



**THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH**

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

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Executive Summary

This report 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 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 includes a lifecycle assessment (LCA) case study examining the feasibility of incorporating select CCUS technologies on a current TxDOT project. The document outlines technical, financial, and regulatory considerations and provides a decision-making framework based on the case study to guide project-level evaluations.

This document 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 CO₂ 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:

- **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 CO₂ 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 is intended as a forward-looking resource and should be revisited as technologies mature, incentives evolve, and TxDOT's sustainability priorities advance.

1. Introduction

1.1. Background on CCUS in Transportation

Carbon Capture, Utilization, and Storage (CCUS) refers to a suite of technologies designed to capture carbon dioxide (CO₂) 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 rely heavily on carbon-intensive materials including portland-based cement, steel, and asphalt. Concrete alone accounts for approximately 5–8% of global CO₂ 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 CO₂ 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 CO₂ 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 (LC³) 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 CO₂ 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.

1.2. Organization of Report

This report 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: Introduction.** Introduces the relevance of CCUS to transportation infrastructure and outlines the report’s purpose, intended use, and scope limitations.
- **Section 2: CCUS Industry Readiness in Texas.** Highlights the current landscape of material producers, CCUS technology providers, and CO₂ storage infrastructure in Texas. This section identifies entities active in decarbonization efforts in cement, concrete, asphalt, and steel.
- **Section 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: CCUS Policy Considerations and Stakeholder Perspectives.** Summarizes key 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 TxDOT-specific guideline.
- **Section 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: 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.

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 1 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).

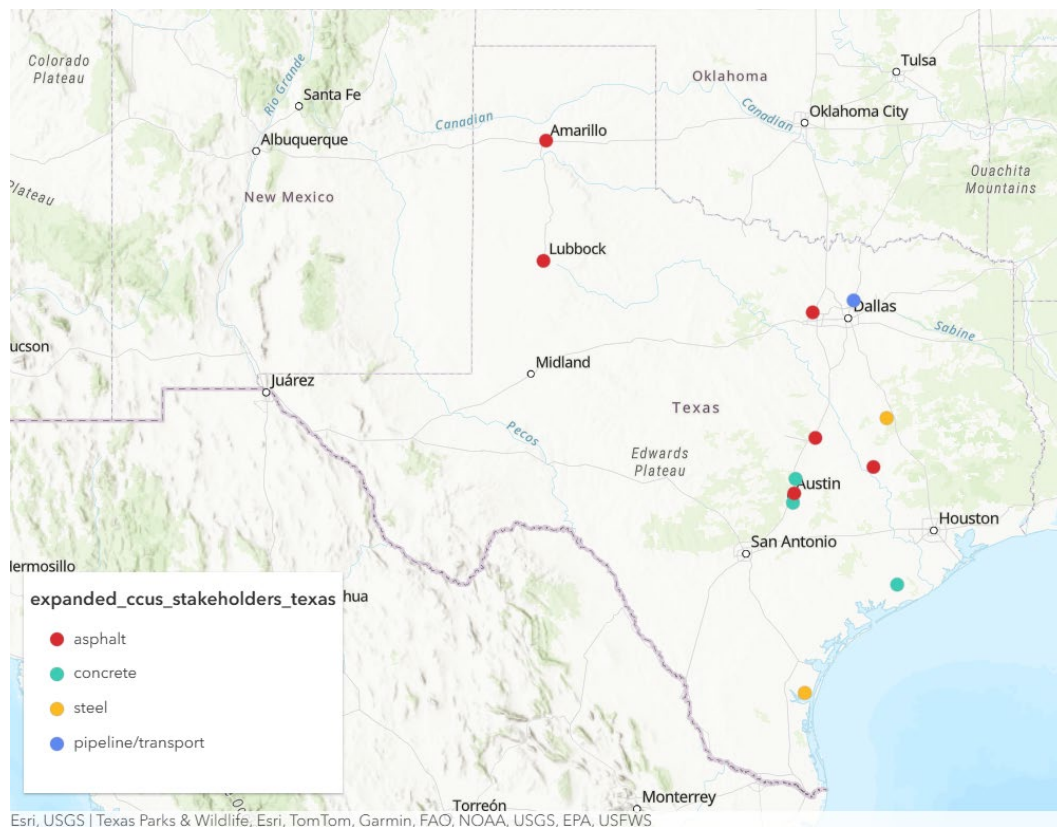


Figure 1: Map view of active CCUS stakeholders in Texas. Categories covered: asphalt, concrete, steel and pipeline/transport. Image produced in ArcGIS by the authors.

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 CO₂ emissions and 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.

