

# Central Appalachian Basin CO<sub>2</sub> National Network for Enhancing Carbon Transport Infrastructure Onshore/Offshore (CO<sub>2</sub>NNECTION) Intermodal Transport Hubs

## FINAL PROJECT REPORT

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## Final Project Report

### 1.0 Introduction and Background

Carbon dioxide (CO<sub>2</sub>) transport will be required to implement carbon capture utilization storage (CCUS) in instances where a CO<sub>2</sub> source does not overlie a viable storage target or generates a volume of CO<sub>2</sub> that requires more than one well to store. Most studies have looked at pipeline transport of CO<sub>2</sub>, as this is the most economical mode for large volume transport and is traditionally considered the most viable option (Onyebuchi et al., 2018; Lu et al., 2020). CO<sub>2</sub> pipeline opposition like the recently mothballed Navigator Pipeline (Dura, 2023) and high-profile accidents like the Satartia, Mississippi pipeline rupture (Kieba et al., 2023), however, means that other modes of transport, such as barge, rail, and truck, may be more viable alternatives for smaller sources. Pipelines also require a larger investment in capital and time, as they often require extensive planning, environmental assessments, and public engagement (Schoots et al., 2011).

Intermodal and/or non-pipeline transport of CO<sub>2</sub> has been previously studied by some peer reviewed literature, although it is not as commonly studied as pipeline transport. Many of the intermodal transport studies focused on pipeline and shipping transport, often for offshore CCUS projects (Kjarstad et al., 2016; Munkejord et al., 2016; Orchard et al., 2021; Roussanaly et al., 2013a, 2013b, 2013c, 2014). Others discuss pipeline, trucking, and/or rail (Carbon Sequestration Leadership Forum [CSLF], 2021; Lu et al., 2020; Han et al., 2015; Simonsen et al., 2024; Mallon et al., 2013; Bergqvist and Monios, 2021; Bielenia et al., 2023; Zhang et al., 2013; Dehdari et al., 2023; Svensson et al., 2004), which are the transport mechanisms considered in this study. Several studies that have considered pipeline transport (Knoope et al., 2013; Onyebuchi et al., 2018; Hasan et al., 2014; Jensen et al., 2013; Grant et al., 2018; Middleton et al., 2012; Morbee et al., 2011; Brunsvold et al., 2011; Peleteri et al., 2018).

One of the most important considerations when developing a transport network is costs. Because CO<sub>2</sub> capture costs are high for many sources, viable transport and storage networks must be efficient to ensure an economically viable carbon mitigation system. The per tonne cost of transport limits the use of trucks and rail for CO<sub>2</sub> transport projects (CSFL, 2021). Svensson et al. (2004) went so far as to say that only pipeline, barge, or a combination of the two modes provide a viable pathway from an economic standpoint. However, other factors may lead to the selection of other modes of transport. Rail transport can be accomplished largely using existing infrastructure. This conclusion led Roussanaly et al. (2017) to conclude that, under circumstances where additional CO<sub>2</sub> processing costs to transport via train are minimal and where risk tolerance is low, rail transport may be the preferable mode. An additional drawback to the use of rail is that the source and sink must be located near a railway (Lu et al., 2020). This is not practical in all areas but is less of a problem in an industrialized area like the study region discussed in this report. Trucks also do not require special investments and may be the preferred mode to move smaller volumes of CO<sub>2</sub> shorter distances. Han et al. (2015), for instance, mention that tanker trucks may be most viable during the early stages of a project prior to the large-scale implementation and prior to a pipeline being built. While trucking is adaptable, the overall costs are high due to fuel and labor (Lu et al., 2020).

Several studies have discussed the economics of CO<sub>2</sub> pipelines. Knoope et al. (2013) studied 14 cost models to determine the efficacy of the models to estimate costs of CO<sub>2</sub> pipelines. The authors note that costs are dependent on mass flow; pipeline length, diameter, and thickness; elevation change; terrain;

impurities; and technology and material costs, which can lead to a large range of costs (Knoope et al., 2013). The authors state that the cost models underestimate CO<sub>2</sub> pipeline costs because they are based on the cost of natural gas pipeline construction in the United States in the 1990s and early 2000s. Additionally, except for weight-based models, these models do not account for the higher operation pressure of CO<sub>2</sub> pipelines and likely higher material costs that occurred over time. Fewer studies have modeled the cost of transport using truck and rail; however, a recent paper by Myers et al. (2024) presents a model for these modes that was used in this study.

Onyebuchi et al. (2018) note that the most important issues facing CO<sub>2</sub> pipeline construction include pipeline integrity, CO<sub>2</sub> availability; costs, and environmental, health, and safety (ES&H) issues. The authors provide a review of available literature to determine the state of knowledge to overcome these issues. Some of the most important findings from their review are related to the impact of impurities and corrosion management. The authors noted the need for careful consideration of CO<sub>2</sub> stream impurities, particularly as multiple streams of CO<sub>2</sub> must be managed in pipeline networks, such as the one being investigated as part of this project. The authors also note the impact of elevation changes and impurities on pressure drop in the line potentially impacting the spacing of pressure booster stations along the line.

The carbon footprint of different transport modes is also an important consideration because greenhouse gas emissions during transport could impact the efficacy of the carbon mitigation project. Several factors influence the lifecycle emissions of intermodal transport, including the type of fuel, age of vehicles, technological advancements of the vehicles, route selection, driving conditions, and logistics (e.g., load factor) (Bielenia et al., 2023; Dehdari et al., 2023). As such, a complex intermodal transport network may need to use multiple different emissions factors to accurately calculate lifecycle emissions.

Studies have discussed modeling intermodal transport and pipeline routing optimization (Zhang et al., 2013; Middleton et al., 2009; Morbee et al., 2011). Zhang et al. (2013) present an intermodal CO<sub>2</sub> transport model that minimizes costs of intermodal transport networks and shows how it can be used to limit CO<sub>2</sub> emissions under different assumed CO<sub>2</sub> costs. Software like the Scalable Infrastructure Model for Carbon Capture Storage (SimCCS), described by Middleton et al. (2009), can help design these optimized routes by providing a robust modeling approach that generates viable, optimized pipeline network based on terrain and other factors that complicate pipeline routes (e.g., environmentally and culturally sensitive areas, critical infrastructure, populated areas, and other obstacles). Similarly, Morbee et al. (2011) describe a model capable of optimizing pipeline routing between multiple sources and sinks across different areas.

Pipeline optimization may improve economics through the optimization of pipeline routes with one or more trunk lines and a series of branches connecting several sources to one or more storage areas (Hasan et al., 2014; Jensen et al., 2013; Grant et al., 2018; Middleton et al., 2012; Morbee et al., 2011). Previous work has shown the potential benefits of this approach through regional (Grant et al., 2018; Jensen et al., 2013; Middleton et al., 2012) and continental (Hasan et al., 2014; Morbee et al., 2011) optimized pipeline networks. The pipeline itself can also help optimize project economics by providing mitigations for project uncertainties or improving efficiencies. Wetenhall et al. (2017) discuss the potential for improving efficiencies by using pipelines as temporary storage vessels for CO<sub>2</sub> to help mitigate storage uncertainties.

Other issues may reduce the overall operational efficiency of pipelines. Two papers note that pipeline designs often do not consider impact of impurities on pipeline performance (Peletiri et al., 2018; Lu et al., 2020). Peletiri et al. (2018) reviewed several aspects of pipeline development and operations that could be impacted by the presence of impurities. They found that improved knowledge of the impact of impurities on density and viscosity of the fluid will help optimize pipeline velocity and operating conditions. Impurities in the CO<sub>2</sub> stream may also complicate optimization of CO<sub>2</sub> transport networks; however,

establishing CO<sub>2</sub> quality standards must be weighed against the economics of separating CO<sub>2</sub> from other constituents, which have different costs for different CO<sub>2</sub> source types (Simonsen et al., 2024).

The CO<sub>2</sub> pipeline industry has a wealth of experience that dates back decades. Best practices for pipeline design and operation have been developed by US institutions like the American Petroleum Institute (API) as well as international organizations like Det Norske Veritas (DNV). Johnsen et al. (2011) report on the DNV (2010) recommended practice, which they state is applicable to onshore and offshore pipelines and intended to supplement the international, national, state, and local regulations governing the pipelines. In addition, API is currently developing a recommended practice for CO<sub>2</sub> transport by pipeline (RP 11CO<sub>2</sub>), which has been drafted but is currently awaiting final approval. Piazza (2024) reports that this standard will address issues related to integrity, impurities, and risks. The guidance will also deal with potential accidents, including causes, consequences, mitigations, and recovery mechanisms for these accidents. Finally, the guidance will address construction and siting requirements. Both DNV and API have recommended practices for pipelines that, in conjunction with national, state, and local regulations, may help guide the construction of CO<sub>2</sub> pipelines.

The selected study area for the project is the tristate region of Ohio, Pennsylvania, and West Virginia. This is an important economic region with many different sources of CO<sub>2</sub>, ranging from industrial facilities like natural gas processing plants, chemical production plants, and steel plants, as well as fossil fuel electric power facilities (United States Environmental Protection Agency [U.S. EPA], 2024). The goal of the project is to develop the pre-Front End Engineering Design (pre-FEED) study of an intermodal transport hub that demonstrates an efficient and economic transport network to transport CO<sub>2</sub>, using multimodal methods, from sources of CO<sub>2</sub> to sinks of CO<sub>2</sub> in this tristate region. The project considered the existing regional infrastructure of roads, rail and river transportation methods along with construction of new infrastructure. The project will also take into consideration the decarbonization incentives and carbon credit policies. The project will coordinate with the Appalachian Regional Clean Hydrogen (ARCH2) Hub Project, also led by Battelle, and include information about other publicly announced projects to ensure the impact aligns with other federal investments. Two top-line objectives defined project success. The first is to develop a conceptual design and a pre-FEED design. The second is to integrate costs, regulations, permitting and decarbonization incentives, and policies into the economics of the project.

This report provides an assessment of the pre-FEED concept and design. The report discusses the following:

- Section 2 discusses developing the intermodal transport network from conceptual design and optimization, design basis, and regional connections to other projects to ensure that the project is appropriately sized and has a realistic scope.
- Section 3 discusses the permitting and regulatory plan and land acquisition plan to ensure that the project can be permitted and that the land and rights-of-way (ROWs) can be obtained.
- Section 4 discusses the project cost estimate and business case analysis (BCA) to ensure the project is economically viable.
- Section 5 discusses risks, including hazard identification (HAZID) and the environmental safety and health (ES&H) assessment to ensure that risks are properly quantified and prioritized.
- Section 6 provides the pre-FEED study for the selected node of the project hub.
- Section 7 discusses the project accomplishments and path forward to progress the project to a full FEED assessment.

## 2.0 Developing Intermodal Transport

The *Developing Intermodal Transport* task had four subtasks. The first was to develop *conceptual designs* that ensured that the intermodal hub is based on realistic source conditions and considered realistic transport options. The second subtask sought to establish *design and optimize the intermodal transport hub*. This involved aligning the sources in logical groups or clusters and developing pooling strategies to ensure that the proper transport modes are selected and that the system is optimized. In addition, a single node was selected for the pre-FEED analysis. The *basis of design* was then completed for the selected pre-FEED node. Finally, the *regional connection* considered how the hub could be expanded and connected to other projects in the area.

### 2.1 Conceptual Design

The Conceptual Design subtask included four goals: (1) identify source sponsors and sink sites, (2) estimate of appropriate transport modes and distances, (3) develop multiple realizations of parameters applicable to multi-modal transport and down-select set of designs are expected to be advanced to the pre-FEED stage, and (4) identify specific site (i.e., a single node) that will serve as the site for subsequent detailed analyses.

#### Goal 1. Identify source sponsors and sink sites

Sources sponsors and CO<sub>2</sub> emissions were identified during the proposal using publicly available data from the U.S. Environmental Protection Agency (U.S. EPA) Greenhouse Gas Reporting Program (GHGRP) (U.S. EPA, 2024). This reference provided source locations and 2023 annual CO<sub>2</sub> emissions. Because these partners do not have immediate plans to capture CO<sub>2</sub> at their plants, the sources were anonymized (Table 1).

Table 1. Anonymized sources for both scenarios considered in the project.

No.	Facility Name	Elevation (ft above mean sea level [amsl])	County	State	Source Type	Capturable CO <sub>2</sub> Emissions (million tonnes per year [MMt/yr])
<b>Existing Anonymized Sources in the First System</b>						
1	NG Compressor A	1031	Washington	PA	NG Compressor	0.04
3	NG Compressor B	1217	Monongalia	WV	NG Compressor	0.03
4	NG Gathering and Boosting A	1132	Allegheny	PA	NG Gathering/Boosting	0.225
5	NG Gathering and Boosting B	732	Allegheny	PA	NG Gathering/Boosting	0.775
6	NG Compressor C	1229	Monroe	OH	NG Compressor	0.07
7	NG Compressor D	1280	Wetzel	WV	NG Compressor	0.04
8	NG Compressor E	1125	Greene	PA	NG Compressor	0.05
9	NG Gathering and Boosting C	978	Washington	PA	NG Gathering/Boosting	0.325
10	NG Compressor F	1005	Washington	PA	NG Compressor	0.075
11	NG Compressor G	971	Monongalia	WV	NG Compressor	0.04
RR1	Railyard 1	1156	Washington	PA	Railyard/Rally Point	0
RR2	Railyard 2	820	Monongalia	WV	Railyard	0
RR3	Railyard 3	696	Wetzel	WV	Railyard	0
ST	Storage	1065	Tuscarawas	OH	Storage Area	0
-	<b>Scenario 1 Total</b>	-	-	-	-	<b>1.67</b>
<b>Hydrogen Plant included in the Second System</b>						
2	Hydrogen Production Facility	648	Doddridge	WV	Hydrogen	0.5
PLM	Pipeline B Meeting Point	1231	Wetzel	WV	Rally Point	0
-	<b>Scenario 2 Total</b>	-	-	-	-	<b>2.17</b>

Potential storage sites were identified by plotting the US Department of Energy (DOE)-sponsored studies in the area (Battelle, 2024; Cumming et al., 2019; Gupta et al., 2014) as well as the projects that have been recently announced by commercial projects (Tenaska, 2024a, b, c). Figure 1 maps out these potential storage sites in relation to sources (Table 1) in the region. Details about the storage sites that were considered are provided in Table 2.

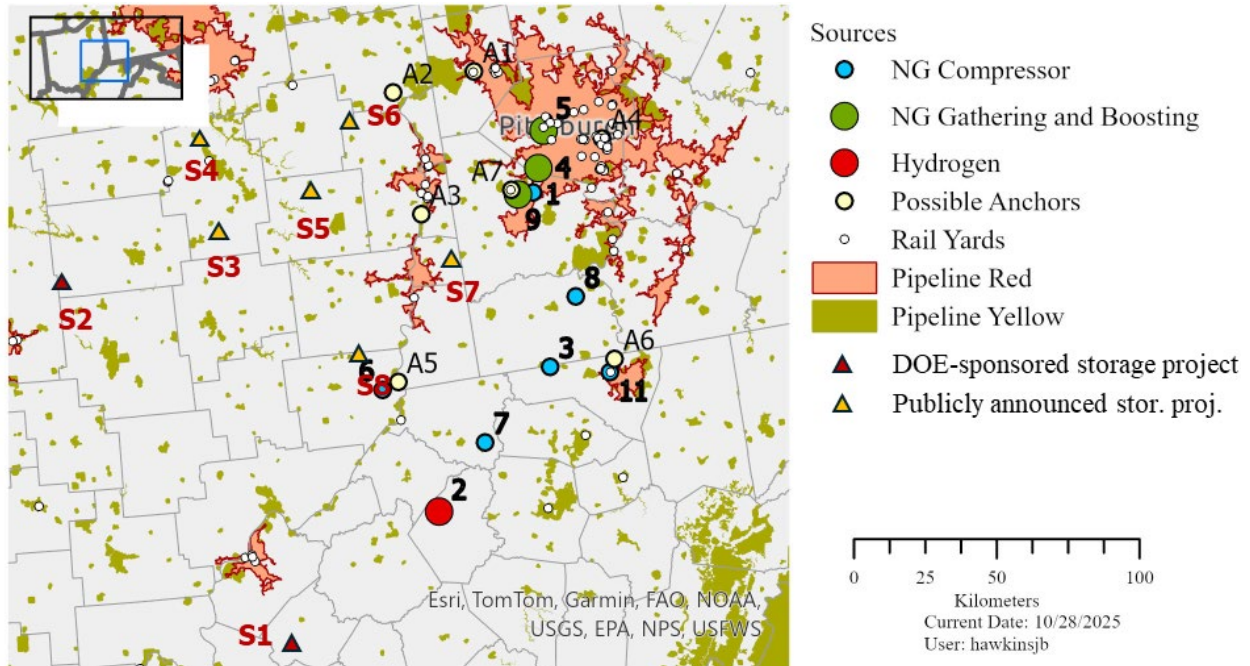


Figure 1. Map of anonymized sources (#), potential storage sites (S#), and anonymized anchor sites (A#). Also shown are areas where pipeline development may be complicated by high populated areas (pipeline red) or other sensitive areas, including other populated areas, sensitive areas, and protected lands (pipeline yellow).

Table 2. Storage sites and capacity estimates for sites considered in the project. Numbers correspond to those on the map in Figure 1.

No.	Storage Site Descriptor	Storage Type	County, State	Elevation (ft amsl)	Capacity <sup>b</sup> (MMt/yr)
S1	Ritchie, WV MRCI Model (Oriskany)	Saline	Ritchie, WV	1,034	Subcomm.
S2	CAB-CS Secondary (Cambro-Ord/Clinton)	Saline/EOR	Tuscarawas, OH	1,036	Comm.
S3	Harrison County, OH	Saline	Harrison, OH	985 <sup>a</sup>	Unk.
S4	Carroll County, OH	Saline	Carroll, OH	1,249 <sup>a</sup>	Unk.
S5	Jefferson County, OH	Saline	Jefferson, OH	1,051 <sup>a</sup>	Unk.
S6	Hancock County, WV	Saline	Hancock, WV	1,087 <sup>a</sup>	Unk.
S7	Washington County, PA	Saline	Washington, PA	1,212 <sup>a</sup>	Unk.
S8	Marshall County, WV	Saline	Marshall, WV	1,164 <sup>a</sup>	Unk.
NA	Mountaineer (Cambro-Ord)	Saline	Mason, WV	590	Comm.
NA	CAB-CS Primary (Cambro-Ord/Clinton)	Saline/EOR	Coshocton, OH	773	Comm.

Notes: a. Exact project location unknown. Elevation is from middle of county. b. Capacity are either unknown (unk.), commercially viable quantities (comm.) (i.e., 1.67 MMt/yr or more), or subcommercial quantities (i.e., less than 1.0 MMt/yr).

## Goal 2. Estimate of appropriate transport modes and distances

Transport modes and distance were initially assessed through a mapping exercise during which the sources were logically clustered, different modes were considered, and distances of transport were estimated. This involved clustering nearby sources, selecting logical transport modes, and making rough estimates of the distances between the selected sources and a selected sink. This work was conducted

using a commercial mapping software and data from the Department of Transportation (United States Census Bureau, 2023; Federal Railroad Administration [FRA], 1995) and the Pipeline and Hazardous Materials Safety Administration (PHMSA, 2019) as seen in Figure 2 below.

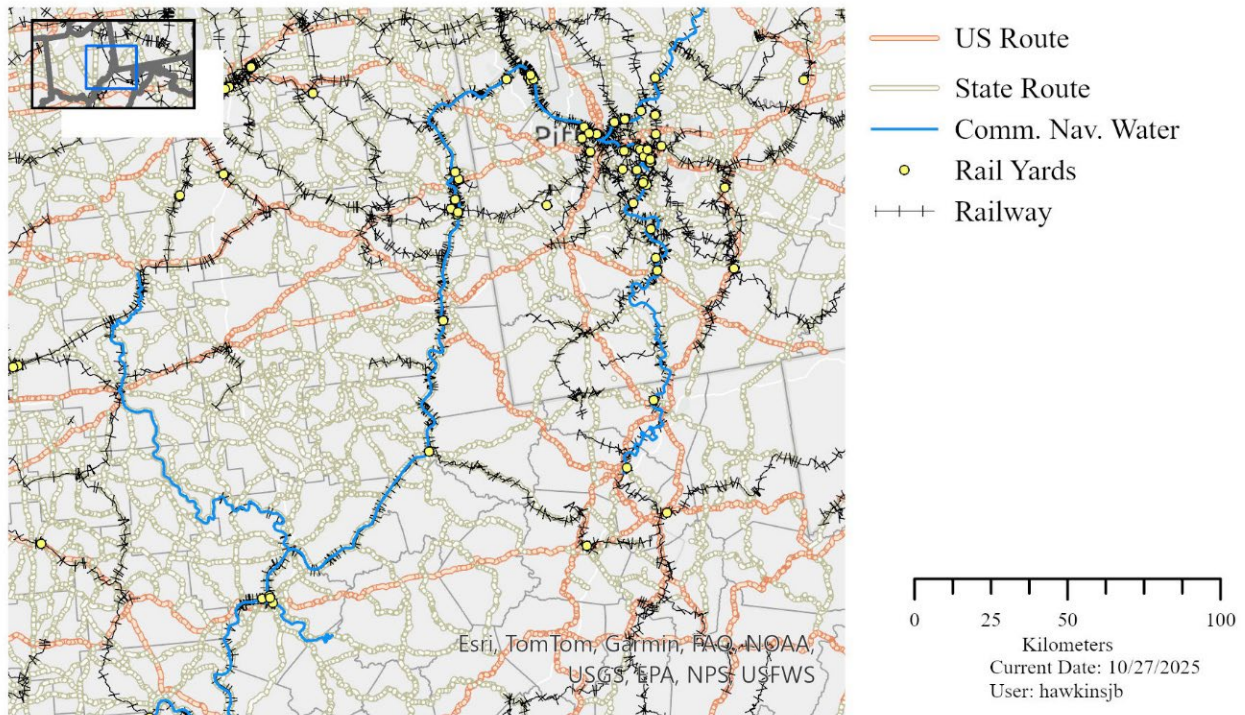


Figure 2. Modes of transport in the study area. Shapefiles are from Department of Transportation (United States Census Bureau, 2023; FRA, 1995) and the PHMSA (2019).

