITM), an advanced material that can transport oxygen ions across membranes, are being developed to perform ITM-based air separation to improve overall efficiency.

Oxy-fuel combustion technologies have potential applications in various industries, such as coal power plants, natural gas plants, or oil power plants. These technologies can be retrofitted into existing power plants or be integrated into new plants. Oxy-fuel combustion technologies can capture up to 95% of CO_2 due to the high concentration of CO_2 in the flue gas (Zhao et al., 2023); however, it does come with many disadvantages. The air separation process used to produce oxygen requires significant energy, the technology used for the oxy-fuel combustion process, such as the air separation unit, can be capital-intensive, and managing nitrogen and other by-products can be complex and resource-intensive. This process also contains some concerns for safety. Using high-purity oxygen increases the risk of fires and explosions, so these concerns require additional investment in proper safety measures and operational protocols.

2.1.4 Chemical Looping Capture

Chemical looping capture (CLC) uses air and fuel reactors to facilitate the combustion of fuels while preventing direct contact between the air and fuel. This process uses a solid oxygen carrier, typically a metal oxide, to transfer oxygen from the air reactor to the fuel reactor. This process simplifies the carbon capture process while increasing the efficiency of gas separation, since it results in separate streams of nitrogen and carbon dioxide (Finney et al., 2019a).

To complete this process, the solid oxygen carrier is exposed to the air stream in the air reactor causing the oxygen carrier to be oxidized and releases heat along with a stream of nitrogen and spent oxygen carrier particles. These solid oxygen carrier particles are mixed with the fuel stream in which the oxygen in the oxygen carrier reacts with the fuel to facilitate combustion. From the combustion process, heat, carbon dioxide, water vapor, and reduced oxygen carrier particles are produced. The reduced oxygen carrier particles are transferred back to the air reactor to be re-oxidized and recycled while the carbon dioxide and water vapor are separated.

Chemical looping capture can be used in coal, natural gas, and oil power plants like other combustion related capture processes; however, it also has high compatibility with biomass and bioenergy plants (Zhao et al., 2023). CLC has a lower energy penalty due to the lack of energy-intensive gas separation processes leading to higher efficiency for power generation and industrial processes. It also eliminates the need for additional separation and capture steps due to the natural consequence of separated nitrogen and carbon dioxide. Despite these benefits, oxygen carrier stability, reactor design, and system integration continue to contribute to the inability to scale-up CLC technology. Oxygen carriers need to have a long lifetime, high reactivity, and low cost. This, along with technology that can manage the attrition and loss of oxygen carrier, prove difficult to develop. The installation of CLC technologies, such as reactors, is prohibiting the integration of CLC in industry plants due to the high capital cost (Zhao et al., 2023).

2.1.5 Direct Air Capture

Direct Air Capture (DAC) refers to technology that directly captures carbon dioxide from the ambient air rather than capturing it from polluting point sources such as industrial plants and processes. Instead of attempting to reduce the amount of carbon dioxide being emitted, the goal of this process is to reduce the pre-existing concentration of carbon dioxide in the atmosphere. This process has some potential use in the transportation and agriculture industries as it does not need to be installed on industrial facilities. The overall process of direct air capture is to have DAC units pull in air from the atmosphere. This air will then be filtered using sorbents or solvents that selectively capture carbon dioxide. After being captured, the filter will go through a process to release the carbon dioxide and compress it for storage or transport.

There are five main categories of DAC processes: liquid scrubbing, solid sorbent, electrochemical, membrane, and cryogenic. Within these categories, there are nine distinct approaches to direct air capture: hydroxide-carbonate DAC, amine-scrubbing DAC, temperature-vacuum swing adsorption (TVSA), moisture-swing-adsorption (MSA), electrolysis DAC, electrodialysis DAC, redox-active based DAC, membrane DAC, and cryogenic DAC (Bouaboula et al., 2024). This is shown in Figure 2.

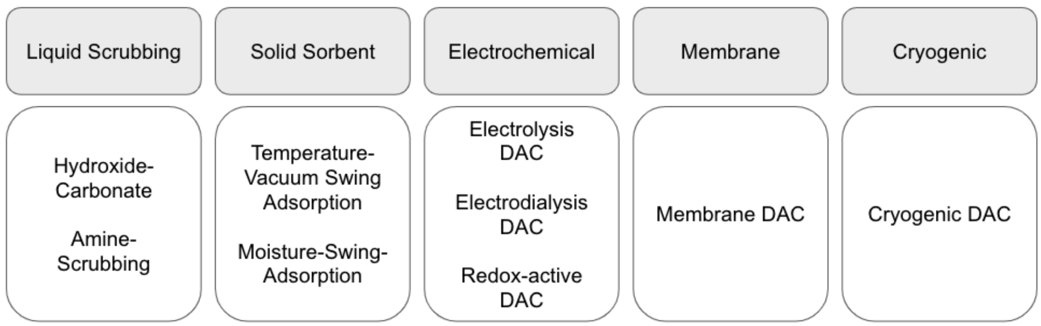


Figure 2. Categories of Direct Air Capture Processes.

In liquid scrubbing, hydroxide-carbonate and amine-scrubbing are the two processes that fall under this category. Liquid scrubbing processes refer to mixing liquid solvents with ambient air to form a CO_2 rich solution. This solution is then heated to regenerate the solvent, in preparation for repeating the cycle, and to release the CO_2 to compact for storage or transport (this compacting involves converting the CO_2 released during the regeneration phase into a denser form for efficient transport or storage).

In solid sorbent processes, temperature-vacuum swing adsorption (TVSA) and moisture swing adsorption (MSA), solid sorbents are used to selectively adsorb carbon dioxide. Ambient air passes through a bed of solid sorbent. Upon contact, the carbon dioxide will attach to the sorbent while the remaining air will be released back into the atmosphere. When the sorbent bed becomes saturated, the material is heated, for TVSA, or humidified, for MSA, to release the captured CO_2 for storage or transport.

For the electrochemical processes, which include electrolysis, electrodialysis, and redox-active, the process is similar to liquid scrubbing methods; however, the process utilizes electrochemical techniques to decrease the energy requirement.

Instead of using heat to release captured carbon dioxide and regenerate the solvents, electrochemical techniques are used (Bouaboula et al., 2024; Sodiq et al., 2023).

Membrane technology for capturing carbon from concentrated gas streams is showing promise, but it is yet to be adopted in direct air capture systems. There are some engineering studies and proof-of-concepts, but this technology has not yet been commercialized. Cryogenic direct air capture technology takes advantage of carbon dioxide's condensation and de-sublimation temperatures to separate it from other gases. In this process, air is pre-cooled as it passes through a heat exchanger. It is cooled again upon entering the deposition chamber using a cryogenic cycle. At this point, the carbon dioxide sinks to the bottom and is successfully separated from the other gases. Table 1 summarizes the benefits and challenges to each process.

Table 1. Benefits and Challenges of Direct Air Capture Technologies.

DAC Process	Benefits	Challenges
Hydroxide-Carbonate	- Fast absorption kinetics in solvents - Easy accessibility of solvents - Solvents are stable in air - Solvents have low volatility and toxicity - Suitable for large scale operations - Uses mature, commercially proven equipment	- High regeneration temperature - Use of Air Separation Unit, increases energy requirement - High capital investment - Water losses through evaporation, especially in dry environments - Limited concentration of solvents which limits absorption capacity
Amine-Scrubbing	- Most industrially utilized system for reversible capture and release of CO_2 - Lower regeneration temperatures - High availability of solvents - Low cost - Strong binding forces - 87% capture rate	- Rarely suggested for direct air capture application - High water evaporation - Large land footprint - High regeneration energy requirement - High volatility and toxicity - Equipment corrosion
Temperature-Vacuum Swing Adsorption	- Lower capital cost compares to liquid scrubbing - Lower regeneration temperature - Higher capture capacity - Can utilize renewable resources for heat generation - Modular design, enables application in small scale settings	- Adsorption of water along with carbon dioxide, lowers adsorption capacity - Remaining air in CO_2 chamber, reduce purity of CO_2 - Thermal degradation, sorbent degrade over time - Higher maintenance and operational costs - Low CO_2 selectivity - Slow sorption kinetics

	- May produce water as by-product in areas with high relative humidity	
Moisture-Swing-Adsorption	- Lower energy requirement compared to other thermal-based approaches - Sorbent can be dried using ambient air	- High sensitivity to weather conditions, adsorption capacity depends on wind speeds and humidity levels - Substantial water loss when drying - Water must be deionized prior to usage in humidifying sorbent
Electrolysis	- Reduced regeneration energy required - Better performance control with adjustable voltage - Easy integration with renewable energy sources - High purity hydrogen gas as a by-product	- Lack maturity, in early stages of development - High energy requirement - Low CO_2 purity - Less economically viable
Electrodialysis	- Higher CO_2 purity than electrolysis - Possibility of combining multiple cells, leads to lower voltage and lower energy requirement	- Uses expensive membranes - Large ohmic losses and poor ionic conductivity - Released CO_2 can cause more cell resistance, current crowding, and heat generation
Redox-Active	- Simple operation - Lower energy requirements - Ability to scale up - Up to 100% CO_2 purity	- Highly sensitive to oxygen, hard to implement on a large scale - Utilizes toxic and expensive electrolytes - Slower kinetics of solid-redox carriers
Membrane	- Smaller footprint - Simpler operation - Scalability - No high-grade heat supply needed	- Significant thermodynamic requirements - Significant energy requirement for membrane permeation - Solutions to existing problems are expensive - Strong parametric sensitivity between membrane selectivity and permeability
Cryogenic	- High purity rate of CO_2, about 99.99% - High CO_2 recovery rate - Avoidance of toxic sorbents - Potential production of CO_2 in liquid state, great for storage and transport	- Energy intensive, less so in very cold climates - Deemed impractical for direct air capture systems - Water may interfere with the CO_2 purity - Water can cause operational issues in sublimation tank

Currently, the largest direct air capture facility has just begun operations in Heidi, Iceland. Climeworks has partnered with Carbfix to create Mammoth, the largest direct air capture and storage plant as of May 2024. This plant is designed to capture up to 36,000 tons of carbon dioxide each year (Climeworks, 2023). It houses 72 collector containers that draw in air from the atmosphere and filter the carbon dioxide from the ambient air. Once these filters are at capacity, the carbon dioxide is then concentrated and purified to start the storage process, which is performed by Carbfix, to be stored for over 10,000 years (Climeworks, 2024). Mammoth also saves on energy consumption by utilizing the abundant geothermal energy in Iceland. Climeworks partners with ON Power to gain the power needed to power the direct air capture process, which requires relatively low-temperature, around boiling water, heat.

While the details of the erection costs are not known to the public, there are details disclosed about the project previous to Mammoth. Orca, the sister plant to Mammoth, is the plant built previously in a similar geographic location. Orca is also located in Hellisheidi, Iceland, and it uses a similar process to capture carbon and store it in the rock formations of Iceland. Orca is about ten times smaller than Mammoth and captures about nine times less. To build, it cost Climeworks about $10-15 million, and it covers less than 20,000 square feet. It is unclear if mammoth is also ten times the size in terms of land coverage or if Mammoth was built taller than Orca.

2.2 Indirect Carbon Capture

2.2.1 Afforestation-Reforestation

Afforestation refers to establishing a forest in an area that previously had no tree coverage. One type of land being considered for future forest sites are abandoned mine lands and adjacent, affected areas. According to the U.S. General Accounting Office, there are about 80,000 to 250,000 abandoned mine lands in the United States, the majority of which have remained idle due to the concerns of safety and environmental impacts (EPA, 2012). Some benefits of afforestation include financial (revenues from timber products and tax incentives), and environmental (carbon storage, wildlife habitat enhancement, and air and water quality improvement). Some challenges of this method include low tree survival rates and high replacement costs. Some areas do not have the qualities necessary for afforestation, so attempting afforestation in these areas will cause investors to lose money.

Reforestation is the process of restoring and maintaining forests that have been damaged or destroyed. Before the industrial revolution, the concentration of carbon dioxide, methane, nitrous oxide, fluorinated and ozone-depleting substances in the atmosphere was at a relatively constant level, however afterwards, these levels skyrocketed. A major part of this was clearing forests more rapidly than carbon dioxide being produced could be naturally sequestered. As such, reestablishing forests in areas that were previously cleared is one approach to capture and sequester atmospheric carbon dioxide. Reforesting areas that were previously forests is advantageous over afforestation, because trees are more likely to survive leading to lower replacement costs.

It is also important to note that afforestation and reforestation can lead to net-negative emissions with proper maintenance, since atmospheric carbon dioxide is captured naturally in the plants' biomass and soil. It is estimated that forests can store an average of 2 to 2.5 gigatons of carbon per year (Santos et al., 2019). One challenge of these solutions is an increase in food prices as there is competition for land between agriculture and forestry. Afforestation also decreases the surface albedo, so this could raise the amount of radiation that is absorbed, increasing the temperature of the surface and lower boundary layer. However, it is also important to note that these natural carbon sinks are continuing to diminish.

2.2.2 Enhanced Weathering

Weathering is a natural cycle where rocks release calcium and magnesium as they erode. As these minerals are exposed to natural forms of carbon dioxide, such as carbonic acid and bicarbonate, they react to form new rocks such as calcium carbonate. This process is a natural way of sequestering carbon dioxide, but this process can take millions of years. Enhanced weathering speeds up this process through several processes that increase the rate at which rock combines with carbon. These processes include grinding rock (e.g., olivine or basalt), into fine particles to increase the contact rate and adding chemical catalysts or living organisms to speed up the chemical reaction (Jagoutz, 2024).

While enhanced weathering is a notable concept theoretically, it is not currently suitable in practice. Mining, grinding, and transporting rock is an energy-intensive process that relies on fossil fuels, so this process may create more carbon emissions than it removes (Jagoutz, 2024). This process also has a large land requirement to sequester a substantial amount of carbon dioxide. Another reason for its impracticality is how unpredictable the chemical reactions involving ground rock, natural soils, and seawater can be. There are studies that suggest that in certain situations, using enhanced weathering can either not work or add carbon dioxide and other pollutants to the atmosphere (Griffioen, 2017). The overall largest challenge is the cost. Enhanced weathering is more expensive than many other carbon capture technologies, and it is highly unlikely to be profitable without government incentives or policy.

In light of these challenges, there are limited projects using this method, but there is one company, UNDO, that specializes in nature-based technology with operations in the United Kingdom. UNDO crushes silicates, such as basalt and wollastonite, sourced from nearby quarries as a by-product from quarry operations (*Project: UNDO | Klimate*, 2024). UNDO then spreads these crushed silicates across agricultural lands using existing machinery to start the enhanced weathering process. This company claims that they have the potential to remove millions of tons of carbon dioxide; however, of the rock that has already been spread since 2023, about 64,000 tons of carbon dioxide will be removed (*Project: UNDO | Klimate*, 2024). Given the high cost of conducting enhanced rock weathering, UNDO relies on the support of individuals and businesses buying carbon offset credits. Another Irish company named Silicate has started trials of spreading crushed waste concrete through agricultural lands in Illinois to amend the soil pH.

In a 2023 study conducted by Wageningen University (te Pas et al., 2023), five potential silicates (crushed olivine minerals, crushed basalt rock, wollastonite, anorthite, and albite) were studied to evaluate their enhanced weathering potential. This study included the impact of silicates on soil quality and CO_2 sequestration by measuring the effects on leachate and inorganic and organic carbon budgets. While all alternatives were found to have improved soil quality and capture some CO_2, the main takeaways from this study were (1) wollastonite has high potential with the second highest CO_2 capture rates, (2) olivine has the highest CO_2 capture rates but is limited by Ni^{2+} leaching, (3) basalt, anorthite, and albite are highly suggested alternatives to olivine with limited Ni^{2+} leaching and potential for high CO_2 capture rates, and (4) albite has the added benefit of producing HCO_3^- concentrations similar to wollastonite (which acts as a long-term inorganic sink and contributes to ocean acidification management).

2.2.3 Bioenergy with Carbon Capture and Storage (BECCS)

Bioenergy with Carbon Capture and Storage, or BECCS, is one of the newest technologies for sequestering carbon from carbon-intensive industries. This process is the integration of bioenergy with pre-combustion, post-combustion, or oxyfuel combustion carbon capture processes to further reduce emissions from industrial processes (Finney et al., 2019b). Biomass is organic material that is produced in plants and animals that capture carbon dioxide from the atmosphere. This organic material exists in various forms, such as animal manure, agricultural residues, wood, vegetable oils and animal fats, and sewage. The bioenergy process starts with cultivating organic material to use as feedstock. This feedstock then undergoes one of two methods to transform into energy, combustion or conversion. Combustion is performed in tandem with one of the combustion-related carbon capture methods to capture the carbon dioxide released in the flue gas. This process is usually associated with using biomass to produce heat for electricity generation or other industrial applications. The conversion process turns biomass into gaseous or liquid fuels through fermentation. The most common fuel produced, bioethanol, omits the need for carbon capture technology as it results in a near-pure stream of carbon dioxide after the fermentation process.

Technology that utilizes biomass to produce energy or fuels is mature and commercially active; however, it is not as widespread as other CCUS technologies. There are notable advances in North America, Japan, and Europe, but as of 2019, there are five facilities and three planned projects that are operating. The largest facility using BECCS is the Illinois Industrial CCS facility, which produces ethanol from corn. This facility captures up to 1 MTPA of carbon dioxide from the fermentation process per year and stores it in the geological sites underneath the facility (Global CCS Institute, 2019).

2.3 Summary of CCUS Technologies

Table 2 summarizes the key attributes, benefits and challenges for each of the CCUS technologies reviewed in this section.

Table 2. Summary of CCUS Technologies with their Key Benefits and Challenges

Technology	Process Description	Technology Readiness Level (TRL)	Benefits	Challenges
Pre-Combustion Capture	Captures CO_2 before combustion by gasifying fuel into syngas, then separating CO_2 from the gas mixture using solvents or adsorption.	7-8	High CO_2 capture efficiency (up to 90%); applicable in various industries.	High cost and energy intensity; complex process; harmful by-products.
Post-Combustion Capture	Removes CO_2 from flue gas after combustion using solvents or adsorption.	3-4 (Ionic Liquid) 6-7 (Temperature Swing Adsorption)	Can be retrofitted to existing plants; high capture potential.	High operating costs; lower efficiency; large-scale equipment needed.

		8 (Amines in Power Plants)		
Oxy-Fuel Combustion	Burns fuel in oxygen, producing a concentrated CO_2 flue gas for easier capture.	5-6 (Gas Turbines) 6-7 (Power Plants)	High CO_2 capture efficiency (up to 95%); suitable for retrofitting or new builds.	High energy and capital costs; safety concerns due to pure oxygen use.
Chemical Looping Capture	Uses metal oxides as oxygen carriers in separate reactors for fuel oxidation, producing pure CO_2 and nitrogen streams.	6	High efficiency; avoids energy-intensive gas separation; compatible with biomass.	High capital costs; stability and cost of oxygen carriers; reactor design challenges.
Direct Air Capture (DAC)	Captures CO_2 from ambient air using sorbents, solvents, or membranes, and regenerates for storage or transport.	7	Removes atmospheric CO_2; independent of point sources; potential for net-negative emissions.	Energy-intensive; expensive; limited CO_2 concentration in air.
Enhanced Weathering	Accelerates natural rock weathering by grinding rocks (e.g., basalt) to capture CO_2 as carbonates.	3-4	Potential for long-term sequestratio n; nature-based solution.	Energy-intensive; high costs; unpredictable reactions; large land requirements.
Afforestation/ Reforestation	Planting trees to capture atmospheric CO_2 and sequester it in biomass and soil.	9	Nature-based solution; enhances biodiversity and ecosystem services.	Land-use conflicts; competition with agriculture; low tree survival in some areas.
BECCS (Bioenergy with CCS)	Combines biomass energy production with carbon capture (e.g., fermentation or combustion).	5-6 (In Power Plants)	Uses renewable feedstocks; potential for net-negative emissions;	High costs; limited biomass availability; land-use and

			mature technology for fermentation.	water resource impacts.
Cryogenic Capture	Cools air to condense CO_2 for separation.	4-5	High CO_2 purity (99.99%); avoids toxic sorbents; potential for liquid CO_2 production.	Energy-intensive; not widely practical for direct air capture; water interference in cryogenic systems.

Each of the reviewed technologies from this chapter are assigned an expected Technology Readiness Level (TRL) as shown in Table 3. To aid with this assessment, the authors of this report synthesize the overall literature, and rely on the following source which conducted their own assessment of carbon capture technology readiness: (Bukar & Asif, 2024).

For clarity, we employ the following definition of TRLs:

- TRL 1 - Basic Principles Observed: Basic principles are observed and reported.
- TRL 2 - Technology Concept Formulated: Concept and/or approach is formulated.
- TRL 3 - Experimental Proof of Concept: Analytical and experimental critical function and/or characteristic proof-of-concept.
- TRL 4 - Component Validation: Component and/or breadboard validation in laboratory environment.
- TRL 5 - System/Subsystem Validation in Relevant Environment: System/subsystem validation in relevant environment.
- TRL 6 - System/Subsystem Demonstration in Relevant Environment: System/subsystem demonstration in a relevant environment.
- TRL 7 - System Demonstration in Operational Environment: System prototype demonstration in an operational environment.
- TRL 8 - System Qualified and Ready for Use: System qualified and ready for use.
- TRL 9 - System Proven in Operational Use: Actual system proven through successful mission operations.

Table 3. Technology Readiness of Carbon Capture Technologies

Technology	Technology Readiness Level	Justification
Pre-Combustion (Natural Gas Processing)	7	Demonstrated in pilot-scale or commercial plants (e.g., in Integrated Gasification Combined Cycle (IGCC) systems). Near full-scale deployment but not widely applied.
Pre-Combustion (Pressure Swing Adsorption)	7-8	Mature technology with full commercial implementation and widespread use in industrial applications
Pre-/Post-Combustion (Vacuum Swing Adsorption)	7-8	VSA systems have been demonstrated at pilot scales for CO_2 capture in industrial settings and power plants.
Post Combustion (Amines in Power Plants)	8	Widely demonstrated at commercial scales in industrial settings. (E.g., Boundary Dam and Petra Nova projects).
Post Combustion (Ionic Liquid)	3-4	While research on ionic liquids for CO_2 capture is extensive, most studies are still in the laboratory phase, investigating the properties of different ionic liquids and their effectiveness in capturing CO_2 under controlled conditions.
Post-Combustion (Temperature Swing Adsorption)	6-7	Prototype development stage, with lab-scale demonstrations and some pilot-scale testing completed, but not yet fully commercialized at a large scale
Post-Combustion (Calcium Looping)	6	It has been tested at a pilot plant scale and demonstrated in relevant environments, with several pilot projects conducted across various applications like coal-fired power plants and cement manufacturing
Oxy-Fuel Combustion (in Gas Turbines)	5-6	Several pilot plants are currently operating, testing the technology in a larger scale and demonstrating key functionalities.
Oxy-Fuel Combustion (in Coal Power Plants)	6-7	Pilot-scale demonstrations of oxy-fuel combustion systems have been conducted in coal-fired power plants. Pre-commercial demonstration projects have also been implemented, such as the Schwarze Pumpe facility in Germany.
Chemical Looping Combustion	6	Several pilot plants are currently operating, testing the technology in a larger scale and demonstrating key functionalities.
Direct Air Capture	7	Notable example of Direct Air Capture for facility in Iceland.

Enhanced Weathering	3-4	Laboratory studies have confirmed the fundamental chemical reactions involved in enhanced weathering, such as the accelerated reaction between ground minerals (e.g., basalt, olivine) and CO_2 to form stable carbonates
BECCS (in Power Plants)	5-6	BECCS is at a demonstration stage with a working prototype and significant validation through pilot projects
Afforestation/Reforestation	9	-
Cryogenic Capture	4-5	Some field tests or pilot projects have been conducted to assess the process in operational conditions, such as in industrial facilities with high CO_2 emissions.

2.4 Carbon Storage, Utilization and By-Products

Along with carbon capture technologies, finding ways to store the captured carbon is an active focus of research and implementation for carbon solutions. By finding storage solutions, entities are permanently removing carbon from the atmosphere and the carbon cycle and decreasing the existing concentration of carbon dioxide. Some of the main storage solutions include geological, mineral carbonation, terrestrial, and ocean storage.

2.4.1 Geological Storage

Geological storage focuses on finding geological locations that have a high potential to store carbon dioxide permanently and safely (note: finding suitable geological features is challenging since they are not ubiquitous globally). Desirable characteristics for these geological sites include highly porous and permeable rock formations with a large storage capacity. The most common types of rock formations are saline aquifers and depleted oil and gas reserves, while less common ones include non-mineable coal seams, basalt formations, and sub-seafloor sediments.

Saline aquifers are porous rock formations filled with highly saline water. These aquifers are widespread and have a large storage capacity. When captured carbon is injected into these formations, the carbon dioxide dissolves in the saline water or gets trapped in the pore spaces. Depleted oil and gas reserves have the ability to trap hydrocarbons for long periods of time. Infrastructure already exists for injecting carbon dioxide into these reserves. This process also contributes to enhanced oil recovery and enhanced gas recovery.

Non-mineable coal seams are characterized by being too deep, thin, or uneconomical to mine coal. When injecting carbon dioxide, the carbon dioxide is absorbed into the coal matrix. This matrix is filled with methane, so the carbon dioxide displaces the methane. This methane can be harvested and used as a fuel source with a process called Enhanced Coal Bed Methane recovery. Basalt formations are another less commonly used formation. They are rich in calcium, magnesium, and iron silicate minerals. Carbon dioxide reacts with these minerals to form stable carbonates.

The process of injecting captured carbon into these geological storage sites mainly employs an injection well, a drill specifically made to inject carbon dioxide underground. The captured carbon is compressed into a supercritical state to allow for easier transportation and injection. This injection site is then monitored to ensure safety and effectiveness, how well the carbon dioxide stays in place and doesn't leak, of storage. These monitored elements include pressure, temperature, and carbon movement.

Geological storage has some potential economic opportunities. Creating plants to store carbon in geological formations can create jobs and economic opportunities in development, operation, and maintenance. This method has also been recommended to be adapted by developing countries for large economic growth as well as decreasing CO_2 emissions. The challenges to developing geological storage plants are the expense and environmental concerns. Constructing and operating injection wells and monitoring systems is costly. The main public concerns with utilizing geological formations to store captured carbon are safety, permanence, leakage, and induced seismicity (as well as perceived environmental risks and long-term safety).

This method is commercially available with many companies partnering with a capture facility to store captured carbon. Carbfix is a carbon storage company that has partnered with Climeworks on their recent Mammoth project. Mammoth is Climeworks' largest operational direct air capture plant that opened in May 2024. Carbfix designed an absorption column to integrate into the Mammoth plant that selectively dissolves the carbon dioxide in water prior to the injection process (Carbfix, 2024). This creates carbonated water that is then injected into reactive rock formations, such as basalt. This carbonated water reacts with the rock and forms stone underground, permanently storing the carbon.

2.4.2 Mineral Carbonation Storage

Mineral carbonation or carbon mineralization is the process of converting captured carbon into a solid and stable carbonate material. These carbonates offer long-term storage with minimal risks of leakage due to their chemically stable and environmentally benign nature. Mineral carbonation is a natural process that occurs slowly, so this offers an acceleration of this process using methods such as in-situ mineralization, ex-situ mineralization, electrochemical mineralization, microbial mineralization and supercritical carbon dioxide mineralization.

In-situ mineralization includes injecting captured carbon into a suitable rock formation, such as peridotite and basalt. The mineral in the rock reacts with the captured carbon to form carbonates. Ex-situ mineralization involves mining and crushing minerals to react with captured carbon within a controlled environment, such as reactors and storage facilities. This allows for more control over the reactions but the overall process –mining, processing, transportation— is energy intensive.

Electrochemical mineralization is the mineralization of captured carbon using an electrochemical process to accelerate mineralization. Through one of the electrochemical processes, an electric current is applied to convert the carbon dioxide more rapidly and selectively. Microbial mineralization employs microorganisms that can change the environment or precipitate carbonate materials to promote mineralization. Supercritical carbon dioxide mineralization is a process that dissolves minerals more effectively; however, the process involves converting carbon dioxide into a supercritical state, so it is more energy-intensive.

2.4.3 Terrestrial Storage

Terrestrial storage involves storing captured carbon in terrestrial ecosystems, such as forests, grasslands, and wetlands, and it relies on the growth and storage capacity of biomass. Since this process relies on the growth and storage of vegetation, the main focuses of terrestrial storage are to enhance the amount of biomass within an area and maximize the capacity of carbon dioxide biomass can capture. One way to do this is land use management. Common practices used are afforestation, reforestation, agroforestry, conservation agriculture, wetland restoration, and grassland management.

Afforestation and reforestation are talked about in more depth in section 2.2.1. Agroforestry refers to integrating trees into established agricultural lands, which can lead to greater carbon sequestration, biodiversity, and crop yields as well as less soil erosion. Conservation agriculture is the practice of minimizing soil disturbance as well as the maintenance of a permanent soil cover. This promotes biodiversity and enhances natural biological processes that can lead to increased water and nutrient use efficiency as well as store more carbon within the soil (United Nations, n.d.). The wetlands are full of carbon rich plants that aid in carbon sequestration. Restoring these wetlands will not only provide benefits such as providing habitat for endangered species and flood control, but it will aid in climate mitigation. Grasslands over about 25% of Earth's land surface with 20% to 25% of these grasslands being degraded, partially due to soil carbon losses. Although restoration is a slow process, restoring these grasslands can potentially sequester three gigaton of carbon per year (Todd Ontl, n.d.).

Some uncommon practices include using biochar in soil (to enhance soil fertility and increase carbon storage, restoring and conserving coastal ecosystems) and increasing green spaces in urban areas (to sequester carbon dioxide, improve air quality, and decrease urban heat islands). These land management practices can be cost effective since many active projects use carbon credits as a funding source. One example of a privately owned company that funds land use practices is Terrapass. This company allows individuals and businesses to buy carbon offset credits that go towards funding community projects that reduce CO_2 gas emissions, such as land restoration projects or renewable energy projects.

Despite these benefits, there are still challenges associated with terrestrial storage. The carbon that is stored as biomass runs the risk of being released into the atmosphere due to land use changes or land disruptions (e.g., natural disasters). These plots of land are also in competition with food production, urban development, and other practices that require land use. Terrestrial storage is also not scalable to meet all the carbon dioxide storage demands, especially long-term demands. Creating systems that can monitor and verify the effectiveness of this storage method is also challenging since there is no process that currently exists. Current research involves improving efficiency and effectiveness of terrestrial storage, increasing biochar production, enhancing soil amendments, and enhancing the production of genetically modified crops to increase the amount of carbon that can be stored in terrestrial biomes.

2.4.4 Ocean Storage

Carbon dioxide can be stored in the ocean as a dissolved gas, a liquid, or as solid hydrates. Captured carbon is stored deep in the ocean where it can dissolve over time and will exist in the ocean for longer. Since this process is already naturally occurring (e.g., marine life needs dissolved carbon dioxide to survive), this storage accelerates the process of ocean absorption. The advantages of storing carbon dioxide in the ocean include large storage capacity, no land use requirement, and several existing implementation methods that already exist. The main concerns for storing captured carbon in the ocean are the potential ecological impacts, ocean acidification, disruptions to marine ecosystems, and the long-term effectiveness.

There are many methods that are currently being explored for ocean carbon storage including ocean fertilization, artificial upwelling, ocean alkalinity enhancement, marine permaculture cultivation, and injection. Ocean fertilization refers to adding nutrients, such as iron, to the ocean surface to stimulate the growth of phytoplankton. Phytoplankton is targeted since it absorbs carbon dioxide from the environment as it grows. Also, when it dies, the biomass will continue to store carbon dioxide and sink to the ocean floor where it will be absorbed. Artificial upwelling refers to an engineered system that pumps cold, nutrient-rich water from the bottom of the ocean to the surface. Enhancing the ocean alkalinity enhances the ocean's ability to absorb and store carbon dioxide. To enhance the alkalinity, alkaline materials, such as crushed limestone or olivine, are added to the ocean's surface. Maintaining the marine permaculture by cultivating seaweed and other marine plants adds another method to store carbon dioxide in marine biomass. These plants can be used to store carbon dioxide for long periods of time or can be gathered to be used as a bioenergy source.

With these methods, there is the advantage of enhancing ocean productivity due to the increase in dissolved carbon dioxide. However, the environmental challenges are not fully understood, especially long term. It is possible that the oceans globally may benefit from ocean storage, but at the local sites of injection could experience a drop in the pH levels that would disrupt the local ecosystems, especially for the organisms that cannot emigrate. This can be avoided by disseminating the carbon dioxide during the disintegration process, but this adds another cost factor to the procedure.

2.4.5 Carbon Dioxide Hydrates

The most common carbon storage method in use is injection into geological storage sites. However, since it has significant challenges, such as leakage, migration, groundwater contamination, and seismic risks, hydrates are considered an alternative to geological storage. Gas hydrates are solid compounds made of water molecules that form a crystalline structure, through hydrogen bonding around carbon dioxide under low temperature and mid-range pressure conditions (Zheng et al., 2020). These hydrates have a higher mechanical strength than ice and a thermal conductivity comparable to water, so it is a stable form of storage for carbon dioxide. These hydrates are also denser than seawater, so they have the potential to be stored on sea beds, which have thermodynamically stable conditions to prevent degradation, with appropriate sealing methods to prevent migration.