2.1.1. Cement and Concrete

Early deployment of CO₂ utilization in concrete has been led by producers licensed to use CarbonCure Technologies. CarbonCure's process injects captured CO₂ 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 CO₂-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 CO₂ 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 CO₂ over the project. The project served as a regional model for how CO₂ 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 CO₂ mineralization technologies and expanded use of supplementary cementitious materials. While direct capture is not yet widespread,

the existence of companies (and pilot projects) adopting CO₂ mineralization indicates a clear trajectory toward deeper integration of CCUS across concrete production in transportation infrastructure.

2.1.2. 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 CO₂ 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 CO₂ 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.

2.1.3. 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 CO₂ 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 CO₂ 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 CO₂-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.

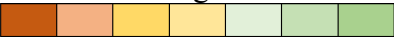
Overall, Texas's asphalt sector is at a moderate stage of CCUS readiness. While few facilities currently deploy direct capture or utilization technologies, many are actively reducing carbon intensity through alternative production methods and materials. These strategies can serve as foundational platforms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

2.2. CCUS Technology Providers Active or Emerging in Texas

Select firms offer hardware, software, or engineered processes for capturing and/or reusing CO₂ at industrial sites, including material production facilities and project construction environments.

Table 1 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 1: 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
Svante	Point-source solid sorbent capture	Pilot project carbon capture plant in Texas announced in 2024
Legend  Less mature for adoption in Texas More mature for adoption in Texas		

2.3. CO₂ 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 CO₂ 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 CO₂ captured from concrete, steel, or asphalt plants used in infrastructure 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 CO₂ annually. While its primary focus is on atmospheric CO₂ 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.

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 2 provides a summary of these rating systems.

Table 2: 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	Air Quality & GHG Emissions, Energy Use,	Lifecycle Carbon Footprint, Energy &

	Efficiency, Innovation	Sustainable Pavements, Innovation	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.

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 CO₂ 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 CO₂ 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.

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.

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 (U.S. Department of Transportation, 2014). 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.

3.4. Summary

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.

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.

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 CO₂ 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 CO₂ to oil facilities to aid with industrial processes. As such, it is difficult to determine the economic viability of utilizing 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 CO₂ or its by-products (Hirsch and Foust 2020).

4.1.1. 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 CO₂ 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 2). There are also eleven northeastern states participating in the Regional Greenhouse Gas Initiative (RGGI), which enacts local carbon policy.

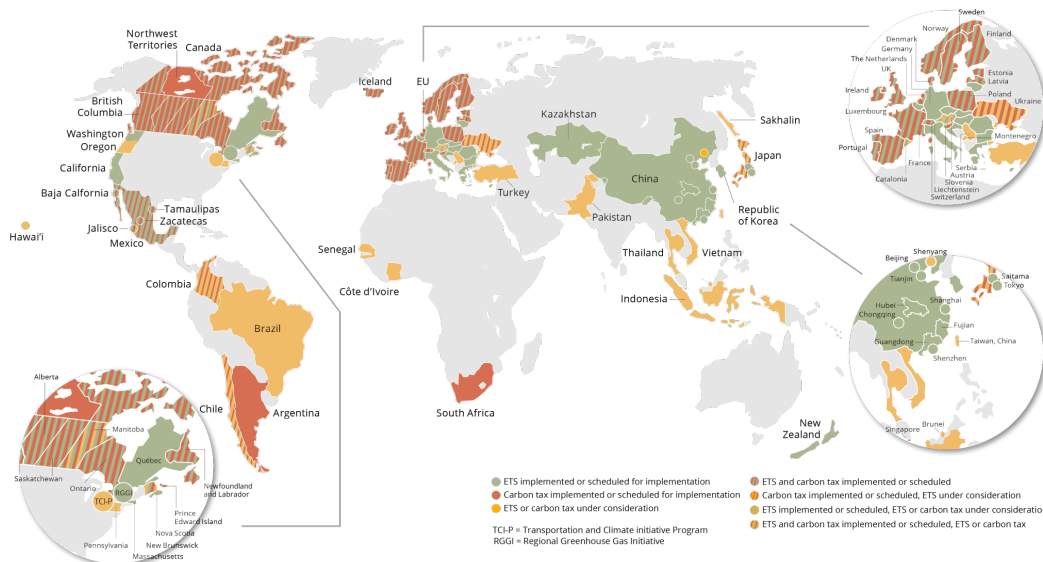


Figure 2. Carbon Pricing Implementation Globally. Source: open access through *State and Trends of Carbon Pricing 2023*. (World Bank, 2023)

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 are 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).