Once sources clusters were established, multi-modal interconnections for the hub were defined using a logical decision tree process that balanced the distance between nodes, the volume of CO<sub>2</sub>, the proximity of railyards, and the feasibility of pipeline construction. These decision trees, along with the rationale for decision points, are presented in Figure 3, Figure 4, and Figure 5 for pipelines that are less than 25 miles from the next node, 25 to 75 miles from the next node, and more than 75 miles from the next node, respectively.

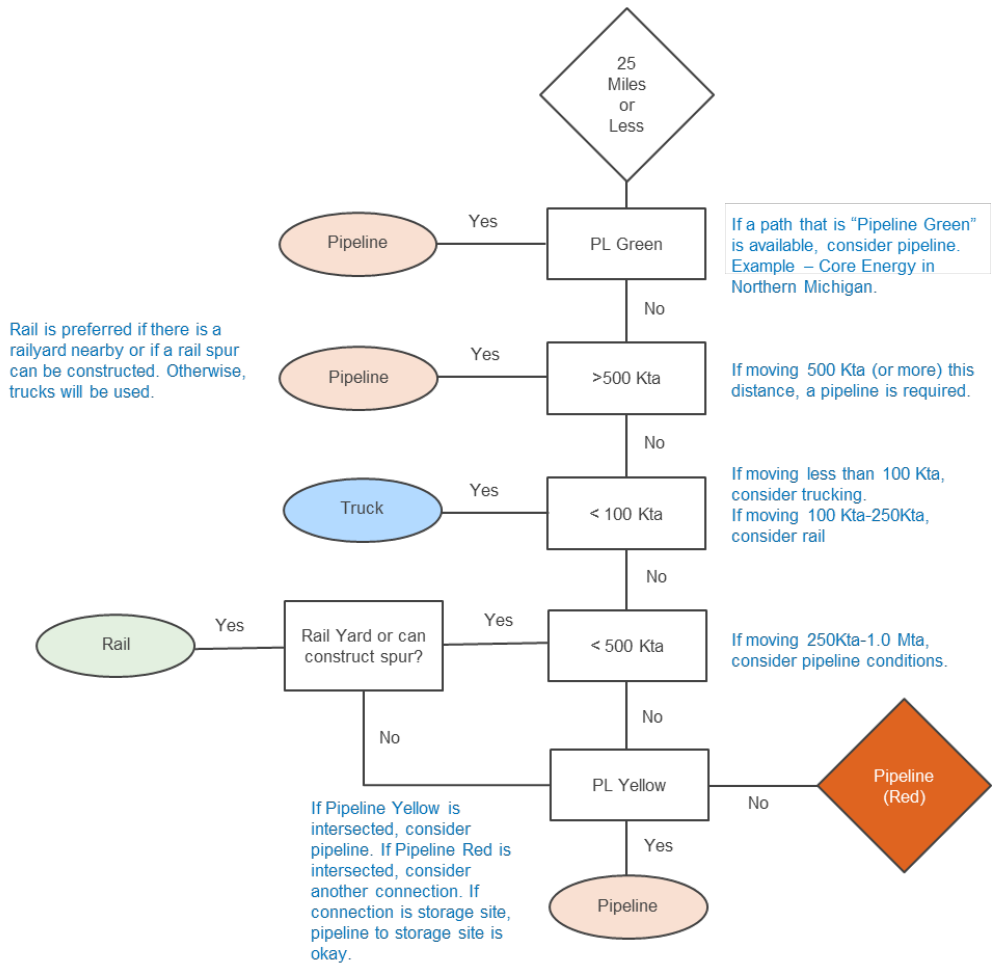


Figure 3. Decision tree for mode selection (less than 25 miles from node to node). Rationale for decision points are presented in blue text.

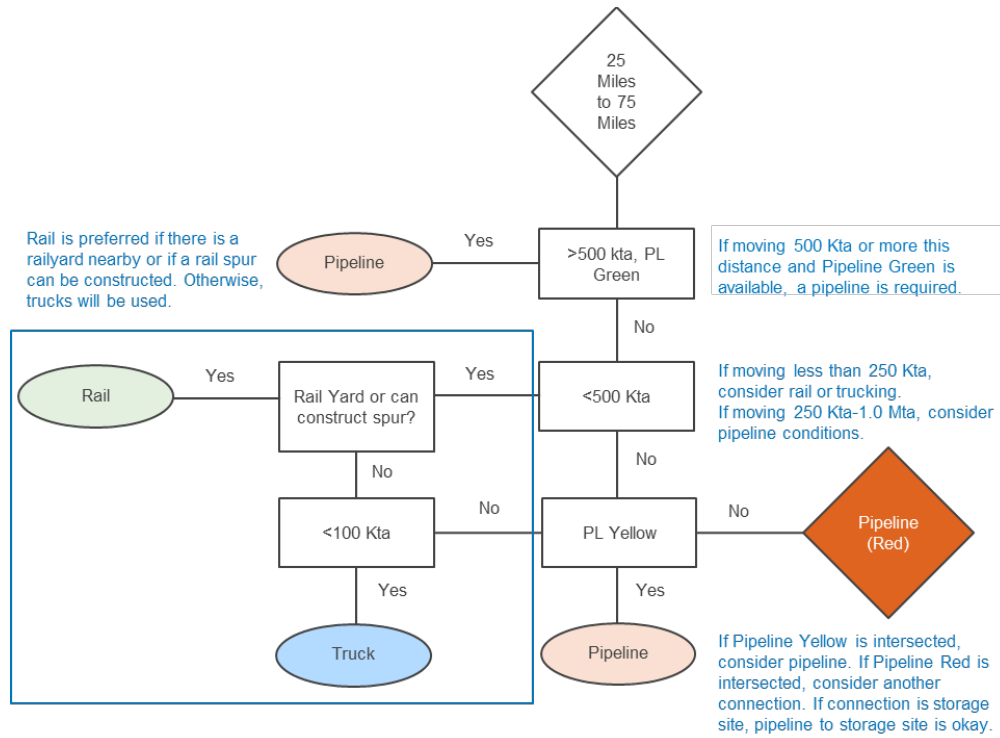


Figure 4. Decision tree for mode selection (25 to 75 miles from node to node). Rationale for decision points are presented in blue text.

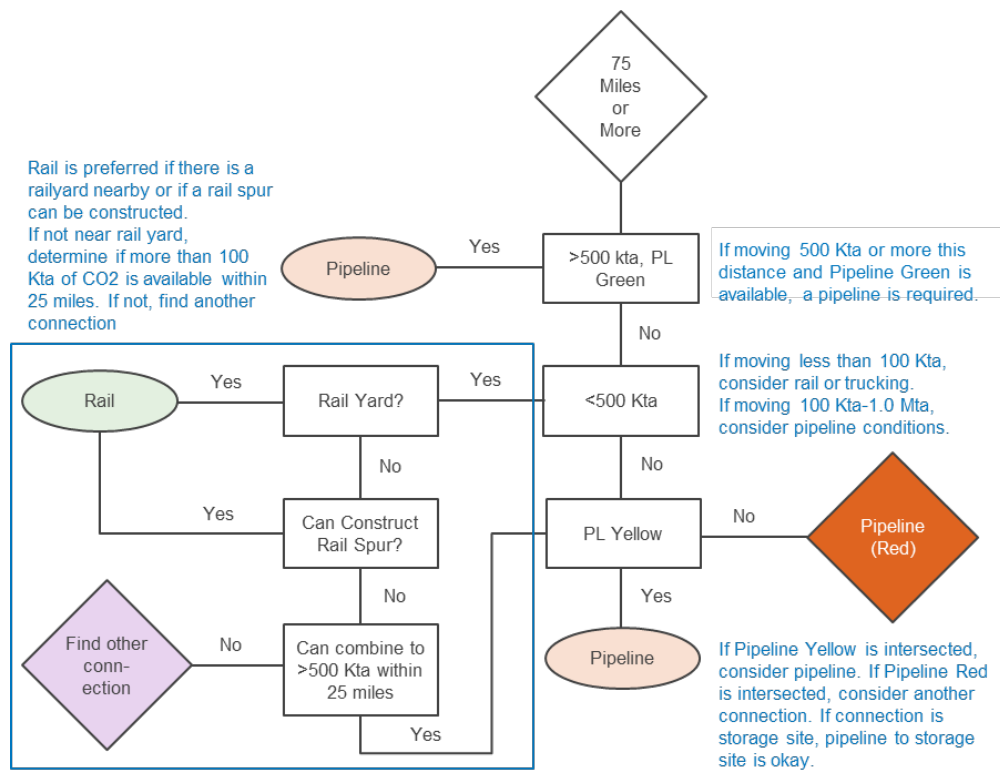
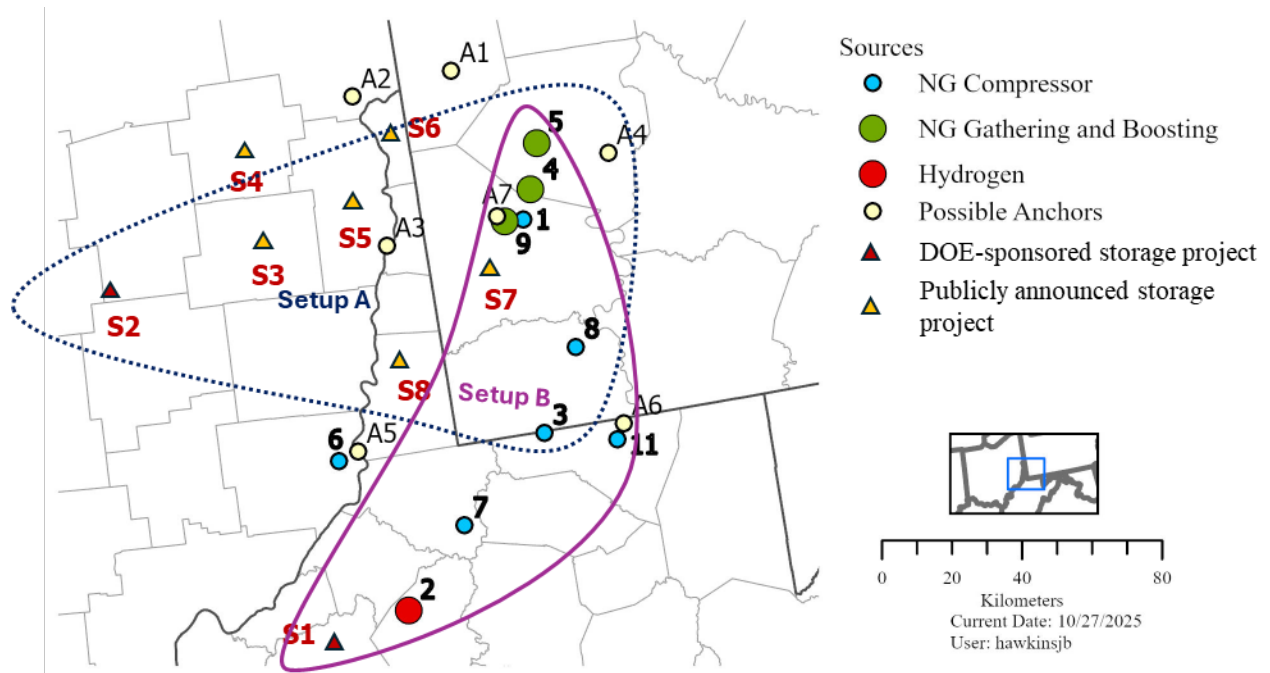


Figure 5. Decision tree for mode selection (more than 75 miles from node to node). Rationale for decision points are presented in blue text.

*Goal 3. Develop multiple realizations of parameters applicable to multi-modal transport and down-select set of designs are expected to be advanced to the pre-FEED stage.*

Two individual setups were developed to connect the sources (Figure 6). Setup A connected the sources in the northern portion of the study area and connected them Storage Area S2 in eastern Ohio. Setup B considered the sources in the Pittsburgh area. These setups were combined to develop a combined scenario that served as Scenario 1. The project team then considered the construction of a hydrogen facility to determine how a newly built facility would impact the network. This is considered Scenario 2. These are discussed in detail below.



*Figure 6. Map showing the initial setups that were combined and modified to develop the sources and sinks used in Scenarios 1 and 2.*

*Goal 4. Identify specific site (i.e., a single node) that will serve as the site for subsequent detailed analyses*

The project team also sought to determine and anchor site for the project. This site would provide a point at which the transport hub could be organized and serve as the point from which all the CO<sub>2</sub> could be routed. As such, the anchor site would serve as a single node within the preferred scenario was selected for subsequent detailed analyses. Seven different anchor sites were considered and are listed in Table 3. Factors considered in the selection included the proximity to partner sources and railyards, which were considered the transport points that would be hardest to build. Six of the seven sites were large sources in the area, including one steel plant (A1), two chemical plants (A2 and A3), and three electric power plants (A4, A5, and A6). The last anchor point (A7), and the selected node, is the Railyard 1 Hub Receiving Area (RY1 Hub Area). The node was selected to ensure that all applicable transport mechanisms are accounted for and that all states are considered. Subsequent analyses like parts of the design basis (see Subtask 2.3), regulations and permitting (Task 3), the BCA (Subtask 4.2), and environmental safety and health analysis (Task 5) are completed considering this node. For issues related to design and optimization (Subtask 2.2), parts of the design basis (see Subtask 2.3), regional connecting (Subtask 2.4), project cost analysis (Subtask 4.1), and long lead material and equipment needs (Subtask 4.3), the entire preferred scenario was considered.

Table 3. Potential anchor sites considered in the project. Numbers correspond to those presented in Figure 1.

No.	CO <sub>2</sub> Emissions (MMt)	Industry	Within 10 Miles of Partner Source	Within 25 Miles of Partner Source	Within 1 mile of Rail Yard	Within 10 miles of Rail Yard
A1	3.0	Steel Plant	Yes	Yes	Yes	Yes
A2	1.4	Chemical Plant #1	No	Yes	Yes	Yes
A3	0.52	Chemical Plant #2	Yes	Yes	No	Yes
A4	3.9	Power Plant #1	No	Yes	No	Yes
A5	10.0	Power Plant #2	No	Yes	No	Yes
A6	3.0	Power Plant #3	No	No	No	No
A7	NA	Railyard 1	Yes	Yes	Yes	Yes

## 2.2 Intermodal Transport Design and Optimization

The intermodal transport design and optimization included two goals: (1) investigating the methods of transport most appropriate for selected sources and (2) detail engineering infrastructure. Two systems are discussed. The first gathers CO<sub>2</sub> from hypothetical locations of sources that currently exist in the study area, focusing on small and medium-sized sources throughout southwestern Pennsylvania, northern West Virginia, and eastern Ohio (Figure 7; Table 1). The second scenario explores how the network would change with the introduction of a hydrogen plant in Doddridge County, WV (Figure 8; Table 1). CO<sub>2</sub> emissions shown are capturable CO<sub>2</sub> emissions.

**Scenario 1 Pipeline Interconnections:** The pipeline for Scenario 1 runs from Pittsburgh to the RY1 Hub Area (Figure 7). It connects four different sources of CO<sub>2</sub> to the Hub:

1. The pipeline originates at the Gathering and Boosting Station B in Pittsburgh and connects to the Gathering and Boosting Station A.
2. The pipeline then connects from the Gathering and Boosting Station A to the Gathering and Boosting Station C and co-located Compressor F.
3. The pipeline connects from the Gathering and Boosting Station C and co-located Compressor F to the RY1 Hub Area where it picks up additional CO<sub>2</sub> from the remaining sources considered in the scenario.
4. The pipeline routes from the RY1 Hub Area to the Storage Area in Tuscarawas County, Ohio.

**Scenario 1 Truck Transport:** Trucking of CO<sub>2</sub> will be accomplished using tanker trucks capable of carrying 20 tonnes of liquefied CO<sub>2</sub> per load (Myers et al., 2024). To minimize disruptions to local traffic patterns, the routes will be restricted to highways (e.g., interstates, state highways, etc.) except when leaving the point of capture or approaching the destination (if facilities are not adjacent to highways). Five distinct trucking routes are planned for Scenario 1:

1. Natural Gas Compressor B to Railyard 2 – One truck approximately every 5 hours traveling 18.0 miles to Railyard 2 for Train transport to RY1 Hub Area.
2. Natural Gas Compressor D to Railyard 2 – One truck approximately every 4 hours traveling 72.9 miles to Railyard 2 for Train transport to RY1 Hub Area.
3. Natural Gas Compressor E to Railyard 2 – One truck approximately every 3 hours traveling 26.6 miles to Railyard 2 for Train transport to RY1 Hub Area.
4. Natural Gas Compressor C to Railyard 3 – One truck approximately every 3 hours traveling 26.6 miles to Railyard 2 for Train transport to RY1 Hub Area.

**Scenario 1 Rail Transport:** Rail transport is accomplished using unit trains of rail tankers. Each rail tanker is assumed to hold 80 tonnes (Myers et al., 2024) and each intermodal car is assumed to hold 20 tonnes. For Scenario 1, two railyards receive CO<sub>2</sub> and transport it to the RY1 Hub Area:

1. Railyard 2 (and co-located Natural Gas Compressor G) to RY1 Hub Area. Around 6400 tonnes are delivered 139.2 miles from Railyard 2 to the RY1 Hub Area every 16-17 days by a tanker unit train.
2. Railyard 3 to RY1 Hub Area. Around 1700 tonnes are delivered 85.8 miles from Railyard 3 to the RY1 Hub Area every seven to eight days.

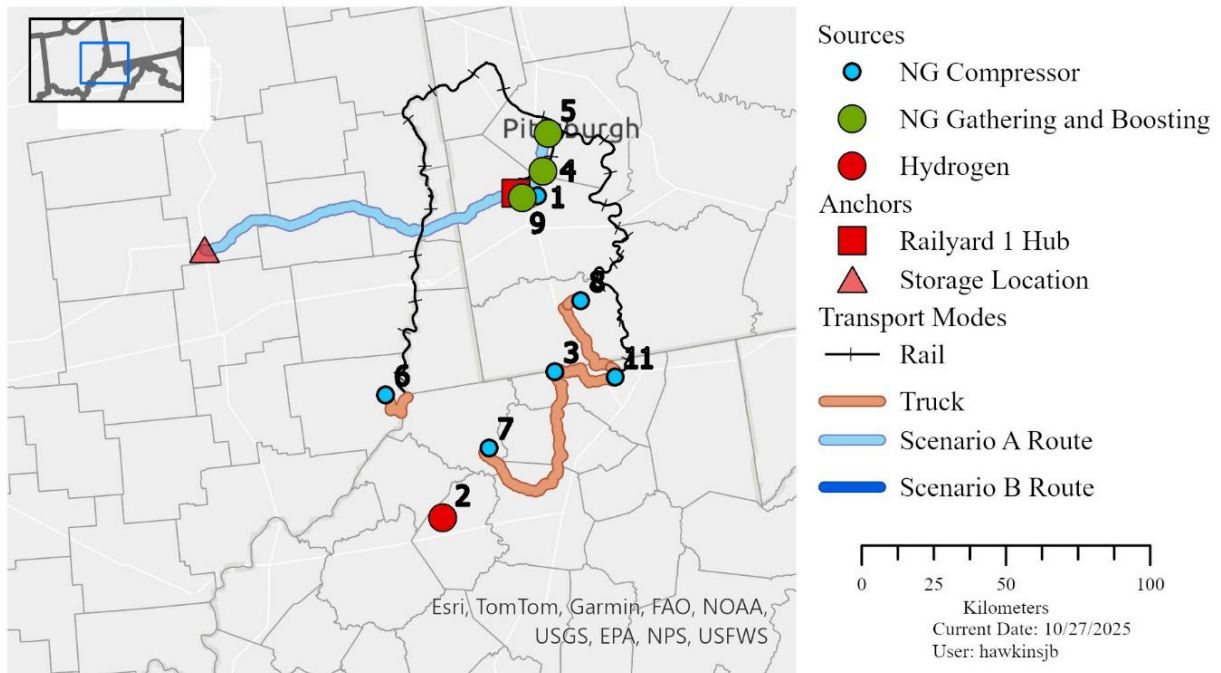


Figure 7. Scenario 1: intermodal transport for existing anonymized sources. Roads and railroads are determined using data from the US Census Bureau (2023) and FRA (1995).