One key technical challenge with hydrates is the formation time is slow; it can take hours to days to form with chemical promotion and mechanical agitation. A study (Bhati et al., 2024) was conducted to improve this, and it found a new technique, using magnesium as a catalyst, that can grow hydrates quickly and eliminates the need for chemical usage. This technology also works with seawater, so it does not rely on a desalination process to create fresh water. With this new technique, hydrates can be easier to implement and have the potential to be used for mass-scale carbon storage.

2.4.6 Utilization of Captured Carbon Dioxide

Carbon utilization refers to the usage of captured carbon dioxide in a variety of applications, either directly or indirectly (chemically altered or transformed). Ideally, the utilization of carbon dioxide will contribute to a circular carbon economy (a framework that applies the principles of a circular economy to managing carbon emissions, aiming to minimize the amount of carbon that needs to be managed by reducing, reusing, recycling, and actively removing excess carbon from the atmosphere and storing it), decrease the reliance on nonrenewable resources, and decrease overall costs. In many cases, facilities produce carbon dioxide as a by-product, so reusing the carbon dioxide, instead of fossil fuels, would eventually lead to lower costs.

One major area of interest is reusing captured CO_2 to manufacture products as they can offset costs related to CCUS and make CCUS economically profitable without external financial incentives. The products manufactured using CO_2 can be divided into different functional chemical groups (Zhao et al., 2023): elemental carbons (graphite, graphene, carbon nanotubes), hydrocarbons (different types of fuel), alcohols and ethers (propanol, methanol, butanol, etc.), sugars and starches (glucose, sorbitol, etc.), aldehyde and ketones (formaldehyde, acetone, etc.), acid, ester, and acetates (formic acid, acetic acid, etc.), and carbonates (sodium carbonate, calcium carbonate). One particular reference (Leclerc et al., 2024) provides an overview of the carbon by-products, arranging them into a tree structure. Of these, hydrocarbons are a large focus, since they can contribute to a circular carbon economy that will reduce fossil fuel demand. Technologies are being developed to convert CO_2 into other products that can absorb the high volume of captured CO_2. Technologies that are currently being deployed on a large scale can convert captured CO_2 into methane and methanol. Since methane and methanol have potential as fuel sources, there has been significant investment in improving the technology readiness levels of these technologies.

The success of the different avenues of CO_2-based products would depend on the investment and operating cost, social acceptability, CO_2 utilization rate, technology readiness level, energy requirements and the overall sustainability of the production process. Avenues that could utilize captured carbon directly include medical uses, fire suppression and concrete curing; however, the demand of carbon dioxide for these uses are not (yet) large enough to justify using captured carbon dioxide. Chauvy and Weireld (2020) performed a thorough review of the different CO_2 utilization pathways from the European perspective and rated the feasibility based on different criteria. This analysis yielded the most mature CO_2 utilization pathways are for methanol, methane and algae, whereas the least mature are syngas, and polycarbonates.

One final aspect to note is the reuse of by-products from pre-combustion capture. For this process, the main products created are carbon dioxide and hydrogen gas. Since carbon dioxide is the targeted product, hydrogen gas is the by-product of this carbon capture method. Hydrogen is used in many industrial processes, such as refining petroleum, treating metals, producing fertilizers, processing foods, rocket fuel, and fuel cells, and it has the possibility to replace natural gas or indirectly store energy for power generation.

2.4.7 Summary of Carbon Storage, Utilization, and By-Products

Each of the reviewed technologies in this section are assigned an expected Technology Readiness Level (please refer to Section 2.3 for definitions of TRLs) as shown in Table 4. To aid with this assessment, the authors of this report synthesize the overall literature, and provide additional references in the 'justification' column as applicable.

Table 4. Technology Readiness Level of Carbon Storage Technologies

Storage Technology	Technology Readiness Level	Justification
Geological Storage (Coal Seams Storage)	3-4	Field testing studies, for instance the one by (Yang et al., 2023)
Geological Storage (Basalt & Ultramafic Rock Storage)	5-6	The Carbfix project in Iceland has demonstrated the successful injection of large quantities of CO_2 into basalt formations,

		providing valuable data on mineralization rates and storage capacity.
Geological Storage (Saline Formations)	9	This is considered to be a mature, deployed technology as per (Ang et al., 2022)
Geological Storage (Depleted Oil & Gas Field Storage)	7-8	Due to its widespread use in Enhanced Oil Recovery (EOR) practices, storing carbon in depleted oil and gas reservoirs is considered a mature technology as per (Raza et al., 2018).
Mineral Carbonation	4-5	Small-scale testing has been done as per (Neeraj & Yadav, 2020)
Ocean Storage	3-4	Laboratory and small-scale field experiments have been conducted to evaluate the behavior of liquid CO_2 injected at depth (e.g., dissolution rates, plume dynamics).
Carbon Dioxide Hydrates	3-4	Limited to preliminary studies (Bhati et al., 2024).

Table 5 summarizes the key attributes, benefits and challenges for each of the CCUS technologies reviewed in this section.

Table 5. Summary of Carbon Storage, Utilization and By-Products

Technology	Description	Benefits	Challenges
Geological Storage	Captures CO_2 in porous rock formations like saline aquifers, depleted oil/gas fields, coal seams, basalt, or sub-seafloor sediments.	High storage potential; existing infrastructure for some sites (e.g., oil fields); economic opportunities (e.g., enhanced oil recovery).	Leakage risks, seismic concerns, high costs, public acceptance.
Mineral Carbonation	Converts CO_2 into stable carbonates via in-situ or ex-situ processes involving reactive rocks like basalt or peridotite.	Permanent and leakage-proof storage; environmentally benign products.	Energy-intensive processes; slow reaction rates; high costs for mining, grinding, and transport.
Terrestrial Storage	Stores CO_2 in biomass through forests, grasslands, wetlands, and soil management practices (e.g., afforestation, agroforestry, biochar).	Nature-based; supports biodiversity; low cost; uses carbon credits.	Competition with land for agriculture; risk of carbon re-release (e.g., due to wildfires, land-use changes).
Ocean Storage	Stores CO_2 as dissolved gas, liquid, or solid hydrates in deep oceans through processes like	Large storage capacity; no land use required.	Ocean acidification; ecological disruptions; high costs; uncertain long-term effects.

	fertilization, alkalinity enhancement, and injection.		
Carbon Dioxide Hydrates	Converts CO_2 into hydrates under low temperature and moderate pressure for storage in stable seabed environments.	Dense and stable form; reduces leakage risk.	Slow formation rates; high energy demand for process initiation.
Depleted Oil & Gas Field Storage	Stores CO_2 in reservoirs previously used for hydrocarbons; often coupled with Enhanced Oil Recovery (EOR).	Well-understood and widely deployed; utilizes existing infrastructure.	Leakage risks; limited availability of suitable reservoirs.
Saline Aquifers	Stores CO_2 in porous rock saturated with saltwater, where CO_2 dissolves or gets trapped in pore spaces.	Widely available; large storage capacity; proven technology.	Monitoring and ensuring long-term stability; risk of groundwater contamination.
Basalt & Ultramafic Rocks	Reacts CO_2 with basalt formations to form stable carbonate minerals (e.g., as demonstrated in Carbfix projects).	Permanent storage; natural chemical stability.	Limited suitable sites; high initial costs.

2.4.8 Conclusions

Eight types of carbon capture processes were reviewed: pre-combustion capture, post-combustion capture, oxy-fuel combustion, chemical looping capture, direct air capture, afforestation and reforestation, enhanced weathering, and bioenergy with carbon capture and storage (BECCS). This memorandum also reviewed different storage options (geological, carbon mineralization, terrestrial, and oceanic) and utilization processes.

Pre-combustion capture, mainly used within power and industry plants, captures carbon from fuels prior to the fossil fuel being combusted. Though pre-combustion capture technologies are mature and commercially available, these technologies require significant energy, sufficient space for large equipment, and high capital cost (since the technology cannot be integrated easily into existing plants). Post-combustion capture intercepts carbon emissions after fuels are combusted. Post-combustion technologies are advantageous because they can be retrofitted to existing combustion equipment; however, it requires significant energy which leads to higher operating costs and lower overall performance.

Oxy-fuel combustion is the process of using pure oxygen to combust fossil fuels leading to a simplified, more efficient, and cost-effective separation. This combustion process can be retrofitted to existing plants and can capture up to 95% of emitted carbon due to the high concentration of CO_2 in the flue gas. Chemical looping capture facilitates the combustion of fossil fuels while preventing direct contact between the air and fuel leading to natural separation of nitrogen and carbon dioxide. While proven at small scales, there are many issues preventing this technology from scaling up, such as oxygen carrier stability, reactor design and system integration. Direct air capture directly captures carbon dioxide from the atmosphere to reduce the existing concentration of carbon dioxide emitted. There are many large-scale projects around the world with Climeworks having the largest direct air capture facility.

Afforestation, the establishment of new forest, and reforestation, the re-establishment of previously existing forests, rely on biomass growth to sequester carbon from the atmosphere. While having many environmental and financial benefits, these processes have difficulty with tree survival rates and land competition. Enhanced weathering is a theoretical process that is currently not suitable or profitable in practice. This process involves carbon (in the forms of carbonic acid or bicarbonate) reacting with calcium and magnesium (released from eroded rock) to form calcium carbonate. Bioenergy with Carbon Capture and Storage is the combination of using biomass instead of fossil fuels and utilizing per-combustion, post-combustion, or oxy-fuel combustion to capture carbon released from combusting the biomass. This process has the advantage of relying on renewable resources; however, the technology is not as widespread as other carbon capture technology.

Carbon storage sites are being researched to ensure captured carbon will not leak back into the atmosphere. Geological storage sites are rock formations with highly porous and permeable rock that can store injected captured carbon for thousands of years. This process can also contribute to enhanced oil recovery, enhanced gas recovery, and enhanced coal bed methane recovery since the captured carbon can be stored in depleted oil and gas reserves and non-mineable coal seams. Mineral carbonation converts captured carbon into a solid and stable carbonate material that can be stored with minimal risks due to their chemically stable and environmentally benign nature. Terrestrial storage relies on the growth and storage capacity of biomass to capture and store carbon from the atmosphere. This proves difficult as land use is in competition with other important industries, such as food production. Ocean storage can store carbon in various ways, such as ocean fertilization, artificial upwelling, ocean alkalinity enhancement, marine permaculture cultivation, and injection. The long-term effects of these processes are still unknown and may cause damage to the local ecosystems.

There are many ways to utilize captured carbon to offset costs related to CCUS, especially to contribute to a circular carbon economy and reduce reliance on nonrenewable resources. These utilizations include elemental carbon products, hydrocarbons, alcohols and ethers, sugars and starches, aldehydes and ketones, acids, esters and acetates, carbonates, and non-transformations. The most technologically advanced carbon conversion processes include the creation of methanol and methane creation.

Chapter 3. Review of CCUS Technologies in the Transportation Sector

3.1 Introduction

As stated in EPA's yearly GHG emission studies from 2012 to 2022 (Environmental Protection Agency, 2025a), the transportation sector emitted the highest amount of greenhouse gases at an average 27.8% of U.S. CO_2 per year, as a result there is interest in identifying processes suitable for the transportation sector that can result in reducing embodied energy or carbon emissions via carbon capture, utilization, and storage (CCUS) technology. While much emphasis has been placed on lowering the embodied carbon footprint of concrete through decarbonization solutions such as replacing ordinary Portland cement with supplementary cementitious materials (SCMs), not many CCUS technologies have been identified to aid in decarbonizing the transportation sector to date.

CCUS technology is a relatively new topic of discussion for public transportation departments, and TxDOT has not conducted any comprehensive studies on whether CCUS technologies can be deployed on projects. Therefore, the objective of this research project is to conduct a review of current technologies in the transportation sector and investigate possible technologies that TxDOT could consider. Recommendations on these technologies will be provided in a subsequent task (and are not the primary focus of this report, which is purely on providing a comprehensive literature review).

3.2 Material-focused CCUS Technologies

3.2.1 Concrete

3.1.1.1. Low Carbon Solutions

It is estimated that Portland cement concrete (PCC) is responsible for approximately 5-8% of global anthropogenic carbon emissions. As shown in Figure 3, the production of cement in Texas emits 5.6 MMT of CO_2 per year. As such, there is a large push for low-carbon PCC to be developed and integrated into existing construction systems. A key strategy for reducing the carbon footprint of PCC is to reduce the amount of clinker—the main reactive component in Portland cement—since the clinkering process is responsible for approximately 60% of cement manufacturing emissions. The most common approach to reducing clinker content is by incorporating supplementary cementitious materials (SCMs) into concrete (Althoey et al., 2023). However, with the shortage of conventional SCMs, various strategies have been explored at the level of the material to reduce the carbon footprint of the concrete (e.g., the use of decarbonated materials like limestone to replace cement clinker, increase carbon sequestration capacity of concrete, increase the use of recycled materials, etc.).

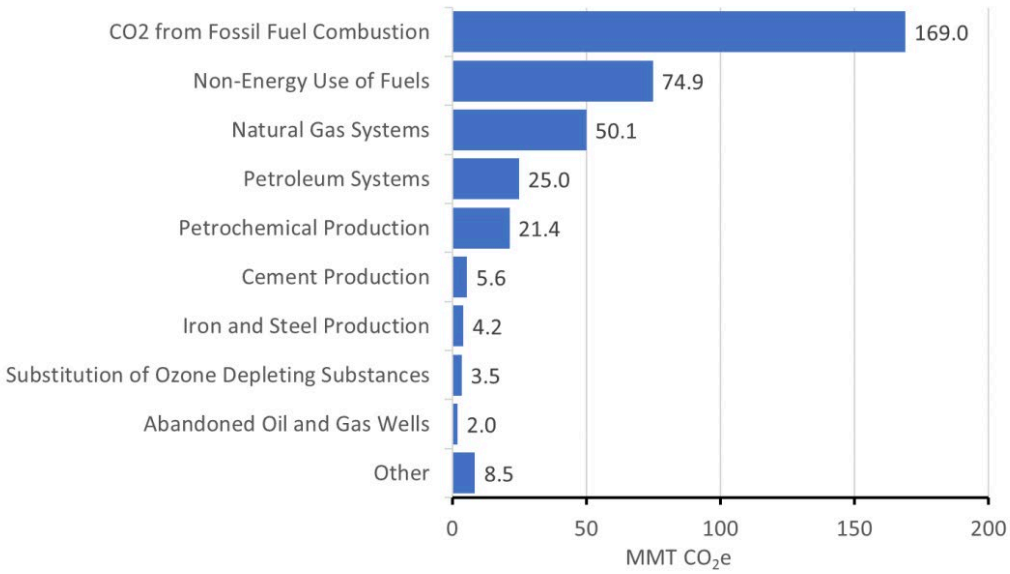


Figure 3: 2021 Texas GHG Emissions from the Industry Sector Source: (TCEQ 2024).

Low-carbon concrete solutions can be described as either a direct or indirect type of CCUS: the difference lies in how CO_2 is handled within a process, whether it is actively captured and used/stored (direct) or whether emissions are prevented/reduced at the source (indirect). To illustrate this, Table 6 provides an overview of three specific low-carbon cement solutions along with a high-level description and classification of types of CCUS.

Table 6: Overview of Low Carbon Cement Solutions and Assessment of Direct vs. Indirect Form of CCUS

Low-carbon Cement Solution	**Description**	**Primary CCUS mechanism (Direct vs. Indirect CCUS)**
Limestone Calcined Clay Cement (LC^3)	Reduces clinker demand, lowering overall CO_2 emissions from cement production	Direct – Offsets emissions by lowering clinker content in Portland cement.
Bio-Cement	Uses microorganisms to absorb and store CO_2 in calcium carbonate, making the cement	Direct – Actively captures and mineralizes CO_2 within the material itself.

	carbon-neutral or carbon-negative.	
Electric Recycled Cement	Repurposes cement from demolished concrete, avoiding the CO_2 emissions from new clinker production.	Indirect – Prevents new emissions but does not capture or store CO_2.

3.1.1.2. Limestone Calcined Clay Cement

One alternative cement solution is limestone calcined clay cement (LC^3), a cement blend consisting of limestone, calcined clay, gypsum, and clinker. Since clay reserves are abundant worldwide (unlike fly ash and slag), calcined clay is an attractive option as the main SCM in LC^3. This cement is being introduced around the world as a sustainable replacement for conventional cement and is being integrated into specification codes like the Indian Standard code and EU regulations.

LC^3-50, a popular LC^3 mix, contains 50% clinker (the remainder portion of the cement is 30% calcined clay, 15% limestone, 5% gypsum). However, LC^3 cements with even greater clinker replacements are emerging (with Ghana's Accra plant expecting to replace up to 70%) due to studies showing good performance in durability, resistance to chloride ingress and sulfate attack, and risk for alkali-silica reactions (due to lowered alkali content) (RMI, 2023). The high clinker replacement of the LC^3 systems results in lowering the embodied energy and cost of the cement. LC^3 is reported to be 25% more cost-effective than Portland cement and reduces carbon emissions by up to 40%.

With many companies around the world already adopting this cement alternative, the scalability of LC^3 production is proven to be possible. Cementos Argos in Rio Claro, Colombia completed its production line in early 2020, which can produce 450,000 tons of LC^3 per year. Compared to the apparent consumption of cement within the United States (which was about 120,000 metric tons in 2023), this cement production could keep up with the demand for a country's needs (assuming LC3 is a one-to-one replacement with Portland Cement). The main barriers to the implementation of LC^3 on a wide scale are (1) investing in new technology to retrofit into existing production lines and (2) revising codes and standards for LC^3 usage.

There are a few demonstration plants that are based in the United States—such as the Lebec Net Zero Project in Lebec, California-, but none are based in Texas yet. However, Summit Materials, Inc. is planning to build four demonstration plants in various locations in the United States, including Elmendorf, Texas and Sulphur

Springs, Texas. These plants, under the project name Low-Carbon Calcined Clay Cement Demonstration, will demonstrate how viable it is to replace limestone-based cement with clay-based products sourced from multiple geographic locations. This project has the potential to reduce a substantial number of emissions with a projection of 1.1 million metric tons of carbon emissions per year being prevented from entering the atmosphere.

3.1.1.3. Bio-Cement

Bio-cement is a cement alternative made from microorganisms and other organic materials. One type of bio-cement involves replacing traditional limestone with algae-grown limestone found in coccolithophores (microalgae that sequester and store carbon dioxide in mineral form) to offset carbon emissions. This method of using algae-grown limestone instead of limestone from quarries could result in a net carbon-neutral way to produce Portland cement. Coccolithophores produce the largest amount of calcium carbonate, and the blooms are enormous.

Coccolithophores can live in fresh or salt water and in cold or warm environments, so there is an abundance of these microalgae around the world, and cultivation is not suspected to be difficult. Limestone production is estimated to need about 1-2 million acres of open ponds, or 0.05% to 0.10% of the U.S. land area, to produce the cement needed in the U.S. To offset the costs of cultivation, these micro-algae also produce lipids, proteins, sugars, and carbohydrates that can be used to produce other commodities, such as biofuels, food, and cosmetics.

In construction practice, another form of bio-cement is a sustainable solution for concrete maintenance. The microorganism *B. pseudofirmus* has been found to induce calcium carbonate precipitation, so it can be used to produce a calcium carbonate-biofilm composite through bioprecipitation (Lors et al., 2019). This composite can be applied onto concrete surfaces as a preventative measure against deterioration as well as to repair micro-cracks in concrete undergoing pressure below 500kPa. Key considerations for this type of bio-cement are the delivery system of the nutrients needed for the bacteria, chemical compatibility between the nutrient systems and the concrete, using proper selection of the bacteria (e.g., using an alphaphile) (Basaran Bundur et al., 2015).

Bio-cement technology is still in the research stage, so it has a low Technology Readiness Level. It has been proven at a small scale, but scaling up affordably is a challenge. There is one company, Prometheus Materials, that uses algae within their masonry blocks. Prometheus Materials has found that using algae to produce masonry blocks made them lighter, reduced heat transmission, and had comparable compressive strength that achieved ASTM C129-22 and C90 performance requirements.

3.1.1.4. Electric Recycled Cement

Unlike other methods that focus on Portland cement replacement, alternative binders, or carbon capture systems, electric recycled cement focuses on recycling used concrete as a feedstock for an SCM. Electric recycled cement utilizes the decarbonated calcium in used concrete as a replacement for the flux needed to purify molten metal during the steel recycling cycle. This flux forms a slag SCM, which is exciting since ground granulated blast furnace slag is a commonly used SCM in concrete.

Electric recycled cement has many benefits, including similar composition, cost savings, and potential carbon emissions reduction. Since the composition of slag is similar to the clinker of Portland cement, its durability is comparable to that of Portland cement. Because it is developed in electric arc furnaces (which are electrically powered by renewable energy), creating electric recycled cement will not produce any carbon emissions compared to the large amount of carbon emitted during the process of making Portland cement. It is envisioned that this process will cost less than making new Portland cement clinker because it utilizes existing infrastructure and processes (Dunant et al., 2024).

There are several challenges that prevent this process from being at a large scale. When a large fraction of the flux in a conventional kiln is hydrated cement paste, the sulfates present increase the belite content of the re-clinkered cement while decreasing alite. This means that the cement will react more slowly than if the alite content were not reduced. These sulfates are also volatile, so it will condense in cooler parts of the kiln and cause operational difficulties. Other challenges also include: reliable renewable energy inputs and a developed supply chain; sourcing sufficient quantities of cement waste, and reaching temperatures required to produce cement.

Currently, this process has a low technology readiness level and a low adoption readiness level, since more evaluations are needed. However, there is one company, Cambridge Electric Cement (CEC), that is researching this process in more depth in their Cement 2 Zero Project (Cambridge Enterprise , 2024). In July 2024, CEC secured £2.25 million ($2.9 million USD) in pre-seeding funding to scale the technology. CEC hopes to produce 30 tons of recycled cement per hour. Electric recycled cement has the potential to reduce carbon emissions by 2 gigatons and have a production of one billion tons annually by 2050.

3.2.2 Carbon Storage and Utilization

Carbon storage is necessary for the carbon capture process. Being able to utilize or store carbon after its capture can free up space in carbon capture technology, contribute to a circular carbon economy, or replace conventional feedstocks in industrial processes. With respect to concrete, there is a lot of interest in utilizing concrete as a storage site for carbon since concrete can store carbon in the form of minerals. Additionally, concrete may benefit from these minerals as property enhancements.

3.1.1.5. Basalt

Basalt is a volcanic rock that forms when lava rich in magnesium and iron cools quickly. The magnesium (and calcium) in basalt can react with CO_2 to make minerals, such as calcite, dolomite, and magnesite (TGS, n.d.), that will permanently store carbon. Basalt is attractive for CCUS applications due to its carbon capture qualities as well as its abundance. There are various ways that basalt can be incorporated into concrete, including, but not limited to, as a fiber or SCM (Environment+Energy Leader, 2024).

Basalt fiber reinforced concrete (BFRC) utilizes basalt fibers instead of traditional fibers, such as steel or glass. In a study conducted by Al-Rousan et al. in 2023, the properties of BFRC were found to have the following properties:

- Basalt fibers decrease the slump of concrete.
- Basalt fibers have a minor impact on compressive strength.
- Basalt fibers increased the flexural and splitting tensile strength with the optimum amount of fiber content at 0.5%.
- Durability properties varied by study.
- BFRC had better resistance to high temperatures.

Another application is using basalt as an SCM. Basalt is categorized as a filled-pozzolanic SCM (Ponzi, 2021) since it presents low pozzolanic activity, a large inert fraction, and a very small particle size. Basalt powder has properties that make it an attractive SCM, such as increasing the material's resistance to CO_2 degradation (i.e., it has minimal reactivity to CO_2), low porosity, and suitable mechanical properties. From the study conducted by Ponzi et al. in 2021, having a low basalt powder content with a high water-to-solids ratio has potential for CCS applications.

3.1.1.6. Hempcrete

The main components of hempcrete are hemp shiv and a lime-based binder, such as natural hydraulic lime or ordinary Portland cement. Hempcrete (or hemp-lime concrete) is reported to store carbon through both carbonation and photosynthesis. Since hempcrete has lower strength relative to other construction materials and low thermal conductivity, it is mainly utilized as an insulation material or in masonry blocks (Arehart et al., 2020).

Hempcrete is of interest, because it has the potential to be carbon negative. Due to this increased interest, more than 30 states in the United States have started hemp agriculture (especially after the legalization of hemp agriculture in 2018). During the growth process, hemp plants will absorb carbon dioxide and store carbon. Along with this, hemp will aid in the storage of carbon in concrete further by gradually sequestering carbon dioxide from the atmosphere and converting it into calcium carbonate (Muhit et al., 2024).

Hempcrete also has the potential to be applied in highway and roadway construction. It can be a durable material that could cut costs and enhance long-term performance while sequestering carbon. Using hemp as a natural fiber can help with greener mixtures that are focused on less production and layout energy consumption, provide surface water attenuation, and reduce noise pollution. Embedding hemp as a fiber can increase the mechanical performance of these greener mixtures, which will be helpful as these greener mixtures are more prone to permanent deformations and have a shorter life span (Muhit et al., 2024).

3.1.1.7. Carbon Mineralization

Carbon mineralization is the process of converting captured carbon into a solid and stable mineral, such as carbonate, by reacting carbon with calcium or magnesium oxide. This is a natural process; however, this carbon sequestration technique accelerates the mineralization process. The resulting mineral can then be transported for storage or utilization purposes. Often, carbon is injected into underground rock formations (USGS, 2019), but there is also the idea of injecting carbon into concrete.

Using the idea of carbon mineralization, CarbonCure injects carbon into concrete with the purpose of reacting with calcium oxide to form calcium carbonates. CarbonCure utilizes captured carbon from various industrial plants. When the carbon is captured, it undergoes purification, and liquification and is injected into pressurized tanks to be transported to concrete production plants. This carbon is then injected into concrete during the mixing process where it mineralizes into solid carbonates.

This addition of carbon not only stores carbon within concrete, but it has also been found to enhance the compressive strength of concrete. Therefore, the concrete requires less cement to achieve a certain compressive strength (CarbonCure, 2021). This method can also contribute to a circular carbon economy as carbon dioxide can be captured from cement production plants and repurposed in concrete.

3.1.1.8. Notable Companies

Heidelberg Materials is developing a project called Brevik CCS (Brevik CCS, n.d.-a). This project was established to create a carbon capture process at Heidelberg Materials' cement plant in Brevik, Norway. This carbon capture technology would be the first full-scale carbon capture plant at a cement plant. In conjunction with this technology, Heidelberg Materials is planning to launch evoZero® to strive for net-zero emissions. The CCS plant was expected to be completed by the end of 2024 with the production of evoZero® starting at the beginning of 2025 (Brevik CCS, n.d.-b).

Fortera is developing a technology called ReCarb® with the first demonstration plant opening in Redding, California where it will capture 6,000 tons of carbon dioxide (Lecamwasam, 2024). This technology is expected to be able to be retrofitted onto existing cement facilities. In tandem with ReCarb®, Fortera will produce low-carbon cement called ReAct™ cement. ReCarb® technology takes the carbon released from the kilns, sends it back into the cement production process, and facilitates the reaction of the captured carbon and calcium oxide to create ReAct™ cement. ReAct™ cement acts as a partial Portland cement replacement with higher strength than Type 1L and higher flow than ordinary Portland cement (Fortera, n.d.).

3.3 Aggregates

Many carbon capture technologies within aggregates relate heavily to carbon sequestration or passive carbon capture. A relatively new approach to carbon sequestration is natural minerals that enhance the carbonation process or synthetic aggregates that can sequester CO_2. These materials that are considered include basalt, biochar, and recycled aggregate.

Basalt is considered a good candidate for an aggregate as it contributes longevity and durability to concrete mixes. Basalt can be weather resistant (low thermal expansion coefficient, low conduction, and low conductivity velocity), so it will last longer, and less frequent repairs and replacements are needed for structures (Aggregate resource Industries, n.d.). In a study conducted by Ikkurthi et al. in 2015, basalt was found to enhance the strength of a concrete mix more than limestone aggregate due to it being denser, more durable, higher workability, and absorbing less water.

Biochar is also being researched for use in concrete mixes as an aggregate. Biochar, whose raw materials are widely available and cost-effective to produce, is seen to be more advantageous for large-scale applications in the construction industry than previously studied adsorbents, such as zeolites and activated carbon (Liu et al., 2023). Biochar can be made into a composite aggregate, with waste materials such as crop waste, wood waste, and food waste, via cold bonding technology (which has low energy consumption). This contributes to biochar being carbon-neutral along with its ability to sequester carbon.

In a study conducted by Liu et al. in 2023, the increase of biochar incorporation into carbon capture artificial aggregates enhanced the carbon sequestration performance within the first 24 hours. In another study, biochar was processed into carbon-rich lightweight aggregates. The aggregate was found to reduce strength and decrease the elastic modulus of the concrete mixture; however, this mixture met the Eurocode 2 strength classes of C20/25 and C30/37. So, this mixture can be applied in areas where this type of concrete is used with less carbon emissions (Wyrzykowski et al., 2023).

Not only does biochar sequester carbon from the atmosphere and have a variety of benefits and uses, it is also the most mature BiCRS (biomass carbon removal and storage) technology. This results in biochar accounting for more than 90% of carbon credits in the carbon removal market (Early, 2023). Though the United Nations' Intergovernmental Panel on Climate Change states that biochar has the potential to contribute significantly impact on carbon mitigation, there are still uncertainties about the longevity of biochar technologies.

Recycled concrete aggregate (RCA) is a process already in production by many construction entities, including TxDOT (Texas Department of Transportation, n.d.). This process includes reclaiming concrete from construction waste and reusing it in new projects. Using RCA has many benefits related to carbon mitigation, but it also has been proven to improve the mechanical properties of concrete mixes (FHWA, 2022).

While this process is not new, Blue Planet has found technology that increases the properties of traditional RCA. Blue Planet uses mineralization technology that uses CO_2 as a feedstock to create carbon-negative aggregate. They produce two different types of aggregate products, $CaCO_3$ aggregate and upcycled recycled concrete aggregate. $CaCO_3$ is a synthetic limestone that contains 44% of sequestered CO_2. Upcycled aggregate from Blue Planet goes through a reformation step that results in their upcycled aggregate being well indurated and harder than the traditional recycled aggregate (Blue Planet Systems, n.d.).

3.4 Asphalt

Asphalt concrete is one of the major materials used for road construction, with the top layer of paving surface being asphalt concrete for more than 90% of roadways in the USA. Although roughly 5% of asphalt concrete by mass is asphalt bitumen and the rest is aggregate, approximately 94% of the CO_2 emission from the materials perspective of asphalt concrete originates from the virgin asphalt binder (Shacat et al., 2024). Thus, the key pathways to decarbonize asphalt concrete involve both asphalt binder and aggregates, out of which aggregates have been discussed in the previous section.

The different ways to reduce the CO_2 emissions associated with asphalt bitumen in asphalt concrete include 1) reducing the quantity of bitumen in asphalt concrete, 2) improving recycling of existing asphalt binder, and 3) manufacturing virgin binder with a lower carbon footprint (Wu et al., 2024).

Incorporating recycled materials, such as reclaimed asphalt pavement (RAP) or waste polymers can significantly reduce the need for virgin materials and lower GHG emissions. RAP has been effectively used in asphalt concrete and with the help of different asphalt rejuvenators, it is common to replace up to 30-50% of virgin binder in asphalt concrete. In some cases, with the help of the correct rejuvenator in the appropriate amount (Behnood, 2019), RAP can replace up to 100% of the virgin binder (Wu et al., 2022).

One of the main sources of CO_2 emissions from asphalt pavement construction involves energy usage during construction, which includes heating the asphalt binder to reduce its viscosity and mixing it with aggregate to manufacture the commonly used Hot Mix Asphalt. Different Warm Mix Asphalt (WMA) additives such as different waxes, polymers, and surfactants are routinely used to decrease the heating temperature. Cold Mix Asphalt (CMA) contains emulsified or cutback asphalt binders that can be used without heating and have a lower CO_2 emission than HMA - however their lower initial strength development often makes them unsuitable for large-scale pavement construction.

The main pathway to reduce the CO_2 footprint associated with virgin petroleum-based asphalt binder is bio-based alternatives. Different companies are actively working on bio-based alternatives to traditional petroleum asphalt, though large-scale commercial adoption remains in progress. Avello Bioenergy is investigating both the economic benefits and carbon sequestration potential of its patented bioasphalt binder. Similarly, a Dutch chemical company manufactures lignin-based bioasphalt, and constructed the first major roadway using it (Vels, 2021). Among the legacy oil producers, Shell manufactures bio-based binders (called Shell Carbon Sink Asphalt), and it can sequester 6 mt of CO_2 into each kilometer of road surface (Reid, 2022). Case studies using Shell Carbon Sink Asphalt binder have already been performed in the UK and France. These bio-based options can potentially reduce CO_2 gas emissions by 30% to 60% compared to conventional petroleum-based asphalt, highlighting bio-oil's promise as a viable substitute for petroleum-based bitumen (Van Roijen et al., 2025).