4.1.2. 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 CO₂ 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 CO₂ 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. As of 2024, the federal government was expected to further incentivize integrated carbon management clusters that could support the transportation sector indirectly by reducing emissions from concrete, steel, and asphalt producers. As of 2025, it is uncertain whether further policies and incentives will be announced.

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 and Climate Bonds Standards. 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 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 environmental or sustainability goals.

4.2. 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 the 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 (CO₂-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.

5. Implementation Framework

To integrate Carbon Capture, Utilization, and Storage (CCUS) effectively into transportation infrastructure projects, it is suggested that project teams 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 3 – each of which is expanded upon in the following subsections.

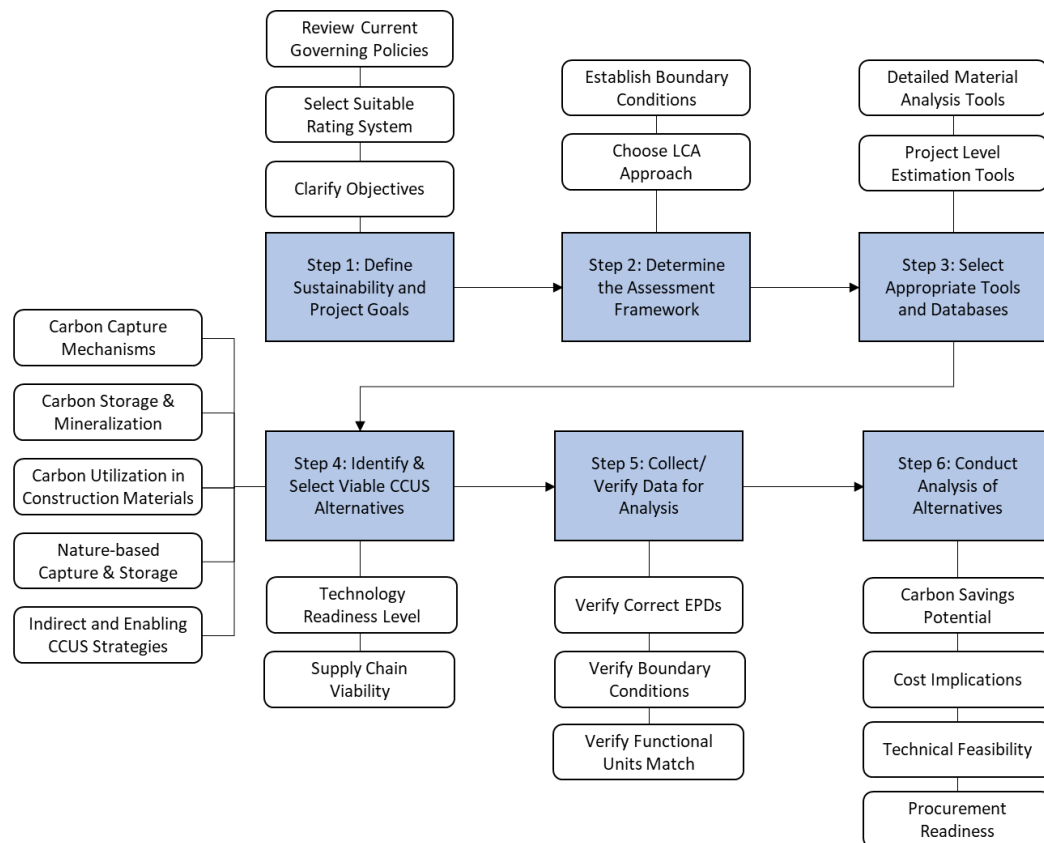


Figure 3: CCUS Implementation Framework for Transportation Infrastructure Projects

5.1. 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 CO₂e 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.

5.2. 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 CO₂-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, CO₂-sequestering aggregates, or soil stabilization with carbon-reactive binders, use of 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 CO₂e) 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.

5.3. 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.

5.3.1. 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 CO₂-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.

5.3.2. 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.

5.4. 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 CO₂ 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 CO₂ 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: CO₂ 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 CO₂ during manufacturing or rely on carbon-storing natural inputs. They can functionally replace conventional materials while delivering carbon mitigation benefits.
- Examples: Biochar-modified aggregates, CO₂-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 CO₂ 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 CO₂ 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.

5.5. 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; 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 m³ 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 necessary 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 CO₂ curing).

If an EPD for the project materials cannot be obtained, using similar data or accessible EPDs for a material with a similar composition would be appropriate. As a final measure (if needed), generalized data, such as the nationwide material estimates from FHWA's ICE Tool, can be used. By verifying data 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.

5.6. 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 CO₂e)
 - 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 m³ 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. Conclusions

This document provides TxDOT with a structured, step-by-step framework for 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, CO₂ 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.

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