Scenario 2 considers the impact of a newly constructed hydrogen plant on the intermodal transport hub (Figure 8). The plant is in Doddridge County, West Virginia, and emits 500,000 tonnes of CO<sub>2</sub> per year. The CO<sub>2</sub> is transported via pipeline northward to RY1 Hub Area. The location of the pipeline impacts the transport of CO<sub>2</sub> from Natural Gas Compressors C and D. The changes resulting from this scenario are detailed in bold text below:

- NG Compressor A: No change from initial plan
- NG Compressor B: No change from initial plan
- NG Gathering and Boosting A: No change from initial plan
- NG Gathering and Boosting B: No change from initial plan
- **NG Compressor C: 70,000 tonnes per year meeting pipeline in Wetzel County, West Virginia**
- **NG Compressor D: 40,000 tonnes per year transported to hydrogen plant by pipeline**
- NG Compressor E: No change from initial plan
- NG Gathering and Boosting C: No change from initial plan
- NG Compressor F: No change from initial plan
- NG Compressor G: No change from initial plan
- **Railyard 2: 40,000 tonnes per year less CO<sub>2</sub> transported (new amount: 110,000 tonnes per year)**
- **Railyard 3: No longer used**
- **RY1 Hub Area: 500,000 tonnes per year additional CO<sub>2</sub> transported**

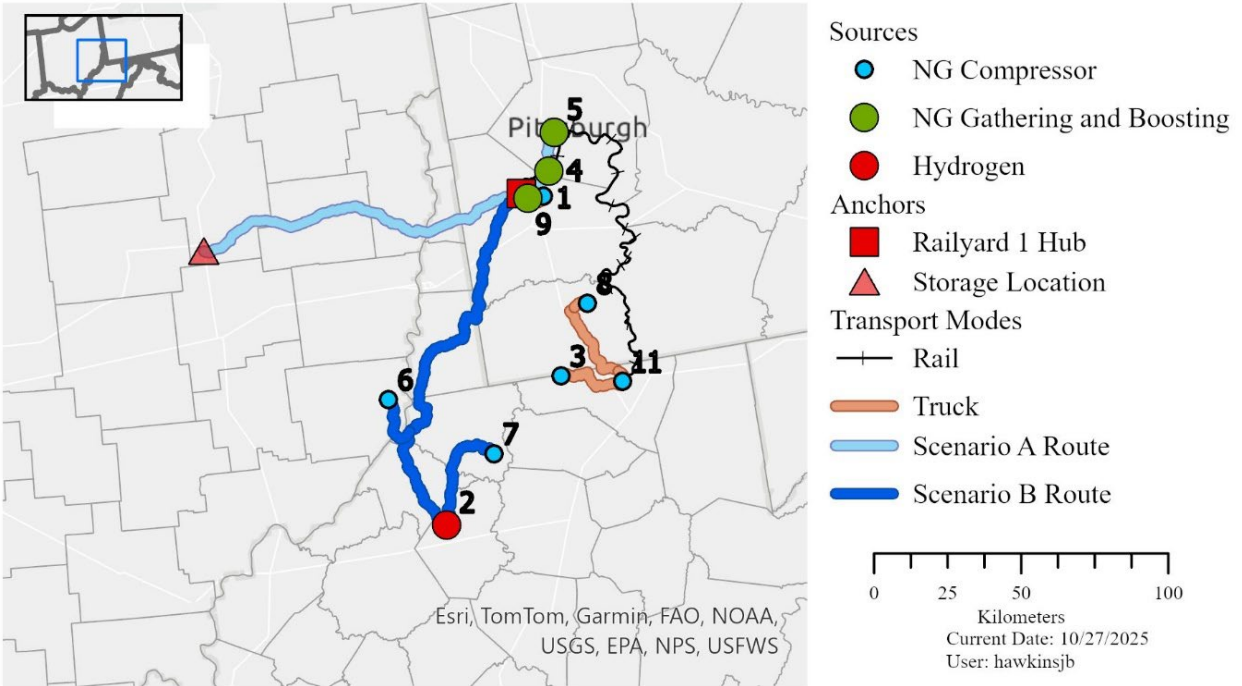


Figure 8. Scenario 2: intermodal transport for existing anonymized sources and a newly built hydrogen plant. Roads and railroads are determined using data from the FRA (1995) and the United States Census Bureau (2023).

For both systems, all CO<sub>2</sub> must meet the pipeline specifications shown in Table 4 prior to arriving at the RY1 Hub Area.

Table 4. Gas specifications for both conceptual scenarios. Gas must meet these specifications prior to entering the RY1 Hub Area.

Component	Limit	Reason
CO <sub>2</sub>	>95 mol% <sup>1,2</sup>	Line efficiency, compression
Water	<50 ppmv <sup>1</sup>	Corrosion
Oxygen (O <sub>2</sub> )	<10 ppmv <sup>2</sup>	Corrosion
Nitrogen (N <sub>2</sub> )	<1 mol% <sup>2</sup>	Line efficiency, compression
Hydrogen (H <sub>2</sub> )	<10 ppmv <sup>1</sup>	Line efficiency, compression
Hydrogen Sulfide (H <sub>2</sub> S)	<10 ppmv <sup>1</sup>	Health risks, acid formation
Total Sulfur	<35 ppmv <sup>1</sup>	Foul odor, acid formation
Carbon Monoxide (CO)	<35 ppmv <sup>2</sup>	Health risks
Glycol	46 ppbv <sup>2</sup>	Damage to pump seals
Ammonia (NH <sub>3</sub> )	<50 ppmv <sup>2</sup>	Health risks, corrosion
Argon (Ar)	<1 mol% <sup>2</sup>	Line efficiency, compression
Particulates	<1 ppmv <sup>2</sup>	Clogging, damage

### 2.3 Design Basis

The purpose of the design basis was to describe the RY1 Hub Area that will serve as the rally point for CO<sub>2</sub> in both scenarios. The facility will be capable of receiving and distributing at least 1.67 million metric tonnes (t) of pipeline grade CO<sub>2</sub> per year for Scenario 1 and at least 2.17 million metric tonnes of CO<sub>2</sub> per for Scenario 2. Assumptions are presented in this section while the remaining items of the pre-FEED are presented in Section 6.

The system is designed from the perspective of a CO<sub>2</sub> transport entity (Figure 9). The transport operator is assumed to be a mid-stream CO<sub>2</sub> pipeline company that is operating near RY1 Hub Area. The transport

operator is purchasing the CO<sub>2</sub> from all sources and selling it to the storage operator for use in a saline storage project in Tuscarawas County, Ohio. This assumes that purification of CO<sub>2</sub> to the specifications required for CO<sub>2</sub> transport and initial compression of CO<sub>2</sub> is handled outside of the examined system. Liquefaction and intermediate storage for trucking and rail and compression to pipeline specifications for pipeline transport are considered within the integrated project design. Executing transport and interconnections between transport modes are also considered to be the purview of the transport operator. Once the CO<sub>2</sub> is transported to the storage location, the storage operator is assumed to be responsible for offloading the CO<sub>2</sub>, providing intermediate storage, and eventual recompression and injection of the CO<sub>2</sub>.

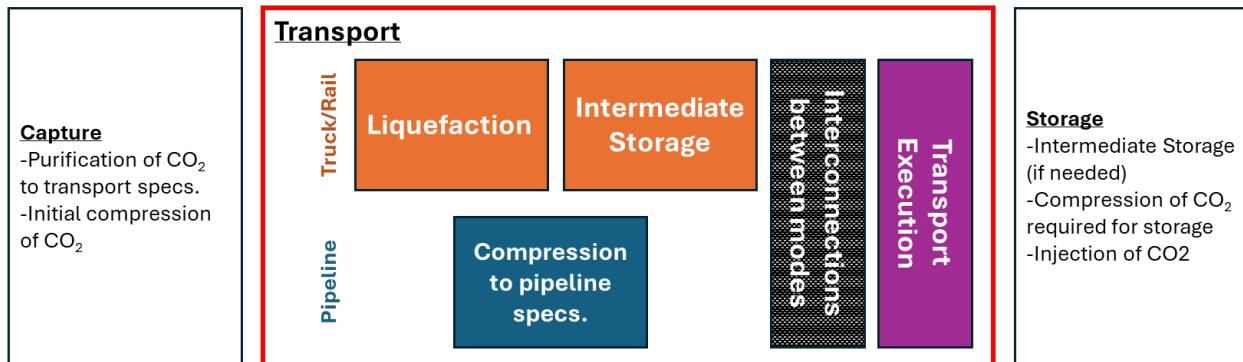


Figure 9. Integrated project considerations. This project considers liquefaction and intermediate storage for rail and trucking, interconnections between modes, and transport execution.

The transport operator is assumed to be in control of all aspects of pipeline and trucking but to be paying a fee for transport via rail. Additional assumptions are provided below:

- The capture systems are assumed to always operate, except during scheduled downtimes. The downtimes are assumed to occur once a year and equal to about seven (7) days, or around 2% of the entire year. These downtimes are assigned randomly and meant to demonstrate scheduled maintenance of the capture systems.
- Trucks are assumed to operate for a single 8-hour shift each day (including weekends). Therefore, storage is required at each source served by a truck for the CO<sub>2</sub> two-thirds of the time.
- Trains are assumed to run as unit trains of 80 cars for both tankers and intermodal transport containers. Additional equipment required at the railyard to move and store CO<sub>2</sub> are considered in this analysis. In addition, the analysis also considers acquisition of all required equipment for the project, including rail tankers and intermodal cars, storage tanks, and required pumps and connections. However, improvements to rail system (e.g., expansion of the track or land, increased employment of railyard workers, or increased capacity to serve cars) are not considered. The analysis assumes there is capacity at the railyard to service all train cars needed for the project. For the economic assessment, the project assumes a single payer is paying a negotiated rate to the railyard to service all unit trains and host storage tanks.
- The pipeline(s) will operate continuously. Required maintenance is expected to be completed in isolated sections to minimize impacts on operations. The pipeline(s) will be developed according to API5L PSL2 X65M.

A conceptual analysis was completed for each of the two Scenarios. This conceptual analysis included a high-level assessment of the required permits for the system; a high-level economic assessment of the operating system (from the perspective of the transport operator); and development considerations, such as pipe size, pressure requirements, equipment availability, population centers, potentially impacted environmental and cultural areas.

## 2.4 Regional Connection

This subtask researched the potential use of the CO<sub>2</sub> transport hub over the next 50 years. The project focuses on natural gas resources, which will continue to be an important part of the study area for the foreseeable future. This is evidenced by the production of natural gas in the Marcellus and Utica/Point Pleasant. Ohio, Pennsylvania, and West Virginia produced a combined 13,000,000 million cubic feet (mcf) of natural gas in 2024 (Energy Information Administration [EIA], 2025a). This accounted for nearly 30% of the natural gas produced in the United States that year. In addition, natural gas consumption is high in the project study area for a number of end users. The three states in the study area accounted for the use of around 3.5 billion cubic feet (bcf) of natural gas in 2023 (EIA, 2025b), around 11% of the gas used in the United States. Most of this was used for power production and residential end users. Around 1.5 bcf of the gas produced in 2023 was used by electric power end users. In addition, 55%, 45%, and 39% of homes using natural gas for heating in Ohio, Pennsylvania, and West Virginia, respectively (EIA, 2023).

Additional sources in the study area include industrial and electric power facilities, ranging from small sources that emitted less than 100,000 tonnes of CO<sub>2</sub> in 2023 to large electric power plants and industrial sources that emitted more than 1.0 million tonnes of CO<sub>2</sub> in 2023 (U.S. EPA, 2024). The sources within 10, 25, and 50 miles of each facility considered in the assessment and the RY1 Hub Area (A7) are shown in Figure 10, and the sum of the emissions, average emissions, and number of sources are detailed in Table 5. This work helps show the potential for hub expansion to include other sources in the region and the potential for individual sources considered in the network to serve as significant nodes in future development.

The mode selection process, outlined in Section 2.1, was applied to the sources within 150 miles of the RY1 Hub Area (Figure 11). The scenario was not optimized like Scenarios 1 and 2 above but was intended to show the function of the decisions trees on selecting modes for other sources in the vicinity of the RY1 Hub Area. Sources within 50 miles of the storage area were not considered because these sources would be closer to the storage area than the RY1 Hub Area. In the scenario presented in Figure 11, sources that emit 500,000 tonnes of CO<sub>2</sub> or more a year would be transported by pipeline because of logistical considerations with the other modes of transport.

Sources within 25 miles of the RY1 Hub Area would largely be transported by truck directly to the storage area (if they emit less than 100,000 tonnes per year) or by rail (if they emit more between 100,000 and 500,000 tonnes per year). One source near the RY1 Hub area could also be served by a pipeline because it is situated in an ideal area for pipeline development.

Most sources 25 to 75 miles from the RY1 Hub Area need to be trucked to a nearby railyard, pipeline inlet, or directly to the RY1 Hub Area. Other sources close to railyards could truck CO<sub>2</sub> to the railyard or construct spurs that would connect to these railyards. These sources largely emit between 100,000 and 500,000 tonnes per year. Other sources that emit between 100,000 and 500,000 tonnes per year but are not within five miles of a railyard may be serviced by pipeline branches that connect to pipeline trunk-lines, railyards or spurs, or directly to the RY1 Hub Area.

Rail is the most common selected mode for sources 75 to 150 miles from the source, particularly in Cleveland where there are several railyards. Alternatively, these sources may eventually be serviced by a pipeline, although its development may be complicated by the population center. Several sources, labeled as “other” are too small to be considered for dedicated pipeline infrastructure and are not close enough to a railyard to construct a spur (i.e., are more than five miles from the nearest railyard). Sources like these may be stranded without additional pipeline infrastructure, other transport options (like barge), or additional optimization beyond the scope of this exercise.

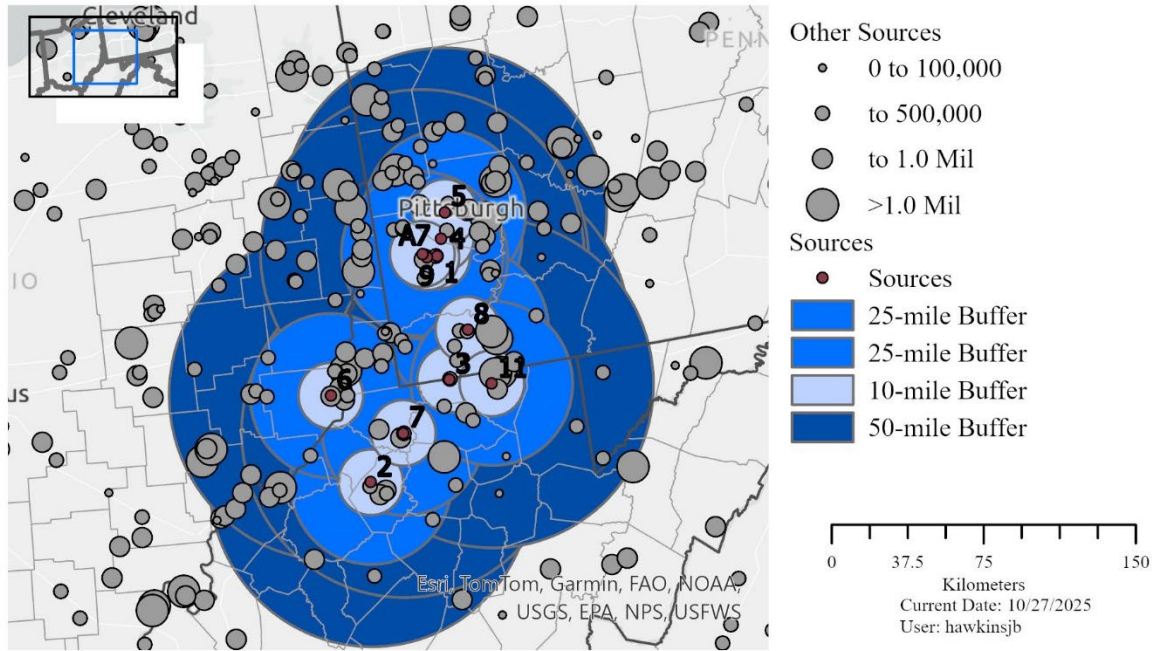


Figure 10. Map of sources considered in the project with 10-, 25-, and 50-mile buffers to show the other sources in the area that may be served by the hub. The emissions from these sources are detailed in Table 5.

Table 5. Other industrial and electric power sources within 10, 25, and 50 miles of the sources considered in this study. Source data includes the sum and average CO<sub>2</sub> emissions in 2023 and the number of facilities U.S. EPA, (2024).

Facility No.	10 miles			25 miles			50 miles		
	CO <sub>2</sub> (MMt/yr)		Count	CO <sub>2</sub> (MMt/yr)		Count	CO <sub>2</sub> (MMt/yr)		Count
	Sum	Mean		Sum	Mean		Sum	Mean	
1	0.3	0.06	4	15.4	0.55	28	47.8	0.54	89
2	0.4	0.09	4	12.2	1.22	10	28.8	0.52	55
3	0.1	0.03	3	25.4	1.02	25	43.4	0.64	68
4	0.2	0.08	3	7.4	0.25	30	51.3	0.57	90
5	0.3	0.04	8	8.9	0.26	34	45.9	0.53	87
6	5.5	0.61	9	6.2	0.29	21	44.0	0.68	65
7	0.2	0.06	3	14.7	0.77	19	40.3	0.68	59
8	3.5	0.58	6	12.8	0.61	21	48.9	0.62	79
9	0.2	0.07	3	15.4	0.53	29	50.9	0.53	97
11	8.9	2.2	4	13.2	0.83	16	33.2	0.53	62
A7	0.2	0.06	4	15.4	0.53	29	52.6	0.53	99

The intermodal hub is positioned well to take advantage of synergies with other carbon removal and CO<sub>2</sub>-enhanced oil recovery (EOR) projects. The intermodal hub is in an area with significant federal investments. Projects like the ARCH2 Hub will provide an additional end-user for natural gas. The ARCH2 Hub seeks to connect producers of blue hydrogen (i.e., hydrogen produced from natural gas with CCS) with hydrogen transporters and consumers. The project also tracked nearby storage system development conducted by the Southern States Energy Board (SSEB) through its Phase III Carbon Storage Assurance Facility Enterprise (CarbonSAFE) effort (Wernette, 2024). These locations were considered for when developing the scenarios presented in Sections 2.1 and 2.2 but were ruled out because they were still under development at the time of the project. Additional carbon capture, storage (CCS) projects, and other carbon removal projects are mapped in Figure 12. These projects could serve as

additional connections for a regional hub or additional redundancies to help defray risks of project investment.

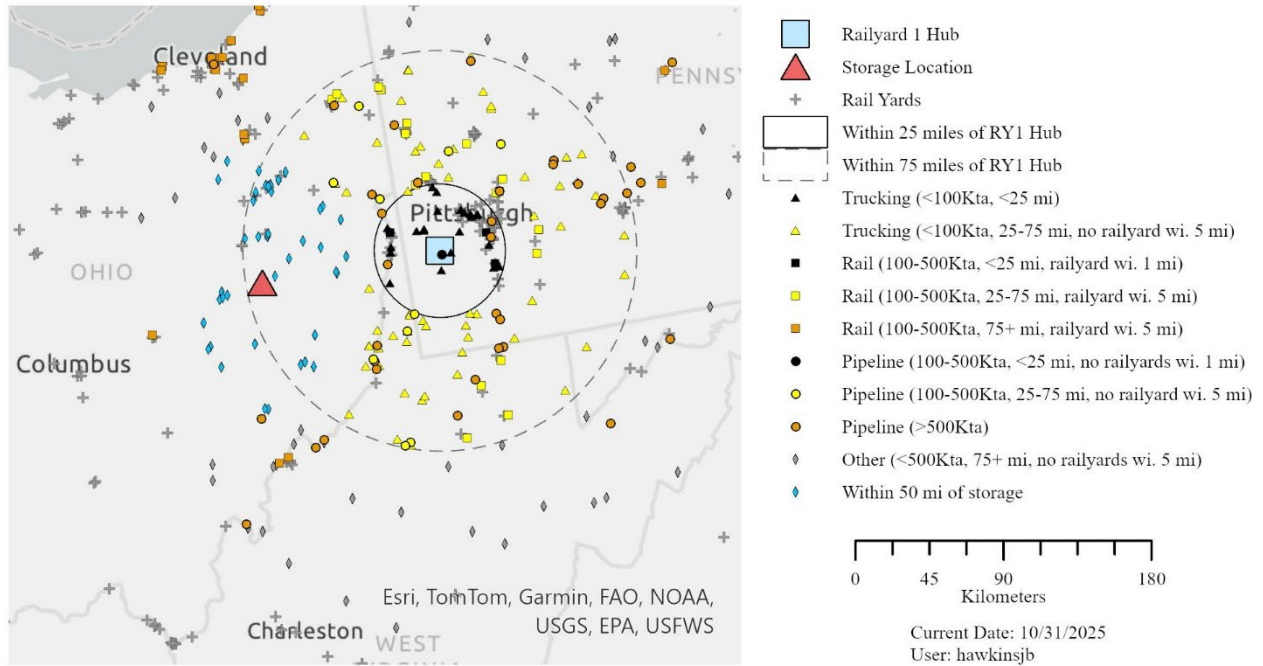


Figure 11. Mode selection for sources within 150 miles of the RY1 Hub Area. Modes were selected using the process outlined in Figure 3 (for sources within 25 miles of the RY1 Hub Area) Figure 4 (for sources 25 to 75 miles from the RY1 Hub Area), and Figure 5 (for sources more than 75 miles from the RY1 Hub Area). Additional optimization would be required for sources labeled as “other” or those within 50 miles of the storage area.

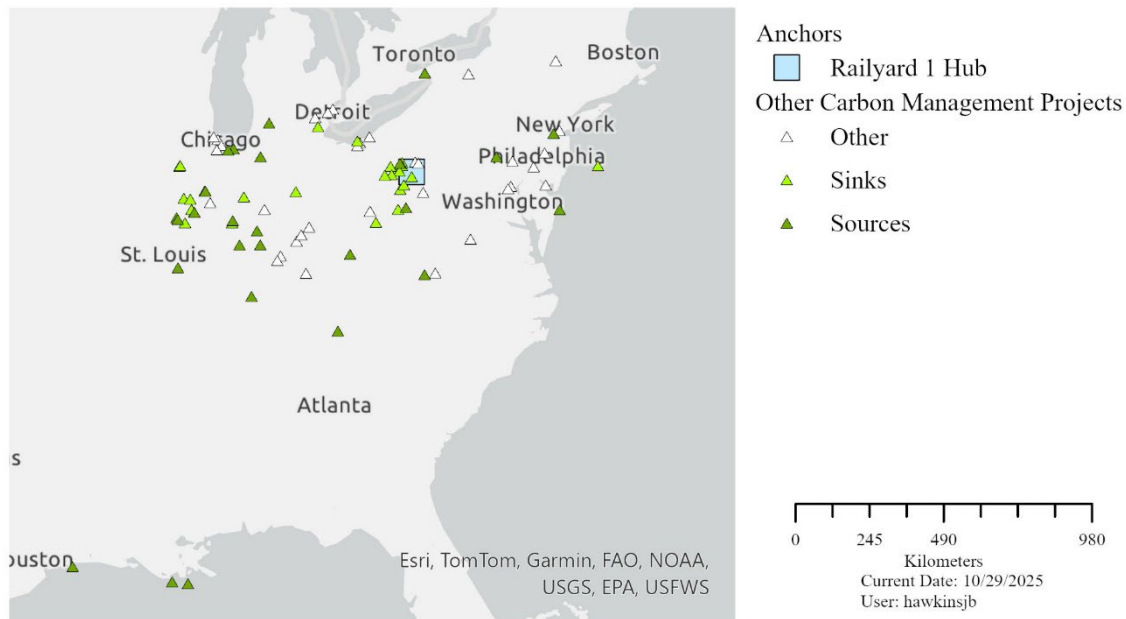


Figure 12. Additional carbon capture (sources), storage (sinks), and other projects near the RY1 Hub Area.