3.5 Steel

Iron and steel are critical materials for transportation infrastructure and the third most abundant man-made materials. Production generally involves fossil fuels to achieve a high processing temperature (>1500 °C), and coke is used to reduce the iron in the iron ore. The iron and steel industry contributes to 2.9 Gt CO_2 yearly emissions globally.

Steel can be recycled efficiently, with steel production from scrap utilizing only one-eighth of the energy required for steel production from iron ore. Further, an electric arc furnace (EAF) can recycle steel from scrap, which does not generate CO_2 emissions associated with fossil fuel, assuming sufficient green electricity is available. According to the American Iron and Steel Institute, approximately 70% of US steel were produced using the electric arc furnace approach. Although many countries are abandoning using blast furnaces to make virgin steel, globally, 70% of steel is still produced from iron ore using the blast furnace method (American Iron and Steel Institute, n.d.). Newer technologies such as hydrogen-based direct reduced iron (DRI) that replaces coke in blast furnaces hold the key to deep decarbonization of steel production. DRI was first scaled up in Europe by SSAB using their HYBRIT technology (SSAB, n.d.). Recently, DOE has funded $500M for a DRI-capable plant to Cleveland-Cliffs Steel Corporation (U.S. Department of Energy, n.d.).

CCUS is one of the key technologies for decarbonizing the steel industry. Blast furnace flue gas has a relatively high amount of CO_2 (22%), CO (22%), and H2 (5%) (De Ras et al., 2019), which makes it a good candidate for synthetic fuel production. British Steel in the UK is currently performing a pilot study using their FluReFin technology to implement this idea. ADNOC and Masdar currently have operational CCUS solutions associated with a steel plant where the blast furnace gas will be used for oil recovery operations. Arcelor Mittal Texas, Nucor Steel, and Indiana Burns Harbor Capture plan to commission CCUS solutions that integrate with steel plants in the USA. However, they are all in the advanced planning stage and not operational yet (Nicholas & Basirat, 2024). Other pathways for CCUS in the steel industry involve using blast furnace flue gas to carbonate EAF slag (a by-product of steel recycling) for manufacturing supplementary cementitious materials. Cocoon Carbon in the UK is working on upscaling this technology (Cocoon, n.d.).

3.6 Soil Stabilization

Soil stabilization is often performed for new pavement construction for two main reasons: (1) to improve the elastic properties of the underlying soil (this can allow a pavement design with a lower thickness of the pavement layers reducing cost and CO_2 footprint of construction), and (2) to reduce soil moisture sensitivity and minimize frost-heave damage (which is particularly important for expansive soils).

Soil stabilization is often performed with cementitious materials such as Portland cement, fly ash, ground granulated blast furnace slag (GGBFS), lime, and cement kiln dust. The CO_2 footprint of the soil stabilization process can mainly be attributed to the soil stabilization process chosen and the quantity of materials required. The CO_2 footprint mitigation strategies of Portland cement production have already been discussed before and fly ash as well as GGBFS are industrial by-products with minimal direct CO_2 emissions associated with them. As a result, in this section, we will consider the decarbonization of lime production.

Lime is generally produced by limestone calcination with a CO_2 footprint of 1.0 to 1.5 tCO_2/t lime depending on the type of kiln used (Simoni, 2022). Three major technologies have recently been developed and being scaled up that can decarbonize lime production – 1) electrochemical production of lime from calcium carbonate and other calcium-containing sources (company – Sublime Systems) (Ellis, 2019), 2) acid-based leaching of calcium silicate rocks for manufacturing lime (company – Brimstone), and 3) chemical reaction between limestone or gypsum and sodium hydroxide to form lime (company – earth4Earth) (Hanein, 2021). Sublime and Brimstone are based in the USA and plan to use lime production further for Portland cement production. They are already building pilot plants with funding from the DOE. Earth4Earth on the other hand, is a company based in the UK and China planning to utilize decarbonized lime for compressed earth block production. Recently, a Zero Carbon Lime (ZeroCAL) process has been proposed where limestone is converted to lime without any direct CO_2 emissions through an aqueous flow-electrolysis/pH-swing process. It should be noted that all the companies focusing on decarbonized lime production are currently planning to use the lime produced for cement or brick production for a higher value-addition instead of selling lime to the open market (Leão, 2024).

When soil stabilization is required for road construction, multiple materials should be evaluated to determine the dosage required for strength development and the CO_2 footprint of those materials. In this way, the CO_2 footprint of soil stabilization can be minimized. Furthermore, if a material is used with almost zero carbon footprint for soil stabilization (e.g., electrochemically synthesized lime or cement), the soil stabilization may even be carbon negative as the added calcium carbonates over time.

3.7 Transportation Sub-sector CCUS Technologies

3.7.1 Highway/Roadway System

In many highway and roadway systems, there are right-of-ways (ROWs) that can be utilized to increase the amount of carbon sequestration. One way is to cover ROW with basalt (Dacey, 2021). Basalt can be introduced to soil in order to improve various qualities, such as carbon dioxide storage, drainage, and acidity level. Along with soil improvements, basalt will naturally sequester carbon and store it as a mineral. One idea presented was to add basalt dust to soil, so the surface area of basalt that will interact with carbon increases (Goll et al., 2021). The challenge to this method is the impact on air quality and the potential health risk of local travelers breathing in the dust.

Studies have been done to explore the effect of silicate minerals on weathering potential on soil. In one study, five silicates (crushed olivine minerals, crushed basalt rock, wollastonite, anorthite, and albite) were assessed for their weathering potential on soil (te Pas et al., 2023). The study found that all materials improved soil quality and sequestered some carbon dioxide:

- Wollastonite demonstrated high potential, achieving the second-highest CO_2 capture rates.
- Olivine captured the most CO_2 but suffered from limitations due to nickel (Ni_2+) leaching.

- Basalt, anorthite, and albite emerged as highly recommended alternatives to olivine, offering limited nickel leaching while maintaining strong CO_2 capture potential.
- Albite provided an additional advantage by producing bicarbonate (HCO_3) concentrations comparable to wollastonite, serving as a long-term inorganic carbon sink and helping address ocean acidification.

While basalt specifically was found to be highly recommended, there are some cases where negative outcomes can occur. In cases where the soil is acidic (note: this is likely not the case for Texas), there may be a negligible effect of carbon sequestration (Holden et al., 2024). On a more serious note, depending on the composition of basalt, there is a chance to leach heavy metals into the ground (heavy metals emerging from natural geological processes or anthropogenic activities for instance) (Wang et al., 2020), which indicates that analyzing the composition of basalt before use on ROW is important.

Carbon emissions from highway/roadway use are approximately 80% of transportation GHG emissions (EPA, 2025b). As an attempt to apply carbon capture technology to mitigate these emissions, mobile carbon capture has been in development. Aramco has been developing technology that can be used on vehicles to capture carbon emissions from the exhaust before the carbon is released. Since 2010, they have developed prototypes for various vehicles and have successfully captured some amounts of carbon. Along with Aramco, there have been other startup companies, like Remora Carbon, that have been designing their version of mobile carbon capture devices. Remora Carbon has claimed that mobile carbon capture has the potential to make semi-trucks carbon-negative when acting in tandem with carbon-neutral fuel sources (Michigan Manufacturers Association, 2021).

3.7.2 Railways

Railway infrastructure construction requires considerable amounts of steel (rail lines and train carriages), aggregates (ballast), and concrete (bridges, tunnels, rail ties), and their corresponding decarbonization pathways have been discussed in the materials section.

One primary source of CO_2 emissions from the railway sector is fossil fuel-based locomotives. The railways in the USA consist mostly of freight-based low-volume railroads with diesel locomotives, which contribute to 35 Mt CO_2 emissions annually (Elgowainy et al. 2018). Deploying overhead line equipment may not be economical in the USA because of the low-traffic railroads, and thus, researchers are exploring using hydrogen-powered and battery-powered trains.

Battery-powered trains have existed since the late 1800s, but recently have gained attention because of the current focus on reducing CO_2 emissions. Recently, Caltrans has procured one battery-equipped electric multiple unit train (BEMU) (Caltrain, 2023). Metra in Chicago has procured 16 battery-powered trainsets using a $169.3 million federal Congestion Mitigation and Air Quality Improvement (CMAQ) grant (Metra, 2024). The major concern regarding battery-powered trains is their range. However, using a box car with a ~240 km range is sufficient to save the US freight sector $94 billion over the next 20 years after accounting for reduced CO_2 emissions and air pollution.

Hydrogen-powered trains are relatively recent compared to battery-powered trains. In the US, Amtrak California has ordered up to 29 hydrogen trainsets from Stadler (Fender, 2022). Caterpillar, BNSF, and Chevron have also formed a coalition to develop hydrogen-powered locomotives for freight service (Caterpillar, 2021). Even though hydrogen-powered railways and other transportation sectors can reduce the carbon footprint significantly, multiple challenges still exist regarding the availability and storage of green hydrogen at a reasonable cost. The current cost of hydrogen is more than ten times that of gasoline, and abundant chap renewable electricity is required to improve the cost-competitiveness of hydrogen technologies (EERE, 2024). Further, potential safety issues regarding storing and transporting hydrogen in high-pressured containers and pipes need to be addressed for large-scale adoption (Gandini et al. 2021).

In terms of direct onboard CCUS in the railway sector, the excess kinetic energy of trains can be utilized for DACC. A lot of kinetic energy is wasted when a train is required to slow down quickly. Most of the trains can convert forward momentum into energy generation to create a frictionless braking force on the train, called dynamic braking, to reduce the speed. The energy generated during dynamic braking is mostly converted into resistance heat and not utilized. In all-electric trains, often the energy stored during the dynamic braking is either supplied to the overhead grid, or utilized for the passenger carriage energy requirements, and this is called regenerative braking. However, in the USA, most of the trains are for moving freight and have a diesel-based locomotive, which has simple dynamic braking and not regenerative braking, as there is no pathway for the energy generated during the dynamic braking to be re-utilized. Recently, Bachmann et al. (2022) proposed using the energy from regenerative braking for direct air carbon capture (DACC). They envisioned using self-contained railcars with CO_2 direct capture systems (DAC car) that are supplied with CO_2 from locomotive emission mitigation (LEM car) with large intakes that connect with the slipstream of the train and collect CO_2-rich air from the diesel engine exhaust through a ramjet-type process. This technology can remove CO_2 at a lower cost than conventional DACC and can be scaled up to remove 2.9 Gt CO_2 by 2050.

3.7.3 Maritime

Marine transportation systems are generally fossil-fuel-based, generating about 2% of anthropogenic CO_2 emissions. Most of the shipping industry currently uses heavy fuel oil (HFO), especially in international water which generates higher amounts of CO_2, SOx, and NOx emissions compared to diesel-powered systems.

The major efforts in reducing CO_2 emissions from marine transportation systems currently focus on using alternative fuels such as ammonia, hydrogen, methanol, bio-LNG, hydrated vegetable oil, etc. However, deploying these technologies is still in the early stages because of on-board safety concerns, unavailability of sufficient production, and cost. The International Maritime Organization (IMO) has a target to reduce CO_2 emissions by 50% by 2050.

On-board CCUS solutions in any transportation sector suffer from the following challenges: 1) on-board space limitations, 2) extra fuel or energy consumption by the CCUS system, and 3) integration with existing machinery. Shipping vehicles are very large and thus have fewer space constraints compared to other modes of transportation and are a better platform for CCUS implementation technologies. Furthermore, the large area of a ship enables the on-board generation of renewable electricity from solar and wind energy, which can partially replace the extra energy requirement with CCUS technology.

Among different companies working on-board CCUS solutions, Seabound employs a second-generation carbon capture technology known as calcium looping, which effectively captures CO_2 from a ship's exhaust and transforms it into solid calcium carbonate pebbles (Seabound, n.d.). These pebbles can be readily offloaded at the port, offering a practical solution for managing captured CO_2, either through reuse in various applications or safe disposal. CarbonRidge is another company that uses modular reactors for separating CO_2 from the flu gas, which is then compressed and stored onboard (Carbon Ridge, Inc.). Hanwha Ocean is exploring the potential use of ammonia water to capture and store CO_2 emissions in mineral form safely (Hanwha Group, 2023).

3.7.4 Aviation

Aviation generates globally 950 Mt of CO_2 emissions per year. Airplanes have traditionally been powered by fossil fuels, and currently, the aviation industry is using sustainable aviation fuel (SAF) to reduce its carbon footprint, while also developing electricity-powered jets. On-board CCUS solutions are currently considered not practical in the aviation sector as the mass of the CCUS systems limits the payload capacity.

Implementing SAF usage in aviation is not challenging as it can be used in current commercial airplanes without any modifications in their engines when it is used as a 50% blend with conventional jet fuel. Recently, Virgin Atlantic carried out its first long-haul flight from London to New York on 100% SAF, consisting of 88% HEFA (Hydro-processed Esters and Fatty Acids) supplied by AirBP and 12% SAK (Synthetic Aromatic Kerosene) (Virgin Atlantic Airways Ltd., 2024). Currently, a major bottleneck in implementing SAF usage on a large scale is scaling up SAF production at a low cost. ASTM D7566 outlines seven ways of manufacturing SAF, but only two of them, HEFA and gasification with Fischer-Tropsh method, are being performed on a commercial scale (Martinez-Valencia et al., 2021). Most of the SAF production uses animal fat and wasted cooking oil as feedstock, that may not be available at a sufficient volume to supply the entire aviation industry. For example, among different major companies producing SAF, the annual production of Neste and World Energy produces about 0.5 Mt and 1 Mt of SAF annually, which is not significant compared to the roughly 350 Mt of aviation fuel demand.

Electric aircraft have existed since the early to mid-1900s, but the challenge associated with electric aircraft is the lower energy density of batteries compared to conventional fuels, which makes it challenging to develop large aircraft with a long-range and high payload capacity. Newer nickel-based batteries have a higher energy density than conventional batteries, and currently, Wright Electric in the USA is developing a 180-seater passenger jet with a roughly 550 km range for European airlines. Parallel hybrid-electric propulsion (HEP) system is also being developed as an in-between solution to electric propulsion and fossil fuel-derived propulsion, and it can potentially reduce CO_2 emissions by 13% for a 2000 km flight (Jiang et al., 2023). Though electric aircraft is feasible for low-range flights with a low payload capacity, currently no technology exists to replace long-haul international flights with electric aircraft.

3.7.5 Public Works

Many public works projects occurring within the United States involve utilizing the reforestation-afforestation technique to increase tree cover to increase the amount of carbon sequestered. Since urban areas experience higher temperatures than rural areas, many projects are planting trees within urban areas. Along with decreasing the urban heat effect, trees in rural areas also increase shade areas, reduce energy use (when near buildings), and improve air quality.

Not only does increasing trees in urban areas have environmental benefits, it also contributes to the walkability and aesthetics of a city. With more shady areas and attractive landscaping, local residents and tourists are more likely to walk longer distances than normal. Despite these benefits (along with more not discussed here), there are many challenges associated with increasing green spaces in urban areas. These challenges include policy and planning limits time available to plant trees, trees failing due to poor soil quality, artificial lighting affecting tree growth, monitoring and maintenance, and projects not having high importance.

One notable public works project that focused on reducing urban heat through reforestation-afforestation is in Boise, Idaho (USDA.gov, n.d.). The City of Boise partnered with local conservancies to implement their plan to plant one tree per household in an urban setting and one tree per resident in a local forest. The city also partnered with local nurseries to host events that gave residents free trees and gave residents a discount when buying a tree from these nurseries.

Since its implementation, this project has increased urban trees in Boise neighborhoods by over 15,000 and increased forest seedlings in Boise National Forest by over 149,000. Through a partnership with iTree Cooperative, this project is expected to have the following benefits over the next 50 years: 39.8 million pounds of carbon removed, 312,000 pounds of air pollutants removed, 47.4 million kWh of energy conserved, and 121 million gallons of stormwater captured and cleaned.

3.8 Case Studies of CCUS on Departments of Transportation (DOT) Infrastructure Projects

In this section, we focus specifically on case studies where CCUS has either been studied by, piloted or fully integrated into existing operations by departments of transportation (DOTs) across the United States or similar entities such as FHWA and AASHTO. Such case studies are organized chronologically.

3.8.1 FHWA Carbon Sequestration Pilot Program

The Federal Highway Administration (FHWA) established the Carbon Sequestration Pilot Program (CSPP) in 2008 to assess whether a roadside carbon sequestration effort through modified maintenance and management practices is appropriate and feasible for state Departments of Transportation (DOTs) when balanced against ecological and economic uncertainties (Earsom et al. 2010). The purpose of the pilot program was to:

- Estimate the amount of revenue that DOTs could earn if they implemented carbon sequestration using native vegetation (as well as extrapolating this to the national scale)
- Create decision support tools for DOTs to determine the efficacy of carbon sequestration programs.

This pilot project program involved a 4-year study by the New Mexico Department of Transportation which quantified the amount of atmospheric carbon that grasslands along highway ROW can sequester (Volpe, 2009). The anticipated outcome of this pilot was to inform DOTs that may be considering the implications of future climate legislation or that independently want to evaluate the cost-effectiveness of using National Highway System (NHS) right of way (ROW) to generate revenue from the sale of carbon credits, offset their own emissions, or meet statewide CO_2 emissions objectives.

This is the first thorough study to quantify the amount of state DOT-managed soft estate acres. The project team analyzed data from Minnesota and several other states to determine the amount of unpaved NHS ROW accessible for carbon sequestration. Distribution of common ROW dimensions and observed vegetation types was obtained by measuring ROW widths at random places across nine states on property maps. The types of land cover around the NHS were revealed by a later geographic information system (GIS) investigation of 1,000 randomly selected locations across the country (as shown in the figure below).

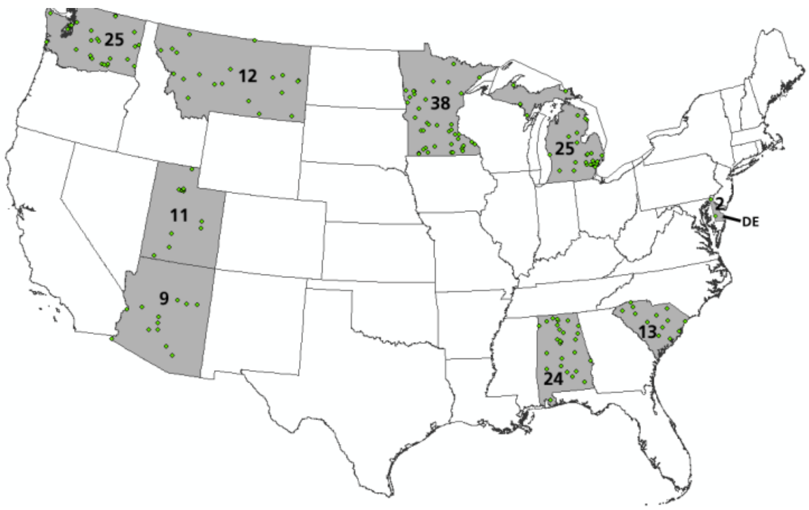


Figure 4: Number and Location of Random Sites used in FHWA Carbon Sequestration Pilot Study, Source: (Earsom et al. 2010)

According to the results, the NHS has roughly 5.05 million acres across the country, with a likely range of 1.4 to 8.7 million acres (Table 7). 68% of this (3.4 million acres) are unpaved. Research indicates that there has not been much of a shift in the land cover since 1992. According to the project team, the NHS ROW now sequesters around 91 million metric tons (MMT) of carbon in vegetation, and it does so at a rate of about 3.6 MMT annually, or 1.06 metric tons of carbon per acre annually. This is equivalent to about 2.6 million passenger cars' worth of carbon dioxide emissions each year. It is projected that the NHS ROW as a whole can sequester 425–680 MMT of carbon at its carbon equilibrium. Using a hypothetical carbon price of $20 per metric ton, this equates to a total potential value of $8.5 to $14 billion nationwide.

Table 7: Overview of National Highway Service Acreage

NHS ROW Acreage	U.S. Estimate (in 000s of acres)
Total	1,400—8,700, likely ~ 5,000
Unpaved	400—6,400, likely ~ 3,400
Grassland	200—2,800, likely ~ 2,200
Woody vegetation	30—460, likely ~ 360
Grassland/woody vegetation mix	36—600, likely ~ 470
Shrub	30—500, likely ~ 390

In addition to this report, the FHWA has created a Highway Carbon Sequestration Estimator to assist DOTs in determining the return on investment for various carbon sequestration scenarios. The decision-support tool enables transportation planners to develop estimates based on state-specific factors[1]. Even in the best-case scenario, revenue from biological carbon sequestration will vary substantially by state, depending on carbon prices, management strategies, and ecological diversity. However, considering the use of vegetation for living snow walls, landslide mitigation, and other forms of human infrastructure protection may, in certain situations, prove to be more cost-effective than standard engineering solutions, particularly when all expenses are included.

3.8.2 NCHRP Right-of-Way Carbon Sequestration and Biomass Generation

As a follow-up to the FHWA Carbon Sequestration Pilot Program, a *Guidebook for Designing and Managing Rights-of-Way for Carbon Sequestration and Biomass Generation* was developed under the National Cooperative Highway Research Program (NCHRP) by the American Association of State Highway and Transportation Officials (AASHTO) in cooperation with the Federal Highway Administration (Proudfoot et al. 2015). The guidebook explores the feasibility and benefits of using vegetation in ROW for carbon offsets or biomass feedstocks for bioenergy. It aims to help state Departments of Transportation (DOTs) make informed decisions about such projects.

The guidebook serves as a toolkit with the following features:

- Includes decision trees, financial modeling tools, and context-sensitive evaluation criteria to help DOTs assess project potential.
- How to assess the technical, financial, and environmental viability of ROW carbon sequestration.
- How to effectively engage stakeholders, support management decisions and facilitate long-term monitoring of projects.

The guidebook incorporates biomass generation into its scope, highlighting opportunities to reduce costs and produce renewable energy feedstocks from ROW vegetation. Notable business models for implementing carbon sequestration on ROW are outlined in Table 8. The guidebook also outlines the following key elements that need to be included as part of successful project planning and documentation: (a) identify and assemble project team, (b) define project activities

[1] Please note that the authors of this report could not locate an active link to this tool – it likely has become obsolete, replaced or embedded into other tools. An additional resource outlines the contents of this tool, specifically in Appendix A: https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/preliminary-investigations/reducing-greenhouse-gases-pi-a11y.pdf

and boundaries, (c) document project eligibility, (d) perform inventory and document baseline and project sequestration scenarios, (e) define monitoring plan, (f) prepare formal project documentation and (g) arrange project financing. An interesting aspect of arranging project financing relates to opportunities for carbon offset trading including the *Verified Carbon Standard*, *Climate Action Reserve,* and *American Carbon Registry* – all of which can be widely sold across (typically) for-profit corporations. In 2011 (when this guidebook was under development), the average price for a carbon offset in the voluntary market was about \$6 per tCO_2e. The default offset price in the Feasibility Toolkit is \$10 per tCO_2e.[2]

Table 8: Business Model Pathways to Implementing Right of Way Carbon Sequestration Projects

Type	Advantages	Disadvantages
Self-service model	Familiarity with the planting and managing of vegetation in the ROW. Do not need formal FHWA approval to change the management regime.	Lack of the agronomic or other expertise necessary to implement a particular production system or find suitable markets for harvested materials or carbon offsets. Lack of the necessary equipment to establish, maintain, and harvest vegetation or crops. The private sector might balk at the prospect of a DOT directly engaging in such an enterprise.
Contract for service model	DOT could rely on the expertise of qualified bidders for the establishment, harvest, and marketing of the agricultural crop. Avoid federal restrictions on accessing the ROW from the established grade of the highway.	DOT would not have direct control over the implementation of a particular production system.
Private entity leasing model	Relies on a proven pathway for developing non-highway uses of the ROW. Many DOTs have established procedures for developing and executing ROW property leases for other non-highway uses. Relies on the expertise and resources of the private entity.	The process for awarding lease agreements can be cumbersome and carries with it other restrictions that make it difficult to implement a project. Federal rules prohibit airspace agreements from allowing access to the leased land adjacent to the Interstate directly from the roadway. The restriction on accessing ROWs from Interstate highways may make leasing for growing biomass impractical.

3.8.3 California Department of Transportation

The California Department of Transportation (Caltrans) conducted research through their Division of Research, Innovation, and System Information in 2018 on the topic of CCUS. They released a preliminary exploratory research report from this project that provided an overview of the current status of carbon capture technologies in major transportation infrastructure projects. In order to finish major transportation infrastructure projects, Caltrans was interested in learning more about the commercial possibilities for using CCUS technologies as well as the

[2] In 2024, the average price of a carbon offset in the US voluntary market was around \$4.80 per ton according to https://carboncredits.com/carbon-credits-in-2024-what-to-expect-in-2025-and-beyond-250b-by-2050/#:~:text=Falling%20Prices%20In%202024%2C%20the%20average%20price,are%20seen%20as%20more%20reliable%20and%20long%2Dlasting.

availability of CCUS-based products. The effects of these materials on the environment, as well as how much they cost and perform in comparison to more conventional building materials, were also of interest. In order to compile this data, CTC & Associates examined both published and ongoing research, spoke with representatives of technology firms and concrete manufacturers, and surveyed various departments of transportation (DOTs) to find organizations that had firsthand knowledge of these materials being used in the field.

The study identified several companies and research groups developing CCUS-based materials, such as Blue Planet Ltd. and CarbonCure Technologies Inc. However, at that time, the project team found "no reported applications [of CCS] on large-scale transportation infrastructure projects in the field" (Wong 2018). They noted that more time was needed for commercially available CCUS-based materials to be used in larger quantities and with greater frequency in the field. Once larger-scale use was more common, they suggested that data could then be collected on the cost, performance and environmental impact of CCUS-based materials to allow for a comparison with traditional construction materials.

3.8.4 Hawaii Department of Transportation

In 2019, the Hawaii Department of Transportation (HDOT) partnered with a local concrete supplier (Island Ready-Mix Concrete) to test a sustainable concrete mix that would reduce the carbon footprint in road construction (HDOT, 2019). To test this new mix, HDOT poured 150 cubic yards of sustainable concrete next to 150 cubic yards of standard concrete on an access road. HDOT used this side-by-side layout to compare the mixes and determine specifications for future use of sustainable concrete.

Using waste carbon dioxide from Hawaii Gas, Island Ready-Mix Concrete partnered with CarbonCure to provide carbon-injected concrete for this project. CarbonCure chemically mineralizes waste carbon dioxide, so when carbon dioxide is injected into the concrete mix, the carbon dioxide gets trapped in the concrete in mineral form. Based on the final specifications, carbon-injected concrete has the potential to reduce embodied carbon by 25 pounds per cubic yard (CarbonCure, 2019). With approximately 21,000 cubic yards of concrete required for a mile of pavement, the HDOT demonstration project will prevent 1,500 pounds of carbon dioxide emissions—equivalent to offsetting the emissions from 1,600 miles of highway driving. Apart from a few webpage articles, there is not a lot of published content regarding the overall success or findings from the pilot study conducted by HDOT.

3.8.5 Minnesota Department of Transportation (MnDOT)

The Minnesota Department of Transportation (MnDOT), in collaboration with Carbon Upcycling Technologies and the National Road Research Alliance (NRRA), conducted a multi-year pilot project (using a research contract of $150,000 from the NRRA pooled fund with Iowa State University) to evaluate the performance of low-carbon concrete in highway construction. The study, (completed in 2024) tested 16 unique concrete mixtures under real-world conditions on an active Minnesota highway. Test slabs were poured at MnDOT's MnROAD facility near Albertville in 2022.

Carbon Upcycling's CO_2-enhanced mix achieved a 12.3% reduction in cement content while matching the workability of traditional concrete, allowing seamless handling, placement, and setting times for construction crews. In addition, the study found the resulting concrete was 28% stronger at 28 days compared to the advanced control concrete and a 32% increase in chloride resistivity for more durable concrete. (AZO Cleantech, 2024). Despite these benefits, no published cost data was found. In addition, some indications (Hertel & Most, 2025) suggest that the overall amount of sequestered carbon by diverting cement may not have been as significant as seen in the Hawaii DOT pilot project.

3.9 Conclusions

Since materials such as concrete and asphalt, contribute more than 8% of global carbon emissions, CCUS technologies are focused on how to enhance materials to be low carbon or to use materials to create carbon storage sites. Since the production of Portland cement contributes heavily to carbon emissions, there are low carbon solutions and carbon storage solutions being developed for use within concrete.

Some low carbon cement solutions include limestone calcined clay cement, bio-cement, and electric recycled cement. Limestone calcined clay cement is a direct capture process that decreases the usage of Portland cement by replacing part it. Bio-cement is a direct carbon capture technology since the microorganisms within the bio-cement absorb and store carbon dioxide in calcium carbonates. Electric recycled cement is an indirect carbon capture method. It decreases the usage of virgin cement which prevents new emissions being occurring, but it does not store or capture carbon dioxide.

The carbon storage solutions discussed include the usage of basalt, hempcrete, and other carbon mineralization. Basalt is one mineral being considered for carbon storage and utilization. It can be used as a fiber or as an SCM with some benefits to the concrete mixture, like a decrease in slump and resistance in elevated temperatures. Hempcrete has the potential to be applied to highway and roadway applications as a durable material with the ability to store carbon and some increase performance of various mechanical properties, like less production and layout energy, provide surface water attenuation, and reduce noise pollution. Carbon mineralization is CCUS technology that is the basis for carbon storage in concrete. The most popular process is using captured carbon to inject into concrete mixes to form calcium carbonates. Some companies (CarbonCure, Heidelberg Materials, and Fortera) that have existing or upcoming technology that carries out this process.

There are also sector focused CCUS technologies in development in transportation sector (highway/roadway, railway, maritime, aviation, and public works). These sectors utilize construction materials, including some discussed in the material section of this report, but there are other ways that these sectors are creating solutions specific to themselves. Along with low carbon solutions, such as carbon-neutral vehicles and fuels for public transportation, the highway/roadway sector is working towards having Mobile Carbon Capture devices to be attached to various vehicles to directly capture carbon emissions from the exhaust gas. Another idea is to utilize basalt's carbon sequestration and soil enhancement abilities in right-of-way green areas to capture and store carbon (however, any soil enhancements would need evaluation and testing of leachate to ensure no adverse effects over time). Railways are also working to implement carbon-neutral vehicles through battery-powered or hydrogen-powered trains. Along with modifying the vehicles used, energy use is being analyzed for efficiency or carbon capture potentials. Trains have a lot of excess kinetic energy that is wasted when slowing down, so options like direct air carbon capture can be used to capture that excess energy to be re-utilized.

Maritime is a sector that heavily uses fossil fuels, so on-board carbon capture solutions are being developed. These solutions include turning the exhaust into solid sodium carbonate particles, separating carbon dioxide from flue gas for compression and storage, and using ammonia water to capture and store carbon dioxide in mineral form. Aviation is switching from fossil fuels to sustainable aviation fuel and electrically powered vehicles to reduce carbon footprint. Sustainable aviation fuel can be used without modifications to existing engines (when used as a 50% blend with conventional jet fuel) and are produced from animal fats and wasted cooking oil. Electrical aircraft have existed for a significant amount of time; however, with the lower energy density of the batteries, these electric aircraft seem to only be feasible for low-range flights with a low payload. Public work projects that mainly include increasing green areas and vegetation in urban areas to combat the urban heat effect as well as increase air quality, quality of life, and improve efficiency in building energy usage. Public works projects can also include beautification of a city to promote walking as a primary mode of transportation.

This report outlined some policy considerations for integrating CCUS into Statewide Transportation Improvement Programs, Metropolitan Planning Organization plans. Funding mechanisms such as the U.S. 45Q Tax Credit, and Department of Energy grants can provide financial support for CCUS deployment (with several projects being done already in Texas). Furthermore, updating DOT-approved material specifications to include CO_2-mineralized concrete, carbon-sequestering aggregates, and alternative binders will help integrate CCUS into standard construction practices.

Pilot and demonstration projects help to evaluate the viability of CCUS technologies in real-world applications. Based on our review, there were only two pilot studies conducted by DOTs for carbon capture employed in concrete mixes for transportation infrastructure projects: Hawaii DOT in 2019 and Minnesota DOT in 2022. This is in parallel to several case studies carried out by various DOTs under the topic of sustainable pavements (FHWA, 2024). The main takeaways from these CCUS pilot projects are that generally the resulting concrete mix appears to be stronger and more resistant to chlorides, however it is unclear what the cost premium is. Other pilot studies are needed on other CCUS applications including bio-char enhanced embankments and other sequestration techniques.

Chapter 4. Simplified Consequential Life Cycle Assessment (LCA) of CCUS on TxDOT Project

This chapter provides a simplified consequential lifecycle assessment of select CCUS technologies on a TxDOT project to build upon existing literature.

4.1 Modeling Approach for Life Cycle Assessment

The objective of this section is to provide an overview of how the data was collected for the baseline life cycle assessment for Task 4 of TxDOT project 0-7231. The baseline life cycle analysis is based on the estimated emissions of the South Capital Express I-35 expansions project (CapEx South) as it is being built. This assessment will provide a cradle-to-gate baseline to investigate how CCUS technologies can reduce emissions. The data sources used for this simplified life-cycle analysis are from the bridge and roadway construction plans provided by TxDOT's "Travis 0015-13-077" volumes 1, 2, and 4.