### 3.0 Regulations and Permitting

This task will result in information about the federal, state, and local regulations and permits needed for the intermodal designed transport hub. In addition, a land acquisition plan to ensure all necessary ROWs for the project can be acquired in future phases will be researched as part of this task.

#### 3.1 Permitting and Regulatory Plan

The relevant federal, state, and local regulations and permits required for each mode of transport included in the hub were reviewed as part of this project. The analysis is summarized below with the full permitting analysis and matrix table in Appendix 1.

**Federal Regulatory Framework:** CO<sub>2</sub> pipelines are subject to multiple federal regulations. The Pipeline and Hazardous Materials Safety Administration (PHMSA) enforces safety standards under 49 C.F.R. Parts 190–199, which cover design, construction, operation, and emergency response. These rules aim to prevent accidents and ensure public safety. Environmental reviews under the National Environmental Policy Act (NEPA) are required for projects involving federal lands or funding. Additionally, permits under the Clean Water Act may be necessary for wetland and stream crossings. Permanent CO<sub>2</sub> storage is regulated through the EPA’s Underground Injection Control (UIC) program for Class VI wells unless states have obtained primacy.

#### Pipeline Transportation

- PHMSA (Pipeline and Hazardous Materials Safety Administration, DOT)
  - Regulates pipeline safety (design, construction, operation, maintenance).
  - Requires detailed engineering plans, safety and emergency response documentation, and ongoing compliance audits.
- NEPA (National Environmental Policy Act)
  - Required for pipelines crossing federal lands or involving federal actions.
  - Involves environmental impact assessments, public engagement, and mitigation planning.
- USACE (U.S. Army Corps of Engineers) Section 404/10
  - Required for water crossings.
  - Requires site plans, impact analyses, and mitigation strategies.

#### Rail Transportation

- PHMSA (DOT)
  - Regulates hazardous materials packaging, labeling, and documentation.
- FRA (Federal Railroad Administration, DOT)
  - Sets safety standards for rail equipment, track, and operations.
- STB (Surface Transportation Board)
  - Approves new or modified rail lines, requiring environmental documentation.

#### Truck Transportation

- PHMSA (DOT)
  - Regulates hazardous materials transport, including packaging and documentation.
- FMCSA (Federal Motor Carrier Safety Administration, DOT)
  - Regulates vehicle and driver safety, requiring training and maintenance records.

***State-Specific Requirements:*** State-level considerations for CO<sub>2</sub> transportation and permitting primarily revolve around property rights, environmental compliance, and regulatory authority for storage. All three states—Ohio, West Virginia, and Pennsylvania—define pore space ownership as belonging to the surface estate, requiring developers to secure rights through agreements or pooling mechanisms. Each state allows some form of unitization for storage projects, with consent thresholds ranging from 70% in Ohio to 75% in Pennsylvania, while West Virginia follows oil and gas pooling principles. Class VI injection wells, essential for permanent CO<sub>2</sub> storage, are regulated under the EPA’s UIC program unless states have primacy; West Virginia currently holds primacy, while Ohio and Pennsylvania are pursuing it. These frameworks ensure that subsurface storage aligns with property rights and environmental safeguards.

Pipeline siting and construction lack dedicated CO<sub>2</sub>-specific statutes in these states, creating uncertainty around eminent domain authority. Developers typically rely on negotiated easements or, in some cases, common carrier status to secure rights-of-way. Environmental permitting remains a critical component, including water obstruction permits for stream and wetland crossings, air permits for compressor stations, and erosion control measures under state programs. Public engagement requirements, liability transfer provisions, and long-term monitoring obligations vary by state but are increasingly emphasized to address safety and environmental justice concerns. Below are the primary regulatory state agencies.

### **Ohio**

- ODNR (Ohio Department of Natural Resources)
  - Oversees oil and gas activities and injection wells.
  - Recently granted primacy for Class VI well permitting.
- PUCO (Public Utilities Commission of Ohio)
  - Regulates intrastate pipeline safety.
- ODOT (Ohio Department of Transportation)
  - Oversees hazardous materials transport by truck and rail.

### **Pennsylvania**

- PA DEP (Department of Environmental Protection)
  - Reviews and monitors underground injection wells.
  - EPA remains the permitting authority for Class VI wells.
- PUC (Public Utility Commission)
  - Regulates intrastate pipeline safety.
- PennDOT (Department of Transportation)
  - Oversees hazardous materials transport by truck and rail.

### **West Virginia**

- WVDEP (Department of Environmental Protection)
  - Permits and regulates underground injection wells.
  - Administers Class VI well program (recently granted primacy).
- PSC (Public Service Commission)
  - Regulates intrastate pipeline safety.
- WVDOT (Department of Transportation)
  - Oversees hazardous materials transport by truck and rail.

**Local Requirements:** In addition to federal and state-level requirements, CO<sub>2</sub> transportation projects typically require local permits and approvals. For pipelines, developers often need road crossing permits from county or municipal authorities, utility coordination agreements, and local zoning approvals for compressor stations or valve sites. Construction activities may also trigger stormwater management permits and erosion control plans under local ordinances.

For truck and rail transport, local permits generally include oversize or overweight vehicle permits for CO<sub>2</sub> tankers, issued by city or county transportation departments. Rail shipments require coordination with local emergency management agencies and compliance with municipal hazardous material handling ordinances. In some jurisdictions, additional fire safety and emergency response planning approvals are required to ensure community preparedness for CO<sub>2</sub> transport incidents.

**Permitting Summary:** The permits and processes required for this conceptual intermodal facility are consistent with previously studied CCS projects. Federal requirements, such as the application for a Class VI well permit or developing an environmental impact summary (EIS) through NEPA, can require a large amount of time and effort. These can take over two years in some cases to complete the required information and apply for appropriate approvals.

Most of the permits that are needed for construction are routine permits that require a short preparation period a modest application fee. They are also generally approved within a few weeks or months. Potential issues with permitting requirements could come from public comments or public opposition to the permit. In particular, the siting of pipelines could possibly prove to be a time-consuming permitting process if formal objections are made to project plans. Permitting generally takes at least one month for approval (with a public comment period) if no comments are received. With comments, however, the process can take up to 12 months. Water quality permits, air quality permits, wetlands permits, and endangered species act permits also have a public comment period and/or iteration with regulators that could potentially delay the project. These permit applications need to be started at the project outset. Application fees are not exorbitant, but public engagement costs to avoid public protests and rejection will be a significant expense.

### *3.2 Land Acquisition Plan*

The project, as envisioned, includes eleven CO<sub>2</sub> emission points (natural gas compressors serving natural gas gathering and transmission pipelines) approximately 135 miles of pipeline, four (4) compressor stations, and three (3) railroad transfer locations. Three CO<sub>2</sub> emission points are adjacent to the planned CO<sub>2</sub> pipeline and the captured and conditioned CO<sub>2</sub> will be injected directly into the CO<sub>2</sub> pipeline. CO<sub>2</sub> emissions from the other eight CO<sub>2</sub> emission points will be captured, conditioned, and transported by truck to one of the railroad transfer locations. An analysis was completed evaluating the estimates steps and affected area of the pipeline Right-of-Way (ROW) acquisition.

**Affected Area:** Table 6 summarizes the counties and property parcels that the pipeline will traverse, the length of the pipeline in the indicated county, and the total acreage for the property parcels in the indicated counties.

Table 6. Summary of Key Statistics for Planned CO<sub>2</sub> Pipeline

County and State	Miles of Pipeline	Property Parcel Count	Acreage
Doddridge, West Virginia	9.03	62	710.9
Greene, Pennsylvania	1.84	12	121.1
Marshall, West Virginia	27.31	166	1659.6
Monroe, Ohio	8.43	45	538.5
Tyler, West Virginia	26.2	148	1793.9
Washington, Pennsylvania	31.79	202	1951.8
Wetzel, West Virginia	30.15	167	2160.3
Total	134.8	802	8936.1

**Land Requirements:** The planned routing represents approximately 75% collocation with existing natural gas pipelines, powerlines, railroads, and road easements. The remaining 25% of the routing will require new easements. In either case, permission from landowners must be obtained to build the planned CO<sub>2</sub> pipeline.

It is anticipated that existing railyards can accommodate the required CO<sub>2</sub> transfer and storage equipment.

It is also anticipated that the eight CO<sub>2</sub> emission locations requiring truck transport of the CO<sub>2</sub> will be able to accommodate the CO<sub>2</sub> compression transfer equipment and have sufficient space to accommodate truck access, maneuvering, and parking. In the absence of adequate space at existing CO<sub>2</sub> emission locations, a truck transfer facility will require 5-10 acres to accommodate operations.

CO<sub>2</sub> compression stations typically require 5 to 10 acres of land to accommodate compression equipment, control buildings and electrical infrastructure, storage tanks, access roads, and safety buffers. This property will have to be acquired or leased by CO<sub>2</sub>NNECTION Project Developers.

**Regulatory Agencies:** The project team developed permitting/notification matrices for each mode of CO<sub>2</sub> transportation in Ohio, Pennsylvania, and West Virginia. These matrices identify the agency having jurisdiction over the issue, permitting or notification requirements for each, any required studies, and typical timelines and costs for the permitting or notification activity.

Although the proposed pipeline is an interstate pipeline, the Federal Energy Regulatory Commission (FERC) does not currently regulate CO<sub>2</sub> pipelines. Note also that implementation of the eminent domain process for acquiring property for CO<sub>2</sub> pipelines is contentious and will be governed by evolving state regulations.

**Right of Way Acquisition Sequence of Operations:** Below are the list of tasks that need to occur to acquire the ROW:

Task 1. Finalize Routing

The conceptual route for the CO<sub>2</sub> pipeline has not been evaluated to determine “constructability” Determining constructability will require a visual assessment of the route and more detailed environmental and cultural assessments than those provided by the Pivvot<sup>®</sup> pipeline routing tool.

Estimated completion time: 3 months, in advance of all other tasks except Task 2, Public Engagement.

Task 2. Public Engagement

Develop and deploy a public engagement strategy to inform stakeholders about the pipeline project and the benefits it will produce. Identify opponents and develop plans to counter anticipated negative messaging.

Estimate completion time: From project inception through the life of the project.

### Task 3. Research Titles and Identify Landowners

Engage a land services firm to conduct title searches and create a database of parcels, landowners, and contact information.

Estimated completion time: 3 months, beginning after completion of Task 1.

### Task 4. Engage Landowners

Authorize the land services firm to contact landowners to negotiate easement agreements for the pipeline and purchase or lease agreements for property required for compression stations or truck transfer locations.

Estimated completion time: 6-12 months, beginning when information from Task 3 is available.

### Task 5. Conduct Property Surveys and Environmental Studies

Conduct formal surveys to finalize the pipeline route and mark right-of-way boundaries. Perform necessary environmental and cultural resources surveys to ensure that mitigation plans are developed to protect endangered or threatened species, cultural resources, and sensitive environmental areas. Advance discussions with regulatory agencies that were initiated during Task 2.

Estimated completion time: 6-12 months following substantial completion of Task 4.

### Task 6. Secure Permits and Regulatory Approvals

Conduct formal and more detailed meetings with regulatory agencies to further explain the carbon dioxide pipeline project. Prepare and submit the required notifications and permit applications to the agencies identified in Appendix 2. Maintain the public engagement strategy developed during Task 2. Participate in public meetings or hearings as required.

Estimated completion time: 18-24 months, following substantial completion of Task 5.

***Begin Pipeline Construction:*** Pipeline construction can begin once all land has been acquired, all notifications have been made, and all permits have been obtained.

## 4.0 Techno-Economic Assessment

The transportation of CO<sub>2</sub> from point source emitters, such as natural gas processing plants, to designated injection wells is a critical component of CCS strategies aimed at reducing greenhouse gas emissions. Thus, it is crucial to understand the impact of different modes of transportation on CCS project economics and feasibility. In Task 4, a techno-economic assessment demonstrating a high-level cost analysis and BCA of the CO<sub>2</sub>NNECTION intermodal transport hub was completed and is available as Appendix 2 to this report. In addition, a preliminary long-lead material and equipment list was developed. The techno-economic assessment and BCA explore the logistical and economic considerations of three primary transportation modes: truck, rail, and pipeline. The initial techno-economic assessment and BCA was submitted to DOE in July 2025; the project team refined the report into a final version that is included as Appendix 2 of this report. The results of the report are summarized in this section.

Each transportation method presents unique advantages and challenges in terms of scalability, cost-effectiveness, infrastructure requirements, and regulatory compliance. Trucking offers flexibility and low initial capital investment, making it suitable for small-scale or early-stage CCS projects, but it is limited by capacity and higher per-tonne transport costs. Rail transport provides a middle ground, offering greater volume capacity and moderate infrastructure needs, though it requires access to rail networks and transloading facilities. Pipelines, while capital-intensive and subject to stringent permitting processes, offer the most efficient and cost-effective solution for large-scale, continuous CO<sub>2</sub> transport over long distances. The BCA reviews the cost of each transportation method of the proposed multi-modal hub in two primary scenarios and three sub-scenarios to determine the impacts of more distant CO<sub>2</sub> sources on the network's economics.

A selection of scenarios and sub-scenarios was considered to understand the influence of various sources and modes of transportation on the project. Two primary scenarios are presented; these scenarios are defined in Table 7. The first gathers CO<sub>2</sub> from hypothetical sources that currently exist in the study area, focusing on small- and medium-sized sources throughout southwestern Pennsylvania, northern West Virginia, and eastern Ohio. The second scenario explores how the network would change with the introduction of a hydrogen plant in Doddridge County, West Virginia. The hydrogen plant is assumed to use natural gas as a feedstock and capture the CO<sub>2</sub> resulting from hydrogen production.

*Table 7. Overview of scenarios and sub-scenarios considered in the discounted cash flow (DCF).*

Scenario	Description
Scenario 1	Gathers CO <sub>2</sub> from hypothetical locations of sources that currently exist in the study area, focusing on small and medium-sized sources throughout southwestern PA, northern WV, and eastern OH
Scenario 2	Considers the impact of a newly constructed hydrogen plant on the intermodal transport hub
Scenario 1A – Only Pipeline	Same as Scenario 1 but excludes all methods of transportation and CO <sub>2</sub> sources other than pipelines and CO <sub>2</sub> originating at pipeline hubs. This scenario was used for the Economic Assessment only.
Scenario 1B – Fewer Trucking Connections	Same as Scenario 1 but excludes three trucking routes that connect at Railyard 2 and one trucking route that connects at Railyard 3. This scenario was used for the Economic Assessment only.
Scenario 1C – No Railyard 3	Same as Scenario 1 but excludes Railyard 3 and its associated CO <sub>2</sub> source. This scenario was used for the Economic Assessment only.

The project's net present value (NPV) and internal rate of return (IRR) were calculated using a discounted cash flow (DCF) model. Based on 45Q credits for geological storage from point-source capture, a revenue of \$85 per net tonne of CO<sub>2</sub> transported was assumed (Carbon Capture Coalition, 2025).

Truck and rail cost estimates (both capital expenditures [CAPEX] and operating expenditures [OPEX]) were obtained using the methodology outlined by Myers et al. (2024) and thus follow the assumptions defined therein. Additionally, simplifying assumptions were made by the CO<sub>2</sub>NNECTION team for the purpose of obtaining a high-level cost analysis. Transport costs and impacts for truck and rail were each calculated as one route transporting the total mass of CO<sub>2</sub> to be transported by each method. The geographical scale and location were selected as “Regional” and “East,” respectively, and the container type was assumed to be intermodal for both truck and rail

After further review by the CO<sub>2</sub>NNECTION project team, it was determined that the Office of Fossil Energy and Carbon Management / National Energy Technology Laboratory (FECM/NETL) CO<sub>2</sub> Transport Cost Model originally specified in the Statement of Project Objectives (SOPO) is not capable of efficiently modeling pipeline networks. Instead, it is more applicable for single source/sink pipeline scenarios. As a result, pipeline capital cost estimates were largely obtained using the methodology outlined by McCollum and Ogden (2006), which estimates capital cost as a function of pipeline length and CO<sub>2</sub> mass flow rate as opposed to conventional inch-mile estimates. The FECM/NETL CO<sub>2</sub> Transport Cost Model (Morgan and Shih, 2024) was only utilized to estimate the CAPEX and OPEX associated with pumping the truck and rail CO<sub>2</sub> volume to pipeline specifications.

Mass flow rates for the intermodal transport network pipelines were rounded up to the nearest of the four values (1,000, 5,000, 10,000, or 20,000 tonnes per day) to match with one of McCollum and Ogden’s four cost curves. Costs were adjusted for inflation using the Chemical Engineering Plant Cost Index (CEPCI) values (averaged over the year) for 2006 and 2024. Annual operating expenses were conservatively assumed to be 4% of capital expenses (Solomon et al., 2024), and other labor costs were assumed to be negligible.

Sub-awardee TRC Companies, Inc. (TRC) provided expertise in pipeline modeling and costing to further refine the techno-economic assessment. TRC used an inch-mile approach to develop a preliminary total installed cost estimate for the pipelines in Scenarios 1 and 2, wherein the product of the pipeline diameter in inches and the pipeline length in miles is multiplied by a unit-cost per inch mile.

TRC based the unit cost per inch-mile on recent expenditures for similar pipelines in the project area. These data were compiled from several sources, including from clients, industry organizations, and publicly available information. Total installed costs include, but are not limited to, elements such as materials (e.g., pipe, valves, and all associated components), construction (including post construction restoration), engineering, surveying, permitting (e.g., environmental, regulatory), and land acquisition. For the CO<sub>2</sub>NNECTION project, historical pipeline costs were adjusted upward due to specialized material requirements for transporting CO<sub>2</sub>, the unique geography of the Appalachian region, and geopolitical factors in the area (namely, the opposition of the installation of new pipelines, which results in higher permitting and land acquisition costs).

The inch-mile estimating approach for pipeline construction offers several advantages. Primarily, this approach is relatively quick and simple, making it useful for early-stage cost estimation when many aspects of the project are still unknown. Additionally, this method can be applied to pipelines of varying sizes and lengths, and it supports benchmarking by facilitating cost comparison with historical projects. However, the inch-mile approach is also subject to limitations. Most notably, this method does not account for project-specific complexities and instead relies heavily on the accuracy of the unit cost per inch-mile, which may or may not be representative of the CO<sub>2</sub>NNECTION project’s specific pipeline material requirements and routing considerations. Completing the next level of cost estimation (Class 4 Feasibility Estimate, +/- 30%) will require additional work by construction, engineering, environmental, right-of-way, and permitting experts to further refine the routes and CO<sub>2</sub> sources.

#### 4.1 Project Cost Estimate

A techno-economic assessment was completed for the selected hub node. The results of the assessment are presented in Table 8, Table 9, and Table 10. Scenario 1A, which uses only pipelines for transportation, was calculated to have the lowest breakeven price of \$5 per net tonne of CO<sub>2</sub> and the highest carbon efficiency of 98.9%. Labor for this scenario was considered negligible, as it is not reliant on physically moving or connecting containers and vessels to the pipeline. Scenario 1 was found to have the highest breakeven price of \$31 per net tonne of CO<sub>2</sub> and the lowest carbon efficiency of 97.6%. All scenario calculations yielded a positive internal rate of return.

Table 8. Key values for scenarios and sub-scenarios

Scenario	NPV (\$)	IRR (%)	Carbon Efficiency (%)	Breakeven Price of CO <sub>2</sub> (\$ / net tonne)
Scenario 1	1,788,817,379	42	97.6	31
Scenario 2	2,730,985,108	42	98.4	22
Scenario 1A	2,253,521,755	105	98.9	5
Scenario 1B	2,135,004,677	73	98.5	13
Scenario 1C	1,953,336,958	53	97.9	23

Table 9. CAPEX, OPEX, and labor costs for scenarios and sub-scenarios

Scenario	Truck CAPEX (\$)	Rail CAPEX (\$)	Pipeline CAPEX (\$)	Total CAPEX (\$)	Total OPEX (\$ / yr)	Total Labor (\$ / yr)
Scenario 1	57,443,758 (27%)	86,920,611 (41%)	68,047,622 (32%)	212,411,991	30,768,949	6,813,574
Scenario 2	28,467,893 (9%)	41,865,846 (13%)	248,150,520 (78%)	318,484,258	23,601,955	4,054,482
Scenario 1A	-	-	67,643,788 (100%)	67,643,788	2,705,752	-
Scenario 1B	19,939,774 (18%)	23,369,272 (21%)	67,754,284 (61%)	111,063,330	8,625,764	3,447,576
Scenario 1C	42,147,067 (26%)	53,212,474 (32%)	67,944,060 (42%)	163,303,601	21,900,390	5,237,172

Table 10. Pipeline total installed cost estimates provided by TRC Companies, Inc.

	Scenario 1	Scenario 2
Pipeline route length (mi)	101.77	241.09
Pipeline cost (million \$)	347	687
Compression / pumping facilities cost (million \$)	54	114
Total installed cost (million \$)	401	801

#### 4.2 Business Case Analysis

The business case for operating the hub was developed using capital and operation and maintenance (O&M) expenses from Subtask 4.1. Potential sources of revenue, cash flows, earnings before interest, taxes, depreciation, and amortization (EBITDA), tax credits and liabilities, and project return on investment were also considered. Additionally, projections for future development scenarios were prepared and the project's potential benefits were quantified, including an evaluation of applying 45Q credits to project costs based on a market analysis of industry practices for offsetting infrastructure expenses.

The CO<sub>2</sub>NNECTION intermodal transport network could generate revenue primarily through carbon credits in the compliance and the voluntary markets, wherein 45Q tax incentive credits could be sold to third parties. As of 2024, over 4,000 companies have committed to reaching voluntary decarbonization targets. Many of these companies rely on carbon credit purchases as well as infrastructure investments to meet their goals. Companies that are capturing their own carbon to fulfill environmental promises need a reliable transportation network if they are not sequestering or utilizing the captured carbon on site. One key requirement for on-site carbon sequestration is the site being located at a geological formation with appropriate storage capacity and characteristics. Projects capturing carbon at a site that does not meet geological requirements must transport CO<sub>2</sub> to a suitable location. Companies may be willing to pay for transportation services to meet voluntary or regulatory environmental commitments. As a transportation project, CO<sub>2</sub>NNECTION would not be able to receive 45Q tax credits directly, but it could instead provide a necessary service to companies seeking to qualify.

The 45Q tax incentive provides tax credits to companies that capture and store or utilize carbon that would otherwise be released into the atmosphere. Currently, the credits offer between \$12 and \$85 per tonne of CO<sub>2</sub> sequestered. These credits can either be used to offset construction and operational costs or sold at a premium to third parties. When a company decides to transfer 45Q credits to a third party, the payment is not taxable to the seller. To qualify for 45Q, a facility must begin construction before 2033. The facility can then claim the credit for up to 12 years (AccountingInsights Team, 2025). Electing to receive the 45Q credits as transferable and selling them at a premium greater than the government rate provides a significant opportunity for generating revenue.

Potential financing structures for the CO<sub>2</sub>NNECTION intermodal transport hub include traditional project financing, tax equity financing, and tax credit monetization. In traditional project financing, project developers secure debt financing from banks or other financial institutions to fund a portion of the project's capital costs. For tax equity financing, investors, such as corporations with tax liabilities, provide upfront capital, in exchange for a share of the tax benefits generated by the project, including the 45Q tax credits. Similar to tax equity financing, tax credit monetization project developers may also monetize the 45Q tax credits directly by selling them to third-party investors or financial institutions. This method provides immediate cash proceeds to the project developer, which can be used to fund project development or repay debt.

While there is a significant number of carbon capture facilities either under development or currently operating on the eastern half of the United States, there are no CO<sub>2</sub> pipelines operating east of the Mississippi River, and only one under development in Mississippi, Louisiana, and Texas (American Carbon Alliance, 2025). As the carbon sequestration market grows, more companies will need reliable transportation for their captured CO<sub>2</sub>. Future projects or expansions of CO<sub>2</sub>NNECTION could partner with companies to connect their facilities with an integrated carbon transportation system based on the original CO<sub>2</sub>NNECTION project.

In the tristate region of Ohio, West Virginia, and Pennsylvania (home to a dense concentration of natural gas processing facilities, petrochemical plants, and coal-fired power stations), future deployment scenarios for CO<sub>2</sub> transportation are expected to evolve rapidly, assuming federal incentives continue to be offered, such as those from the 45Q tax credit and state-level decarbonization goals. In a moderate-growth scenario, CO<sub>2</sub> capture and transport infrastructure would expand incrementally, with early projects relying on truck and rail to move captured CO<sub>2</sub> to nearby injection wells, particularly in areas with limited pipeline access. In a high-growth scenario, driven by aggressive climate policy, carbon markets, and industrial decarbonization mandates, the region could see the rapid buildout of a shared CO<sub>2</sub> pipeline network, similar to the development of natural gas infrastructure in the early 2000s. Strategic deployment would likely prioritize clusters such as the Appalachian Basin, where geological storage potential aligns with high-emission industrial zones.

In 2024, there were 45 facilities globally applying carbon capture, utilization, and storage. These facilities had a combined carbon capture capacity of 50 million tonnes per year; however, to achieve the net zero emissions (NZE) scenario by 2050, 1,300 million tonnes of CO<sub>2</sub> will need to be captured annually by 2050 (International Energy Agency [IEA], 2024). It is estimated that approximately 1,178 million tonnes of CO<sub>2</sub> will be produced by U.S. industry in 2040 (EIA, 2024). A techno-economic assessment of the CO<sub>2</sub>NNECTION project demonstrated the intermodal transport network’s capability of transporting up to 1,630 net kilotonnes of CO<sub>2</sub> per year in Scenarios 1 or 2, 135 net kilotonnes of CO<sub>2</sub> per year in Scenario 2. These capacities correspond to 0.14% and 0.18% of the CO<sub>2</sub> estimated to be produced by United States industry in 2040. A major pipeline project such as CO<sub>2</sub>NNECTION could employ over 500 construction workers for the installation of approximately 100 miles of pipeline alone (Liquid Energy Pipeline Association, 2025a, 2025b). Net-Zero America estimates that over 100,000 kilometers or 62,000 miles of CO<sub>2</sub> pipelines could be needed in the U.S. by 2050 to achieve net zero emissions (Larson et al., 2021). Using this assumption, the Net-Zero America scenario would require up to 310,000 construction jobs to complete. In addition to construction jobs, pipeline installation projects generate hundreds of professional service and management jobs for engineers, architects, and contractors.

### 4.3 Long-Lead Material and Equipment

A list of equipment that is needed to support the hub was developed. The list was used to determine which of these critical supplies have a long-lead time for procurement, which is defined as materials or equipment that will require six months or more lead time. This subtask was completed primarily by TRC Companies, which has substantial experience with large-scale infrastructure projects. TRC Companies determined that many of the materials and equipment required for the hub have long lead times (Table 11). Additionally, it is pertinent to note that permitting requirements for the various intermodal facilities and the acquisition of right-of-way for the pipelines will take several years.

Table 11. Long-lead material and equipment list for the CO<sub>2</sub>NNECTION project.

Item	Modes or Locations Requiring	Purpose	Lead Time
CO <sub>2</sub> conditioning equipment	Class VI well, CO <sub>2</sub> emission sources	Equipment to compress, dehydrate, and clean up CO <sub>2</sub> to meet pipeline or injection well specifications	12-18 months
Circuit breakers and switchgear	Substations servicing various intermodal operations	Control, protect, and isolate electrical circuits within the substation	6-12 months
Compressor/pump stations	Pipeline	Maintain CO <sub>2</sub> pressure and flow in pipeline	12-18 months
Cryogenic or pressurized tanks	Any location requiring CO <sub>2</sub> storage or buffering capacity	Storage of CO <sub>2</sub> at transfer locations.	6-12 months
Drilling rig and equipment	Class VI well	Construction of the Class VI well	6-12 months to schedule the drill rig use
Fittings and flanges	Pipeline, truck, rail	Connection of pipeline or piping components	6-8 months
Liquefaction and vaporization equipment	Truck, rail	Liquefaction of pipeline CO <sub>2</sub> for truck or rail transport. Vaporization of CO <sub>2</sub> from truck or rail tanks to pipelines	12-24 months
Metering and regulating stations	Pipeline	Measure and control CO <sub>2</sub> flow and pressure in the pipeline	8-12 months
Monitoring and testing equipment	Class VI well	Equipment for monitoring well integrity, CO <sub>2</sub> plume migration, and environmental impacts	6-12 months
Pipe and coatings, 8", 12", 18", 24"	Pipeline, truck, rail	Transport of CO <sub>2</sub> over long distances as well as at intermodal operation facilities	6-18 months, depending on size, grade, and coating requirements

Supervisory Control and Data Acquisition (SCADA) systems	All	Supports remote monitoring and control of the various intermodal operations	6-12 months
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#### 4.4 Discussion and Conclusion

Based on the results of the techno-economic assessment, the following conclusions were drawn:

1. All scenarios show economic viability when supported by the 45Q tax credit.
2. It is anticipated that the majority of capital costs would be incurred at the capture and/or injection sites, not by the transportation network itself.
3. The scenario with the lowest identified breakeven cost, Scenario 1A, only utilizes pipeline as a transportation method. This outcome is reasonable based on CO<sub>2</sub> transport literature (McCoy and Rubin, 2008).
4. Truck and rail are viable transportation methods for smaller carbon sources, but their implementation needs to be balanced by considering their impacts to the overall transportation project.

The economic models for pipelines implemented in the analysis, although robust, are becoming outdated and do not necessarily reflect recent technological advances or information specific to the CO<sub>2</sub>NNECTION project. Additionally, these general models rely on national averages or outdated figures, which may not reflect the unique terrain, permitting environment, and labor costs in the Appalachian region today. Thus, sub-awardee TRC provided more recent and region-specific data for pipeline cost estimates to improve the quality of the techno-economic assessment and BCA. TRC estimated total installed costs of \$401 million and \$801 million for the pipelines in Scenarios 1 and 2, respectively. These estimates are higher than those determined in the original analysis, which is not unexpected. TRC's unit cost per inch-mile of pipeline is based on more recent financial data and accounts for elements that were not included in the original economic assessment, such as land acquisition, surveying, and permitting.

To further develop this BCA, areas for cost optimization across the proposed transportation network should be identified. This step would include tasks such as 1) evaluating economies of scale in pipeline diameter selection, 2) identifying opportunities for co-location with existing rights of way, and 3) researching potential for shared infrastructure among emitters. Furthermore, benchmarking CO<sub>2</sub>NNECTION against comparable recent projects would highlight aspects of CO<sub>2</sub>NNECTION that can be further refined to maximize the project's benefit.

## 5.0 Hazard Identification and Sensitive Areas/High Consequence Areas (HCAs)

The *Hazard Identification and Sensitive Areas/High Consequence Areas (HCAs)* Task had two subtasks: HAZID and ES&H Analysis. The results of the HAZID are presented in Appendix 3 and summarized below.

### 5.1 Hazard identification (HAZID)

The HAZID study included two parts: (1) an accounting of the potentially sensitive areas that might be impacted by the intermodal hub and (2) an assessment of the likelihood and severity of potential leakage scenarios from each transport mode. Surface conditions, including HCAs, critical infrastructure, and other sensitive areas, were identified using a process described by Battelle (2024). The project team used publicly available shapefiles to define or approximate the HCAs and sensitive areas, considered how the development of pipelines could impact these areas, discussed the prioritization of minimizing impacts, and presented possible mitigation options. Important impacts were evaluated using the Bowtie Risk Assessment methodology described by Alizadeh and Moshashaei (2015). This analysis included evaluations of top-line events (hazards), causes and consequences of the hazards, control measures to prevent hazards, recovery mechanisms to recover from a hazard, and threats to these control measures. The potential impacts of development were evaluated using a qualitative risk assessment, which included an assessment of the likelihood of the impact occurring (on a scale from 1-5) and its severity (also on a scale of 1-5). A Risk Ranking was calculated by multiplying the likelihood and severity. The qualitative assessment was through a risk roundtable during which the bowtie assessments were also evaluated and revised.

***Pipeline, Rail and Trucking Hazards:*** CO<sub>2</sub> transport by pipeline, trucks, and rail carries distinct risks related to mechanical failure, environmental exposure, and public safety. Understanding these risks is essential for designing resilient infrastructure and implementing effective mitigation strategies, particularly in regions with active or planned CCS deployment. This section presents literature review of CO<sub>2</sub> transport infrastructure in the United States.

Carbon dioxide transport infrastructure has experienced a range of failure modes across pipelines, trucking, and rail systems. According to Xi et al. (2023), analysis of 112 accident records from the Pipeline and Hazardous Materials Safety Administration (PHMSA) reveals that equipment failure is the most frequent cause of pipeline incidents, accounting for over 53% of cases. However, this failure mode does not correspond to the highest economic or environmental impact. Natural force damage, though rare, results in the greatest economic losses (67.21%), while material failure, particularly manufacturing defects, contributes most significantly to carbon emissions (52.26%), see Figure 13. The regulatory definition of a CO<sub>2</sub> pipeline accident, as per 49 CFR §195.50, includes any event involving unintentional explosion or fire, release of more than five gallons of CO<sub>2</sub>, casualties requiring hospitalization, or property damage exceeding \$50,000.

Vitali et al. (2022) further analyzed PHMSA data from 1994 to 2021, identifying 113 incidents involving onshore CO<sub>2</sub> transmission pipelines. Notably, no fatalities were recorded and only one injury was officially reported, though the Satartia, Mississippi incident in 2020 involved 46 hospitalizations. According to these authors, the most common failure types included leaks, pinholes, connection failures, and valve discharges under unwanted conditions. Approximately 19% of incidents were linked to relief valves, while ruptures accounted for only 3%, confirming that leakage is the dominant failure mode. The average shutdown duration was around 53 hours, with extreme cases like Satartia requiring up to 246 days for full recovery.

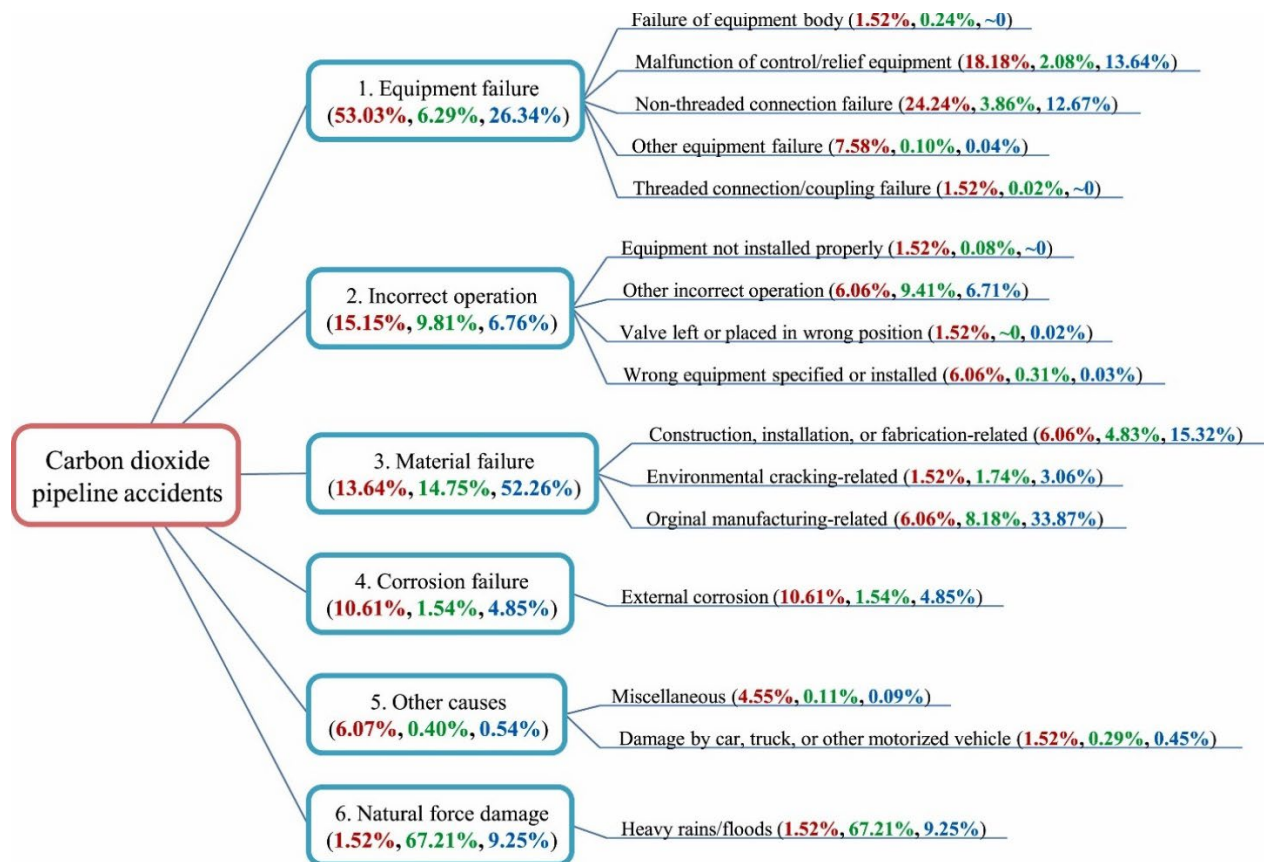


Figure 13. Primary and secondary causes of accidents in carbon dioxide pipelines (reproduced from Xi et al., 2023). Note: Red represents the proportion of accident frequency, green represents the proportion of economic losses, and blue represents the proportion of carbon emissions.

Duguid et al. (2022) conducted a risk assessment of accident data from PHMSA for four different pipeline types: natural gas transmission, natural gas distribution, non-CO<sub>2</sub> hazardous liquid, and CO<sub>2</sub> pipelines. The authors found that CO<sub>2</sub> pipelines carried significantly lower risk than the other three pipeline types, particularly because the severity of the consequences of failures are often lower for CO<sub>2</sub> pipelines, with the average CO<sub>2</sub> pipeline accident costing \$23,808 (median of \$6,334) compared to \$740,000 to over \$1.0 million (median of \$25,000 to \$122,000) for the other three pipeline types.

To complement these findings, updated PHMSA data through 2024 was compiled for this report and is presented in Figure 14. This data confirms the predominance of equipment failure, now accounting for 56 incidents, followed by material failure of pipe or weld (22 incidents) and corrosion (12 incidents). Other causes such as excavation damage, incorrect operation, and natural force damage remain less frequent. These results are consistent with previous studies (Xi et al., 2023 and Vitali et al., 2022). The proportional distribution of incident causes is further illustrated in Figure 15, where equipment failure represents 48% of all cases, followed by material failure (19%), corrosion (10%), and other causes each contributing less than 10%.

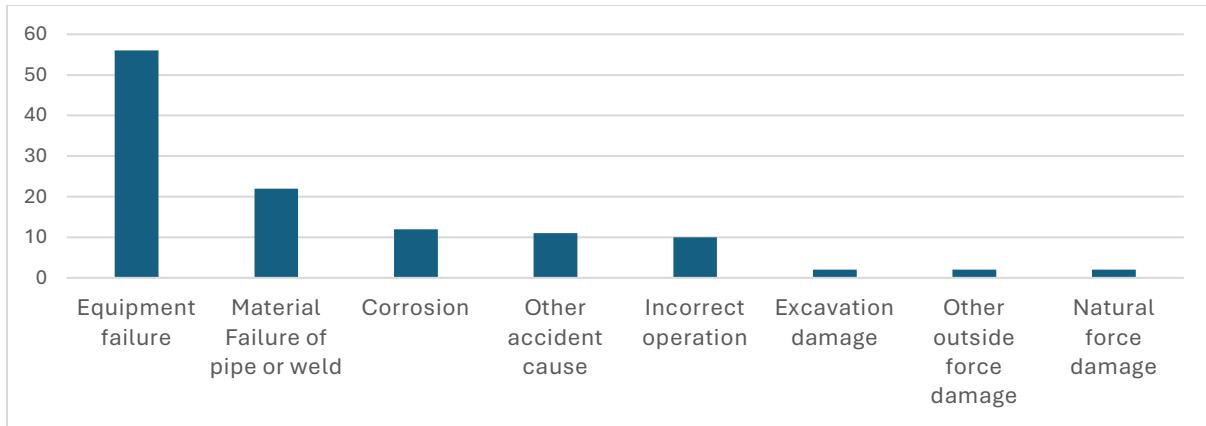


Figure 14. Number of incident causes in CO<sub>2</sub> pipelines reported to PHMSA (1994–2024) (Vitali et al., 2022).

The nature of release types in pipeline incidents is further detailed in Figure 15, which shows the distribution of failure modes from 1994 to 2024, based on PHMSA data. Leaks account for nearly 49% of all incidents, followed by relief valve discharges (18%) and pinhole leaks (16%). Ruptures remain rare at 3%, while 14% of cases lack specific release type information. These proportions align closely with the findings of Vitali et al. (2022), who noted that leakage is the dominant failure mode and that relief valves are frequently involved in unwanted discharges.

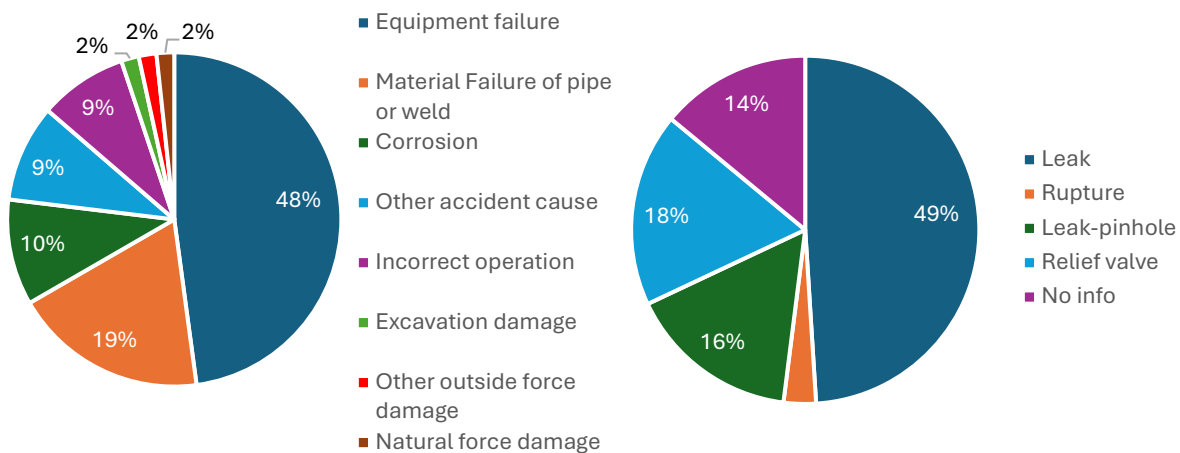


Figure 15. Causes (left) and types (right) for CO<sub>2</sub> pipeline accidents reported to PHMSA (1994-2024) (Vitali et al., 2022).

Trucking and rail transport, though less studied, show high incident rates but lower release volumes. Railcars, in particular, benefit from specialized design features that reduce the likelihood of failure. Nevertheless, the limited availability of public data on truck and rail incidents presents a challenge for comprehensive risk assessment. Highway trucking has a high incident rate among CO<sub>2</sub> transport modes, averaging 11.95 incidents per year between 2003 and 2022 (Ho et al., 2024). Most of these incidents were unscheduled releases, often due to over pressurization or component failure. Despite the frequency, trucking results in relatively low CO<sub>2</sub> release volumes 13.67 tonnes of CO<sub>2</sub> per year, compared to pipelines (2,553.33 tonnes of CO<sub>2</sub> per year). Rail transport, while less frequent in terms of incidents (3.25 incidents per year), also shows a low release volume (40.32 tonnes of CO<sub>2</sub> per year) and has maintained a steady transport volume of around 900,000 tonnes annually from 2013 to 2021. Failures in rail systems are typically linked to pressure relief valve malfunctions and frangible disc failures.