The FHWA's Infrastructure Carbon Estimator (ICE) Tool version 2.2.8 (MnDOT, n.d.) was used to calculate the estimated carbon emissions the project will produce. This tool can be used for various infrastructure types, as seen in Figure 5.

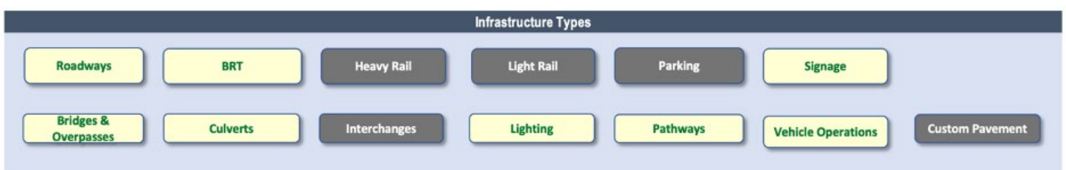


Figure 5: Infrastructure Types Available for Analysis in FHWA's ICE Tool. (MnDOT, n.d.)

4.2 Governing Assumptions

As identified in Chapters 2 and 3, the most prominent CCUS technologies being integrated into transportation projects are focused on carbon reduction within the materials. Since concrete and asphalt are the most used materials, this project will focus on the materials within bridges and roadways. Furthermore, this project will only calculate the carbon emissions from roadways and bridges.

For simplicity (and for ease of comparison of options), the carbon estimations for this project only consider embodied carbon emissions and not operational carbon emissions. From the user guide, the ICE Tool is set up to only consider embodied emissions associated with material extraction, production, and transportation. All other environmental product declarations (EPDs) used are for Life Cycle Assessment (LCA) Stages A1-A3 (Figure 6). Therefore. It is assumed that all emissions are embodied carbon emissions in LCA Stages A1-A3.

PRODUCTION Stage (*Mandatory*)			CONSTRUCTION Stage		USE STAGE					END-OF-LIFE Stage			
Extraction and upstream production	Transport to factory	Manufacturing	Transport to site	Installation	Use	Maintenance	Repair	Replacement	Refurbishment	De-construction/ Demolition	Transport to waste processing or disposal	Waste processing	Disposal of waste
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**C1**	**C2**	**C3**	**C4**
X	**X**	**X**	**MND**	**MND**	**MND**	**MND**	**MND**	**MND**	**MND**	**MND**	**MND**	**MND**	**MND**
Note: MND = module not declared; X = module included.													

Figure 6: Life Cycle Assessment Stages. (CEMEX, 2023)

4.3 Bridges Data Collection Process for ICE Tool

From the ICE Tool, the following data are needed to complete the analysis for bridges and overpasses:

- Type of construction work (reconstruction, new, add lane)
- Structure type (single-span, two-span, multi-span)
- Number of bridges
- Average number of spans per bridge
- The average lanes per bridge
- Total number of lane-spans

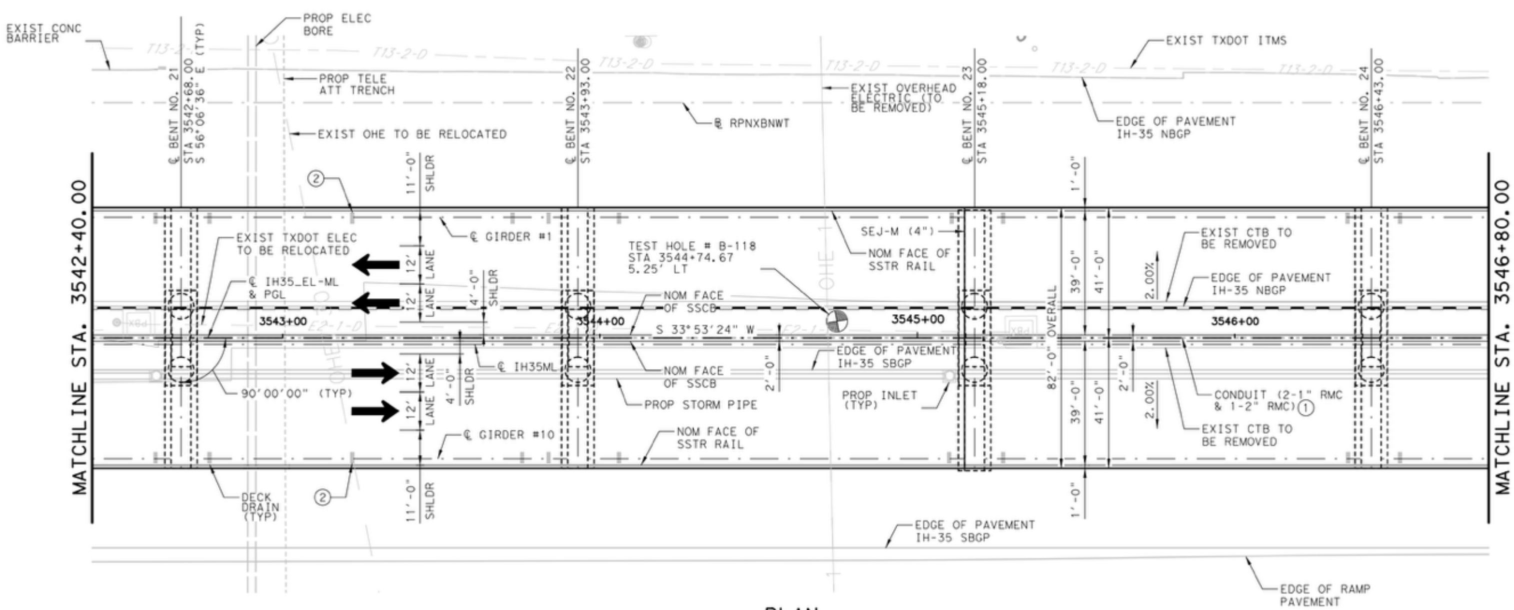
Figure 7 shows a screenshot of the ICE Tool for a sample bridge project. Note, the total number of lane spans is automatically calculated by the ICE Tool by multiplying the average number of lanes and the average number of spans.

The data were obtained from manual analysis of the bridge layouts, typical sections, and girder layouts. From the bridge layouts (Figure 8), the plans show the overall length of the bridge. The typical sections (Figure 9) show the number of lanes as indicated by the dark colored arrows. The girder layouts (Figure 10) show the number of spans within the structure.

Bridges & Overpasses

Bridge/Overpass Structure	Construct New Bridge/Overpass				Reconstruct Bridge/Overpass				Add Lane to Bridge/Overpass			
	Number of bridges & overpasses	Average number of spans per structure	Average number of lanes per structure	Total number of lane-spans	Number of bridges & overpasses	Average number of spans per structure	Average number of lanes reconstructed per structure	Total number of lane-spans	Number of bridges & overpasses	Average number of spans per structure	Average number of lanes per structure added	Total number of lane-spans
Single-Span		1		0		1		0		1		0
Two-Span		2		0		2		0		2		0
Multi-Span (over land)				0				0				0
Multi-Span (over water)				0				0				0

Figure 7: Chart from ICE Tool for Bridges and Overpasses Variables. (MnDOT, n.d.)



PLAN

Figure 8: Bridge Layout Example from Highway Project Plans (TxDOT, 2022d)

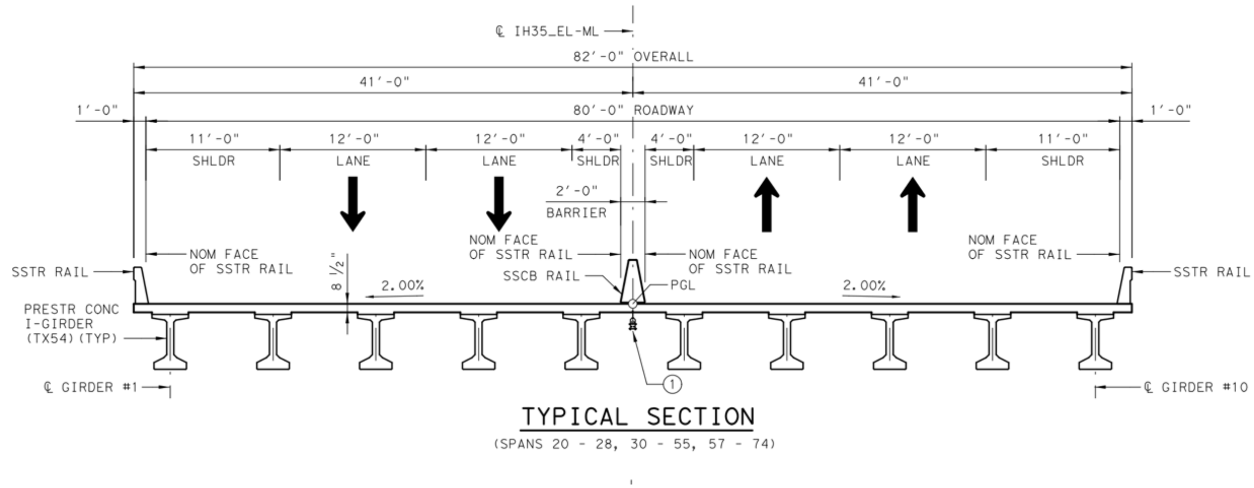


Figure 9: Typical Section Example from Highway Project Plans (TxDOT, 2022d)

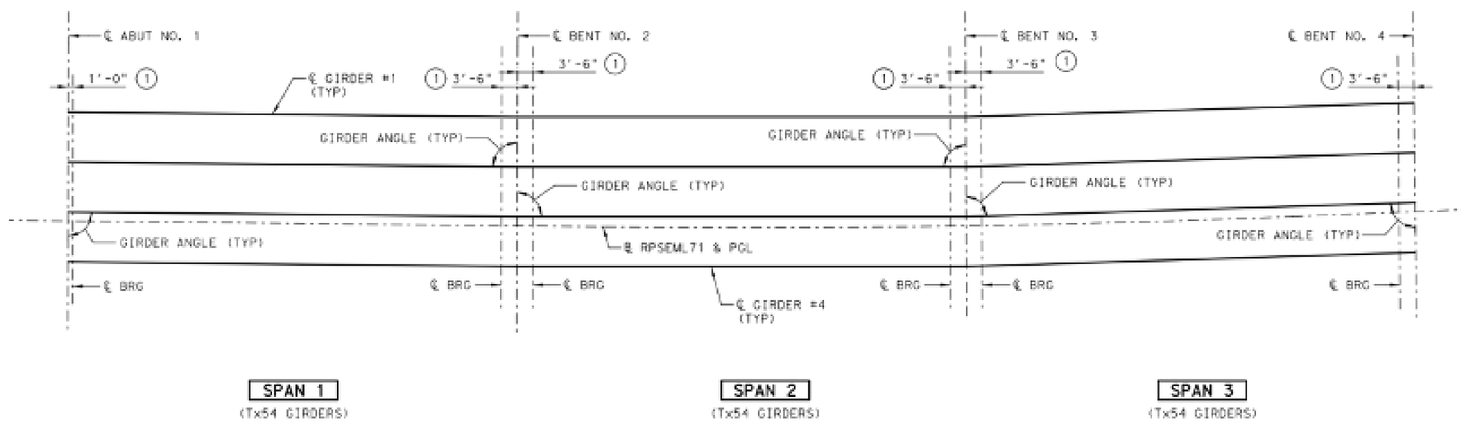


Figure 10: Bridge Spans Example in Highway Project Plans (TxDOT, 2022d)

Based on the initial manual analysis, it was determined that the project plans contain 18 bridges—2 new bridges, 9 reconstructed bridges, and 7 widened bridges. The total project length of the bridges is listed as 20,005.27 feet (3.789 miles) in the project plans (Figure 11); however, the total length of the bridges initially calculated using the ICE tool was 22,106 feet (4.187 miles). Since the length 11 of the 18 bridges were confirmed by Figure 11, the remaining bridges were re-evaluated to determine the discrepancy. From the re-evaluation, it was noticed that some of the bridges were listed by showing direction of traffic flow (e.g., east-west or north-south) which may have led to overestimating the total project length of the bridges by counting some bridges twice. Thus, the data was reanalyzed so that the directional flow of the bridges was ignored, and such bridges were counted as one bridge versus two. Specifically, the South Boggy Creek General Purpose South Bound and North Bound bridges are considered the same bridge, the Onion Creek North Bound and South Bound bridges are considered the same bridge, and the Slaughter Creek North Bound and South Bound bridges are considered the same Bridge. As a result, the total number of bridges decreased to 15 bridges, and the total length of the bridges was 20,531.27 feet (3.889 miles).

	Roadway Length		Bridge Length		Total Length	
CSJ	(FT)	(MI)	(FT)	(MI)	(FT)	(MI)
0015-13-077	20,507.51	3.884	517.15	0.098	21,024.66	3.982
0016-01-113	27,654.41	5.238	1,901.30	0.360	29,555.71	5.598
*	0.00	0.000	17,586.82	3.331	17,586.82	3.331
PROJECT LENGTH	48,161.92	9.122	20,005.27	3.789	68,167.19	12.910

Figure 11: Table of Project Length Values for Bridges and Roadways (TxDOT, 2022b)

*	Bridge Length	
	(FT)	(MI)
0015-13-077 BRIDGES		
ELEVATED MANAGED LANE BRIDGE	12,570.00	2.381
IH35 SB ENTRANCE RAMP BRIDGE	787.84	0.149
IH35 NB EXIT RAMP BRIDGE	614.98	0.116
SLAUGHTER LANE ENTRANCE RAMP	1,375.00	0.260
IH35 NB ENTRANCE RAMP MLWN	210.14	0.040
S. BOGGY CREEK NBFR BRIDGE	140.00	0.027
S. BOGGY CREEK NB EXIT RAMP BRIDGE	193.00	0.037
CSJ: 0015-13-077 SUBTOTAL	15,890.96	3.010
0016-01-113 BRIDGES		
SLAUGHTER CREEK NBFR WIDENING	309.86	0.059
SLAUGHTER CREEK SBFR WIDENING	304.00	0.058
ONION CREEK NBFR BRIDGE WIDENING	544.00	0.103
ONION CREEK SBFR BRIDGE WIDENING	538.00	0.102
CSJ: 0016-01-113 SUBTOTAL	1,695.86	0.321
PROJECT TOTAL	17,586.82	3.331

Figure 12: Overall Length of Select Bridges. (TxDOT, 2022b)

The ICE Tool has a disclaimer that states it cannot accurately calculate greenhouse gas emissions for bridges over 1,000 feet (ICF, 2020). Looking at TxDOT's previous project that used the ICE Tool, the Central Capital Express (CapEx

Central) I-35 expansions project (TxDOT, 2022a), TxDOT dealt with this issue by splitting bridges over 1,000 feet into smaller bridges. There is no disclaimer that this procedure would impact the embodied carbon emissions (GHG from materials), but there is a suspicion that this may impact the operational carbon emissions (GHG from construction activities). To follow this procedure, the two bridges over 1,000 feet, the Elevated Managed Lanes bridge and the Onion Creek bridge, were split. The Elevated Managed Lanes bridge was split into 16 bridges with 6 spans on each bridge. The Onion Creek bridge was split into 2 bridges with 6.5 spans per bridge.

From this process of data collection, Figure 9 shows the inputs for the bridge section of the ICE Tool.

4.4 Roadway Data Collection

Figure 7 displays the total length of bridges and roadways. 0015-13-077 refers to the project section from State Highway 71 to West Slaughter Lane, and 0016-01-113 refers to the project section from West Slaughter Lane to Main Street. As seen in Figure 13, the total roadway length is 9.122 centerline miles, and the total bridge length is 3.789 centerline miles.

	Roadway Length		Bridge Length		Total Length	
CSJ	(FT)	(MI)	(FT)	(MI)	(FT)	(MI)
0015-13-077	20,507.51	3.884	517.15	0.098	21,024.66	3.982
0016-01-113	27,654.41	5.238	1,901.30	0.360	29,555.71	5.598
*	0.00	0.000	17,586.82	3.331	17,586.82	3.331
PROJECT LENGTH	48,161.92	9.122	20,005.27	3.789	68,167.19	12.910

Figure 13: Table of Project Length Values for Bridges and Roadways (TxDOT, 2022b)

From the ICE Tool, the following data is needed to complete the analysis for the roadway:

- Total existing centerline miles
- Total newly constructed centerline miles
- Total existing roadway
- Type of construction work (new roadway or additional lane)
- Facility type

This data is outlined in Figure 14 below as seen in the ICE Tool. To simplify the calculations, the existing roadway lane-miles were approximated by multiplying the total existing centerline miles by the number of lanes each facility type has. As seen in Figure 15, the number of lanes on the bridge is indicated by a dark arrow. These arrows were counted to determine the number of lanes a roadway contains. To simplify, the urban interstates were considered to have 9 lanes—7 for the general-purpose lanes, 2 for the exit and entrance ramps—while the urban principles were considered to have 6 lanes.

Source: https://en.wikipedia.org/wiki/Low-water_crossing#/media/File:Roanoke_River_low_water_crossing.jpg

Bridge/Overpass Structure	Construct New Bridge/Overpass				Reconstruct Bridge/Overpass				Add Lane to Bridge/Overpass			
	Number of bridges & overpasses	Average number of spans per structure	Average number of lanes per structure	Total number of lane-spans	Number of bridges & overpasses	Average number of spans per structure	Average number of lanes recon-structed per structure	Total number of lane-spans	Number of bridges & overpasses	Average number of spans per structure	Average number of lanes per structure added	Total number of lane-spans
Single-Span	0	1	0	**0**	0	1	0	**0**	0	1	0	**0**
Two-Span	0	2	0	**0**	3	2	2	**12**	0	2	0	**0**
Multi-Span (over land)	16	6	4	**384**	4	5.5	1	**22**	4	4	2.0625	**33**
Multi-Span (over water)	1	2	1	**2**	2	6.5	6	**78**	2	7	1	**14**

Figure 14: Inputs for Bridge Section of ICE Model

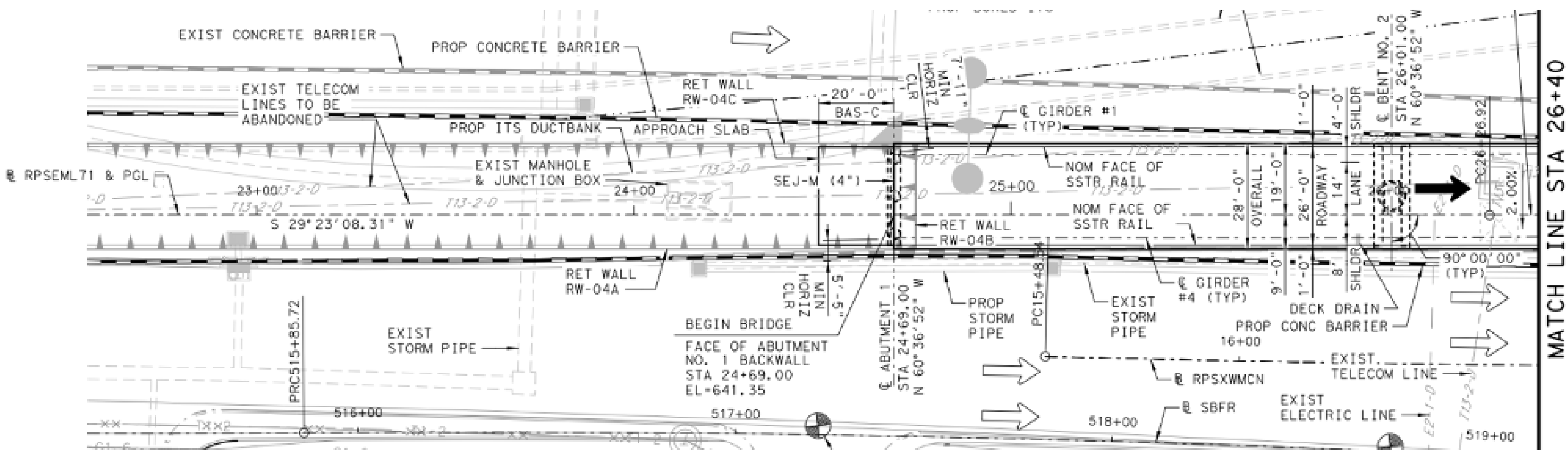
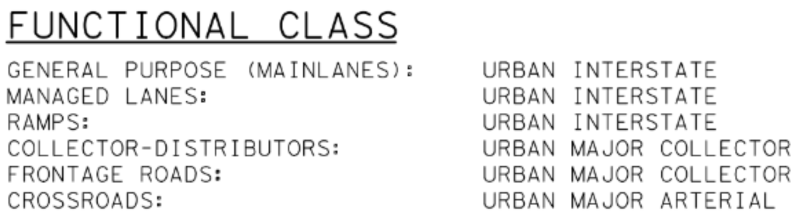


Figure 15: Lane Layout Example from Highway Project Plans (TxDOT, 2022c)

To collect data for roadway inputs, each road type was separated into facility types as outlined in Figure 16. For each road, the length of the road undergoing construction was counted. Since the CapEx Central project only used the “New Roadway” and “Construct Additional Lane” inputs, the only construction types included in these calculations are widening and total reconstruction. The length of each road was calculated by subtracting the beginning STA location from the ending STA location. For example, in Figure 17, the beginning STA location (12+71.72 or 1271.72 ft) was subtracted from the ending STA location (15+56.27 or 1556.27 ft) to get a distance of 293.55 ft. The widening activity was assumed to be half a lane wide.


FUNCTIONAL CLASS

GENERAL PURPOSE (MAINLANES):	URBAN INTERSTATE
MANAGED LANES:	URBAN INTERSTATE
RAMPS:	URBAN INTERSTATE
COLLECTOR-DISTRIBUTORS:	URBAN MAJOR COLLECTOR
FRONTAGE ROADS:	URBAN MAJOR COLLECTOR
CROSSROADS:	URBAN MAJOR ARTERIAL

Figure 16: Functional Classification of Each Roadway Type (TxDOT, 2022b)

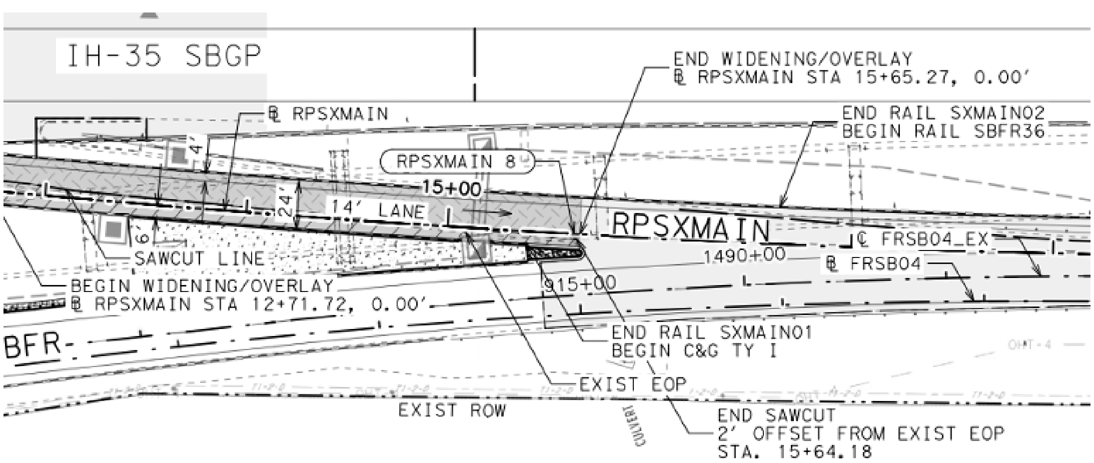


Figure 17: Construction Plans Example from Highway Project Plans (TxDOT, 2022c)

Roadway System	
Total existing centerline miles	9.122
Total newly constructed centerline miles	6.2056

Roadway Projects						
Facility type	Roadway System	Roadway Construction				
	Existing Roadway (lane miles)	New Roadway (lane miles)	Construct Additional Lane (lane miles)	Realignment (lane miles)	Lane Widening (lane miles)	Shoulder Improvement (centerline miles)
Rural Interstates	0	0	0	0	0	0
Rural Principal Arterials	0	0	0	0	0	0
Rural Minor Arterials	0	0	0	0	0	0
Rural Collectors	0	0	0	0	0	0
Urban Interstates / Expressways	82.098	15.5461	7.8792	0	0	0
Urban Principal Arterials	54.732	1.8471	10.8342	0		0
Urban Minor Arterials / Collectors	0	0	0	0	0	0

Include roadway rehabilitation activities (reconstruct and resurface)	No
% roadway construction on rocky / mountainous terrain	0%

Figure 18: Variables and Inputs for Roadway Section of ICE Model

4.5 Vegetation Data Collection

For alternatives 2, 3, and 4, the surface area of the right-of-way is needed. This was calculated by adding the total square yards of the "furnishing and placing topsoil (4")" as labeled in Figure 14. The total area from this is 431,656 yd^2 or 360,919 m^2.

ITEM NO.			DESCRIPTION	UNIT	QUANTITY
160	-	6003	FURNISHING AND PLACING TOPSOIL (4")	SY	10512
162	-	6002	BLOCK SODDING	SY	1172
164	-	6003	BROADCAST SEED (PERM) (RURAL) (CLAY)	SY	9340
164	-	6009	BROADCAST SEED (TEMP) (WARM)	SY	4670
164	-	6011	BROADCAST SEED (TEMP) (COOL)	SY	4670
166	-	6001	FERTILIZER	AC	2.2
168	-	6001	VEGETATIVE WATERING	MG	304
169	-	6003	SOIL RETENTION BLANKETS (CL 1) (TY C)	SY	1138
169	-	6005	SOIL RETENTION BLANKETS (CL 2) (TY E)	SY	651

Figure 19: Vegetation Items Example from Highway Project Plans; 10512 SY of ITEM 160-6003; Vol. 6 only (TxDOT, 2022e)

4.6 ICE Tool Greenhouse Gas Results

From the ICE Tool results, Table 9 and Table 10 show greenhouse gas emissions by infrastructure type and by material type, respectively. It is important to note that stages A1-A3 are inclusively considered as these represent key parts of the embodied carbon emissions of installed materials. The emissions in these tables is calculated by industry average emissions values (for A1, A2, and A3 stages) which are then scaled by the quantities of materials in the bridges and roadways in the case study.

Table 9: Greenhouse Gas Emissions by Infrastructure Type

	GHG Emissions	
	($kgCO_2e$)	($MTCO_2e$)
Bridges	43,713,503	43,714
Roadway	18,420,915	18,421

Table 10: Greenhouse Gas Emissions by Material

	GHG Emissions	
	($kgCO_2e$)	($MTCO_2e$)
Bridges		
Aggregate	845,000	845
Bitumen	-	-
Cement	24,211,000	24,211
Steel	9,254,000	9,254
Water	28,000	28
Roadway		
Aggregate	891,000	891
Bitumen	1,344,000	1,344
Cement	3,759,000	3,759
Steel	1,677,000	1,677
Water	1,000	1

4.7 Concrete Mix Greenhouse Gas Emissions

To further analyze the materials used in the project, specifically the concrete used in the bridge plans, the default mixes from the ICE Tool (ICF, 2020), along with three project mixes of similar 28-day strength (3600-4000 psi).

The first mix, with a 28-day strength of 4000 psi, is a standard Portland cement mix with no admixtures or supplementary cement materials. The second mix, with a 28-day strength of 4000 psi, is a blended hydraulic cement consisting of Portland cement and 1.3% fly ash. The three mixes from the CapEx South project are all made of type 1L cement from CEMEX with varying levels of fly ash with 28-day strengths of 3600 psi.

The composition of each mix is detailed in Table 11.

Table 11: Mix Design of Studied Concrete Mixes

	ICE Mix – Portland[1] (kg/m³)	ICE Mix – Blended Hydraulic[1] (kg/m³)	C30 – Type 1L[2] (kg/m³)	COOMASS – Type 1L[3] (kg/m³)	C35MASS1 – Type 1L[4] (kg/m³)
Water	165.65	165.65	150.69	148.32	148.32
Cement	366.79	366.79	234.34	332.23	216.55
Fly Ash	0	0	100.86	0	115.69
Type A Admixture	0	0	1.19	1.19	1.19
Type D Admixture	0	0	0.59	0.59	0.59
Coarse Aggregate	958.39	958.39	1032.3	1032.3	1032.3
Fine Aggregate	875.57	875.57	790.24	827.62	794.99

[1]ICF, 2020, [2]TxDOT, 2023a, [3]TxDOT, 2023b, [4]TxDOT, 2023c

To estimate the embodied carbon emissions from each mix, the global warming potentials (GWP) outlined in Table 12 were used. Since specific EPDs for the other materials used in the CapEx South project concrete, are not public, the global warming potentials for the aggregates and water were considered the same for all mixes. These potential differences in GWP for aggregates and water are considered to be negligible, since cement and supplemental cement materials have significantly more influence. These data were found in the ICE Tool User Guide. The fly ash GWP was estimated to be 6 kgCO_2e per MT from a 2022 study by Witzleben. The admixture GWP was estimated to be 2250 kgCO_2e per MT from a 2023 study by Schiefer and Plank.

Table 12: Global Warming Potential Constants for Each Mix Component

	ICE Mix – Portland (kgCO_2e /MT)	ICE Mix – Blended Hydraulic (kgCO_2e /MT)	C30 – Type 1L (kgCO_2e /MT)	COOMASS – Type 1L (kgCO_2e /MT)	C23MASS1 – Type 1L (kgCO_2e /MT)
Water	1.74[a]				
Cement	1040[a]	892[a]	756[b]		
Fly Ash	6[c]				
Type A Admixture	2250[d]				
Type D Admixture	2250[d]				
Coarse Aggregate	4.51[e]				
Fine Aggregate	4.87[e]				

[a]ICF, 2020, [b]CEMEX, 2023, [c]Witzleben, 2022, [d] Schiefer & Plank, 2023, [e]These values were calculated by finding the average GWP of the materials based in the United States. Data is from ICE User Guide (ICF, 2020).

To get the total GWP of the materials per MT of concrete, the GWP constants from Table 11 were multiplied by the corresponding mix component value from Table 12. The results of these calculations are listed in Table 13. The total GWP shows the total embodied carbon emitted per MT of concrete. See Appendix F for example calculations.

Table 13: Global Warming Potential Results by Component

	ICE Mix – Portland (kgCO_2e/m^3)	ICE Mix – Blended Hydraulic (kgCO_2e/m^3)	C30 – Type 1L (kgCO_2e/m^3)	COOMASS – Type 1L (kgCO_2e/m^3)	C23MASS1 – Type 1L (kgCO_2e/m^3)
Water	0.288	0.288	0.26	0.26	0.26
Cement	381.462	327.177	177.16	251.17	163.71
Fly Ash	0	0	0.61	0	0.69
Type A Admixture	0	0	2.68	2.68	2.68
Type D Admixture	0	0	1.33	1.33	1.33
Coarse Aggregate	4.322	4.322	4.66	4.66	4.66

Fine Aggregate	4.264	4.264	3.85	4.03	3.87
Total GWP	390.337	336.052	190.54	264.11	177.20

The CapEx South I-35 project modeled in FHWA's ICE Tool resulted in greenhouse gas emissions of 62,135 $MTCO_2e$ when only considering the embodied carbon of the bridge and roadway materials. From the 62,135 $MTCO_2e$ of total carbon emissions, 25,084 $MTCO_2e$ was the result of 155,200 MT of bridge concrete. When recreating the calculations of the embodied carbon due to the bridge concrete using the CapEx South project, the total was an average of 27,395 $MTCO_2e$ for 180,800 MT of bridge concrete. This results in there being a 6.25% difference between the ICE Model and the calculations done manually. Since this difference is small, it can be assumed that the ICE Model is accurate when it comes to bridge concrete carbon emissions.

4.8 CCUS Alternatives

4.8.1 Alternative 1: CO_2 Injected Concrete (CarbonCure)

Carbon mineralization is the process of converting captured carbon into a solid and stable mineral, such as carbonate, by reacting carbon with calcium or magnesium oxide. This is a natural process; however, this carbon sequestration technique accelerates the mineralization process. The resulting mineral can then be transported for storage or utilization purposes. Often, carbon is injected into underground rock formations (USGS, 2019), but there is also the idea of injecting carbon into concrete.

Using the idea of carbon mineralization, CO_2 is injected into concrete with the purpose of reacting with calcium oxide to form calcium carbonate. This mineralization occurs during the concrete mixing process. This addition of carbon not only stores carbon within concrete, but it has also been found to enhance the compressive strength of concrete. Therefore, concrete requires less cement to achieve a certain compressive strength (CarbonCure, 2021).

CarbonCure claims that this process results in an average of 90% of the injected carbon being mineralized in the concrete (Truscott, 2025). There is a risk that a small amount of CO_2 leakage will occur at the injection site; however, CarbonCure does not take this leakage into account when conducting environmental analysis as “the injected carbon dioxide is comprised of industrial process emissions that were displaced prior to being utilized/absorbed/lost” (Monkman, 2024).

CarbonCure has a Type S admixture that can per used on TxDOT projects (TxDOT, 2022f). This admixture, a cement hydration-enhancing admixture, is added to concrete to partially replace cement while adding CO_2 to the concrete mix. This addition of carbon will promote carbon mineralization within the concrete, so the carbon will be trapped, along with providing mechanical strength (CarbonCure, 2023).

When tested in an AASHTO compliance study (CarbonCure, 2024), the admixture was used to replace 0.2% of the cement. The concrete mix used for this study had a compressive strength of 5,000 psi and a water-to-cement ratio of 0.46. From this study, the admixture can remove about 15-25 $lbCO_2e/CY$ of concrete. Assuming an average of 20 $lbCO_2e/CY$ of concrete or 11.86 $kgCO_2e/m^3$ can be directly subtracted from the total global warming potential, Table 14 shows the new total GWP of each mix outlined above. The values were converted from kg CO_2e/m^3 to kg CO_2e/MT by assuming the density of concrete is 2,400 kg/m^3.

The total amount of concrete for the South CapEx project bridge portion was calculated to be 180,800 MT or 75,300 m^3. Table 15 shows the total GWP of the bridge concrete with and without CarbonCure. The global warming potentials for the project mix designs (C30, COOMASS, M35MASS1) were converted from $kgCO_2e$ to $MTCO_2e$ by using the average density of normal concrete, 2400 kg/m^3. This was done to easily compare carbon emissions with the other alternatives, whose units are in $MTCO_2e$.

Table 14: Global Warming Potential per Unit of Concrete from Bridges

		ICE Mix – Portland Cement	ICE Mix – Blended Hydraulic Cement	C30 – Type 1L cement	COOMASS – Type 1L Cement	C35MASS1 – Type 1L Cement
GWP ($kgCO_2e$)	Per m^3 of Concrete	390.3	336.1	190.5	264.1	177.2
	Per MT of Concrete	162.6	140.0	79.4	110.1	73.8

GWP with CarbonCure ($kgCO_2e$)	Per m^3 of Concrete	378.5	324.2	178.67	252.3	165.3
	Per MT of Concrete	157.7	135.1	74.5	105.1	68.9

Table 15: Total Global Warming Potential of Concrete from Bridges

	ICE Mix – Portland Cement	ICE Mix – Blended Hydraulic Cement	C30 – Type 1L cement	COOMASS – Type 1L Cement	C23MASS1 – Type 1L Cement
Total GWP ($MTCO_2e$)	29,400	25,300	14,360	19,900	13,350
Total GWP with CarbonCure ($MTCO_2e$)	28,500	24,400	13,470	19,000	12,460

From CO_2 injected concrete, the mix designs have an average carbon emission decrease of 891 MT or 4.78%. CarbonCure has a licensing model with a cost that isn't made public and varies by producer. CarbonCure claims that there is no upfront cost and there is a decrease in cement that offsets the licensing cost (Monkman, 2017). For the cost analysis of implementing CarbonCure admixtures, the cost is assumed to be $0 additional to the concrete because of this assumption. Therefore, there is no additional cost to adding CarbonCure admixtures to save about 891 $MTCO_2e$.

4.8.2 Alternative 2: Basalt Dust on ROW

Basalt is a naturally occurring mineral known to be able to store sequestered carbon via mineral carbonization. This would allow for the basalt to sequester carbon and form stable carbonates that will permanently house the CO_2. While there are many forms of basalt, using basalt dust is ideal as a smaller particle size increases the surface area exposed to the atmospheric CO_2 and increases how quickly the basalt can capture CO_2.

Typically, sequestered/captured carbon is injected into basalt rock formations; however, based on a study done by Baek et al. in 2023, spreading basalt dust on soil can sequester carbon from the atmosphere. In North America, the annual application of 10 tons of basalt powder per hectare can sequester about 1 ton of CO_2 per year. Using the project vegetation area of 361,000 m^2 or 36.1 hectares from Section 1.4, the annual basalt powder requirement would be 361 tons. The approximate price per ton of basalt dust is $375 (Rock Dust Local, 2022). Therefore, the total cost for this project would be $135,000 per year. For each ton of CO_2 sequestered, the cost would be $3,800.

4.8.3 Alternatives 3 and 4: Vegetation on ROW

In Texas, there are many native plants such as wildflowers and turfgrass. For this study, the focus will be Bermuda as an example of a native turfgrass. With native plants, especially those with deep root systems, the sequestered carbon can be stored more than 30 centimeters underneath the soil surface (Wang et al, 2023). However, disrupting the soil can cause a lot of this carbon to be released into the atmosphere. Plant decay also results in the carbon being kept in the plant organic material being released back into the atmosphere.

Unlike common vegetation, like grasses and wildflowers, cacti have a unique way of storing sequestered carbon. In common vegetation, the plants sequester carbon from the atmosphere and either use it in internal processes or send it through its root system to store it in the surrounding soil for decades (Energy.gov, n.d.). With cacti, carbon is sequestered in a similar way, but the main difference is how the carbon is handled during plant decay.

Cacti are made of calcium oxalate biominerals called whewellite and weddellite with whewellite being the main biomineral in Opuntia cacti (Monje and Baran, 2002). When cacti start to decay, the organic matter decays within 2 years, leaving behind the calcium oxalates. Over the course of 10 to 20 years, the biominerals transform into monohydrocalcite which then dehydrates to calcite (Garvie, 2006).

This process takes sequestered carbon and adds it to the soil in the form of inorganic carbon or minerals, which can stay trapped for decades to centuries. There are several Opuntia species native to Texas including astrispina, imbricata (tree cholla), lindheimeri (Texas prickly pear), macrorhiza (common prickly pear), and phaeacantha (purple-fruited prickly pear) (FHWA, n.d.). For this study, the focus will be Opuntia cacti as a whole.

In common turfgrasses, like Bermuda, the amount of carbon sequestered per year is on average 1.1 $kgCO_2/m^2$ (Wang et al, 2022). Within the project vegetation area (360,919 m^2 as previously calculated), this results in 397,000 $kgCO_2$ being sequestered by the grass per year. From a case study performed on Opuntia Stricta in Brazil (Jardim et al., 2023), the amount of carbon that can be sequestered per year is 1.3 $kgCO_2/m^2$. If every square meter of the project vegetation area was covered with Opuntia, the cacti could sequester 469,194.7 $kgCO_2$.

Because this cactus species is native to Texas, for cost analysis, it is assumed that the cost is similar to that of native wildflower seeds. From volume 1 of the project plans, the total cost of the seeds used in the project was projected to be $450. The cost of the block sodding, assuming it is Bermuda, was projected to be $3,890 (TxDOT, 2022b). If the vegetation area was covered in nothing but block sodding, the estimated carbon sequestered would be 397 metric tons with an initial cost of $3890. If the area was covered in only cacti, the carbon sequestered would be 469 metric tons with an initial cost of $450. Overall, the cost of sequestering one ton of carbon with grass would be $9.80, and with cacti it would be $0.96. These cost estimates do not include the maintenance costs of the vegetation area.

Table 16: Vegetation Alternatives Summary

		Bermuda Turfgrass	Opuntia Cactus
CO_2e mitigated per m^2	$kgCO_2e$	1.1	1.3
Total CO_2e mitigated	$kgCO_2e$	397,000	469,195
	$MTCO_2e$	397	469
Total Cost	$	3890	450
Cost per $MTCO_2e$	$	9.80	0.96

4.8.4 Non-considered CCUS Alternative

Another alternative that was taken into consideration was the use of basalt aggregates and fibers within concrete mixes. There were many studies that showed that it would be beneficial to concrete mechanical properties; however, there were not many benefits in terms of sequestering carbon. Since the carbon is sequestered by basalt via direct contact and the basalt being mostly covered within the concrete mix, the carbon would have to penetrate the cement matrix to reach the basalt. This process would be very slow as the cement matrix has very low permeability. Another idea with this alternative was to use basalt aggregate that was already carbonated to its full capacity; however, there are no suppliers. So, this alternative was not considered to be viable.

4.9 Summary of CCUS Alternatives

Table 17 summarizes the cost estimations for each CCUS alternative analyzed after the first year and after 20 years. 20 years is the time frame chosen, since the project analysis in the ICE Tool was set to 20 years (modeled after the CapEx Central project).

Table 17: Cost Estimations for Each CCUS Alternative

		CO_2 Injected Concrete (CarbonCure)	Basalt Dust	Vegetation: Cactus	Vegetation: Bermuda
Cost of $MTCO_2e$ mitigation	1st Year	$0[c]	$135,000	$450	$3890
	After 20 years	$0	$2,700,000	$450[a]	$19,450[b]
$MTCO_2e$ mitigated	1st Year	891 MT	36.1 MT	469 MT	397 MT
	After 20 Years	891 MT	722 MT	9,380 MT	7,940 MT
Cost per $MTCO_2e$	1st Year	$0	$3,800	$0.96	$9.80
	After 20 Years	$0	$3,800	$0.05	$5.00

[a] *This cost only considers the cost of vegetation materials. The cost excludes the cost of initial labor and maintenance. Since Opuntia cactus can last 20 to 30 years (Lindsey, 2023), it is assumed cactus will only be planted once in this period.*

[b] *This cost only considers the cost of vegetation materials. The cost excludes the cost of initial labor and any maintenance. Since Bermuda grass lasts on average 4 years (Engels, 2025), it is assumed the grass will be replaced 4 times after the initial planting.*

[c] *CarbonCure technology is assumed to be $0, because of the licensing model that is offset by the cost savings of cement (Section 2.1).*

4.10 Conclusions

The main objective of this LCA was to study four different CCUS alternatives that would reduce the embodied carbon emitted from TxDOT's South Capital Express (CapEx South) I-35 expansion project. The four alternatives studied were CO_2 injected concrete, basalt dust, Bermuda grass, and Opuntia Cactus.

To study how CO_2 injected concrete can decrease carbon emissions, the bridge concrete mixes were studied in two ways: the ICE Model and calculations by hand. Since there is no way to modify the mix designs in the ICE Tool, the ICE Model only consists of the default concrete mix. The hand calculations were done to check the ICE Tool as well as study the mixes provided in the CapEx South Project.

From the bridge concrete, five mixes were compared: two from the ICE Model, and three from the CapEx South Project. These mix designs were compared by how much embodied carbon was emitted via global warming potential. After the total global warming potential was calculated for each mix, 11.86 $kgCO_2e/m^3$ was subtracted to model how much carbon emissions are saved by using CarbonCure's Type S admixture. From this, we find that using CarbonCure technology would save about 891 MT of CO_2 from standard mix designs. Since CarbonCure operates on a licensing model and saves producers money in cement reduction, the overall cost of the technology is assumed to be $0 more than typical concrete costs.

The last three alternatives relate to carbon sequestration in the project right-of-way. The first of these three alternatives, or alternative 2, is spreading basalt dust on the right-of-way. To have the maximum impact of sequestering 36.1 $MTCO_2e$, about 361 tons of basalt dust will have to be spread evenly on the right-of-way every year. This would cost about $135,000 per year for the material alone and would result in one metric ton of carbon being sequestered for $3,800. Over a period of 20 years, this would result in an overall cost of $2.7 million and sequestering 722 $MTCO_2e$. The last two alternatives compare the use of Bermuda turfgrass and Opuntia cactus on the right-of-way. The Bermuda turfgrass is assumed to be planted once every four years at a material cost of $3890 each time it is planted. After 20 years, the grass would sequester 7,940 $MTCO_2e$ at a cost of $19,450. Opuntia cactus would last a long time, so over a 20-year period, it is assumed that it will not have to be replanted. The cost of seeds is assumed to be $450. After one year, cacti will sequester 469 $MTCO_2e$, and after 20 years, the cactus will sequester 9,380 $MTCO_2e$. This results in a metric ton of carbon being sequestered for less than a dollar.

The most unstable alternative would be the Bermuda turfgrass. Since the carbon sequestered is stored in the plant and surrounding soil, this alternative has the highest risk of releasing the captured carbon within a couple of years. The captured carbon in all other alternatives is more likely to stay captured for an extended period of time due to the carbon being stored in minerals rather than biomass.

Overall, the least expensive alternatives to add to the CapEx South project are the CarbonCure admixture and the Opuntia cactus. For the CarbonCure alternative, one factor that would need to be investigated further is the actual cost of concrete from a supplier that uses CarbonCure technology. The cost discussed in this technical memorandum is the cost to the concrete ready-mix plants, so it may not be the same cost savings for TxDOT. For the Opuntia cactus, the main factor to be investigated is how much the cost of the plants will be for TxDOT, since this technical memorandum used an estimate based on the CapEx South cost of wildflower seeds. The amount of carbon sequestered is based on full-grown Opuntia cacti, so either less carbon will be sequestered while the plants grow to full size or the cost of the plants will be increased to plant full-grown plants.

Chapter 5. Current CCUS Adoption and Perspectives Among DOTs

As part of this project, the research team created and distributed a survey to various Department of Transportation employees within the United States. The purpose of this survey was to get an idea of the current perspectives on and adoption of CCUS technologies. See Appendix G: Survey Questions for the full list of questions and answer choices given. Overall, the survey resulted in 61 recorded responses; however, many of these responses were mostly blank or added no important data (meaning only the consent or demographic questions were answered). Because of this, the only responses kept were those who answered at least three questions, which resulted in 28 responses being used in data analysis.

5.1 Survey Demographics

The demographics collected from this survey are the department type (Question 1) and the role type (Question 2) of the respondent. The first question resulted in 27 responses answering "State", while 1 respondent, an engineer, answered "Federal". The second question, seen in Figure 20 resulted in 2 project managers, 17 engineers, 2 research analysts, 3 policy advisors, and 4 respondents answering "Other". The respondents who answered "Other" specified their roles to be the following: manager of the materials lab, senior manager, director, and emergency manager.

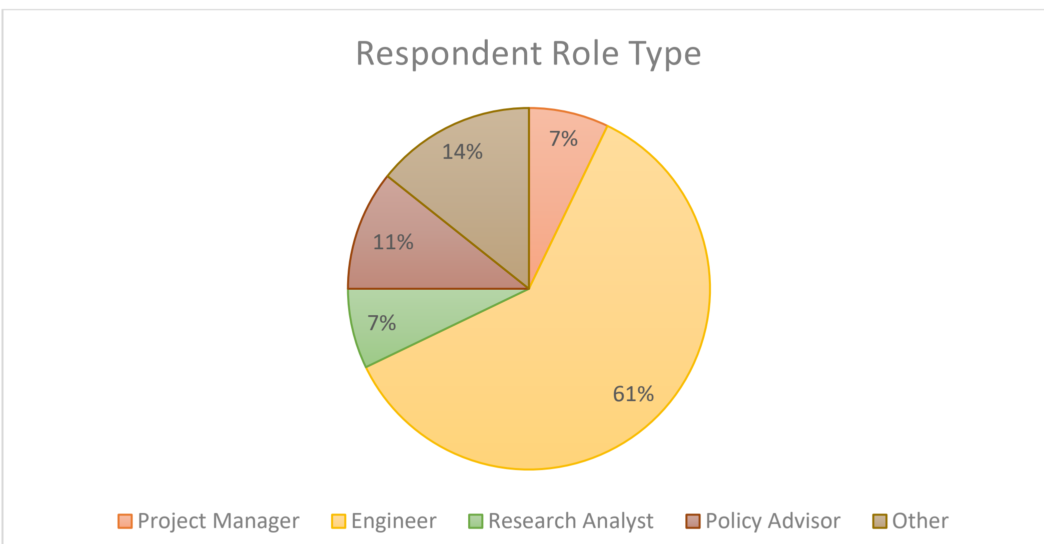


Figure 20: Demographics of Survey Respondents by Role Type. (Rausch, 2025c)

5.2 CCUS Technology Familiarity

Questions 3 and 4 asked for the familiarity of CCUS technology in general and within the transportation sector. In general, as seen in Figure 21, nine respondents were not familiar at all, 14 were somewhat familiar, 5 were moderately familiar, and none of the respondents were very familiar with CCUS technology. Of the 17 engineers, six were not familiar at all, 7 were somewhat familiar, and 4 were moderately familiar. Two of the policy advisors, the research analysts, and the project managers were all somewhat familiar with CCUS. The last policy advisor was not familiar at all. Of the roles marked "Other", one was moderately familiar, one was somewhat familiar, and two were not familiar at all.

Overall, only 6 of the 28 respondents had a different answer to Question 3 and 4. Four of them were engineers, where two had a decreased familiarity from general CCUS to CCUS in transportation, one had an increased familiarity, and one did not answer Question 4. One was a policy advisor who had a decrease in familiarity, and the last was the manager of a materials lab who had an increase in familiarity.

From this, 78.6% of the respondents had the same familiarity of CCUS in general and within the transportation sector, 7% had an increased familiarity, and 11% had a decrease in familiarity. This suggests that at least 75% of the employees within the DOT system have equal familiarity with CCUS in general and in the transportation sector.

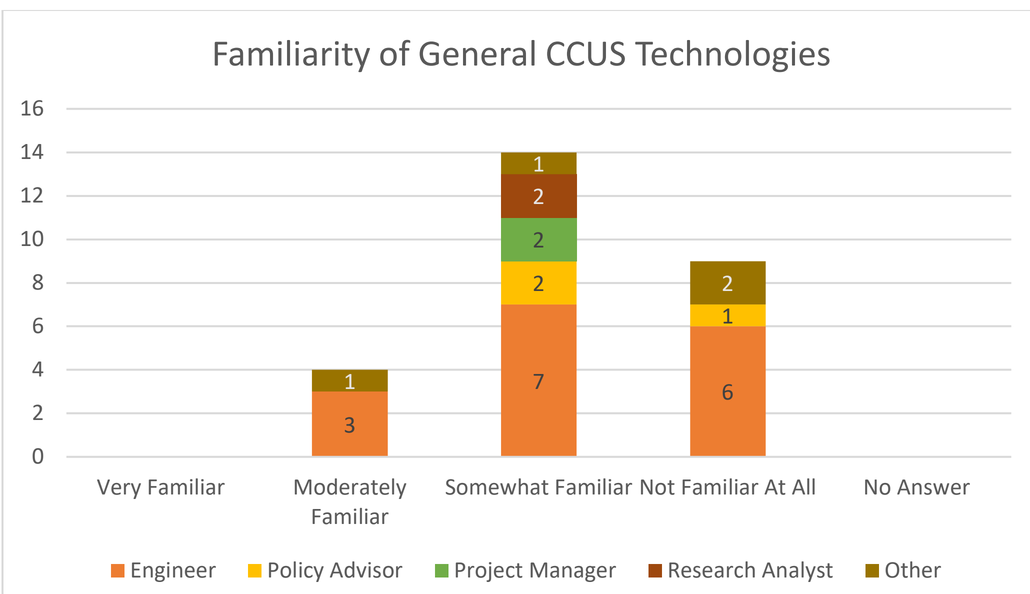


Figure 21: Familiarity with General CCUS Technology of the Respondents by Role Type. (Rausch, 2025c)

Figure 22 shows the familiarity with CCUS technology within the transportation sector by role type.

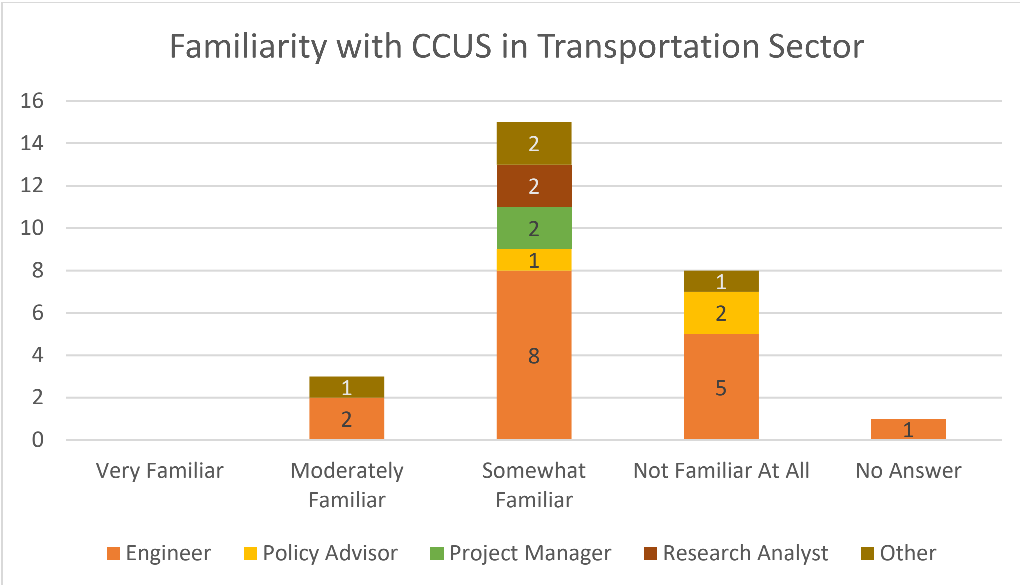


Figure 22: Familiarity with CCUS Technology in the Transportation Sector of the Respondents by Role Type. (Rausch, 2025c)

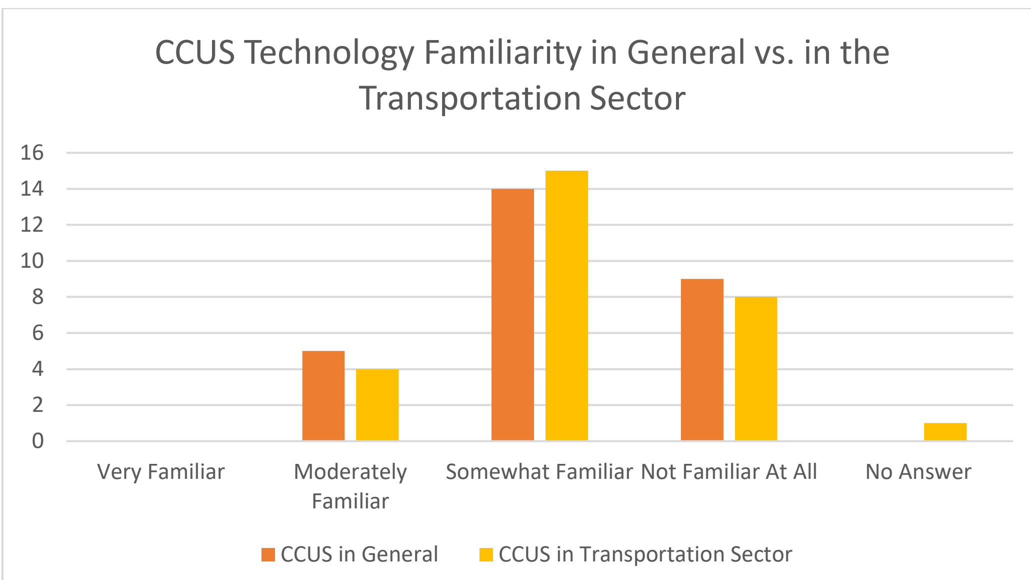


Figure 23: CCUS Familiarity in General versus in the Transportation Sector. (Rausch, 2025c)

For Question 5, three out of the 28 respondents (10.7%) indicated that they did know some incentives for CCUS technology within their state. However, only one respondent (State Engineer) elaborated with "Act 59 of 2023 30 x 30 and 50 x 50". This response refers to the Community Resilience and Biodiversity Protection Act of 2023 in Vermont, which sets a goal of conserving 30% of Vermont's landscape by 2030 and 50% by 2050 (Vermont Housing & Conservation Board, 2025). This provides some insight that suggests that a substantial number of DOT employees are unaware of environmental programs, requirements, incentives, or initiatives that relate to their state. No assumptions can be made about knowledge of nationwide programs and incentives as this question was not asked.

5.3 DOT Current and Future Projects

For Question 6, only one respondent indicated that their DOT had done some work with CCUS technology in the past. Because Question 7 is dependent on whether a DOT has conducted a CCUS technology project, this question was only shown to those who selected "Yes" in Question 6. The sole response to these questions was "*N[ebraska]DOT has conducted a small-scale research project to determine if injecting captured* CO_2 *into our concrete mixes would be beneficial to the performance of our mix designs*".

For Question 8, six of the 28 respondents indicated that their DOT was considering using CCUS technology in future projects. The technologies being considered include accelerated carbon mineralization, carbon utilization, and hydrogen fuel cells in MHDVs. Nebraska's DOT indicated that they were "*considering CCUS technologies in future projects, however it is general, and we don't specific projects, plans, or technologies in mind at this time*". Virginia's DOT referenced two research studies currently being conducted, "*Reducing Carbon Foot-Print in Concrete Applications*" and "*Effect of Carbon-Negative Carbon Black on Concrete Properties*".

Since questions 9 and 10 depended on Question 8, only respondents who answered "No" or left question 8 blank were not shown questions 9 and 10. From the results of Question 9 (Figure 24), the three engineer respondents agreed that pilot projects are necessary for the implementation of CCUS technologies, while only one thought that interagency collaboration was important. One engineer commented, "*N[ebraska]DOT requires validated research to implement new technologies. Our agency will vet materials, and upon satisfactory test results and performance, materials can be approved for use in our construction projects*" under the "Other" answer choice; thus, emphasizing the importance of pilot projects and satisfactory research results. While the research analyst was given the question, the only answer given was "*processes have not yet been implemented*".

In Figure 25, the responses to Question 10 are included. The policy advisor agreed that all given options are imperative for CCUS implementation and added "existing infrastructure limitations" as another factor that influences the implementation of CCUS technology in DOT projects. Of the 3 engineers that answered, all agreed high cost was important, while only 2 agreed for the importance of the other factors.

The research analyst was given the question but chose not to answer. Overall, high cost was the factor with which all respondents agreed was important.

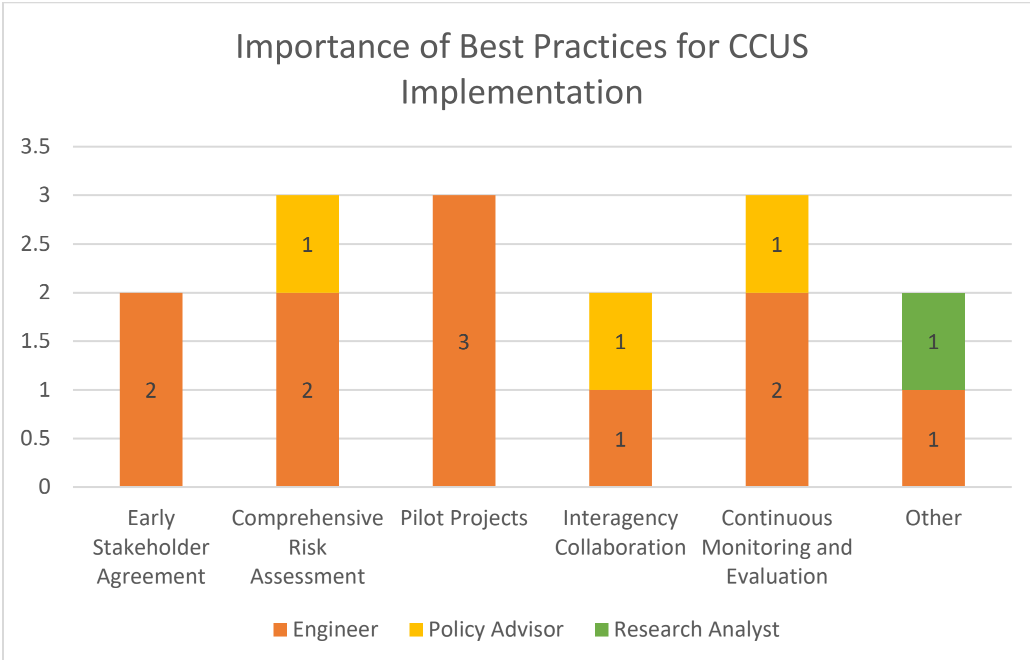


Figure 24: Identified Best Practices for CCUS Implementation by Role Type. (Rausch, 2025c)

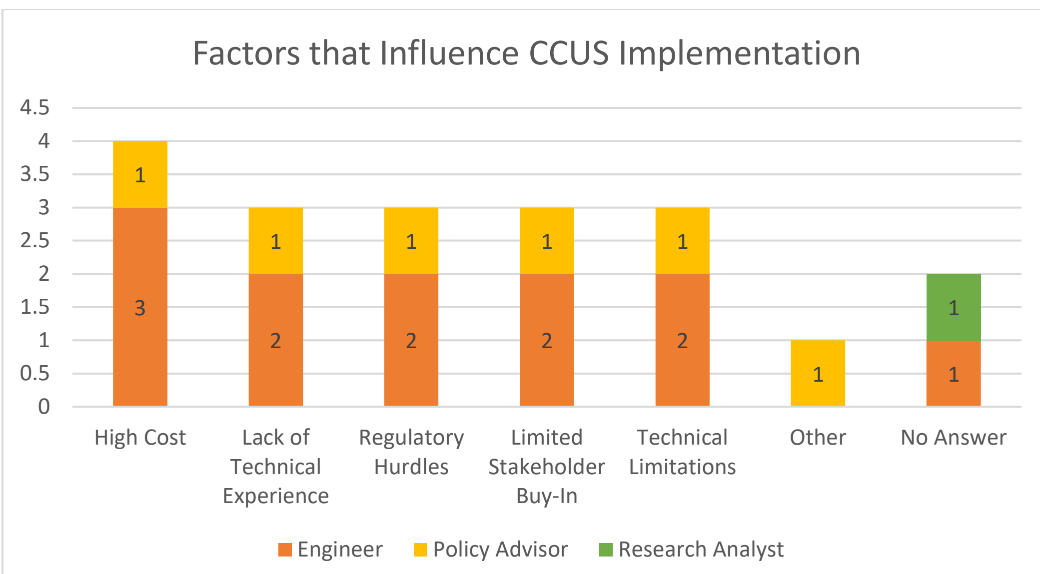


Figure 25: Importance of Factors that Influence CCUS Technology Implementation by Role Type. (Rausch, 2025c)

5.4 Viability of CCUS Technology

Questions 11 and 12 focused on the viability of CCUS technology to be implemented in DOT projects. Question 11 asked if CCUS technology was currently viable for DOT use. As seen in Figure 26, of the respondents that answered, CCUS technology was either somewhat viable or viability was not analyzed. Since 70% of these respondents have not analyzed the viability of CCUS technology, this suggests that implementing CCUS technology is not a serious, widespread idea in DOTs. With the other 30% stating that the technology was somewhat viable, it can be assumed that there is a large barrier that hinders the implementation of CCUS technology in DOT projects.

Some suggestions as to what these barriers are include the answers from Question 12, seen in Figure 27. Besides the category "viability has not yet been analyzed", the three highest factors are high cost, technical feasibility, and stakeholder support.

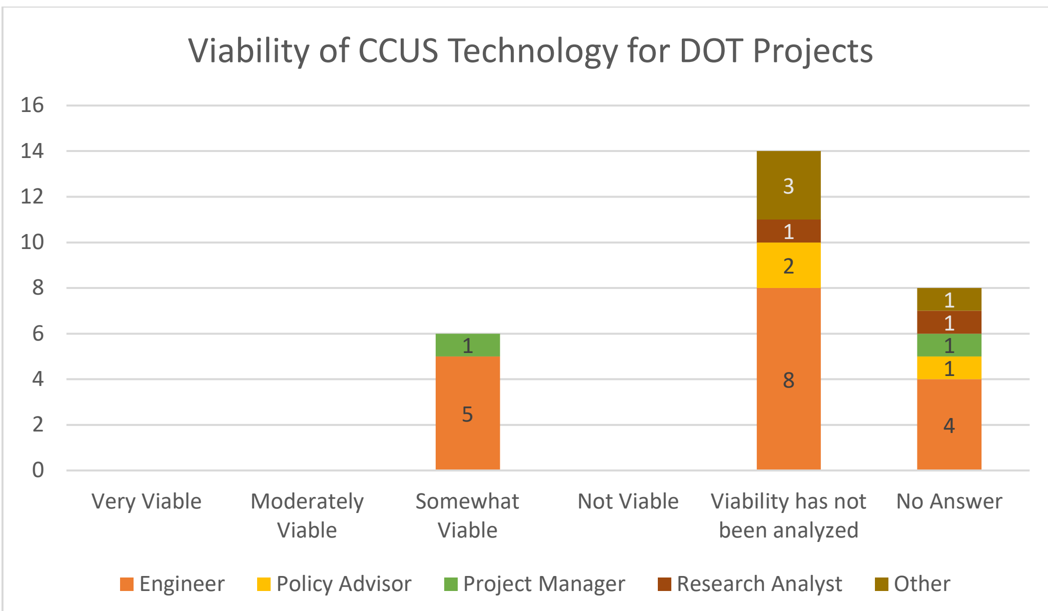


Figure 26: Viability Rating of CCUS Technology for DOT Projects by Role Type. (Rausch, 2025c)

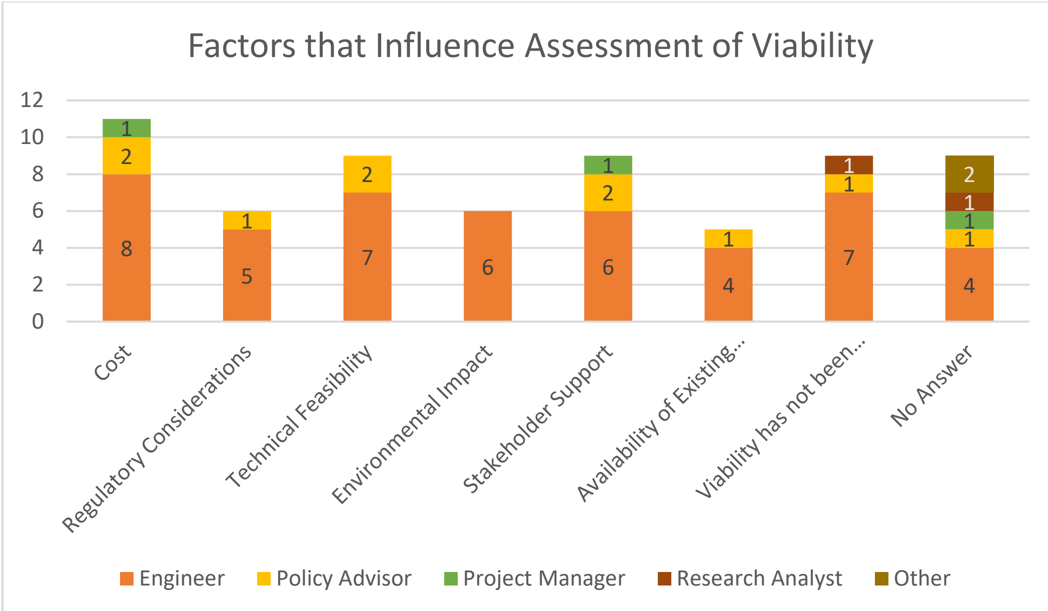


Figure 27: Importance of Factors that Influence the Assessment of Viability of CCUS Technology for DOT Projects by Role Type. (Rausch, 2025c)

5.5 Implementation Guideline

Questions 13 and 14 asked participants about the usefulness of the development of a CCUS technology implementation guideline as well as what should be included in said guideline. From Figure 28, most of the respondents (89.5%) indicated that the guideline would be moderately useful, slightly useful, or neither useful nor useless. Two respondents indicated that the guideline would be slightly useless (Senior Manager) or extremely useless (Policy Advisor). Overall, a guideline for the implementation of CCUS technology in DOT projects may be helpful, especially for engineers.