Maty and Wright (2022) and Ho et al. (2024) emphasize that CO<sub>2</sub> is transported in DOT 105-J500W tank cars, which are jacketed, insulated, and pressure-regulated to safely handle liquefied CO<sub>2</sub>. These tankers are classified as Class 2.2 hazardous materials—non-toxic and non-flammable, under U.S. Department of Transportation regulations. Their specialized design has contributed to the relatively low incident rate in rail transport.

Trucking, though more prone to incidents, tends to result in smaller releases and is more flexible for short-distance transport. Rail offers a middle ground, with low incident rates and moderate release volumes, making it a viable option for regional CO<sub>2</sub> distribution. The likelihood and severity of CO<sub>2</sub> leaks vary significantly depending on pipeline characteristics, and failure type. According to Xi et al. (2023), pipelines in service for 0 to 10 years exhibit the highest frequency of accidents and the greatest proportion of carbon emissions, while those aged 11 to 20 years are associated with the highest economic losses. Bielka et al. (2024) reports an average of 5.11 CO<sub>2</sub> pipeline incidents per year between 2004 and 2021. Palmer et al. (2007) noted that CO<sub>2</sub> pipelines have a safety record comparable to natural gas and oil pipelines, with an incident rate of 0.00032 per km per year and no recorded fatalities from 1990 to 2002.

Leak types in CO<sub>2</sub> pipelines range from pinholes to ruptures, each with distinct implications. Mazzoldi et al. (2011) and Duncan and Wang (2013) describe pinholes as the most common failure mode, accounting for 65.1% of leakage incidents. These small, millimeter-scale holes typically produce visible white vapor plumes and are considered non-lethal and easily detectable. Punctures, which represent 15.1% of leakage incidents, are usually 2 to 4 inches in diameter and may depressurize slowly, delaying automatic valve shutoff. Ruptures, though rare, are the most severe, capable of releasing large volumes of CO<sub>2</sub> rapidly and generating shock waves with potentially fatal effects within a 5-meter radius (Mazzoldi and Oldenburg, 2013).

The volume and rate of CO<sub>2</sub> leaked is influenced by several factors, including pipeline diameter, hole size, operating pressure, distance between block valves as well as environmental and operational conditions, such as soil type, groundwater presence, pipeline depth, and impurities in the CO<sub>2</sub> stream (Koornneef et al., 2009; Nyborg et al., 2011) also play a role in leak probability and behavior. The behavior of leaked CO<sub>2</sub> in the environment is influenced by leak size, pipeline orientation, flow rate, CO<sub>2</sub> phase, and atmospheric conditions.

Upon release, liquid CO<sub>2</sub> vaporizes and, due to its density being 1.53 times greater than air, can displace oxygen and pose a serious asphyxiation risk to humans and animals (Bielka et al., 2024). The resulting CO<sub>2</sub> plume size behavior can depend on the type of leak. Hu et al. (2022) investigated the behavior of supercritical CO<sub>2</sub> released from high-pressure pipelines, combining large-scale experiments with computational fluid dynamics (CFD) modeling. Their findings show a three-stage concentration evolution: rapid rise, peak, and gradual decay. Larger leak diameters lead to higher peak concentrations and longer hazard distances. Spatial migration patterns reveal strong gradients in the near-field and slower dispersion in the far-field. The study also confirmed that temperature drops, phase changes, and radial jet expansion significantly influence the fate of leaked CO<sub>2</sub>. Herzog et al. (2013) observed that larger leaks (e.g., 0.6 m) produce broader and taller plumes than smaller ones (e.g., 0.04 m), due to stronger inertial forces during the jet phase. The plume undergoes rapid vertical and lateral expansion, followed by slower passive dispersion. Shang et al. (2024) focused on buried pipeline leaks, noting that soil interaction leads to the formation of dry ice balls, frozen soil layers, and jet-induced cavities. These phenomena can alter soil pH, electrical conductivity, and organic matter content. This, in turn, can disrupt microbial communities and potentially affect groundwater quality.

After the leak occurs and the CO<sub>2</sub> plume forms and begins to move in the environment, hazard zones (i.e., where the plume could potentially impact human health or the environment) can be determined. Flow rate, leak size, pipeline geometry, leak orientation, and surrounding topography can all play a critical role

in determining the size of the hazard zone. Small leaks generally pose limited risk, with dispersion zones confined to a few meters. However, large ruptures can affect areas up to hundreds of meters in radius, especially under low wind conditions that hinder plume dilution (Kuckshinrichs and Hake, 2015; Bielka et al., 2024). Leak orientation and location can also lead to different results. Bielka et al. (2024) conducted simulations that revealed that buried pipelines, while generally more contained, can still produce extensive dispersion zones if the rupture is large. In addition, the authors found that leaks from an above ground pipeline that were oriented toward the ground had larger dispersion zones.

The phase of CO<sub>2</sub> gas, liquid, or supercritical, affects dispersion behavior and hazards. Gas phase releases produce the smallest hazard zones (~2.0 m), while supercritical CO<sub>2</sub>, due to its expansion potential, results in broader dispersion (~5.7 m) (Bielka et al., 2024). The initial jet phase of a CO<sub>2</sub> release has a significant impact on dispersion. Mazzoldi et al. (2009) demonstrated that jet velocity (~49 m/s) drives rapid entrainment of ambient air, diluting the plume more effectively than static models suggest. The direction of the jet influences plume shape more than wind speed or atmospheric stability, with horizontal releases producing higher ground-level concentrations. Hu et al. (2025) expanded on this by using neural networks and simulations to predict hazard boundaries for 4% CO<sub>2</sub>, the Immediately Dangerous to Life or Health (IDLH) threshold defined by National Institutes for Occupational Safety and Health (NIOSH) (See Section 5.2).

Pipelines remain the most extensively studied and widely used mode of CO<sub>2</sub> transport due to their efficiency and capacity. However, they also pose the highest risk in terms of volume released during failures. Equipment failure is consistently identified as the most frequent cause of pipeline incidents, accounting for nearly half of all reported cases. Material failure and corrosion follow as secondary contributors. While these failures often result in minor leaks, large ruptures, though rare, can lead to significant environmental and economic impacts. The Satartia, Mississippi incident in 2020 serves as a critical example of the potential severity of CO<sub>2</sub> pipeline failures, despite the absence of formally recorded fatalities.

Overall, the findings underscore the importance of robust design, monitoring, and emergency response strategies for CO<sub>2</sub> transport infrastructure. While pipelines are indispensable for large-scale carbon management, their risks must be carefully managed through targeted maintenance and real-time leak detection systems. Rail and truck transport offer viable alternatives, particularly for regional distribution, but require further study to fully understand their risk profiles. Future work should focus on closing data gaps for non-pipeline transport modes and refining dispersion models to improve hazard prediction and mitigation planning.

***Special Risk Topics:*** During the risk roundtable discussion, three topics potentially requiring additional investigations were identified: (1) the impact of acid mine drainage on pipelines, (2) the impact of road salt on pipelines, and (3) the impact of agricultural inputs (e.g., fertilizer and herbicides and pesticides) on pipelines. Preliminary literature reviews of these topics were completed and are presented below.

***Impact of Acid Mine Drainage (AMD) on Pipeline Infrastructure:*** The safe and efficient transport of CO<sub>2</sub> through pipeline infrastructure is a critical component of CCS strategies. In regions with extensive mining histories, such as the Tri-State Area of Ohio, Pennsylvania, and West Virginia, environmental conditions pose unique risks to pipeline integrity. One of the significant concerns is AMD, a geochemically driven process that can severely impact carbon steel infrastructure through corrosion. AMD originates from the oxidation of sulfide minerals, particularly pyrite, upon exposure to oxygen and water. This reaction produces ferrous iron, sulfate, and hydrogen ions, significantly lowering the pH of surrounding waters. Subsequent oxidation of ferrous iron to ferric iron and its precipitation as iron hydroxide further contributes to acidity, often forming the characteristic orange sediments observed in AMD-affected streams. Microbial activity, particularly under low pH conditions, accelerates these

reactions, intensifying the release of metals and acidity (Daniels et al., 2020). In the Appalachian coalfields, AMD is commonly associated with the weathering of metal sulfides in coal-bearing strata, resulting in drainage that is highly acidic, with elevated concentrations of iron, aluminum, manganese, sulfate, and trace elements such as copper, zinc, selenium, and arsenic (Daniels et al., 2020; Robb and Robinson, 1995).

The project area is particularly vulnerable to AMD due to its extensive legacy of coal mining and high-sulfur geology (Appalachian coalfields, 2025). In these areas, the natural buffering capacity of surrounding rock formations is often insufficient to neutralize acidic discharges, leading to persistent AMD generation (Daniels et al., 2020). Cravotta et al. (1999) identified a bimodal pH distribution in Pennsylvania's mine drainage, with one group of waters exhibiting strongly acidic conditions (pH 2.5–4) and another showing near-neutral pH (6.0 to 7.0), reflecting variability in geochemical and hydrological settings. The widespread presence of AMD in this region poses a significant threat to infrastructure, particularly pipelines, which are highly susceptible to corrosion under acidic and metal-rich conditions (Fortes et al., 2022). The corrosive nature of AMD is further exacerbated by factors such as dissolved oxygen, temperature, and microbial activity, all of which accelerate degradation processes in metallic materials (Fortes et al., 2020).

As shown in Figure 16, mining activity is widespread across the study area, with a dense concentration of abandoned coal mines along the Pittsburgh coalfield, particularly intersecting the Scenario 1 pipeline route. These legacy sites are known sources of AMD and pose a risk to pipeline infrastructure due to their proximity and the likelihood of acidic groundwater intrusion. Additionally, the Scenario 2 pipeline crosses areas with underground mines and active permit sites, which also present potential exposure to AMD. The spatial overlap between these mining-impacted zones and proposed pipeline routes highlights the importance of incorporating risk assessments into infrastructure planning.

The corrosive nature of AMD presents a significant threat to pipelines, particularly in regions with legacy mining activity. As Daniels et al. (2020) noted, AMD is chemically aggressive due to its low pH and high concentrations of dissolved metals and sulfates, which can initiate and accelerate corrosion processes in steel infrastructure. This is especially concerning for CO<sub>2</sub> transport systems, where pipeline integrity is critical for operational safety and long-term containment. Experimental studies have provided strong evidence of AMD's corrosive impact on carbon steel. Fortes et al. (2022) conducted a 30-week immersion test using thirty carbon steel plates exposed to AMD water with a pH of 2.9. Weekly measurements revealed progressive weight loss and volume reduction, confirming severe material degradation. The study established a direct correlation between exposure time and corrosion severity, highlighting the cumulative nature of AMD-induced damage. These findings are consistent with Fortes et al. (2023), who observed generalized corrosion across the entire surface of steel plates, resulting in section thinning and reduced structural integrity.

Further insights into the mechanical consequences of AMD exposure were provided by Sarmiento et al. (2024), who evaluated AISI 1020 carbon steel under both static (chemical corrosion) and dynamic (erosion corrosion) scenarios. In static conditions over 80 days, steel specimens experienced a 0.5% weight loss and a 28% reduction in fatigue strength. In dynamic conditions, degradation accelerated dramatically, with up to 35% weight loss and a 50% drop in fatigue strength within just four days. These results underscore the vulnerability of steel components not only in external pipeline structures but also in internal systems such as valves, joints, and compressors, which may be exposed to AMD.

The chemical aggressiveness of AMD is influenced by several factors, including pH, sulfate concentration, dissolved oxygen, temperature, and microbial activity (Fortes et al., 2020). Low pH values (<4.0) increase the solubility of iron oxides, while elevated sulfate levels contribute to the formation of expansive corrosion products. Temperature accelerates reaction kinetics, and acidophilic bacteria such as

Acidithiobacillus ferrooxidans enhance corrosion by producing sulfuric acid and forming biofilms. These combined effects lead to thinning, cracking, and fatigue failure in steel infrastructure, as observed in both laboratory and field studies (Daniels et al., 2020; Fortes et al., 2020, 2022, 2023, 2024; Sarmiento et al., 2024). Complementary research by Mohammed et al. (2023) on carbon steel immersed in sulfuric acid solutions further supports these findings. Over a 20-day period, the study documented weight loss, corrosion penetration rates, and mechanical property degradation, reinforcing the conclusion that acidic environments (whether synthetic or naturally occurring as AMD) pose a serious risk to steel durability. Taken together, these studies provide a robust foundation for assessing the chemical impacts of AMD on pipeline systems and emphasize the need for corrosion-resistant materials and protective strategies in CO<sub>2</sub> transport infrastructure.

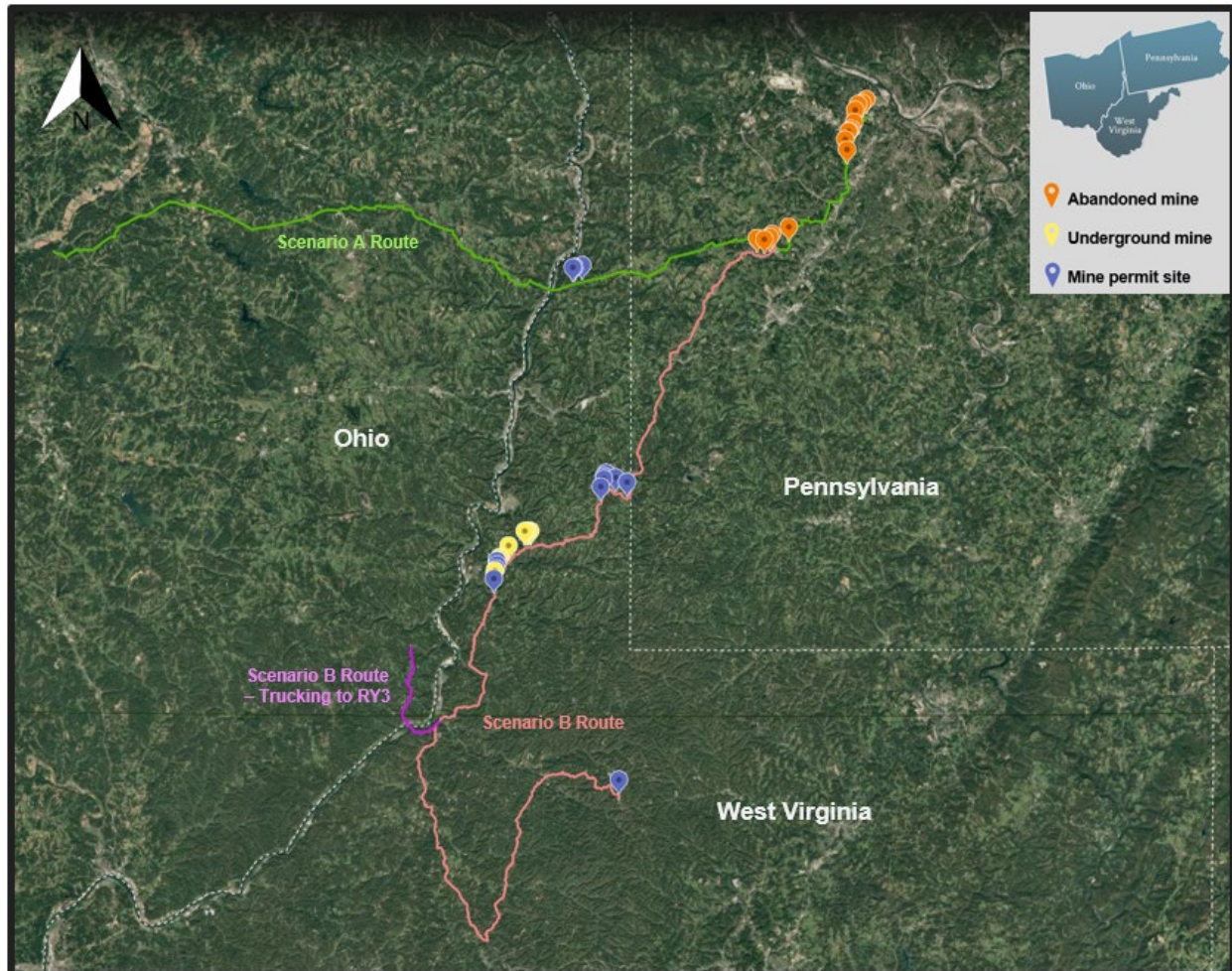


Figure 16. Proposed CO<sub>2</sub> transportation routes across the Tri-State Region with locations of abandoned, underground, and permitted mines. Co-locations were determined using the Pivvot Tool, developed by TRC Companies.

To mitigate the corrosive effects of AMD on pipelines and associated infrastructure, some operational and design strategies should be considered. First, it is essential to limit water exposure in pipeline systems because moisture accelerates corrosion, especially in environments with high sulfate and low pH levels. Additionally, direct exposure to radiant heating and high flow velocities should be avoided, as these factors increase turbulence and enhance the rate of chemical attack on steel surfaces. For systems handling acidic fluids, anodic protection has proven to be an effective method for reducing corrosion

rates. This technique promotes the formation of a stable passive layer on the steel surface, significantly improving resistance to acid attack (Panossian et al., 2012). These recommendations are particularly relevant for both external and internal pipeline structures and equipment such as tanks, and valves that may be exposed to AMD or similar acidic environments.

***The Impact of Road Salt on Steel:*** Several studies were found that cover the impact of road salt on steel. Pieper et al. (2018) studied the chloride levels in groundwater in various areas in and around highways. The highest salt levels in groundwater were found downgradient of salt storage barns, and the second highest concentrations were found within 30 meters of a major roadway. The authors conducted a laboratory experiment on well pipes and found increased corrosion with increasing chloride concentrations. Because major highways and road salt barns could increase the chloride concentrations in the subsurface, these must be mapped to ensure that pipeline infrastructure for the hub is properly protected and analyzed in these locations. Several authors have also studied the impact of chloride concentrations in soils on pipeline infrastructure (Song et al., 2017; Zhang et al., 2020; Deyab and Keera, 2012; Gao et al., 2022; Ahmed et al., 2023; Chung et al., 2021). These authors provide the impact of chloride on carbon steel in several different environments and concentrations. This information can be used to determine the impact of expected chloride concentrations that pipeline infrastructure will be exposed to. This will be an important component of a FEED study. Finally, alternative salts to rock salt have been developed and tested. Lawlor et al. (2023), for instance, tested road salts and less corrosive alternatives on steel rebar and found that the rock salt caused greater loss of material than the less corrosive alternatives. These rock salt alternatives should be explored to clear ice near hub infrastructure at the RY1 Hub Area.

***Impact of Agricultural Inputs on Pipeline Infrastructure:*** Although a less common topic than the impact of rock salt, some studies did look at the impact of agricultural inputs on steel in the context of agricultural equipment. Sundaram et al. (2019); Fachikov et al. (2006); and Correa et al. (2023) studied the impact of ammonium fertilizers on steel corrosion. Sundaram et al. (2019) studied urea ammonium nitrate (UAN) and its impact on stainless steel and two alloys of mild steel to determine the best metal to use for a furrow open operated by a tractor. The authors found that the commercially available mild steel corroded more when exposed to UAN than the non-commercial mild steel. Fachikov et al. (2006) studied the impact of ammonium sulfate fertilizer on low-carbon steels. The author found that increasing concentrations of ammonium sulfate (range of 1% to 40%) is a less important factor than increasing temperature (range of 20 °C to 60 °C), both of which are positively correlated with corrosion rates. Correa et al. (2023) studied the impact of potassium chloride and urea on corrosion, mass loss, and thickness loss of galvanized steel and stainless steel to determine the impact of fertigation (fertilizer application during irrigation) on steel equipment. The authors found that stainless steel corroded less than galvanized steel in their experiments and that zinc coatings on galvanized steel were effective at protecting the underlying steel. Carbon steel is the most common material used for pipelines (Jansto, 2022); however, the results from Sundaram et al. (2019), Fachikov et al. (2006), and Correa et al. (2023) demonstrate the corrosive nature of nitrogen fertilizers on steel. This means that tests of materials used for pipes, safety equipment, and other equipment may be warranted for agricultural areas that have pipeline infrastructure.

## 5.2 Environmental Safety & Health (ES&H) Analysis

An ES&H analysis was completed for each relevant mode of transportation. The ES&H analysis included an evaluation of the air and water emissions; solid wastes; solvents and sorbents used in the technology; environmental degradation, bioaccumulation, and toxicological properties of substances used; potential dangerous or harmful properties of any chemicals used; regulatory compliance; analysis of potential engineering controls; and safe handling practices. These are defined in Table 12.

Table 12. ES&H Factors relevant to the intermodal hub.

Safety Factor	Analysis						
Air and water emissions	<p>Emissions from construction of pipelines and the RY1 Hub Area will include exhaust from equipment and dust during excavation and construction. Emissions from trucking from vehicles and fugitive emission of CO<sub>2</sub>, particular from connections. Emissions from trains will include emissions from the engine and fugitive emissions of CO<sub>2</sub>, particularly from connections. Proper engineering controls will be implemented to mitigate the impact of these emissions.</p> <p>CO<sub>2</sub> emissions from operations of RY1 Hub Area. These emissions may include the co-contaminants outline in Table 4.</p>						
Solids wastes	<p>Solid waste may be expected from the construction of pipelines and the RY1 Hub Area. Solid waste would be expected to include the following:</p> <ul style="list-style-type: none"> <li>• Soil derived from excavating the site</li> <li>• Scaffolding, lumber, and other disposable construction materials and equipment</li> <li>• General refuse, including plastic coverings/wrappings, disposable personal protective equipment (e.g., Tyvek, disposable hearing protection, disposable gloves, etc.), and other trash</li> </ul> <p>All solid wastes will be reused, where possible, or recycled or disposed of in approved facilities to be identified during the FEED Study.</p> <p>Solid waste expected during operations is expected to be limited but may include non-hazardous waste derived from maintenance activities. This will be similar to the solid waste generated during construction activities and will be reused, where possible, or recycled or disposed of in approved facilities to be identified during the FEED Study.</p> <p>Singificant solid waste is not expected from rail or trucking operations.</p>						
Solvents and sorbents	<p>Solvents and sorbents are not expected to be used in the RY1 Hub Area. Depending on the capture technology, amines or other capture derivatives may be present at trace concentrations.</p>						
Environmental degradation, bioaccumulation, and toxicological properties of substances used	<p>When CO<sub>2</sub> escapes from a pressurized pipeline, the rapid phase change can form dry ice, with other CO<sub>2</sub> leaking a jet that expands, disperses as a cloud, and moves in the direction of the wind (Kieba et al., 2023; Vitali et al., 2021; Gorenz et al., 2023). Leaked CO<sub>2</sub> from pipelines has the tendency to accumulate in low-lying areas (Kieba et al., 2023; Liu et al., 2015). In these instances, CO<sub>2</sub> could become an asphyxiant. Eventually, CO<sub>2</sub> will escape into the atmosphere, a process helped along by wind (Vitali et al., 2021; Liu et al., 2015).</p>						
Potential dangerous or harmful properties of any chemicals used	<p>The NIOSH published the health impacts of CO<sub>2</sub> exposure (NIOSH, 2019). Specific health hazards include “headache, dizziness, restlessness, paresthesia; dyspnea (breathing difficulty); sweating, malaise (vague feeling of discomfort); increased heart rate, cardiac output, blood pressure; coma; asphyxia; convulsions; frostbite (liquid, dry ice)” (NIOSH, 2019). Concentrations of CO<sub>2</sub> that identified by NIOSH as being :</p> <table border="0" style="width: 100%;"> <tr> <td style="padding-right: 20px;">IDLH:</td> <td>40,000 ppm</td> </tr> <tr> <td>Short-Term Exposure Limit (SEL) for 15 minutes:</td> <td>30,000 ppm</td> </tr> <tr> <td>Permissible Exposure Limit (PEL) for 8-hour (weighted avg):</td> <td>5,000 ppm</td> </tr> </table>	IDLH:	40,000 ppm	Short-Term Exposure Limit (SEL) for 15 minutes:	30,000 ppm	Permissible Exposure Limit (PEL) for 8-hour (weighted avg):	5,000 ppm
IDLH:	40,000 ppm						
Short-Term Exposure Limit (SEL) for 15 minutes:	30,000 ppm						
Permissible Exposure Limit (PEL) for 8-hour (weighted avg):	5,000 ppm						
Regulatory compliance	<p>All pipeline operations will comply with PHMSA and industry standards and adhere to 49 CFR §192. All other operations will comply with regulatory and industry standards and permitting requirements as described in Section 3 and Section 6 of this report.</p>						
Analysis of potential engineering controls	<p>Potential engineering controls for pipeline operations, include SCADA systems, automatic and manual shutoff valves, markers, and other safety equipment. These systems will adhere to the standards set forth in 49 CFR §192 and consider additional protectiveness for pipelines routed through HCAs. Monitoring systems will also be implemented as part of the RY1 Hub Area to ensure leaks of CO<sub>2</sub> are identified and personnel can be alerted to potential hazards in the area.</p>						
Safe handling	<p>Safe handling procedures, including safety equipment and PPE, will be defined during the FEED study.</p>						

## 6.0 Pre-FEED RY1 Hub Area

### 6.1 Process Description/Narrative

The RY1 Hub Area is intended to be an adaptable rally point for CO<sub>2</sub> transported in the intermodal transport hub (Figure 17). The pipeline in Scenario 1 and the additional pipeline in Scenario 2 are both routed here prior to transport. All CO<sub>2</sub> transported by truck or rail in both scenarios is gathered here prior to adding it to the pipeline for its final transport to the storage site via pipeline. Daily amounts of CO<sub>2</sub> by mode are plotted for each scenario. Items that require information that will be developed in future phases (e.g., vendor information or additional engineering) are highlighted in gray.

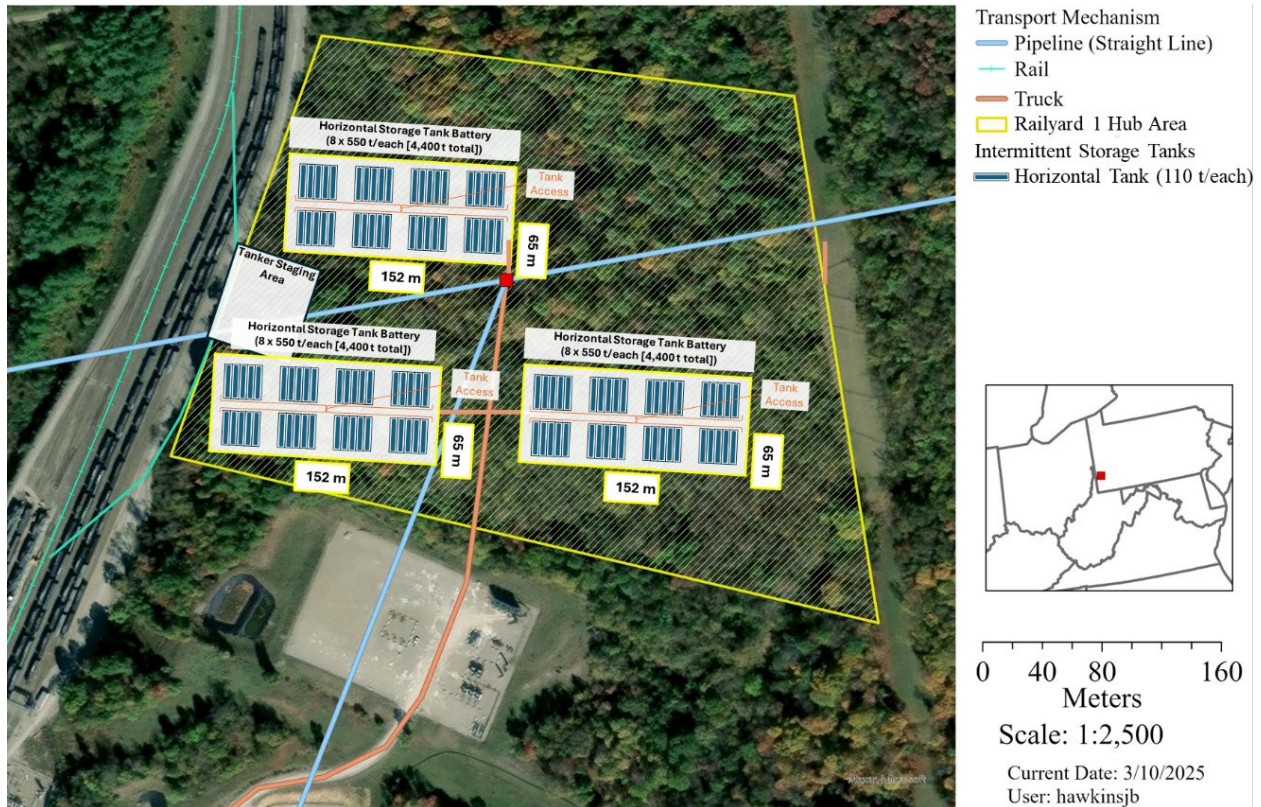


Figure 17. Map showing the conceptual RY1 Hub Area, including transport modes connecting to the area and above ground storage tanks.

#### **Both Scenarios:**

**Modes.** Trucks and rail will transport liquefied CO<sub>2</sub>, and pipelines will transport supercritical CO<sub>2</sub>.

**Liquefied CO<sub>2</sub> conditions.** Liquefied CO<sub>2</sub> will meet the pipeline specifications in Table 4 and be between -20 to -40 °F and 150 to 300 psi.

**Supercritical CO<sub>2</sub> conditions.** Supercritical CO<sub>2</sub> flowing into the RY1 Hub Area will meet the pipeline specifications in Table 4 and be between 40 to 90 °F and 1600 to 1800 psi. Supercritical CO<sub>2</sub> flowing out of the RY1 Hub Area will meet the pipeline specifications in Table 4 and be between 40 to 90 °F and 1800 to 2000 psi.

*Above ground storage.* Horizontal above ground storage tanks will provide intermediate storage of CO<sub>2</sub> from unit trains and trucks. CO<sub>2</sub> will be stored in a liquid form in these tanks. Pressure between 150 to 300 psi and temperature of less than 0 °C will be maintained during storage. These 110 tonne tanks will be staged in three batteries of 40 tanks each spread across the site (see Figure 17). This will provide a maximum above ground storage capacity of 13,200 tonnes at any given time.

**Scenario 1:** Scenario 1 is shown in the block flow diagram (BFD) provided in Figure 18.

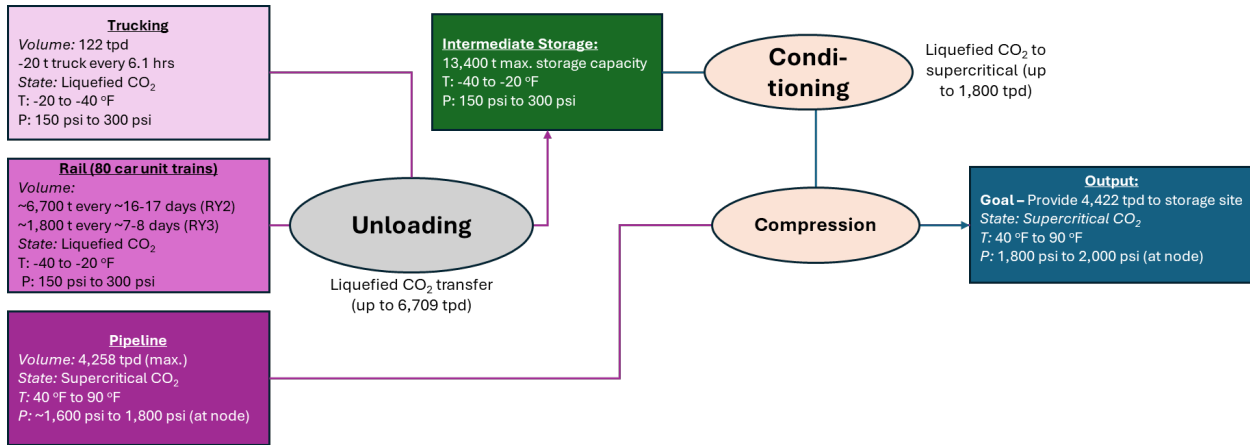


Figure 18. BFD for Scenario 1 at the RY1 Hub Area.

*Total flow rates:* CO<sub>2</sub> arriving via pipeline will remain in the pipeline and be supplemented by CO<sub>2</sub> from storage to maintain an average flow of approximately 4544 tonnes per day (Figure 19). For most days, the flow rate will be the maximum flow rate of 4645 tonnes per day. Lesser amounts flow from the system due to maintenance occurring on capture systems. The above ground storage of CO<sub>2</sub> onsite, however, ensures that at least 3000 tonnes of CO<sub>2</sub> are flowing every day. The CO<sub>2</sub> arriving at the site ranges from 1230 tonnes per day to 12,496 tonnes per day. Modal inflow is 4645 tonnes per day arriving via pipeline, truck, and rail (Figure 19). This is exceeded for 55 days of the year and not reached for 28 days of the year. During these times, CO<sub>2</sub> stored on-site will be used to ensure flow assurance.

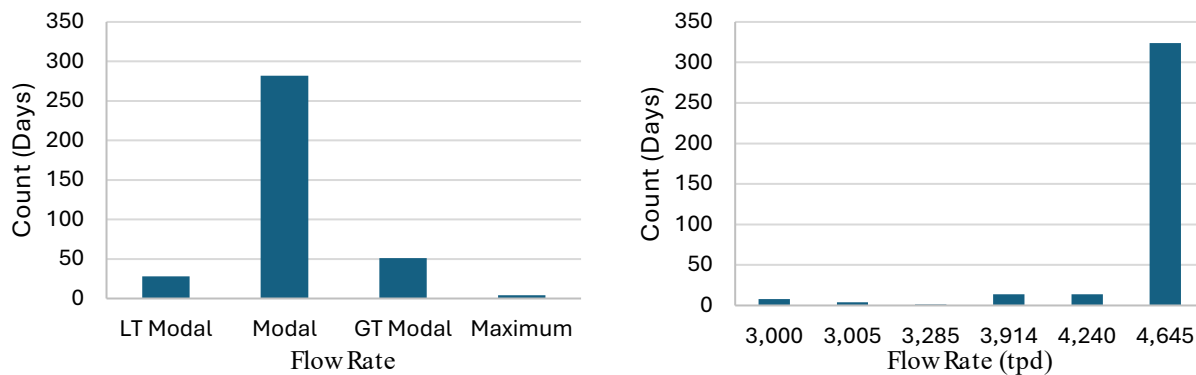


Figure 19. Number of days with specific inflow rates (left) and outflow rates (right) from RY1 Hub Area for Scenario 1. For inflow rates, the modal rate is 4026 tonnes per day. This modal rate is not reached for 28 days and amounts greater than the modal rate flow to the RY1 Hub Area 55 days of the year, including 4 where the maximum rate of 12,496 tonnes arrives via pipeline, truck, and rail. Modal outflow to the storage site is 4645 tonnes per day (the maximum amount of CO<sub>2</sub> transported), which is achieved 324 days out of the year. Lesser amounts flow from the system due to maintenance occurring on capture systems. The above ground storage of CO<sub>2</sub> onsite, however, ensures that at least 3000 tonnes of CO<sub>2</sub> are flowing every day.

*Flow by transport mode:* Inflow rates, by transport type, are shown for Scenario 1 in Figure 20. A truck arrives every 6 hours and delivers 20 tonnes of liquefied CO<sub>2</sub> per truck. This averages to be about 122 tonnes per day over the year. CO<sub>2</sub> will be transferred from trucks, assuming a rate of 500 kg/min, meaning the truck will be emptied in about 40 minutes.

A Unit Train of intermodal cars arrives carrying a total of around 1800 tonnes of CO<sub>2</sub> once every seven to eight days carrying liquefied CO<sub>2</sub>. This will be offloaded and transferred to intermediate storage tanks using three lines (one for each storage tank battery) capable of transferring CO<sub>2</sub> at a rate of 500 kg/min, meaning the train will be unloaded in approximately 20-24 hours.

A Unit Train of tanker cars arrives carrying a total of around 6700 tonnes of CO<sub>2</sub> once every 16-17 days. This will be offloaded and transferred to intermediate storage tanks using three lines (one for each storage tank battery) capable of transferring CO<sub>2</sub> at a rate of 1000 kg/min, meaning the train will be unloaded in approximately 36-40 hours.

Pipeline provides most of the CO<sub>2</sub> arriving at the RY1 Hub Area transporting around 3914 tonnes of CO<sub>2</sub> per day to the RY1 Hub Area. CO<sub>2</sub> from the pipeline is considered must-move and thus will not go into intermediate storage but, rather, will continue transporting through the pipeline on to the storage area. The amount of CO<sub>2</sub> transported into the RY1 Hub Area via pipeline decreases to around 3700, 3000, and 1100 tonnes per day as individual gathering and boosting stations come offline for annual maintenance.

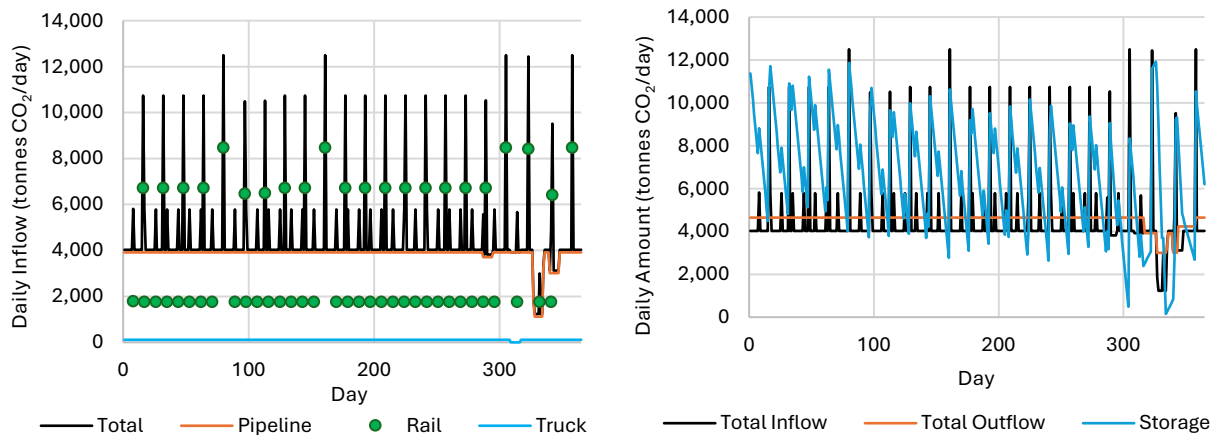


Figure 20. Daily inflow by Transport Mode (left) and Inflow and Outflow and Storage (right) at the RY1 Hub Area under Scenario 1.

*Above ground storage requirements:* In instances where pipeline flow drops below 3000 tonnes per day when larger sources are offline for maintenance, CO<sub>2</sub> from storage will be important to manage the minimum amount of flow required (3000 tonnes per day). Conditioning and compression of CO<sub>2</sub> from storage to the pipeline will occur at a rate of up to 1900 tonnes per day, although in most days only 730 tonnes or less will be required. Total above ground storage capacity at the RY1 Hub Area is 13,200 tonnes. Most days this capacity will not be used, instead around 3000 to 9000 tonnes of CO<sub>2</sub> (or around 20% to 70% of the overall capacity) is stored most days of the year (Figure 21, left). The storage outflow is constant over the year (Figure 21, right) except for when the storage must be built up over time in anticipation of the larger sources going offline for maintenance toward the end of the year (See Figure 20, right). During this time, flow is maintained at 3000 tonnes through an input of just under 1900 tonnes a day from storage for seven days and around 1200 tonnes a day from storage for five additional days.

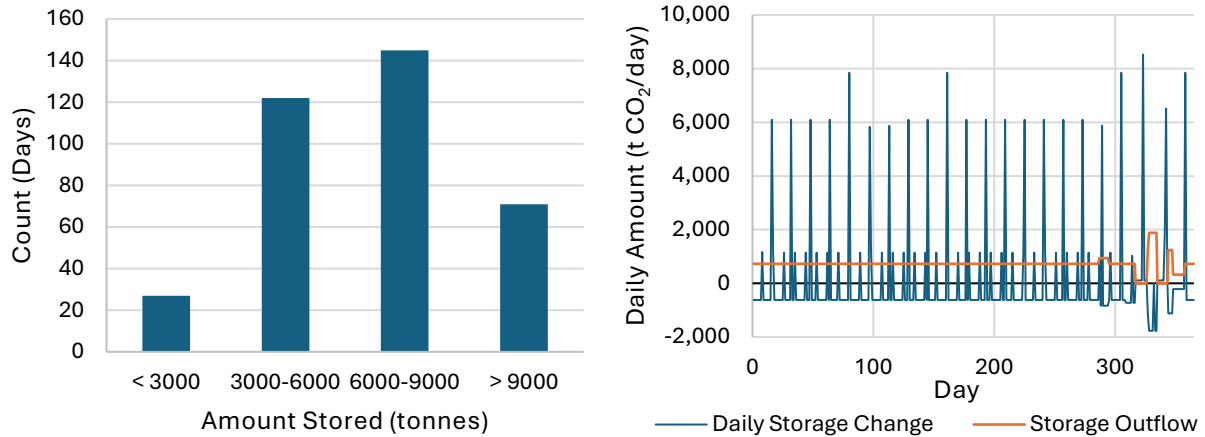


Figure 21. Number of days with specific volumes in above ground storage (left) and storage outflow and daily change in storage (right) at the RY1 Hub Area under Scenario 1.

**Scenario 2:** Scenario 2 is shown in the BFD provided in Figure 22.

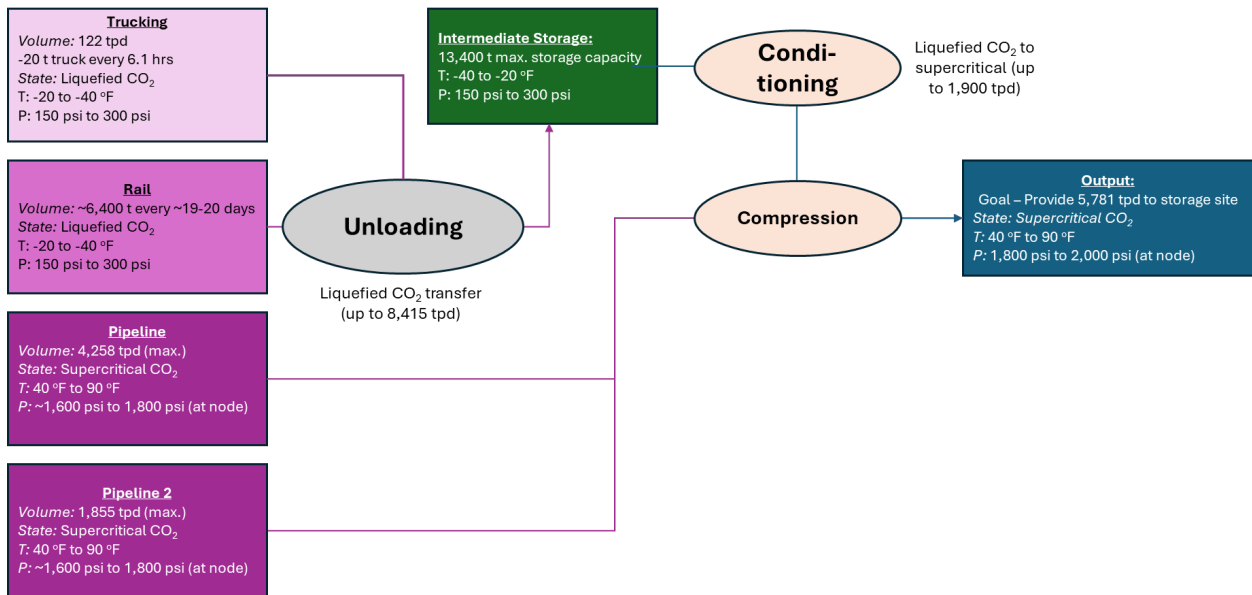


Figure 22. BFD for Scenario 2 at the RY1 Hub Area.

**Total flow rates:** CO<sub>2</sub> arriving via pipeline will remain in the pipeline and be supplemented by CO<sub>2</sub> from storage to maintain an average flow of around 5927 tonnes per day (Figure 23, left). For most days, the flow rate will be 5919 tonnes per day or the maximum flow rate of 6300 tonnes per day. Lesser amounts flow from the system due to maintenance occurring on capture systems. The above ground storage of CO<sub>2</sub> onsite, however, ensures that at least 3800 tonnes of CO<sub>2</sub> are flowing every day. The CO<sub>2</sub> arriving at the site ranges from 2824 tonnes per day to 12,440 tonnes per day. Modal inflow is 5731 tonnes per day arriving via pipeline, truck, and rail (Figure 23, right). This is exceeded for 17 days of the year and not reached for 49 days of the year. During these times, CO<sub>2</sub> stored on-site will be used to ensure flow assurance.