From Figure 29, cost assessments would be the best inclusion within a CCUS technology implementation guideline, with incentives for adoption following close behind. Governance structures also had some indication that it would be important to include; however, it does not have as many votes as the first two. All options given to the participants had at least 50% of the respondents agree, and there were no options added to this list.

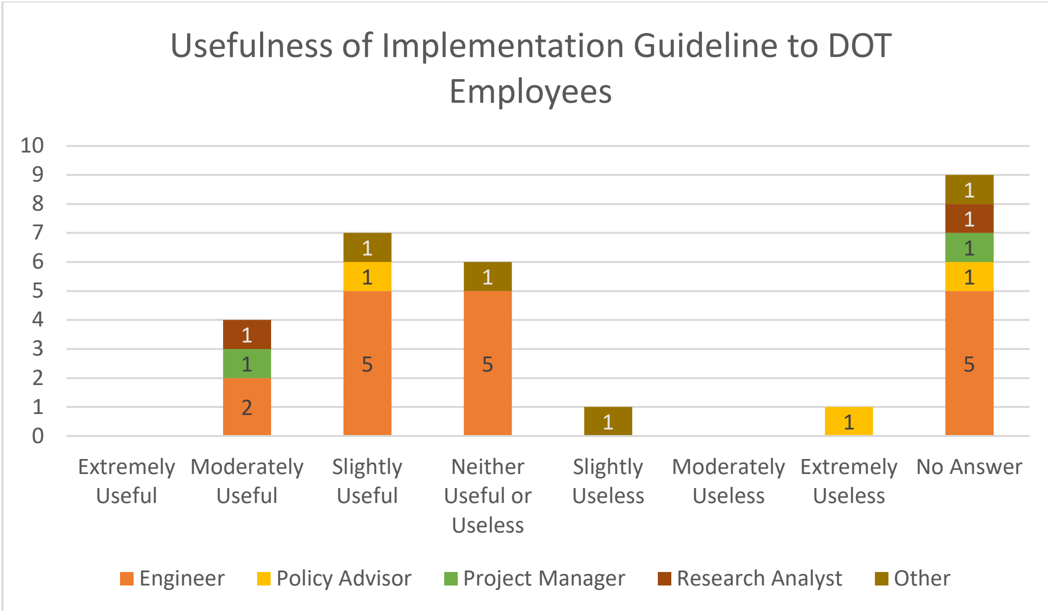


Figure 28: Usefulness of a CCUS Implementation Guideline by Role Type. (Rausch, 2025c)

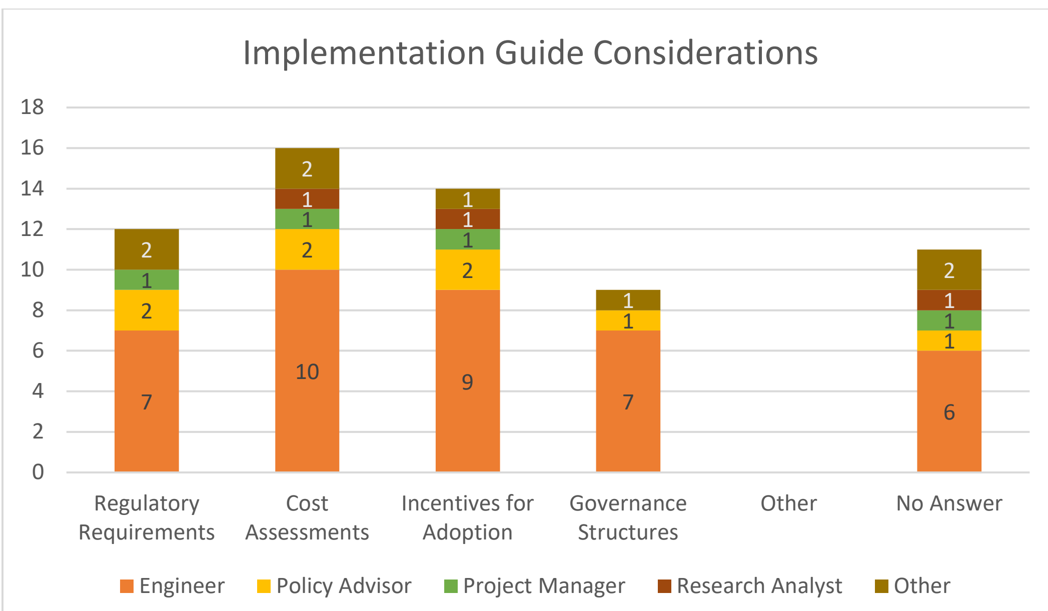


Figure 29: Implementation Guideline Considerations by Role Type. (Rausch, 2025c)

5.6 Questions for Additional Comments

Questions 15 and 16 asked if there were any additional resources that would help with understanding, analyzing the use of, and implementing CCUS technology. For understanding and analyzing the use of CCUS technology, the suggestions made by the survey participants include a comparison of the net carbon capture between

CCUS alternatives, the impact of CCUS on the environment, the cost-to-benefit ratio of CCUS alternatives, training opportunities, state or local government peer exchanges, and examples of how other DOTs have analyzed CCUS technologies. For guidance of the implementation of CCUS technologies, survey participants included the same responses as the previous question with the addition of pilot projects that include the implementation process.

Question 17 was included to allow additional information concerning CCUS in the transportation sector to be given by the participants, especially if they had something to share that wasn't asked. One participant included information about the carbon sequestration certification program run by the Oklahoma Conservation Commission; however, the Oklahoma DOT is not directly involved in any carbon capture initiatives.

5.7 Survey Results Summary

Overall, the survey collected 28 responses, one from an engineer from a federal transportation department, and 27 from state department employees, including engineers, project managers, research analysts, and policy advisors. For general CCUS applications, 52% were somewhat familiar, 15% were moderately familiar, and 33% were not familiar at all. For CCUS applications in the transportation sector, 55% were somewhat familiar, 11% were moderately familiar, and 30% were not familiar at all. 78.6% of the respondents had the same familiarity between CCUS applications in general and in the transportation sector.

When it came to knowledge about in-state initiatives for CCUS technology, three respondents (10.6%) indicated that they had some knowledge; however, only one indicated which initiative they had knowledge about. Only one respondent indicated that their DOT had done some research towards implementing CCUS technology via a small-scale research project that tested using carbon-injected concrete. Six of 28 respondents said that their agency was considering the use of CCUS technology, such as accelerated carbon mineralization, carbon utilization, and hydrogen fuel cells in MHDVs.

For best practices of CCUS implementation, all three engineers thought pilot projects were important with two agreeing that early stakeholder agreements, comprehensive risk assessments, and continuous monitoring and evaluation were important. The policy advisor only indicated that comprehensive risk assessments, interagency collaboration, and continuous monitoring and evaluation were important best practices. All respondents agreed that high cost influences the implementation of CCUS with the other choices having only 3 of the 6 agree.

70% of respondents have not analyzed the viability of CCUS technologies, while the other 30% said that CCUS technology is somewhat viable. Some factors that contribute to the assessment of viability are high cost, technical feasibility, and stakeholder support. To support the viability assessment of CCUS technology, the idea of an implementation guideline was proposed in the survey. 90% of respondents indicated that the guideline was either moderately useful, slightly useful, or neither useful nor useless Some topics that would be useful for the implementation guideline include cost assessments, incentives for adoption, regulatory requirements, and governance structures, with which 94%, 82%, 71%, and 51% of the respondents agreed respectively. Some additional suggestions made that would increase understanding, analysis, and implementation of CCUS technology include carbon capture comparison of CCUS technology, training opportunities, peer exchanges, and pilot projects from other DOTs.

Chapter 6. Guidelines for Implementing Carbon Capture, Utilization and Storage (CCUS) Technologies on TxDOT Projects

This chapter provides the direct output of Product 1 (P1) produced in this research project, “Chapter 6. Guidelines for Implementing Carbon Capture, Utilization and Storage (CCUS) Technologies on TxDOT Projects”. Since it is intended to be a standalone document, aspects of this chapter may be repeated from previous chapters. For clarity and where applicable, parentheses, e.g., [Chapter] are provided to improve readability for the purpose of including this Product into this final report.

6.0 Executive Summary

This report [Chapter] provides guidance to the Texas Department of Transportation (TxDOT) on the potential implementation of Carbon Capture, Utilization, and Storage (CCUS) technologies in transportation infrastructure projects. It synthesizes recent developments in CCUS funding, policy, and technical applications, with the understanding that many of these developments (particularly financial incentives and regulatory frameworks) are evolving rapidly and may not reflect the current state at the time of use. This report [Chapter] should be viewed as a forward-looking resource to help TxDOT prepare for and respond to emerging opportunities in CCUS deployment.

The intent is not to necessarily prescribe immediate actions but to frame how CCUS could be integrated into TxDOT projects if and when funding, policy, and market conditions are favorable. The report [Chapter] includes a lifecycle assessment (LCA) case study examining the feasibility of incorporating select CCUS technologies on a current Tx-DOT project.

The document [Chapter] outlines technical, financial, and regulatory considerations and provides a decision-making framework based on the case study to guide project-level evaluations. This document [Chapter] provides TxDOT with a practical and adaptable framework for exploring and implementing CCUS technologies in transportation infrastructure projects. Specifically, it includes:

- **An overview of CCUS technology readiness in Texas**, with a focus on material suppliers in cement, concrete, steel, and asphalt that are actively engaging in decarbonization strategies.

- **A review of CCUS-enabling infrastructure**, including CO_2 transport and storage networks that may support material production relevant to TxDOT projects.
- **Analysis of sustainability rating systems** (e.g., Envision, INVEST, Greenroads®) and how CCUS strategies align with project scoring criteria related to emissions reductions and innovation.
- **A policy-focused discussion** of federal and regional incentives (e.g., 45Q tax credits, DOE funding), along with economic and governance considerations that affect CCUS deployment.
- **Insights from a national DOT survey**, highlighting perceived barriers, best practices, and content priorities for CCUS implementation guidelines.
- **A six-step implementation framework** that guides TxDOT project teams through defining goals, selecting tools, evaluating CCUS alternatives, and integrating technologies into project delivery.

To maintain focus and applicability, the following topics are intentionally excluded from the scope of this document [Chapter]:

- **CCUS Technologies for Vehicles or Mobile Emissions.** This guideline does not explore CCUS applications for on-road or off-road vehicles, such as mobile carbon capture on freight trucks or retrofits to heavy-duty diesel fleets. These technologies are still in early stages of development and are outside the scope of materials and infrastructure-focused planning.
- **CCUS Applications for Power Generation or Oil & Gas.** While energy-sector carbon capture plays a critical upstream role, this document does not provide guidance on CCUS deployment at power plants, refineries, or enhanced oil recovery (EOR) sites. References to these projects are included only to illustrate potential synergies with material supply chains (e.g., access to CO_2 pipelines).
- **Lifecycle Analysis of Vehicle Operations.** This document emphasizes embodied carbon and material emissions, not operational GHG emissions from vehicle use (e.g., tailpipe emissions from future TxDOT-owned fleets or highway users).
- **Statewide Carbon Accounting or Net-Zero Strategy.** The guideline does not define or prescribe TxDOT's carbon reduction targets, nor does it address broader net-zero planning at the agency level. Instead, it provides tools and frameworks for evaluating CCUS options at the project level within existing policies and programs.
- **Detailed Regulatory Compliance Pathways**. While the guideline offers general insight on permitting and procurement considerations, it does not

provide exhaustive legal or environmental permitting procedures, as these are project- and location-specific.

- **Construction Fleet Electrification or Hydrogen Deployment.** Technologies such as hydrogen fuel cell equipment or electrified construction fleets are beyond the scope of this guideline, though they may align with broader decarbonization strategies.

This document [Chapter] is intended as a forward-looking resource and should be revisited as technologies mature, incentives evolve, and TxDOT's sustainability priorities advance.

6.1 Introduction

Carbon Capture, Utilization, and Storage (CCUS) refers to a suite of technologies designed to capture carbon dioxide (CO_2) emissions from industrial and energy-related processes, preventing them from entering the atmosphere, and either storing the emissions underground or repurposing them into usable products. While CCUS has been most widely applied in power generation and heavy manufacturing, its relevance is growing in sectors like transportation, particularly in reducing emissions associated with construction materials and project delivery.

Transportation infrastructure—such as highways, bridges, and transit facilities—relies heavily on carbon-intensive materials including portland-based cement, steel, and asphalt. Concrete alone accounts for approximately 5–8% of global CO_2 emissions (Nature 2021), primarily from the production of clinker in portland cement. Similarly, asphalt production and steel fabrication generate substantial greenhouse gases due to their reliance on fossil fuel-based processes. CCUS technologies offer an avenue to reduce these emissions by capturing CO_2 during material production or by substituting traditional materials with low-carbon or carbon-sequestering alternatives.

In the transportation sector, CCUS applications are emerging in several forms. For example, carbon-infused concrete technologies inject captured CO_2 into fresh concrete, where it is mineralized and permanently embedded, enhancing both strength and sustainability. Alternative binders and low-carbon cement blends like Limestone Calcined Clay Cement (LC^3) and biogenic cements made from algae also offer significant emissions reductions. Asphalt innovations include bio-based binders and warm mix technologies that lower the energy intensity of pavement materials. Steel manufacturing is also seeing early-stage applications of carbon capture, particularly in electric arc furnace systems.

Beyond materials, right-of-way (ROW) areas along transportation corridors offer opportunities for passive carbon sequestration through soil enhancements (e.g., basalt amendments) or vegetation-based solutions. In mobile applications, emerging technologies are being developed to capture CO_2 directly from vehicle exhausts—an approach that may become relevant for heavy-duty freight in the long term.

Together, these developments represent a growing toolkit for transportation agencies seeking to reduce embodied carbon in their infrastructure. As CCUS technologies mature and federal incentives expand, their integration into agency planning and procurement processes may become more viable for agencies like TxDOT to pursue cost-efficient sustainability goals.

This report [Chapter] is organized to serve as a practical implementation guideline for TxDOT and other transportation agencies evaluating how CCUS technologies can be applied in infrastructure projects. The structure is designed to guide readers from high-level context to actionable strategies:

- **Section 1 [Chapter 6.1]: Introduction.** Introduces the relevance of CCUS to transportation infrastructure and outlines the report's purpose, intended use, and scope limitations.
- **Section 2 [Chapter 6.2]: CCUS Industry Readiness in Texas.** Highlights the current landscape of material producers, CCUS technology providers, and CO_2 storage infrastructure in Texas. This section identifies entities active in decarbonization efforts in cement, concrete, asphalt, and steel.
- **Section 3 [Chapter 6.3]: Sustainability Rating Systems.** Reviews how CCUS technologies align with major infrastructure sustainability frameworks (Envision, INVEST, Greenroads®), helping TxDOT understand where CCUS supports credit-earning opportunities and project recognition.
- **Section 4 [Chapter 6.4]: CCUS Policy Considerations and Stakeholder Perspectives.** Summarizes recent federal incentives (e.g., 45Q, DOE funding), pricing policies, and economic conditions influencing CCUS adoption. It also presents findings from a national survey of DOT professionals, highlighting perceived barriers and desired components of a DOT-specific guideline.
- **Section 5 [Chapter 6.5]: CCUS Implementation Framework.** Provides a detailed, six-step process for identifying, analyzing, and selecting CCUS strategies in transportation projects: from defining goals and selecting lifecycle tools to evaluating alternatives and conducting lifecycle analysis.

- **Section 6 [Chapter 6.6]: Conclusion.** Offers a high-level summary of key findings and suggestions, emphasizing the importance of pilot projects, inter-agency coordination, and capacity building for CCUS deployment.

6.2 CCUS Industry Readiness in Texas

In order to fully realize CCUS, deployment for transportation infrastructure requires a coordinated network of entities spanning carbon capture, material manufacturing, transportation, storage, and utilization. Figure 30 provides an overview of 12 CCUS stakeholders in Texas with active deployment (e.g., beyond just research) as of 2025. The following subsections identify key entities in each part of the value chain within Texas, as well as prospective entities (i.e., those in early research phases, or prospective stakeholders with active CCUS capabilities who may enter Texas in the future).

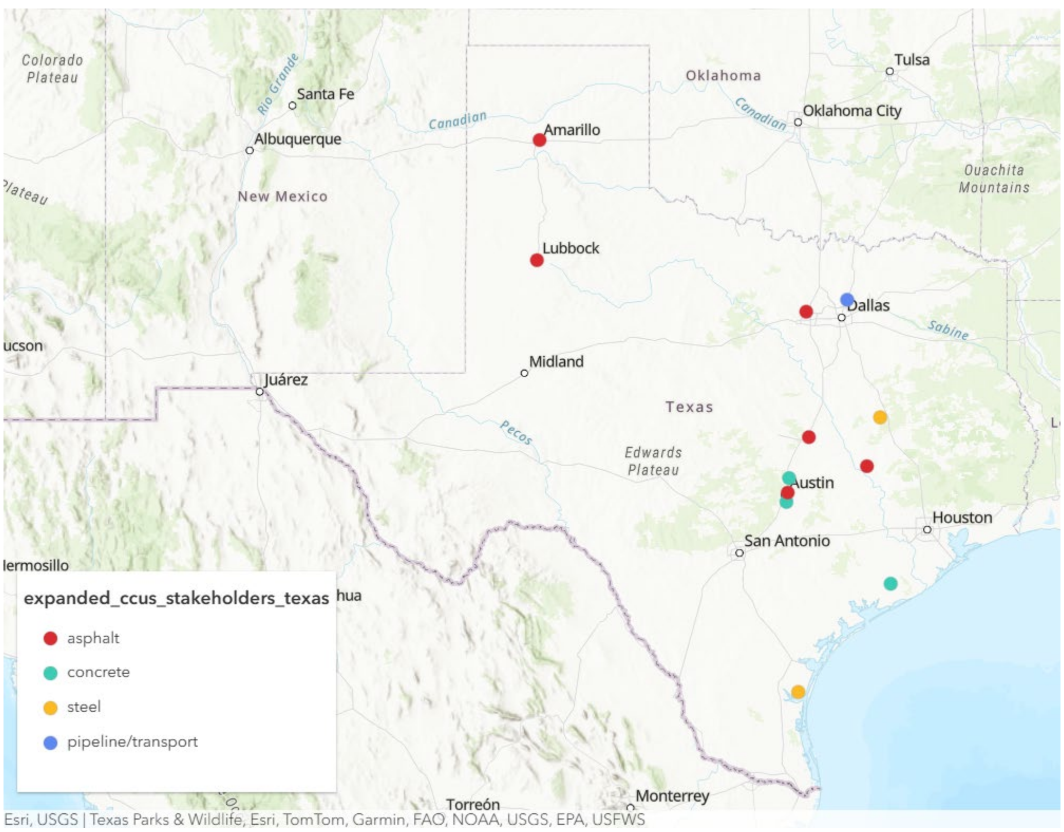


Figure 30: Map view of active CCUS stakeholders in Texas. Categories covered: asphalt, concrete, steel and pipeline/transport. Image produced in ArcGIS by the authors.

6.2.1 Material Producers in Texas

The construction of transportation infrastructure relies heavily on materials such as cement, concrete, asphalt, and steel. These industries represent both significant sources of CO_2 emissions and prime opportunities for carbon mitigation through CCUS technologies. Several material producers in Texas have already initiated steps toward decarbonization, while others show strong potential for future integration of CCUS.

6.1.1.1. Cement and Concrete

Early deployment of CO_2 utilization in concrete has been led by producers licensed to use CarbonCure Technologies. CarbonCure's process injects captured CO_2 into fresh concrete during mixing, permanently mineralizing it and increasing compressive strength (CarbonCure Technologies, 2023). Lauren Concrete, based in the Austin area, and Matagorda Concrete, serving South-Central Texas, both actively deploy this technology. These companies are supplying CO_2-mineralized concrete to municipal and transportation projects, demonstrating commercial readiness for CCUS-aligned material manufacturing (Lauren Concrete, 2023).

In December of 2020, Lauren Concrete supplied approximately 6,004 cubic yards of CarbonCure-treated concrete for the construction of the H-E-B Lake Austin store in Texas (CarbonCure, 2023). The ready-mix concrete incorporated captured CO_2 injected during mixing, which permanently mineralized into the concrete matrix without altering its performance characteristics. The mixes were designed to maintain target strengths while reducing cement content by 5%, resulting in a carbon savings of approximately 90,000 pounds of CO_2 over the project. The project served as a regional model for how CO_2 mineralization can be deployed in high-volume commercial infrastructure without requiring changes to standard construction practices (CarbonCure, 2023).

Larger producers such as Holcim US, Martin Marietta, and Cemex USA are advancing supplementary cementitious materials (SCMs) such as fly ash, slag, and blended cements to reduce clinker content. Holcim’s Midlothian plant and Martin Marietta’s Hunter facility have active R&D or SCM adoption programs. Though not yet fully integrated with carbon capture, these initiatives support long-term CCUS compatibility. Cemex, operating across Houston and Central Texas, has not publicly announced Texas-specific CCUS pilots but maintains global leadership in low-carbon cement and net-zero roadmaps (Cemex USA, 2024).

CalPortland, though with limited presence in Texas, is engaged in early testing of low-carbon binders and blended cements, positioning it as a potential partner in future CCUS deployments (NRMCA, 2023).

Texas's cement and concrete sector is demonstrating early readiness for CCUS through the use of CO_2 mineralization technologies and expanded use of supplementary cementitious materials. While direct capture is not yet widespread, the existence of companies (and pilot projects) adopting CO_2 mineralization indicates a clear trajectory toward deeper integration of CCUS across concrete production in transportation infrastructure.

6.1.1.2. Steel

Steel is an essential material in transportation infrastructure, used in bridges, guardrails, rebar, and structural systems. Traditionally, steel production has been one of the most carbon-intensive industrial processes, largely due to reliance on blast furnace technologies that use coal-derived coke as a reducing agent. However, Texas-based producers are increasingly adopting Electric Arc Furnace (EAF) technology, which emits significantly less CO_2 and is inherently more compatible with point-source carbon capture.

One of the most notable facilities in Texas is operated by Steel Dynamics, Inc. (SDI) in Sinton. This flat-roll steel mill, which began operations in 2021, is one of the most advanced EAF facilities in North America. Its facility incorporates energy-efficient equipment and automation systems, and its use of recycled scrap as the primary feedstock reduces overall emissions intensity. Although the Sinton plant does not currently integrate CCUS, its modern design and large single-point emission sources make it a strong candidate for post-combustion capture technologies. SDI has indicated long-term interest in low-carbon steel production, aligning with industry decarbonization pathways (Steel Dynamics, 2024). Nucor Corporation, another major U.S. steel producer, operates two EAF mills in Texas, located in Jewett and Longview. Nucor has long been a leader in sustainable steelmaking, consistently emphasizing circular production through recycled content and low emissions per ton of steel produced. Nationally, Nucor is investing in research partnerships focused on hydrogen-based steelmaking and CCUS retrofits for existing EAF facilities. While no Texas-specific pilots have been publicly announced, Nucor's strategic direction and the modular nature of its Texas operations suggest high potential for future integration of carbon capture systems (Nucor, 2023).

Both SDI and Nucor benefit from proximity to Texas's growing CO_2 transport and storage infrastructure, including pipeline networks operated by companies like Denbury Inc. and the planned South Texas DAC Hub. This geographical advantage could facilitate the development of capture-and-storage clusters that include steel production facilities.

Texas's steel industry demonstrates strong alignment with CCUS technologies, although current deployment remains limited. These facilities represent valuable early opportunities for scaling carbon capture within the industrial supply chain of transportation infrastructure projects.

6.1.1.3. Asphalt

Asphalt production and road paving operations contribute to greenhouse gas emissions primarily through the combustion of fossil fuels during material heating and the embodied carbon of petroleum-derived binders. While direct carbon capture technologies have not yet been widely applied to asphalt plants, the industry is progressing toward decarbonization through the use of warm-mix asphalt (WMA), bio-based binders, and technologies that could incorporate CO_2 mineralization into pavement materials.

Ergon Asphalt & Emulsions, one of the most prominent asphalt suppliers in Texas, operates multiple terminals and blending facilities across the state, including locations in Lubbock, Temple, and Saginaw. The company offers a range of WMA and emulsion products, which allow asphalt to be produced and laid at lower temperatures—reducing both fuel use and CO_2 emissions during construction. Ergon has publicly committed to developing carbon-reducing materials and has supported pilot efforts involving alternative binders (Ergon Asphalt, 2023).

Knife River Corporation also maintains a strong presence in Texas, with aggregate and asphalt operations in regions such as Bryan and Amarillo. Knife River employs warm-mix technologies in select markets and incorporates sustainability tracking into its material supply chains. While the company does not currently implement carbon capture or utilization at its asphalt plants, its materials are compatible with mineralization strategies, such as the incorporation of CO_2-reactive aggregates or binders in pavement base layers (Knife River Corporation, 2023).

Austin Materials, which operates in the greater Austin metro region, supplies asphalt and aggregates for regional transportation projects. While not currently deploying CCUS technologies, the company's facility infrastructure and market responsiveness suggest readiness for pilot projects, particularly those involving carbon mineralization in recycled pavement bases or low-carbon binder substitution. Incentives from state or federal programs could play a decisive role in accelerating such adoption.

Overall, Texas's asphalt sector is at a moderate stage of CCUS readiness. While few facilities currently deploy direct capture or utilization technologies, many are actively reducing carbon intensity through alternative production methods and materials. These strategies can serve as foundational platforms for future integration of CCUS in road construction and resurfacing projects.

6.2.2 CCUS Technology Providers Active or Emerging in Texas

Select firms offer hardware, software, or engineered processes for capturing and/or reusing CO_2 at industrial sites, including material production facilities and project construction environments.

Table 18 shows an overview of these firms, and they are depicted in terms of maturity (maturity is based on the current technology's readiness level and current plans for deployment in Texas).

Table 18: Overview of companies providing active or emerging CCUS capabilities to organizations within Texas

Company	Technology Focus	Texas Presence/Projects
CarbonCure Technologies	CO_2 mineralization in concrete	Active in Austin and Matagorda
Blue Planet Systems	CO_2-to-aggregate synthetic limestone	Exploring U.S. infrastructure pilots; no public Texas site yet
Solidia Technologies	CO_2-cured concrete	Has demonstrated interest in working with DOTs; no TX deployment confirmed
Heirloom Carbon	Direct air capture (DAC)	Partner in DAC hubs in Texas (with 1PointFive)
1PointFive (Oxy Low Carbon Ventures)	DAC and storage	Operator of South Texas DAC Hub; major player in carbon storage infrastructure
Remora	Mobile CO_2 capture for freight trucks	Not active in Texas yet
Svante	Point-source solid sorbent capture	Pilot project carbon capture plant in Texas announced in 2024

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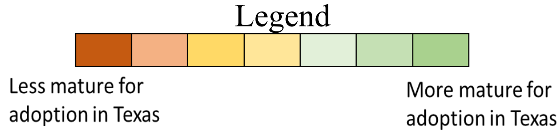

6.2.3 CO_2 Transport and Storage Infrastructure

Texas is considered to have one of the most mature carbon transport and storage ecosystems in the United States. Texas benefits from both legacy infrastructure developed for Enhanced Oil Recovery (EOR) and recent federal investments aimed at permanent geologic storage. While most carbon transport and storage initiatives in Texas are not directly tied to transportation infrastructure projects, they form a critical backbone for the state's broader CCUS ecosystem. This existing and emerging infrastructure enhances the feasibility of deploying carbon capture at material production sites (e.g., cement, steel, asphalt), which are integral to the transportation supply chain.

Denbury Inc. operates over 1,300 miles of CO_2 pipelines across the Gulf Coast, originally developed for Enhanced Oil Recovery (EOR). These pipelines connect industrial emitters to key geologic formations and could be leveraged to support permanent storage for CO_2 captured from concrete, steel, or asphalt plants used in TxDOT projects. Though not infrastructure-specific, Denbury's network lowers the barrier for regional CCUS deployment by offering transport access without the need for new right-of-way development.

Additional large-scale projects reinforce Texas's position as a national CCUS hub. 1PointFive, through its South Texas DAC Hub, is developing capture and saline storage capacity near Kingsville capable of handling over 1 million metric tons of CO_2 annually. While its primary focus is on atmospheric CO_2 removal, the supporting infrastructure could accommodate point-source emissions from industrial sectors, including transportation and material suppliers.

In summary, while these transport and storage projects are not explicitly designed for TxDOT or infrastructure-related carbon capture, they are foundational to enabling CCUS across the construction materials supply chain. Their availability and maturity significantly influence the technical and economic viability of deploying capture technologies at the production sources of cement, steel, and asphalt used in transportation projects.

6.3 Sustainability Rating Systems

Sustainable rating systems promote efficiency in projects to help contribute to greener construction. These systems achieve this goal by providing guidelines to indicate the sustainability level of a project. The sustainable rating systems discussed are the Envision rating system, Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), and Greenroads®. Table 19 provides a summary of these rating systems.

Table 19: Summary of Sustainability Rating Systems and their Application to Transportation Projects

Criteria	Envision	INVEST	Greenroads®
Purpose	Self-assessment tool that evaluates sustainability & resilience of infrastructure projects across various sectors.	Web-based self-assessment tool to help transportation agencies improve project sustainability.	Independent, third-party sustainability rating system focused on awarding points for transportation infrastructure projects.
Author	Institute for Sustainable Infrastructure	FHWA	University of Washington
Structure	Credit-based rating system with required and optional credits.	Self-evaluation framework with voluntary criteria and scoring.	Credit-based system with prerequisites and optional points.
Primary Focus Areas	Environmental, social, economic, and resilience criteria.	Sustainability in transportation planning, project development, and operations.	Environmental impact, resource efficiency, and community benefits.
Recognition Levels	Bronze, Silver, Gold, Platinum	No formal certification; used for internal agency evaluation.	Certified, Silver, Gold, Evergreen
CCUS-Specific Credits	No explicit CCUS credit, but aligns with GHG reduction, energy use, and innovation credits.	No explicit CCUS credit, but supports GHG reduction, energy efficiency, and climate resilience strategies.	No explicit CCUS credit, but aligns with carbon footprint reduction, sustainable materials, and innovation credits.

Relevant Categories for CCUS	Climate & GHG Emissions, Energy Efficiency, Innovation	Air Quality & GHG Emissions, Energy Use, Sustainable Pavements, Innovation	Lifecycle Carbon Footprint, Energy & Carbon Emissions, Innovation
Innovation Credits	Awards points for novel sustainability strategies (e.g., Innovate category).	Recognizes cutting-edge solutions that improve transportation sustainability.	Allows for Custom Credits for new sustainability practices.
Climate Resilience	Strong focus on climate adaptation and resilience.	Supports climate resilience strategies but not a primary focus.	Integrated into certain credits but no dedicated resilience category.
Carbon Footprint Reduction	Encourages low-carbon materials, energy efficiency, and emissions reduction strategies.	Supports reductions in GHG emissions, particularly in construction & operations.	Awards points for sustainable materials & lifecycle carbon footprint reductions.
Applicability to DOTs	Widely used for large-scale infrastructure projects.	Primarily used by state and local DOTs for evaluating project sustainability.	Commonly applied to roadway and transportation infrastructure projects.

6.3.1 Envision Rating System

The Envision Rating System, developed by the Institute for Sustainable Infrastructure (ISI), is a framework designed to evaluate the sustainability and resilience of infrastructure projects across various sectors, including transportation (Institute for Sustainable Infrastructure, 2021). ISI was developed by the American Public Works Association (APWA), American Society of Civil Engineers (ASCE), and American Council of Engineering Companies (ACEC). Envision awards points across multiple categories focused on environmental, social, and economic sustainability. While the system does not specifically provide points for carbon capture, utilization, and storage (CCUS) technologies, projects incorporating CCUS can contribute to higher scores in categories related to CO_2 emissions reduction, climate resilience, and innovation.

Envision recognizes projects that actively reduce environmental impacts, particularly in areas addressing GHG emissions and climate adaptation. Since CCUS technologies help lower atmospheric CO_2 levels, their integration into a transportation project could support point-earning criteria related to energy use, emissions reduction, and environmental impact mitigation. Projects that utilize low-carbon materials, renewable energy, or carbon capture solutions would align with these sustainability objectives and could earn points, particularly in the Environmental Impact category.

The Innovation category within Envision rewards projects that incorporate emerging technologies and forward-thinking strategies. CCUS, as an advanced approach to reducing carbon emissions, could be considered an innovative solution if implemented in a way that exceeds standard sustainability practices. Projects utilizing CCUS to actively capture and store carbon emissions may earn points under the Innovation and Climate Action subcategories, provided they demonstrate measurable environmental benefits.

Envision also emphasizes long-term sustainability and climate resilience. Transportation projects that integrate CCUS as part of a broader emissions reduction strategy can strengthen their overall sustainability performance by mitigating the long-term effects of carbon emissions. If a project demonstrates a proactive approach to carbon management, it may score well in categories related to climate resilience and sustainable systems.

6.3.2 FHWA's INVEST Program

The Federal Highway Administration's (FHWA) INVEST program (Infrastructure Voluntary Evaluation Sustainability Tool) is designed to help transportation agencies assess and improve the sustainability of their projects (Federal Highway Administration, n.d.). While INVEST does not explicitly reference CCUS, it provides pathways for integrating emissions reduction strategies into transportation infrastructure. One of INVEST's core focuses is reducing GHG emissions and enhancing climate resilience, which are important elements in evaluating sustainability. Projects that incorporate CCUS as part of a broader carbon reduction strategy could align with criteria related to Energy and Emissions and Environmental Stewardship by demonstrating measurable emissions reductions.

The program encourages innovation and best practices, so transportation projects implementing emerging carbon reduction technologies, such as CCUS, could align with sustainability management and environmental impact categories. However, as a self-evaluation tool, INVEST does not grant formal points or credits; instead, agencies use it to assess how well sustainability strategies contribute to overall project performance.

The Climate Change and Resilience criteria in INVEST evaluate projects on their ability to mitigate risks and adapt to climate change. While CCUS directly reduces atmospheric carbon, it would need to be part of a broader strategy that enhances infrastructure resilience to align with this category. INVEST also promotes sustainable construction practices and materials, meaning that carbon-captured materials or processes could support sustainability evaluations under Sustainable Pavements and Infrastructure Condition.

6.3.3 Greenroads®

Greenroads® is a sustainability rating system designed to evaluate the environmental, social, and economic impacts of transportation infrastructure projects (Sustainable Transport Council, n.d.). Greenroads® was started from an unfunded research project at the University of Washington, is now operated and owned by the non-profit organization Greenroads Foundation. Unlike other sustainability frameworks, Greenroads® awards points across multiple categories, including environmental sustainability, resource efficiency, and community impact. While the system does not explicitly reference CCUS, transportation agencies may integrate these technologies into broader sustainability efforts to earn points.

One of the primary objectives of Greenroads® is to reduce the environmental footprint of transportation projects, including lowering GHG emissions. Although there is no direct credit for CCUS, projects implementing low-carbon technologies or materials with reduced embodied carbon could align with credits such as Energy & Carbon Emissions (ECE-1: Lifecycle Carbon Footprint Reduction) and Materials & Resources (MR-2: Pavement Lifecycle Impact Reduction). For instance, the use of carbon-captured concrete or asphalt in transportation projects could support Greenroads® sustainability goals.

Greenroads® also recognizes innovation and best practices in sustainable transportation. The Custom Credit option allows project teams to propose new sustainability measures beyond existing criteria. If CCUS is integrated as a novel emissions reduction strategy, it may qualify under the Innovation category, provided it demonstrates significant sustainability benefits beyond standard practice.

Greenroads® emphasizes sustainable resource management, encouraging projects to minimize waste, reduce reliance on carbon-intensive materials, and adopt sustainable construction practices. If CCUS is incorporated into materials or energy processes to reduce a project's carbon footprint, it could align with credits focused on resource efficiency and emissions reductions.

Although Greenroads® does not have a standalone climate adaptation category, several credits support climate resilience and long-term environmental sustainability. Projects integrating CCUS into a larger strategy to mitigate carbon emissions and enhance environmental performance may align with credits related to stormwater management, energy efficiency, and lifecycle carbon footprint reductions. However, CCUS alone would not automatically contribute to resilience unless linked to broader climate adaptation measures within the project.

6.3.4 Summary of Sustainability Rating Systems

In summary, sustainability rating systems such as Envision, FHWA's INVEST, and Greenroads® provide structured guidance for evaluating transportation projects based on environmental and social performance. While none explicitly recognize carbon capture, utilization, and storage (CCUS) technologies, each includes criteria such as GHG emissions reduction, sustainable materials, innovation, and climate resilience where CCUS-aligned strategies may contribute to improved sustainability scores. As part of a broader decarbonization approach, CCUS can enhance a project's alignment with these frameworks, even if it is not formally credited.

6.4 CCUS Policy Considerations and Perspectives

This section provides a brief overview of the recent government policies and incentives that could be applicable for CCUS deployment. It is important to note that this section contains policies and incentives that may not currently be applicable, but are provided as part of identifying what prospective policies and incentives could look like in the future.

6.4.1 Economic Considerations for Deploying CCUS in the United States

Recent estimates for the cost of CCUS deployment within the US range from $15-$120 per metric ton captured, not including additional costs to transport and store the captured carbon dioxide (Congressional Research Service, 2023). The investment required to build a CO_2 transport network has been estimated at several billion dollars for a regional network and several hundred billion dollars for a national network. There are currently very few operational CCUS facilities in the US (only 15 as of 2023), of which nearly all provide captured CO_2 to oil facilities to aid with industrial processes. As such, it is difficult to determine the economic viability of the utilization of captured carbon from CCUS within the US outside of the specific application to oil facilities. Overall, the economic viability of CCUS depends on incentives/subsidies or novel business models for the utilization of captured CO_2 or its by-products (Hirsch & Foust, 2020).

6.4.2 Carbon Pricing

According to the Center for Climate and Energy Solution (Center for Climate and Energy Solutions, 2023), the general strategy behind carbon pricing is as follows: (1) the government sets a price which emitters pay for each ton of CO_2 produced (2) businesses are then incentivized to either switch to low carbon (alternative) fuels, or adopt new technologies with lower carbon intensity to avoid paying more taxes, and (3) necessary economic conditions are created for cap-and-trade systems, carbon credit purchases, etc.

Although the United States currently does not have a federal price on carbon, there are 37 carbon tax programs globally (see Figure 31). There are also eleven northeastern states participating in the Regional Greenhouse Gas Initiative (RGGI), which enacts local carbon policy.

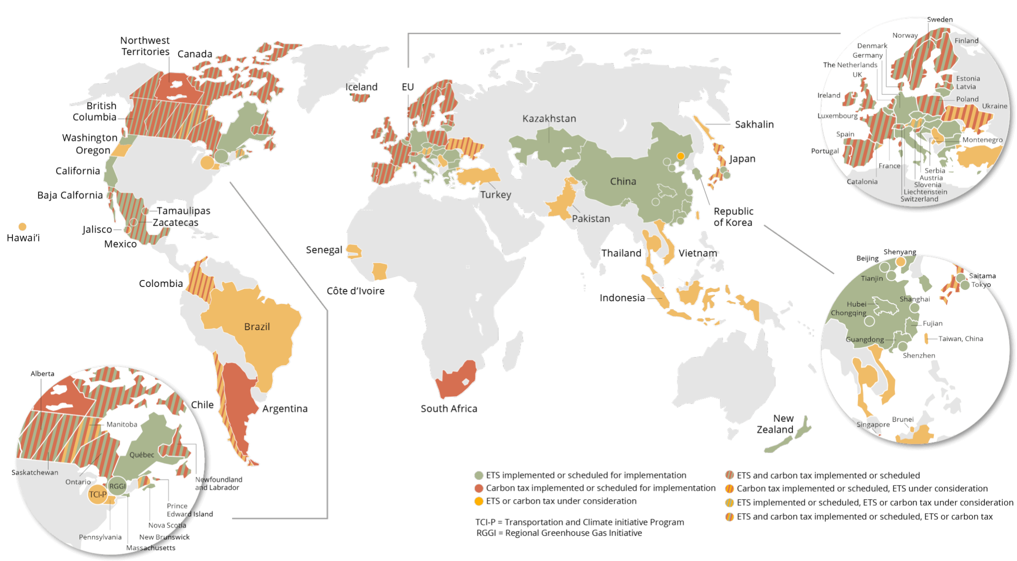

Figure 31. Carbon Pricing Implementation Globally. Source: open access through State and Trends of Carbon Pricing 2023. (World Bank, 2023)

RGGI was the first mandatory cap-and-trade carbon program in the US intended to reduce emissions from the power sector. In 2005, the governors of Connecticut, Delaware, Maine, New Hampshire, New Jersey, New York, and Vermont signed a Memorandum of Understanding (MOU) to reduce carbon dioxide emissions within the northeastern and mid-Atlantic region. In 2007, RGGI was expanded to include Maryland, Massachusetts, and Rhode Island. RGGI mandates that fossil fuel power plants with capacities over 25 megawatts secure an allowance for every ton of carbon dioxide emitted annually. Plants can meet this requirement by acquiring allowances through quarterly auctions, trades with other regional generators, or offset projects. From 2009 to 2017, RGGI states is said to have experienced a net economic gain of $4.7 billion from the program (Center for Climate and Energy Solutions, n.d.). This revenue is generated by auctioning off allowances which are sold to power plants and other entities (e.g., which functions essentially as a tax).

6.4.3 Recent CCUS Incentives in the United States

Over the past five years, federal policy and funding have significantly expanded support for carbon capture, utilization, and storage (CCUS) technologies in the United States. These incentives—ranging from tax credits to direct funding programs and market-driven financing instruments—provide critical context for understanding how transportation infrastructure projects in Texas might leverage similar mechanisms moving forward.

The Section 45Q Tax Credit remains the cornerstone federal incentive for CCUS. This tax credit provides up to $85 per metric ton of CO_2 permanently stored in geological formations, and up to $180 per metric ton for carbon removed via direct air capture (DAC). Facilities must meet minimum capture thresholds depending on their type (e.g., 500,000 metric tons/year for power plants, 18,750 for industrial sources). Projects can claim the credit for 12 years following startup, with additional bonuses available for paying prevailing wages and meeting apprenticeship requirements. Although the 45Q credit does not specifically target infrastructure construction, it can be utilized by material producers (e.g., cement plants) that serve transportation projects, helping to reduce embodied carbon across the supply chain.

U.S. Department of Energy (DOE) Programs, particularly through the Office of Clean Energy Demonstrations (OCED), have also mobilized billions in funding to support carbon management infrastructure. OCED's programs include large-scale capture demonstrations, DAC hubs, and engineering design studies that bridge the gap between early research and commercial deployment. For example, the Baytown Carbon Capture Project, led by Calpine, received $12.5 million in 2024 for Phase 1 engineering work at a natural gas plant—positioning it as a potential future supplier of low-carbon energy to industrial users. Similarly, the South Texas DAC Hub, backed by 1PointFive and awarded $50 million, will remove and permanently store CO_2 captured from ambient air, supporting regional carbon removal goals. While these projects are not directly integrated with transportation infrastructure, they offer critical upstream support for decarbonizing the materials and fuels that TxDOT projects rely on. DOE funding opportunities continue to evolve, including new Notices of Intent (NOIs) for large-scale point-source capture pilots and DAC commercialization. These announcements signal the federal government's ongoing commitment to scaling CCUS networks—particularly in regions like Texas with existing pipeline infrastructure and geologic storage capacity. Future calls are expected to further incentivize integrated carbon management clusters that could support the transportation sector indirectly by reducing emissions from concrete, steel, and asphalt producers.

Finally, green bonds represent a complementary financial mechanism for funding environmentally focused infrastructure. These debt instruments are used by corporations and municipalities to raise capital for sustainability-aligned projects, following voluntary frameworks like the Green Bond Principles (U.S. Department of Energy, 2023) and Climate Bonds Standards (Climate Bonds Initiative, n.d.). Though not CCUS-specific, green bonds could be used by cities or agencies to fund infrastructure projects that incorporate low-carbon materials produced using CCUS. Their increasing popularity (e.g., more than $50 billion issued in the U.S. in 2019 alone) suggests a growing appetite for market-based approaches to climate-aligned investment in public works.

Together, these incentive mechanisms form a policy and funding landscape that, while not always infrastructure-specific, lays a strong foundation for reducing emissions in the transportation construction sector. Whether through direct capture at industrial plants or by financing cleaner materials and processes, these tools can help transportation agencies and their supply chain partners align with emerging climate goals.

6.5 Current CCUS Adoption and Perspectives Among DOTs

A national survey was conducted by the project team to assess the current awareness, adoption, and perceived barriers to CCUS technologies among transportation agency professionals. A total of 61 responses were received, with 28 responses included in the final analysis based on completeness (i.e., respondents answered at least three substantive questions).

The survey results offer practical insight into the readiness of state and federal DOTs to adopt CCUS strategies and highlight what elements could be prioritized in a TxDOT implementation guideline. Four key findings emerged from this survey which are summarized below based on their relevance to successful deployment of CCUS technology on transportation projects. These findings have been incorporated into the proceeding section, which outlines a high-level decision framework for deploying CCUS technology on DOT projects.

Finding 1: Implementation Barriers Focus on Cost, Technical Uncertainty, and Limited Experience. The top barriers to CCUS adoption identified by respondents were:

- High implementation cost
- Technical feasibility concerns
- Limited stakeholder support
- Lack of pilot projects or performance data
- Uncertainty around regulatory approval or material specifications

Only one DOT reported prior research or field testing with a CCUS-related material (CO_2-injected concrete).

Implication for Guidelines: Address these concerns by including:

- Cost range estimates
- Regulatory and procurement guidance
- Pilot project pathways and sample evaluation metrics

Finding 2: Pilot Projects and Clear Guidance Are Seen as Essential Enablers. Pilot projects were cited as the most important best practice for supporting CCUS adoption, particularly among engineers. Other key enablers included:

- Early stakeholder engagement
- Risk assessments and evaluation frameworks
- Clear roles and governance structures

Implication for Guidelines: Include a step-by-step template for identifying, scoping, and monitoring CCUS pilot projects within DOT workflows.

Finding 3: Strong Demand for a Structured Implementation Resource. Approximately 90% of respondents found a CCUS implementation guideline to be moderately, slightly, or at least somewhat useful. The most requested content included:

- Cost assessments and economic considerations
- Available incentives or funding (e.g., 45Q tax credit, DOE programs)
- Regulatory pathways and technical standards
- Governance models for implementation

Implication for Guidelines: Ensure these content areas form the core structure of the guideline, and that guidance is presented in a way that can support project planning, procurement, and reporting.

Finding 4: Need for Supporting Tools and Training. Respondents expressed interest in:

- Peer agency examples
- Lifecycle comparisons between CCUS strategies
- Training opportunities or workshops
- Workflow templates for implementation

Implication for Guidelines: Include references or links to additional resources, case studies, and tools. Suggest next steps for training or agency knowledge-building efforts.

The survey findings confirm strong interest in CCUS across the transportation sector but also point to major gaps in cost clarity, technical feasibility, and regulatory familiarity. TxDOT's implementation guidelines could directly respond to these needs by providing:

- Cost and feasibility analysis tools
- Pilot project frameworks
- Procurement and regulatory guidance
- Access to peer learning and training resources

These components will enable TxDOT and its partners to make informed decisions and advance CCUS integration in transportation infrastructure projects.

6.6 Implementation Framework

To integrate Carbon Capture, Utilization, and Storage (CCUS) effectively into transportation infrastructure projects, project teams should adopt a methodical and scalable decision-making framework. This framework ensures that CCUS strategies are aligned with project sustainability goals, feasible within the delivery timeline, and quantifiably beneficial from an environmental and economic perspective. The following steps outline this structured approach.

Our project team has compiled a series of suggested steps as shown in Figure 32 – each of which are expanded upon in the following subsections.

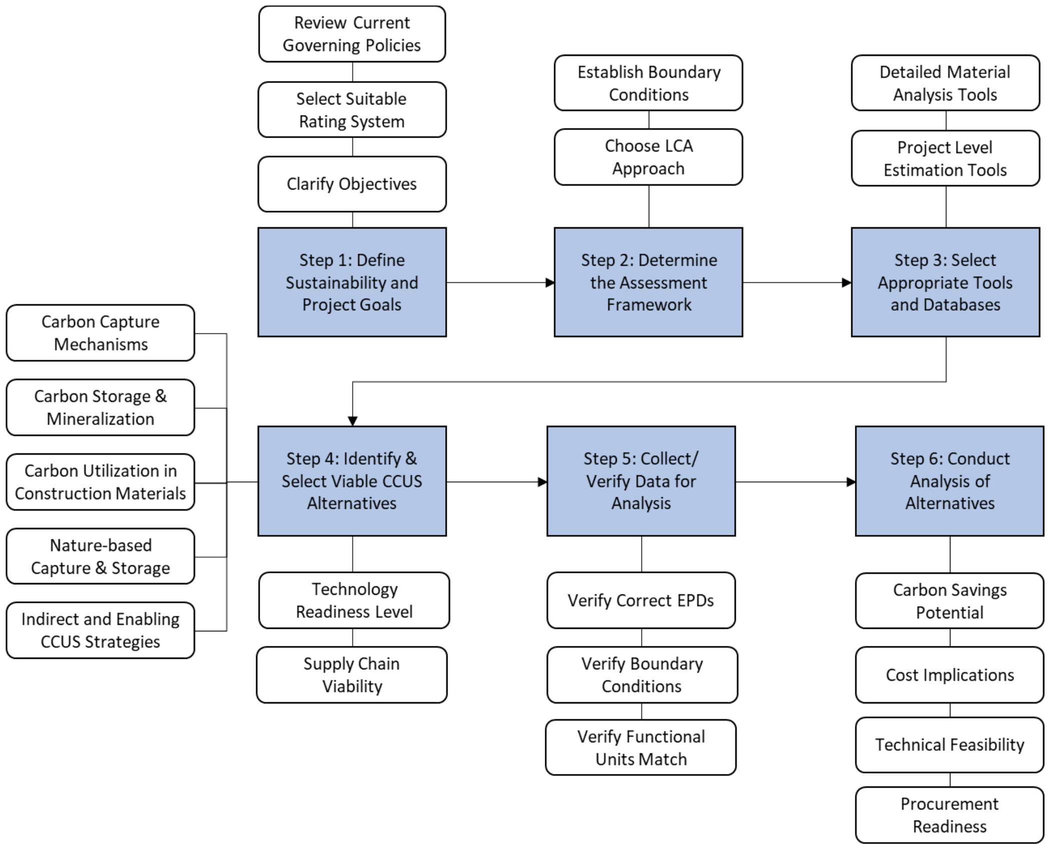

Figure 32: CCUS Implementation Framework for Transportation Infrastructure Projects

6.6.1 Step 1: Define Sustainability and Project Goals

The foundation of a successful CCUS implementation effort begins with a clear identification and understanding of the overall sustainability and project goals. Stakeholders should determine the primary objectives that CCUS strategies are expected to support—whether that be reducing embodied carbon, meeting agency-wide net-zero targets, enhancing lifecycle resilience, or qualifying for carbon-related funding programs.

During this stage, it is also important to review current or pending policies that may govern or drive decision making in the project regarding sustainability. Not only should policy be reviewed for each project, but it is also suggested that the implementation framework be updated to be consistent with the national and state policies surrounding CCUS technologies.

Early in the planning phase, it is important to identify the relevant sustainability frameworks or rating systems that will guide project-level decisions. Systems such as Envision, FHWA's INVEST, or Greenroads® provide structured guidance on emissions reduction, materials optimization, and climate resilience—often with specific credit categories that CCUS strategies can help fulfill (e.g., Envision CR1.1 "Reduce Embodied Carbon"). Please refer to Chapter 3 for more information about these specific Rating Systems.

This step also includes clarifying:

- Performance metrics (e.g., kg CO_2e per lane-mile, carbon intensity of materials)
- Regulatory or funding requirements
- Scope of influence—whether CCUS decisions are limited to materials procurement or if they can also be extended to operations, maintenance, or contractor selection

Establishing these goals upfront allows subsequent steps to align CCUS strategies with project priorities, procurement constraints, and environmental reporting requirements. This alignment helps ensure that the selected CCUS interventions are both impactful and implementable.

6.6.2 Determine the Assessment Framework

Once project goals are clearly defined, the next step is to establish a rigorous and transparent assessment framework that will guide how potential CCUS strategies are evaluated. This involves selecting the appropriate type of life cycle assessment (LCA) and defining the boundary conditions and scope of analysis. These decisions ensure consistency across alternatives and allow meaningful comparisons of carbon performance and co-benefits.

The first decision is choosing between an Attributional LCA (aLCA) or a Consequential LCA (cLCA). An attributional LCA is the most common for infrastructure projects and is used to quantify the environmental impacts associated with a specific product or system under current conditions. It is particularly well-suited for comparing CCUS-enhanced materials such as CO_2-injected concrete or carbon-storing aggregates against conventional alternatives. In contrast, a consequential LCA considers broader system-wide impacts that result from changes in demand or policy, such as shifts in supply chains, market uptake, or regional carbon dynamics. While less common in project-level evaluations, cLCA may be appropriate when modeling longer-term or large-scale implementation of CCUS strategies, such as statewide procurement shifts or decarbonized supply chains.

Next, the boundary condition of the LCA must be defined. Cradle-to-gate assessments include emissions from raw material extraction through manufacturing and delivery to the project site. Cradle-to-site boundaries extend this to include transport to and placement at the construction site. Cradle-to-grave assessments encompass the full lifecycle, including use-phase impacts, maintenance, rehabilitation, and end-of-life treatment or disposal. For most CCUS alternatives used in transportation infrastructure—such as mineralized concrete, CO_2-sequestering aggregates, or soil stabilization with carbon-reactive binders—a cradle-to-site or cradle-to-grave boundary is suggested to fully account for both immediate emissions reductions and the potential long-term carbon storage or durability benefits of the material.

However, it is important to ensure that when comparing alternatives, particularly those that address embodied carbon (e.g., through material substitution or carbon mineralization) versus operational carbon (e.g., mobile carbon capture or fuel substitution), the temporal and spatial boundaries are aligned and compliant. Mismatched boundaries—for example, comparing cradle-to-gate impacts of a cement mix with cradle-to-grave savings from vehicle decarbonization—can distort decision-making and misrepresent the relative benefits of each option.

Finally, projects should specify the impact categories to be tracked. While Global Warming Potential (GWP, typically in kg CO_2e) remains the primary focus for CCUS assessment, it may also be appropriate to include categories such as water use, acidification, or resource depletion, depending on project priorities and regulatory expectations.

By establishing a robust and transparent assessment framework early in the decision process, agencies can ensure that CCUS strategies are evaluated consistently and credibly across a range of design, procurement, and policy contexts.

6.6.3 Step 3: Select Appropriate Tools and Databases

With the assessment framework in place, the next step is to identify the appropriate tools and supporting data sources to evaluate CCUS alternatives. Tool selection should reflect the scale of analysis (project-level vs. material-specific), the lifecycle boundaries established in Step 2, and the data resolution required to support credible comparisons. Tools generally fall into two categories: 1) project-level estimation tools for high-level screening, and 2) detailed material evaluation tools for mix-level or product-level analysis.

6.1.1.4. Project-Level Estimation Tools

These tools are designed to provide broad carbon impact estimates for entire transportation projects, and are most useful during planning, feasibility assessment, or early-stage sustainability analysis. They enable rapid scenario comparisons and are well-suited for evaluating the potential scale of impact of integrating CCUS strategies (such as low-carbon materials or soil-based carbon sinks) across full project scopes.

FHWA's Infrastructure Carbon Estimator (ICE): Offers high-level, lifecycle GHG emissions estimates for highways, bridges, and other infrastructure projects. ICE uses national average inputs for materials, construction activities, and vehicle operation. It is useful for identifying project-level carbon baselines and estimating the order-of-magnitude effects of CCUS interventions.

There are two modes offered in the ICE tool, planning and project. Planning mode allows the user to estimate GHG emissions for multiple types of infrastructure at once, while the project mode only allows for the estimation of one type of infrastructure. Planning is best for a quicker, high-level estimation of an infrastructure project; however, it has no options for customization. While some of the infrastructure types are the same in project and planning mode, some infrastructure types, such as bridges and overpasses, in project mode have customization options to better estimate the GHG emissions. Project mode also has the option to walk the user through the steps of the analysis done by the tool.

Each infrastructure type has different inputs needed to complete the analysis. Generally, the tool needs information that relates to the quantity and size of the infrastructure components. For example, the roadway analysis calls for the roadway type, length, and width. The vehicle operation analysis is a bit different, as the inputs needed include the vehicle miles traveled (VMT) for both the opening year and the last year of project analysis. These inputs are very generalized, so the tool does not consider projects that need more or less material than average or projects that have specialized requirements that may add to the GHG emissions.

The ICE tool allows the user to choose from several mitigation strategies, such as in-place roadway recycling or alternative fuel usage, to get an idea of how these strategies will decrease the GHG emissions within a project. These mitigation strategies do not include newer CCUS technologies, such as CO_2 injected concrete, so these newer strategies may have to be analyzed separately.

Since this tool has the capability of analyzing the lifecycle GHG emissions, it is imperative to understand which emissions are embodied (i.e., emissions from materials) and operational (i.e., emissions from vehicle operations), as embodied carbon impacts the project once, while operational carbon impacts the project continuously. The tool assumes that the user understands this difference and does not provide a distinction.

These tools typically rely on generalized default data and are not intended for detailed procurement or specification decisions. However, they are valuable for screening multiple CCUS scenarios, assessing policy-level impacts, or informing early design choices.

6.1.1.5. Detailed Material Evaluation Tools

For projects that require granular analysis of CCUS-enhanced materials, detailed tools are needed to assess product-specific environmental performance. These tools support cradle-to-gate, cradle-to-site, or cradle-to-grave analysis of individual construction components, often based on mix designs, product formulations, or supplier-specific inputs.

LCA Pave: Developed by FHWA, this tool provides lifecycle environmental impacts for pavement systems based on detailed input parameters such as material thickness, traffic load, and maintenance schedules. It is especially useful for evaluating the benefits of CCUS-integrated concrete and asphalt solutions (e.g., mineralized binders or bio-based additives) over time.

This tool provides a project-level life cycle analysis to aid in assessing, quantifying, benchmarking, and communicating the environmental impacts of a pavement system. Other potential detailed evaluation tools to consider include OpenLCA, SimaPro, and GaBi. These full-featured LCA platforms allow for customized modeling of complex supply chains, emerging CCUS technologies, and novel material systems. They are ideal for evaluating materials or strategies that do not yet have publicly available EPDs and for conducting uncertainty or sensitivity analysis. They can also be used to simulate carbon removal or storage mechanisms under multiple boundary conditions.

Regardless of which detailed LCA tool is selected, it is critical to note that success depends on access to reliable and properly scoped input data. This includes:

- Product-specific EPDs that reflect appropriate functional units and boundary conditions
- Life Cycle Inventory (LCI) databases such as Ecoinvent or the U.S. LCI Database
- Vendor-supplied data for novel materials not yet captured in public databases

By selecting the right combination of tools and databases, project teams can ensure that CCUS alternatives are assessed with analytical rigor and contextual relevance, supporting both early-stage screening and final design or procurement decisions.

6.6.4 Step 4: Identify Viable CCUS Alternatives

The next step is to identify a range of viable CCUS alternatives that align with project goals, infrastructure type, and local implementation conditions. Rather than focusing on a single technology or product, this step involves categorizing potential CCUS strategies into meaningful groups, enabling project teams to compare functionally similar options and tailor solutions to the transportation context. Each category includes considerations for technology readiness level (TRL) and supply chain viability, which are essential for determining real-world feasibility and integration potential.

The five primary categories of CCUS alternatives applicable to transportation infrastructure are:

1. **Carbon Capture Mechanisms.** These are front-end technologies that capture CO_2 from industrial sources (e.g., cement plants, steel mills) or ambient air. The captured carbon can then be stored or utilized downstream in infrastructure materials.
   - Examples: Post-combustion capture from cement kilns, oxy-fuel combustion, chemical looping, Direct Air Capture (DAC), Mobile Carbon Capture (MCC)
   - TRL: Medium to High (6–9), depending on system maturity and scale
   - Supply Chain Viability: Often requires upstream coordination with material producers; practical primarily for suppliers already engaged in emissions reduction efforts. MCC may have future potential for on-site use in construction fleets, but is not yet mature.

2. **Carbon Storage and Mineralization**. These technologies store CO_2 in stable mineral forms, often by injecting it into concrete or aggregates during production. In transportation projects, this enables carbon sequestration through everyday construction materials.
   - Examples: CO_2 mineralized concrete (e.g., CarbonCure), synthetic limestone aggregate (e.g., Blue Planet), geopolymers, basalt-enhanced soil stabilization, reactive fill layers in ROW
   - TRL: High for concrete injection (8–9); medium for newer storage media and soil applications
   - Supply Chain Viability: Readily available through select concrete producers; implementation depends on material spec flexibility and supplier capabilities in the target region

3. **Carbon-Utilizing Construction Materials**. These are building products that incorporate CO_2 during manufacturing or rely on carbon-storing natural inputs. They can functionally replace conventional materials while delivering carbon mitigation benefits.
    - Examples: Biochar-modified aggregates, CO_2-cured blocks, hempcrete, bio-asphalt binders
    - TRL: Medium to High, depending on maturity and standardization
    - Supply Chain Viability: Some solutions have limited regional availability or are not yet AASHTO/ASTM-approved. Integration may require performance testing or alternate bid pathways. Useful for pilot programs or sustainability scoring credits.

4. **Nature-Based Capture and Storage**. These strategies enhance natural carbon sinks along the transportation right-of-way or within broader infrastructure corridors. While not embedded in materials, they can be integrated into the project footprint to increase overall carbon capture.
    - Examples: ROW afforestation, enhanced weathering with minerals like olivine or wollastonite, biochar soil amendments, green infrastructure
    - TRL: Mixed—high for afforestation and biochar; low to medium for enhanced weathering
    - Supply Chain Viability: Dependent on land availability, permitting, and maintenance capacity. These strategies are best suited to rural or corridor-scale projects with room for ecological integration.

5. **Indirect and Enabling CCUS Strategies**. These alternatives reduce carbon emissions indirectly or support CCUS deployment through supply chain decarbonization. They may not store CO_2 themselves but offer substantial lifecycle reductions in embodied carbon or facilitate future CCUS adoption.
    - Examples: Low-carbon blended cements (e.g., LC3), electric recycled cement, decarbonized lime for stabilization, hydrogen DRI steel, SCMs produced with CO_2 curing or mineralization
    - TRL: Medium to High; many are commercially available but not widely adopted
    - Supply Chain Viability: Often available through progressive suppliers; may require revisions to specs or mix design submittals. Attractive for agencies with decarbonization mandates or Buy Clean requirements.

As part of this step, project teams should create a preliminary shortlist of CCUS strategies aligned with their infrastructure type (e.g., roadway, bridge, rail), geographic location, procurement approach, and risk tolerance. Alternatives should then be advanced to Step 5 for data collection and Step 6 for comparative evaluation. This categorical structure not only supports clearer tradeoff analysis but also facilitates communication with contractors, material suppliers, and sustainability reviewers.

6.6.5 Step 5: Collect and Verify Data for Analysis

Once a set of viable CCUS alternatives has been identified, the next critical step is to collect, curate, and verify the environmental data required for robust evaluation. The credibility of any CCUS comparison hinges on the quality, consistency, and appropriateness of the underlying data—particularly as it relates to lifecycle carbon impacts. This step focuses on ensuring that all data sources are functionally comparable, bounded correctly, and aligned with project goals.

At the core of this data collection effort is the verification of Environmental Product Declarations (EPDs). EPDs provide standardized, third-party-verified information on the environmental performance of construction materials and are typically governed by Product Category Rules (PCRs). However, not all EPDs are directly comparable and there are three key dimensions that must be carefully verified:

1. **Verify Functional Units**. Ensure that all EPDs report impacts using the same functional unit, such as:
   - Per 1 cubic meter of concrete
   - Per metric ton of cement or asphalt binder
   - Per square yard-inch of pavement layer. Comparisons across differing functional units (e.g., comparing 1 ton of cement to 1 m^3 of finished concrete) can result in invalid conclusions. All material comparisons must be functionally normalized.

2. **Verify Boundary Conditions.** Confirm that all data sources share consistent system boundaries, such as:
   - *Cradle-to-gate*: Includes raw material extraction through product manufacturing
   - *Cradle-to-site*: Includes transport and placement at the construction site
   - *Cradle-to-grave*: Includes use-phase, maintenance, and end-of-life impacts

     For many CCUS-enhanced materials—especially those that involve durability improvements or long-term carbon sequestration—cradle-to-site or cradle-to-grave boundaries are preferred to fully capture environmental benefits. It is especially important when comparing embodied decarbonization strategies (e.g., mineralized concrete) to operational carbon strategies (e.g., mobile capture or soil amendments) that boundary alignment is maintained.

3. **Verify EPD Relevance and Source Quality**:
   - Use regionally appropriate EPDs (e.g., supplier-specific or North American datasets for U.S. projects)
   - Check the publication year and ensure the EPD is valid and based on an up-to-date PCR
   - Confirm that the EPD reflects typical or representative products used in the proposed design.
     For novel CCUS materials without available EPDs, teams should request supplier-specific lifecycle inventories (LCIs) or use trusted databases (e.g., Ecoinvent, USLCI) to model impacts.

In addition to these verifications, it is also important to capture and document the following:

- Material sourcing distances and transport modes, as these influence emissions and may differ between conventional and CCUS-enabled products.
- Energy sources and carbon intensity of manufacturing processes, particularly when electric equipment, DAC, or hydrogen inputs are involved.
- Performance characteristics that affect service life, structural requirements, or maintenance intervals (e.g., strength gain from mineralization or improved durability from CO_2 curing).

By verifying EPD integrity, boundary alignment, and functional unit consistency, project teams ensure that CCUS alternatives are evaluated using credible comparisons. This step provides the analytical foundation for defensible decision-making in Step 6.

6.6.6 Step 6: Conduct Analysis of Alternatives

With all CCUS options identified and verified data curated, the next step is to conduct a comparative analysis of alternatives. The goal of this step is to move from data collection to decision-making by evaluating how each CCUS strategy performs across key environmental, economic, and implementation criteria. This structured analysis allows agencies to identify the most appropriate and impactful solutions for the specific context of the transportation project. A robust analysis of alternatives should include the following components:

1. **Environmental Performance**. At the core of the evaluation is a comparison of carbon reduction potential across alternatives, based on consistent functional units and boundary conditions established in Steps 2 and 5. Project teams should quantify:
    - Total lifecycle GHG emissions (kg or tons CO_2e)
    - Relative reduction compared to baseline materials or practices
    - Additional environmental indicators if relevant (e.g., energy use, water consumption, acidification)

   Results should be presented both in absolute terms and as percent reductions, allowing decision-makers to easily distinguish high-impact strategies. When feasible, normalize emissions data by project scope (e.g., per lane-mile, per m^3 of concrete placed) to facilitate integration with sustainability rating systems or grant documentation.

2. **Cost Considerations**. Estimate the cost implications of each CCUS option, accounting for:
    - Material unit costs and any price premiums associated with CCUS modifications
    - Delivery and logistics costs, particularly for materials sourced from outside the typical regional supply chain
    - Installation or operational costs, including specialized equipment or training
    - Potential cost offsets, such as eligibility for tax credits (e.g., 45Q for sequestration), emissions reduction incentives, or green procurement preference programs

3. **Technical Feasibility**. Assess whether each alternative can be implemented using current design standards, construction methods, and quality assurance/quality control (QA/QC) protocols. Key considerations include:
    - Compliance with AASHTO, ASTM, or project specifications
    - Contractor familiarity and constructability
    - Availability of field performance data or case studies
    - Testing or certification requirements for approval
    - CCUS options that require minimal deviation from standard practice may have a lower barrier to adoption and greater acceptance among contractors and inspectors.

4. **Procurement Readiness and Supply Chain**. Evaluate the practical availability and readiness of supply chains to deliver the proposed CCUS strategy. This includes:
    - Supplier capacity and regional coverage
    - Availability of EPDs or documentation needed for compliance or certification
    - Compatibility with existing procurement pathways (e.g., DOT-approved materials lists, alternate bid structures)

    Consider whether the option is already in commercial use, undergoing pilot deployment, or still in R&D. High-performing strategies with low market readiness may require further evaluation or phasing.

6.7 Summary of Implementation Guideline

This document [Chapter] provides TxDOT with a structured, step-by-step framework to begin evaluating and deploying CCUS technologies in appropriate infrastructure contexts. It synthesizes technical data, market readiness, policy drivers, and industry perspectives to help guide early decision-making, while acknowledging that widespread deployment will depend on continued innovation, cost reductions, and supportive policy environments.

While CCUS is not yet standard practice in transportation infrastructure, the groundwork is being laid through advancements in low-carbon concrete, alternative binders, CO_2 mineralization, and nature-based solutions. Early action through pilot projects, procurement updates, and cross-sector coordination can help shape the supply chain, reduce risk, and prepare the agency for future business opportunities.

Looking ahead, the success of CCUS implementation will require ongoing collaboration with material producers, researchers, regulators, and TxDOT districts to adapt to evolving technologies and funding mechanisms. This guidance serves as a starting point for that journey, providing the tools, frameworks, and insights necessary to consider lower-carbon transportation infrastructure.

Chapter 7. Conclusions

This research presents a comprehensive assessment of Carbon Capture, Utilization, and Storage (CCUS) technologies and their potential application in transportation infrastructure, with a specific focus on potential future operational and sustainability objectives. Through technical reviews, material assessments, lifecycle case studies, a national survey, and the development of an implementation guideline, the research provides a roadmap for integrating CCUS strategies into project-level decision-making.

7.1 Cross-Industry CCUS Technologies (Chapter 2)

A wide array of carbon capture approaches exists, including direct (e.g., pre-combustion, post-combustion, direct air capture) and indirect methods (e.g., afforestation, enhanced weathering, BECCS). These methods vary in readiness, scalability, and suitability for transportation projects. Material technologies, such as solid sorbents and calcium looping, offer mid-level readiness, while post-combustion with amines and some DAC processes (e.g., Climeworks' Mammoth plant) are already operational at scale.

Storage techniques such as geological injection into saline aquifers or depleted oil fields are proven and in active use, though public acceptance and monitoring challenges remain. Mineral carbonation, terrestrial storage, and carbon utilization (e.g., converting CO_2 into fuels or building materials) offer scalable but often energy-intensive alternatives. Many of these processes offer dual benefits such as product creation or enhanced soil fertility but require targeted integration to be economically viable.

7.2 Transportation Sector-Specific Applications (Chapter 3)

CCUS-relevant technologies that align with TxDOT’s project types include:

- CO_2-mineralized concrete (e.g., CarbonCure, Solidia),
- Supplementary Cementitious Materials (SCMs) such as fly ash and slag,
- Low-emissions asphalt mixes (e.g., WMA and recycled asphalt),
- Carbon-injected aggregates,
- And advanced steel production with reduced emissions.

Many of these materials are commercially available, and some are already in limited use within the U.S. transportation sector. Chapter 3 also outlined how carbon utilization in concrete curing or SCM substitution can lower emissions without requiring changes to TxDOT design standards or specifications.

7.3 Lifecycle Analysis (Chapter 4)

A high-level case study was conducted on the I-35 CapEx South project to assess the emissions impact of five CCUS-aligned alternatives, including concrete-based and ROW-based strategies. The LCA found that some materials (e.g., SCM-blended concrete) can reduce carbon emissions by over 20% compared to the baseline. However, others (e.g., biogenic ROW solutions) were less impactful or data-limited. The study emphasized that meaningful emissions reductions are achievable without significant cost increases, especially when using already-approved materials or those supported by EPDs and LCAs.

7.4 DOT Stakeholder Feedback (Chapter 5)

A national survey of DOTs conducted by the project team revealed that most agencies are still in the early stages of CCUS exploration. While awareness of key technologies is growing, implementation remains limited by cost, regulatory uncertainty, and lack of performance data. Respondents expressed interest in pilot projects, guidance documents, and case studies—highlighting a key opportunity for TxDOT to play a leadership role in advancing adoption.

7.5 Implementation Framework (Chapter 6)

The final guideline synthesized findings from literature, case studies, and survey results into a practical implementation tool. The framework outlines how TxDOT can:

- Identify CCUS-aligned materials and practices,
- Evaluate project-specific emissions reductions using lifecycle tools,
- Align procurement with sustainability goals,
- And prioritize solutions that are cost-effective, scalable, and TRL-ready.

This chapter serves as the actionable core of the report, translating research into practical steps for project teams, contractors, and material suppliers.

7.6 Value of Research Summary

Project 0-7231 was developed to evaluate the feasibility and practical considerations of integrating Carbon Capture, Utilization, and Storage (CCUS) technologies into transportation infrastructure. While current adoption of CCUS in highway and public infrastructure remains limited, this project provides strategic positioning for TxDOT in the event that future federal or state policies, funding incentives, or sustainability requirements prioritize CCUS deployment.

Rather than immediate implementation, the primary value of this research lies in the foundational knowledge and readiness framework it establishes, enabling TxDOT to respond efficiently and credibly if CCUS is elevated as a policy or regulatory priority.

To assess the value of research, three core functional areas were identified: Level of Knowledge, Management and Policy, and Environmental Sustainability (Table 20).

Table 20: Functional Areas of Project 0-7231

Benefit Area	**Qualitative**	**Economic**	**Both**	**TxDOT**	**State**	**Both**
Level of Knowledge	X			X		
Management and Policy	X			X		
Environmental Sustainability	X			X		

The qualitative benefits related to the performance of this project are summarized as follows:

<u>Level of Knowledge</u>

Project 0-7231 developed a structured, evidence-based knowledge base on CCUS technologies and their relevance to transportation infrastructure:

- Created a comprehensive technology review aligned to the transportation sector, including material-focused solutions (e.g., CO_2-injected concrete, SCMs, basalt aggregates) and emerging technologies (e.g., mobile carbon capture).
- Delivered an LCA modeling framework that quantifies the embodied carbon impact of various CCUS strategies using TxDOT project data, enabling future life cycle comparisons under new procurement or permitting guidelines.

- Identified regional and project-level barriers (e.g., SCM availability, TX-specific soil conditions, retrofit compatibility), enabling targeted research and pilot planning if policies drive adoption.

Strategic Benefit: TxDOT can be equipped with baseline technical competence to act quickly and credibly in the event of new legislative mandates, executive orders, or market signals that incentivize CCUS integration.

Management and Policy

The project provides implementation pathways and decision-making support tools that align with evolving state and federal frameworks:

- Developed a decision matrix for evaluating CCUS suitability based on project type, carbon reduction potential, and cost-effectiveness, which is useful if future regulations require carbon footprint accounting.

- Outlined a governance and funding strategy, including how CCUS technologies intersect with programs (e.g., such as the U.S. 45Q Tax Credit and past grant programs).

- Mapped material specification updates needed for adoption (e.g., inclusion of CO_2-mineralized aggregates or CCUS-verified cements), setting the stage for future revisions of TxDOT standards.

Strategic Benefit: TxDOT can use the proposed framework in this project as a starting point for policy response, should CCUS become a compliance requirement or funding eligibility criterion in future transportation planning or environmental permitting.

Sustainability

Project 0-7231 aligns TxDOT with forward-looking sustainability practices that may be required by regulation or incentive structures in the future:

- Demonstrated that CCUS strategies (e.g., biochar aggregates, native vegetation such as Opuntia cactus) can be deployed on right-of-way land with long-term mitigation benefits.

- Quantified potential GHG reduction metrics (e.g., 9,380 $MTCO_2e$ over 20 years for Opuntia cactus) that support future project sustainability requirements.

- Showed alignment between CCUS and sustainability rating systems (Envision, Greenroads®, INVEST), which may be referenced in future project prioritization or grant scoring.

Strategic Benefit: TxDOT can be well-positioned to meet future sustainability performance targets or reporting obligations that include Scope 3 emissions or embodied carbon requirements.

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Appendix A. Raw Data of Project Bridges

	Construction Type	Length (ft)	Spans	Lanes
Elevated Managed Lanes	New Over Land	12,570.00	96	4
South Boggy Creek NB Exit Ramp	New Over Water	193.00	2	1
I-35 SB Entrance Ramp	Reconstruction Over Land	787.84	6	1
I-35 NB Exit Ramp		614.98	5	1
Slaughter Lane Entrance Ramp		1375.00	11	1
NB Entrance Ramp MLWN		210.14	2	1
South Boggy Creek NBGP	Reconstruction Over Water	199.97	2	3
South Boggy Creek SBGP		201.91	2	3
South Boggy Creek NBFR		140.00	2	2
Onion Creek SB		1579.00	13	6
Onion Creek NB		1579.00	13	6
Slaughter Lane	Widen Over Land	317.18	3	2
Slaughter Creek NBML		320.00	7	6
Slaughter Creek SBML		322.30	7	6
Slaughter Creek NBFR		309.86	3	1
Slaughter Creek SBFR		304.00	3	1
Onion Creek SBFR	Widen Over Water	538.00	7	1
Onion Creek NBFR		544.00	7	1

Appendix B: Combination of Double-Counted Bridges

Before Combination				After Combination		
	Length (ft)	Spans	Lanes	Length	Spans	Lanes
South Boggy Creek NBGP	198.32	2	3	200.12	2	3
South Boggy Creek SBGP	201.91	2	3			
Onion Creek NB	1,579.00	13	6	1579.00	13	6
Onion Creek SB	1,579.00	13	6			
Slaughter Creek NBML	320.00	7	6	321.15	7	6
Slaughter Creek SBML	322.30	7	6			

Appendix C: Split of Bridges Over 1,000 Feet

	Before Split			After Split		
	# of Bridges	Spans	Lanes	# of Bridges	Average Spans	Average Lanes
Elevated Managed Lanes	1	96	4	16	6	4
Slaughter Lane Entrance Ramp	1	11	1	2	5.5	1
Onion Creek NB+SB	1	13	6	2	6.5	6

Appendix D: Bridge Data After Alterations

<table>
<tr><th></th><th>Construction Type</th><th># of Bridges</th><th>Total Length (ft)</th><th>Average Spans</th><th>Average Lanes</th></tr>
<tr><td>Elevated Managed Lanes</td><td>New
Over Land</td><td>16</td><td>12,570.00</td><td>6</td><td>4</td></tr>
<tr><td>South Boggy Creek NB Exit Ramp</td><td>New
Over Water</td><td rowspan="3">1</td><td>193.00</td><td>2</td><td rowspan="5">1</td></tr>
<tr><td>I-35 SB Entrance Ramp</td><td rowspan="4">Reconstruction
Over Land</td><td>787.84</td><td>6</td></tr>
<tr><td>I-35 NB Exit Ramp</td><td>614.98</td><td>5</td></tr>
<tr><td>Slaughter Lane Entrance Ramp</td><td>2</td><td>1,375.00</td><td>5.5</td></tr>
<tr><td>NB Entrance Ramp MLWN</td><td rowspan="3">1</td><td>210.14</td><td rowspan="3">2</td></tr>
<tr><td>South Boggy Creek NBGP+SBGP</td><td rowspan="3">Reconstruction
Over Water</td><td>200.12</td><td>3</td></tr>
<tr><td>South Boggy Creek NBFR</td><td>140.00</td><td>2</td></tr>
<tr><td>OnionCreek NB+SB</td><td>2</td><td>1,579.00</td><td>6.5</td><td>6</td></tr>
<tr><td>Slaughter Lane</td><td rowspan="3">Widen
Over Land</td><td rowspan="3">1</td><td>317.18</td><td>3</td><td>2</td></tr>
<tr><td>Slaughter Creek NBML+SBML</td><td>321.15</td><td>7</td><td>6</td></tr>
<tr><td>Slaughter Creek NBFR</td><td>309.86</td><td>3</td><td>1</td></tr>
</table>

Slaughter Creek SBFR			304.00		
Onion Creek SBFR	Widen Over Water		538.00	7	
Onion Creek NBFR			544.00		

Appendix E: Environmental Product Declaration for CEMEX Type 1L Cement

CEMEX

https://www.cemexusa.com

Cemex Balcones Cement Plant

Environmental Product Declaration

General Information

This cradle to gate Environmental Product Declaration covers bulk cement products produced at the Balcones Cement Plant. The Life Cycle Assessment (LCA) was prepared in conformity with ISO 21930, ISO 14025, ISO 14040, and ISO 14044. This EPD is intended for business-to-business (B-to-B) audiences.

Cemex Construction Materials South, LLC ("Cemex")
Balcones Cement Plant
2580 Wald Road,
New Braunfels, TX 78130

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EPD 451
May 4th, 2023
Valid for 5 years

LCA/EPD Developer
Climate Earth, Inc.
137 Park Place, Suite 204
Pt Richmond, CA 94801
415-391-2725
https://www.climateearth.com

ISO 21930:2017 Sustainability in Building Construction-Environmental Declaration of Building Products: serves as the core PCR NSF PCR for Portland, Blended, Masonry, Mortar, and Plastic (Stucco) Cements V3.2 serves as the sub-category PCR
Sub-category PCR review was conducted by Thomas P. Gloria, PhD. (t.gloria@industrial-ecology.com) • Industrial Ecology Consultants
Independent verification of the declaration, according to ISO 21930:2017 and ISO 14025:2006.: ☐ internal ☒ external
Third party verifier Thomas P. Gloria, PhD. (t.gloria@industrial-ecology.com) • Industrial Ecology Consultants
For additional explanatory material Manufacture Representative: Anand Krishnan (anand.krishnan@cemex.com) This LCA EPD was prepared by: Melissa Diaz Segura, LCA and EPD Project Manager • Climate Earth (www.climateearth.com)
EPDs are comparable only if they comply with ISO 21930 (2017), use the same sub-category PCR where applicable, include all relevant information modules and are based on equivalent scenarios with respect to the context of construction works.

General Information

Producer

Cemex is one of the largest building materials companies in the world with operations in the Americas, the Caribbean, Europe, Africa, Middle East, and Asia. Cemex employs over 41,000 employees worldwide and is committed to sustainable practices and CO_2 reduction goals in the communities in which it operates. Cemex Balcones cement plant has been producing high quality products since 1980 and employs nearly 140 people. The plant has an annual cement production capacity of over 2 million metric tonnes and provides cement for the construction needs in Texas and surrounding states.

Product

The cement products covered in this EPD meet UN CPC 3744 classification and the following standards:

Product Type	Applicable Standard	Standard Designation
Portland Limestone Cement	ASTM C595, C1157, AASHTO M240	Type IL
Portland Cement	ASTM C150, C1157, AASHTO M85	Type I/II

This EPD reports environmental information for two cement products produced by Cemex at its Balcones, TX facility. Type I/II cement is used as the key ingredient in many products such as ready-mix concrete and in a wide variety of applications such as concrete pipes, pre-stressed concrete, roads, foundations, bridges, soil stabilization, rooftile and more. Type IL cement is a general use cement engineered to reduce the carbon footprint by inter grinding a higher ground limestone content than permitted in Type I/II cement. It is typically used in all applications in which Type I/II cement is used.

Product Components

Inputs	Type IL	Type I/II
Clinker	85%	92.3%
Limestone, Gypsum & other	15%	7.7%

Declared Unit

The declared unit is one metric tonne of Type I/II and Type IL cement.

Life Cycle Assessment

System Boundary

This EPD is a cradle-to-gate EPD covering A1-A3 stages of the life cycle.

PRODUCTION Stage (*Mandatory*)			CONSTRUCTION Stage		USE STAGE					END-OF-LIFE Stage			
Extraction and upstream production	Transport to factory	Manufacturing	Transport to site	Installation	Use	Maintenance	Repair	Replacement	Refurbishment	De-construction/ Demolition	Transport to waste processing or disposal	Waste processing	Disposal of waste
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4
X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND
Note: MND = module not declared; X = module included.													

Cut-Off

Items excluded from system boundary include:

- production, manufacture and construction of manufacturing capital goods and infrastructure;
- production and manufacture of production equipment, delivery vehicles, and laboratory equipment;
- personnel-related activities (travel, furniture, and office supplies); and
- energy and water use related to company management and sales activities that may be located either within the factory site or at another location.

Allocation Procedure

Allocation follows the requirements and guidance of ISO 14044:2006, Clause 4.3.4; NSF PCR:2021; and ISO 21930:2017 section 7.2. Recycling and recycled content is modeled using the cut-off rule.

This study recognizes fly ash, silica fume, granulated blast furnace slag, cement kiln dust, flue gas desulfurization (FGD) gypsum, post-consumer gypsum, and sawdust as recovered materials and thus the environmental impacts allocated to these materials are limited to the treatment and transportation required to use as a cement material input. Recycled and recovered materials with fuel content and used as fuels, such as refused derived fuels (RDF), scrap tires and agricultural waste, are considered nonrenewable or renewable secondary fuels. Impacts allocated to these fuels are limited to the treatment and transport required for their use from point of generation along with all emissions from combustion.

Life Cycle Inventory (LCI)

Primary sources of LCI Data:

Electricity: US-EI custom process "Electricity, high voltage, at grid, eGrid (2021), TRE/US US-EI U"
Limestone: Manufacture specific primary data (2021)
Natural Gas: ecoinvent 3.8 (2021) Market for natural gas, high pressure US"
Petroleum Coke: US-EI (2021) "Petroleum coke, at refinery US"
Truck Transport: USLCI (2015) "Transport, combination truck, long-haul, diesel powered, South /tkm/RNA"
Truck Transport: USLCI (2015) "Transport, combination truck, short-haul, diesel powered, South /tkm/RNA"

Electricity grid mix includes: 46.27% Natural Gas, 17.81% Coal, 21.88% Wind, 9.61% Nuclear, 3.49% Solar, 0.43% Petroleum Coke, 0.0% Geothermal, 0.16% Hydro, 0.18% Biomass, 0.06% oil, with a global warming potential of 0.564 kg CO2eq per /kWh

Life Cycle Assessment

Balcones Cement Products[1], bulk shipped: Type I/II, Type IL per 1 metric tonne.**

Impact Assessment	Unit	Type IL	Type I/II
Global warming potential (GWP)[2]	kg CO_2 eq	756	816
Depletion potential of the stratospheric ozone layer (ODP)	kg CFC-11 eq	8.70E-06	9.34E-06
Eutrophication potential (EP)	kg N eq	2.59E-01	2.74E-01
Acidification potential of soil and water sources (AP)	kg SO_2 eq	1.40	1.50
Formation potential of tropospheric ozone (POCP)	kg O_3 eq	30.8	33.1
Resource Use			
Abiotic depletion potential for non-fossil mineral resources (ADPelements)*	kg Sb eq	4.37E-06	4.57E-06
Abiotic depletion potential for fossil resources (ADPfossil)	MJ, NCV	5,241	5,628
Renewable primary energy resources as energy (fuel), (RPRE[3]) *	MJ, NCV	144	150
Renewable primary resources as material, (RPRM[3]) *	MJ, NCV	0.00E+00	0.00E+00
Non-renewable primary resources as energy (fuel), (NRPRE[3]) *	MJ, NCV	5,504	5,902
Non-renewable primary resources as material, (NRPRM[3]) *	MJ, NCV	0.00E+00	0.00E+00
Consumption of fresh water, (FW[3])	m^3	1.96	2.00
Secondary Material, Fuel and Recovered Energy			
Secondary Materials, (SM[3]) *	kg	0.00E+00	0.00E+00
Renewable secondary fuels, (RSF[3]) *	MJ, NCV	214	232
Non-renewable secondary fuels (NRSF[3]) *	MJ, NCV	297	322
Recovered energy, (RE[3]) *	MJ, NCV	0.00E+00	0.00E+00
Waste & Output Flows			
Hazardous waste disposed, (HW[3]) *	kg	2.24E-04	2.33E-04
Non-hazardous waste disposed, (NHWD[3]) *	kg	3.54	3.68
High-level radioactive waste, (HLRW[3]) *	kg	1.42E-07	1.49E-07
Intermediate and low-level radioactive waste, (ILLRW[3]) *	kg	7.21E-07	7.55E-07
Components for reuse, (CRU[3]) *	kg	0.00E+00	0.00E+00
Materials for recycling, (MR[3]) *	kg	0.00E+00	0.00E+00
Materials for energy recovery, (MER[3]) *	kg	1.05E-02	1.09E-02
Recovered energy exported from the product system, (EE[3]) *	MJ, NCV	0.00E+00	0.00E+00
Additional Inventory Parameters for Transparency			
CO_2 emissions from calcination and uptake from carbonation[4]	kg CO_2 eq	446	484

* Emerging LCA impact categories and inventory items are still under development and can have high levels of uncertainty that preclude international acceptance pending further development. Use caution when interpreting data in these categories. The following optional indicators are not reported and also have high levels of uncertainty: Land use related impacts, toxicological aspects, and emissions from land use change.

**Only EPDs prepared from cradle-to-grave life-cycle results and based on the same function, quantified by the same functional unit, and taking account of replacement based on the product reference service life (RSL) relative to an assumed building service life, can be used to assist purchasers and users in making informed comparisons between products.

[1] These products contain no materials that are considered hazardous as defined by the PCR.
[2] GWP 100; 100-year time horizon GWP factors are provided by the IPCC 2013 Fifth Assessment Report (AR5).
CO2 from biogenic secondary fuels used in kiln are climate-neutral (CO2 sink = CO2 emissions), ISO 21930, 7.2.7.
[3] Calculated per ACLCA ISO 21930 Guidance.
[4] Calcination emissions were calculated based on the Cement CO2 and Energy Protocol detailed output method (B1) published by the World Business Council for Sustainable Development (WBCSD) Cement Sustainability Initiative (CSI).

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Additional Environmental Information

To learn more about the importance of sustainability at Cemex, please visit:
www.cemex.com/sustainability/future-in-action
www.cemexusa.com/sustainability

Appendix F: Example Calculations of Global Warming Potentials for Concrete Mixes

ICE Portland Cement Mix

	Mass Ratio	SSD Density from C30 mix	Volume Ratio	Volume Ratio Normalized	SSD Weight (kg/m^3)	GWP Constant ($kgCO_2e$)	Total GWP ($kgCO_2e/m^3$)
Water	0.070	1.00	0.070	0.166	166.0	1.74	0.288
Cement	0.155	3.14	0.049	0.117	367.4	1040	381.462
Coarse Aggregate	0.405	2.50	0.162	0.383	957.5	4.51	4.322
Fine Aggregate	0.370	2.62	0.141	0.334	875.1	4.87	4.264

ICE Water, given: Mass Ratio = 0.07, Density = 1.00, GWP = 1.74 $kgCO_2e$

$$Volume\ Ratio = Mass\ Ratio * SSD\ Density$$

$$0.07 = 1.00 * 0.07$$

$$Normalized\ Ratio = \frac{Volume\ Ratio}{\sum Volume\ Ratio}$$

$$0.166 = 0.07/0.422$$

$$SSD\ Weight = Normalized\ Ratio * SSD\ Density * 1000$$

$$166\frac{kg}{m^3} = 0.166 * 1.00 * 1000$$

$$Total\ GWP = SSD\ Weight * GWP\ Constant$$

$$0.288\,\frac{\mathrm{kgCO2e}}{\mathrm{m}^3} = 166\,\frac{kg}{m^3} * 1.74\ kgCO2e$$

Total GWP for ICE Portland Cement Mix

$$Total\ GWP = [0.288 + 381.462 + 4.322 + 4.264]\,\frac{kgCO2e}{m^3}$$

$$Total\ GWP = 390.337\ \frac{kgCO2e}{m^3}$$

$$Total\ GWP\ with\ CarbonCure = 390.337\ \frac{kgCO2e}{m^3} - 11.86\ \frac{kgCO2e}{m^3}$$
$$= 378.5\ \frac{kgCO2e}{m^3}$$

C30 Concrete Mix

	SSD Weight (lb/yd^3)	SSD Weight (kg/m^3)	GWP Constant ($kgCO_2e$)	Total GWP ($kgCO_2e/m^3$)
Water	254	150.69	1.74	0.26
Cement	395	234.34	756	177.16
Fly Ash	170	100.86	6	0.61
Type A Admixture	2	1.19	2250	2.68
Type D Admixture	1	0.59	2250	1.33
Coarse Aggregate	1740	1032.3	4.51	4.66
Fine Aggregate	1332	790.24	4.87	3.85

C30 Water, given: SSD Weight = 254 lb/yd^3, GWP = 1.74 kgCO_2e

$$254\frac{lb}{yd^3} * 0.5932764213 = 150.69\frac{kg}{m^3}$$

$$150.69\frac{kg}{m^3} * 1.74\ kgCO2e = \ 0.26\frac{kgCO2e}{m^3}$$

Total GWP for C30 Concrete Mix

$$Total\ GWP = [0.26 + 177.16 + 0.61 + 2.68 + 1.33 + 4.66 + 3.85]\frac{kgCO2e}{m^3}$$

$$Total\ GWP = 190.54\ \frac{kgCO2e}{m^3}$$

$$Total\ GWP\ with\ CarbonCure = 190.54\ \frac{kgCO2e}{m^3} - 11.86\ \frac{kgCO2e}{m^3}$$
$$= 178.68\ \frac{kgCO2e}{m^3}$$

Appendix G: Survey Questions

Question 1: What type of agency are you affiliated with?

Answer Choices:

- Federal
- State
- Other (Textbox)

Question 2: What is your role within your agency?

Answer Choices:

- Project Manager
- Engineer
- Research Analyst
- Policy Advisor
- Planner
- Other (Textbox)

Question 3: How familiar are you with Carbon Capture, Utilization, and Storage (CCUS) Technologies, in general?

Answer Choices:

- Very Familiar
- Moderately Familiar
- Somewhat Familiar
- Not Familiar At All

Question 4: How familiar are you with Carbon Capture, Utilization, and Storage (CCUS) Technologies, in the Transportation Sector?

Answer Choices:

- Very Familiar
- Moderately Familiar
- Somewhat Familiar
- Not Familiar At All

Question 5: Are you aware of any environmental programs, requirements, incentives, or initiatives specific to your state that relates to CCUS technology? If so, please list them.

Answer Choices:

- Yes (Textbox)
- No

Question 6: Is your agency currently using (or have previously used) CCUS technologies in a project?

Answer Choices:

- Yes
- No

*Question 7: Please specify which CCUS technologies are/were used. Please utilize the textbox to provide details of where and how it is being applied. (Select all that apply)

Answer Choices:

- Direct Air Capture (Textbox)
- Post-Combustion Capture (Textbox)
- Pre-Combustion Capture (Textbox)
- Oxy-Fuel Combustion (Textbox)
- Accelerated Mineral Carbonation (Textbox)
- Other (Textbox)

Question 8: Is your agency considering any CCUS technologies to implement in the future? If yes, select all choices that apply.

Answer Choices:

- Direct Air Capture (Textbox)
- Post-Combustion Capture (Textbox)
- Pre-Combustion Capture (Textbox)
- Oxy-Fuel Combustion (Textbox)
- Accelerated Mineral Carbonation (Textbox)
- Other (Textbox)
- No

[+]Question 9: What best practices have you identified to be helpful in implementing CCUS technologies in transportation projects? (Select all that apply)

Answer Choices:

- Early Stakeholder Agreement

- Comprehensive Risk Assessment
- Pilot Projects
- Interagency Collaboration
- Continuous Monitoring and Evaluation
- Other (Textbox)

+Question 10: What challenges have you faced while implementing CCUS technologies? (Select all that apply)

Answer Choices:

- High Cost
- Lack of Technical Expertise
- Regulatory Hurdles
- Limited Stakeholder Buy-In
- Technological Limitations
- Other (Textbox)
- Not Applicable

Question 11: How would you rate the viability of CCUS technologies for DOT projects within your state?

Answer Choices:

- Very Viable
- Moderately Viable
- Somewhat Viable
- Not Viable
- Viability has not been analyzed

Question 12: What factors influence your assessment of CCUS viability within transportation projects? (Select all that apply)

Answer Choices:

- Cost
- Regulatory Considerations
- Technical Feasibility
- Environmental Impact
- Stakeholder Support
- Availability of Existing Infrastructure
- Other (Textbox)
- Viability has not been analyzed

Question 13: How useful would a comprehensive CCUS technology implementation guideline be for your agency?

Answer Choices:

- Extremely Useful
- Moderately Useful
- Slightly Useful
- Neither Useful nor Useless
- Slightly Useless
- Moderately Useless
- Extremely Useless

Question 14: What considerations should be included in implementation guidelines for CCUS deployment? (Select all that apply)

Answer Choices:

- Regulatory Requirements
- Cost Assessments
- Incentives for Adoption
- Governance Structures
- Other (Textbox)

Question 15: What additional resources or support would be beneficial for your agency in understanding or analyzing the use of CCUS technologies? (Select all that apply)

Question 16: What additional resources or support would be beneficial for your agency in adopting CCUS technologies? (Select all that apply)

Question 17: Do you have any additional comments or suggestions regarding CCUS technologies in transportation infrastructure?

*Question was only shown to those who answered "Yes" for Question 6.

[+]Question was not shown to those who answered only "No" to Question