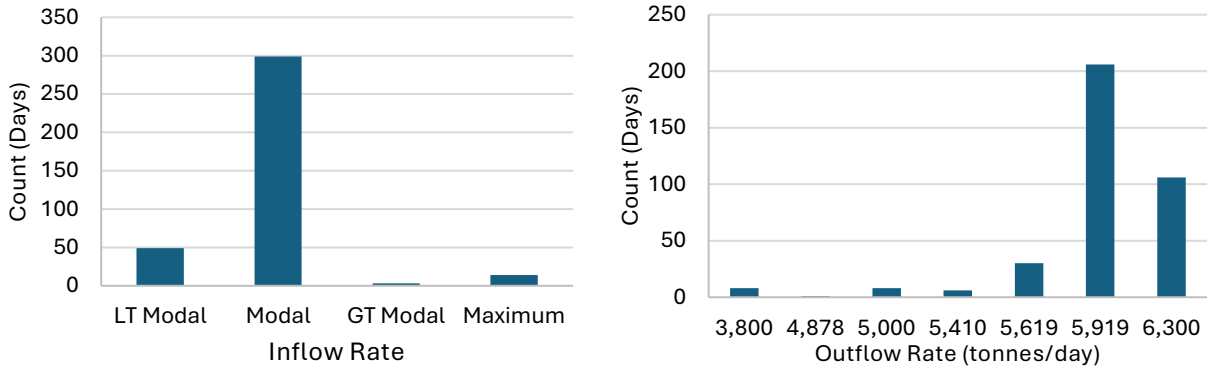


Figure 23. Number of days with specific inflow rates (left) and outflow rates (right) from RY1 Hub Area for Scenario 2. For inflow rates, the modal rate is 5731 tonnes per day. This modal rate is not reached for 49 days and amounts greater than the modal rate flow to the RY1 Hub Area 17 days of the year, including 14 where the maximum rate of 12,440 tonnes arrives via pipeline, truck, and rail. Modal outflow to the storage site is 5919 tonnes per day, which is achieved 206 days out of the year. The maximum amount of CO<sub>2</sub> transported per day (6300 tonnes) is reached 106 days out of the year. Lesser amounts flow from the system due to maintenance occurring on capture systems. The above ground storage of CO<sub>2</sub> onsite, however, ensures that at least 3800 tonnes of CO<sub>2</sub> are flowing every day.

*Flow by transport mode:* Inflow rates, by transport type, are shown for Scenario 2 in Figure 24. A truck arrives every 6 hours and delivers 20 tonnes of liquefied CO<sub>2</sub> per truck. This averages to be about 122 tonnes per day over the year. CO<sub>2</sub> will be transferred from trucks, assuming a rate of 500 kg/min, meaning the truck will be emptied in about 40 minutes.

A Unit Train of Tanker cars arrives carrying a total of around 6700 tonnes of CO<sub>2</sub> once every 16-17 days. This will be offloaded and transferred to intermediate storage tanks using three lines (one for each storage tank battery) capable of transferring CO<sub>2</sub> at a rate of 1000 kg/min, meaning the train will be unloaded in approximately 36-40 hours.

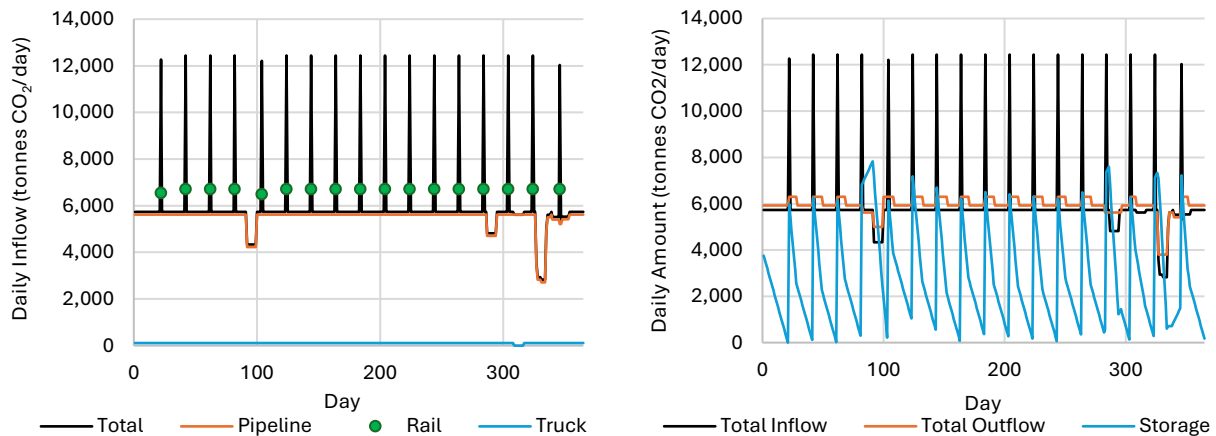


Figure 24. Daily inflow by Transport Mode (left) and Inflow and Outflow and Storage (right) at the RY1 Hub Area under Scenario 2.

Pipeline provides most of the CO<sub>2</sub> arriving at the RY1 Hub Area transporting around 3914 tonnes of CO<sub>2</sub> per day to the RY1 Hub Area. CO<sub>2</sub> from the pipeline is considered must-move and thus will not go into intermediate storage but, rather, will continue transporting through the pipeline on to the storage area. The amount of CO<sub>2</sub> transported into the RY1 Hub Area via pipeline decreases to around 3700, 3000, and 1100

tonnes per day as individual gathering and boosting stations come offline for annual maintenance. A second pipeline from northern West Virginia supplies additional CO<sub>2</sub>.

*Summary of equipment / process flow diagram:* The process begins with a CO<sub>2</sub> delivery truck containing liquefied CO<sub>2</sub> at low temperature and moderate pressure or providing CO<sub>2</sub> from the temporary storage tanks. A cryogenic pump transfers the liquid from the truck/tanks and boosts its pressure to around 300 psig. This pump is designed for low-temperature service and prevents cavitation by maintaining adequate suction pressure. The vaporizer heats the pressurized liquid CO<sub>2</sub> to convert it into gas. This step ensures the fluid is in the correct phase for compression. Vaporizers can be ambient air, steam, or electrically heated units, and they include temperature and pressure controls to avoid dry ice formation.

After vaporization, the CO<sub>2</sub> gas enters a multi-stage compressor system. Each stage progressively raises the pressure to pipeline specifications (typically 1,500–2,200 psig). Interstage cooling is used to manage temperature rise and prevent excessive thermal stress. Compressors are equipped with vibration monitoring, pressure and temperature sensors, and recycle valves for control. The final stage is an aftercooler, which reduces the temperature of the compressed CO<sub>2</sub> to near ambient (60 °F) before entering the pipeline. This cooling step ensures compliance with pipeline specifications and protects downstream equipment. Heat exchangers are typically air-cooled or water-cooled, with flow and temperature control loops. A summary of the equipment and conditions is shown below in Figure 25.

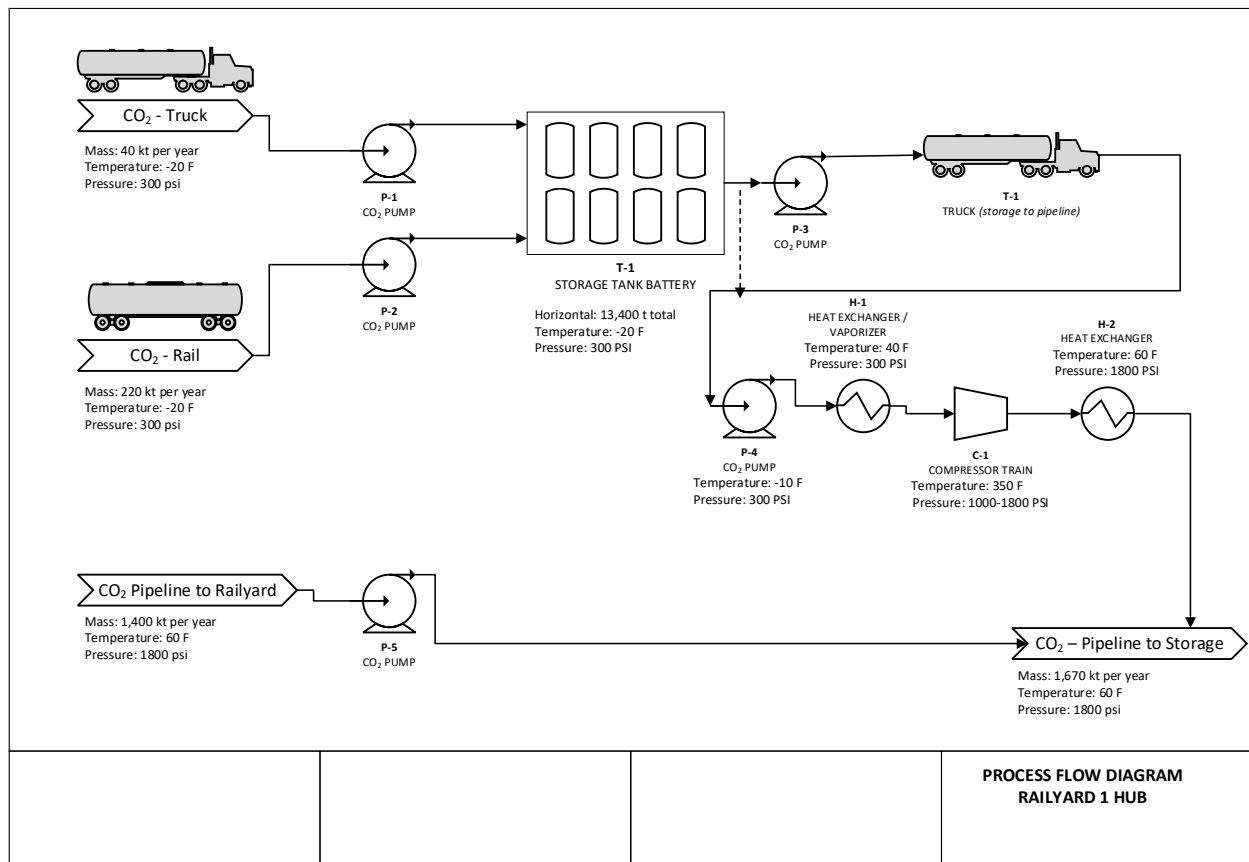


Figure 25: High-level Process Flow Diagram for Railyard 1.

One alternative equipment configuration uses a high-pressure cryogenic pump to raise the pressure of liquid CO<sub>2</sub> directly above the supercritical threshold (~1,070 psia). After pumping, the fluid passes through a heater to increase its temperature above 60 °F, ensuring it becomes a supercritical fluid. This

approach eliminates the need for a vaporizer and multi-stage compressors, significantly reducing energy consumption since pumping liquid requires far less work than compressing gas. However, it demands specialized pumps capable of handling very high pressures and precise temperature control to avoid dry ice formation during heating. This configuration is common in supercritical CO<sub>2</sub> extraction and can be adapted for pipeline injection where supercritical conditions are acceptable.

## 6.2 Codes and Standards

The intermodal hub network is located in northern West Virginia, eastern Ohio, and southwestern Pennsylvania. The Railyard 1 Hub Receiving Area is in Washington County, Pennsylvania. Codes and standards applicable to the study are shown in Table 13.

Table 13. Applicable Codes and Standards for the RY1 Hub Area.

Area	US Requirements
Control Building	-International Fire Code (IFC) -International Building Code (IBC) -NFPA (Fire Suppression) -American Society of Civil Engineers (ASCE) 7 (Building Foundations) -Occupational Safety and Health Administration (OSHA) Requirements
Electrical	Developed Later with Additional Specifications
Intermediate Storage – Horizontal Tank	-American Society of Mechanical Engineers (ASME) Section VII, Div. 1 -American National Standards Institute (ANSI) Schedule 80 seamless pipe/isolation valves (Engineering Toolbox, 2003) -Relief valves (safety)
Intermediate Storage – Vertical Tank	-ASME Section VIII, Div. 1 -ANSI Schedule 80 seamless pipe -Relief valves (safety) -ANSI Schedule 80 (Standard Pipe Specifications)
Piping	-Det Norske Veritas (DNV) RP-J202 (Design and Operation of CO <sub>2</sub> Pipelines) (International Standard) -American Petroleum Institute (API) (2022) -49 CFR §192
Compressors	Developed Later with Additional Specifications
Heat Exchangers	Developed Later with Additional Specifications
Health Safety and Environment	-OSHA 1910 -OSHA 1910.36-37 (Means of Egress)

## 6.3 Operational Conditions (Site and Climate Data)

This section defines the environmental and operational conditions under which the Railyard 1 Hub Area (pre-FEED) system must operate, including location and elevation information, pressure, temperature, wind, precipitation, soil, seismic conditions, corrosive conditions, and current land use.

### Plant Location and Elevation:

- **Area:** 1.367 million ft<sup>2</sup> (127,400 m<sup>2</sup>) / 31.4 acres (0.127 km<sup>2</sup>) (Figure 26)
- **Perimeter:** 4,820 ft (1,470 m)
- **Elevation:** 1096 ft amsl (334.1 m amsl) to 1,259 (383.7 m amsl). Gently sloping from east-northeast to west-southwest. Average slope of approximately 0.1. Southern portion of site has a slope of approximately 0.02 (Figure 27)



Figure 26. Land sat image of the Railyard 1 Hub Area. The yellow hashed area is the potential location for the hub. The elevations of the corners of the lot are shown in yellow text. The linear distance of the edges of the lot are shown in white text. The area of the lot is also shown.

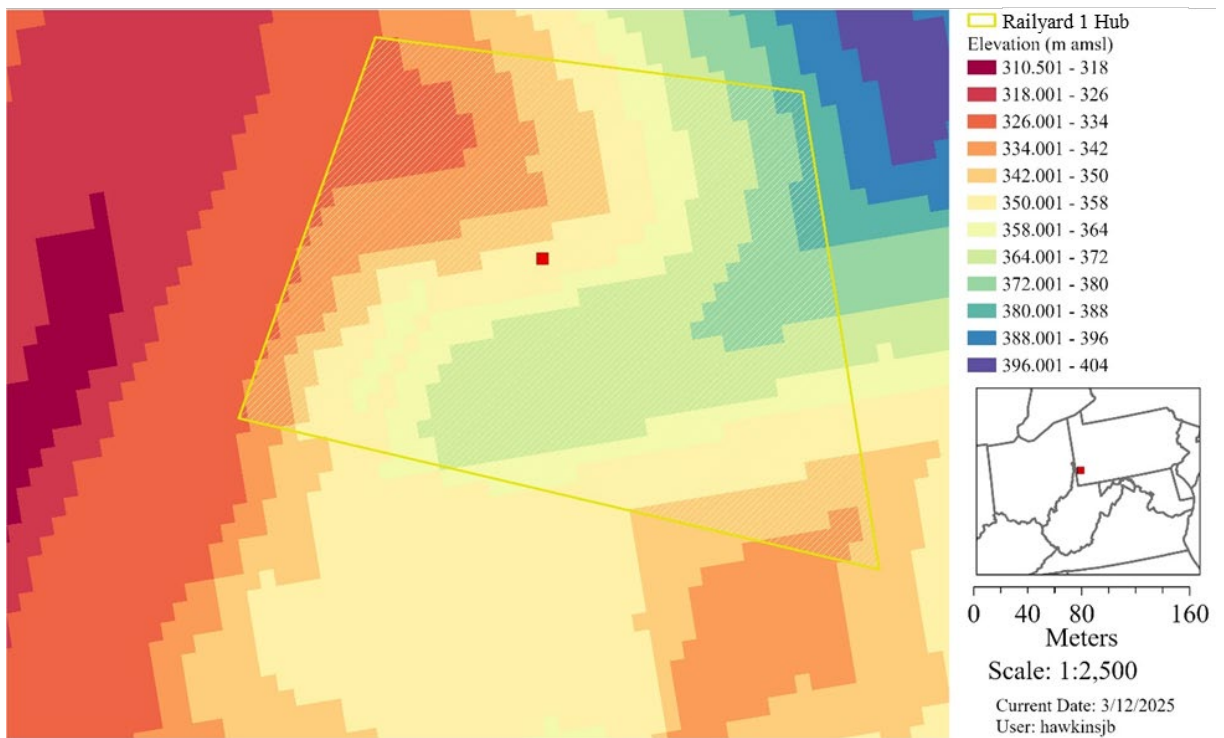


Figure 27. Elevation of the Railyard 1 Hub Area (United States Geological Survey [USGS], 2023).

**Pressure:** The facility will be at the ground surface and be subject to normal atmospheric pressure.

**Temperature and Precipitation:** The minimum, maximum, and average temperature and rainfall are shown, by month, for calendar years 2018 to 2024 in Figure 28. Temperatures ranged from -11 °F to 95 °F (average of 52.6 °F). Monthly average rainfall ranged from 1.83 inches in July to 3.84 inches in February and totaled an average of 33.71 inches in the reviewed years.

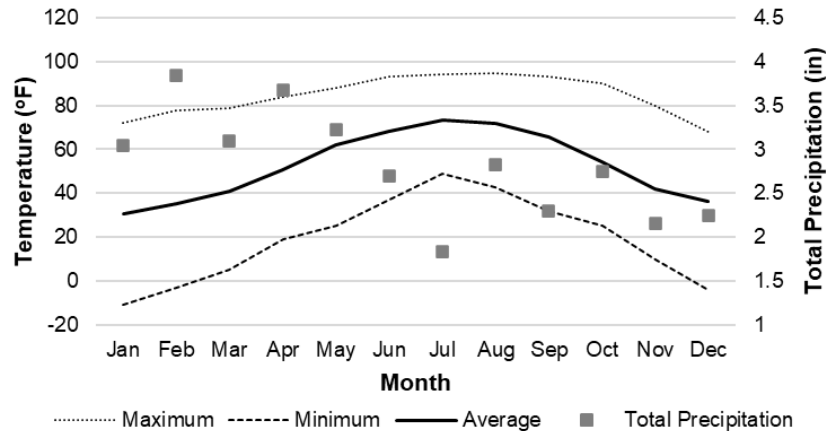


Figure 28. Average, maximum, and minimum temperature and total precipitation, by month, for calendar years 2018-2024 (National Oceanic and Atmospheric Administration [NOAA] Regional Climate Centers [RCCS], 2025).

**Soil Conditions:** The USDA has classified the soils in the area as silt loam and mine dumps with some sloping (Figure 29).

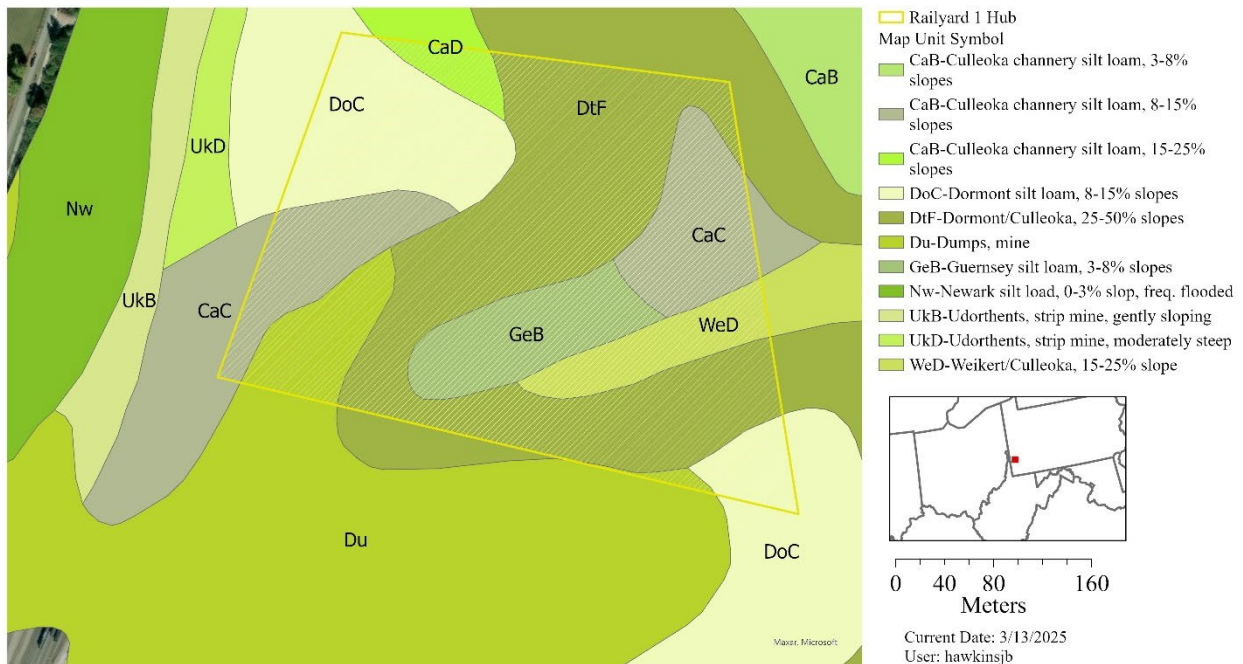


Figure 29. United States Department of Agriculture (USDA) soil analysis in the Railyard 1 Area (United States Department of Agriculture [USDA], 2024).

**Seismic:** The seismic risk in the project area is the lowest seismic risk according to the United States Geological Survey (USGS, 2022).

**Corrosive Conditions:** The corrosive conditions experienced by equipment in the Railyard 1 intermodal hub include external conditions and internal conditions. External conditions that impact corrosion are freeze/thaw, precipitation, earth movement, etc. (Sections 5.3 and 5.5). Internal conditions that impact the corrosion of the pipeline include trace components in the CO<sub>2</sub> stream, specifically water, oxygen, H<sub>2</sub>S, and SO<sub>2</sub>.

**Current Land Use:** The site is currently a deciduous forest (USGS, 2019). The adjacent site is an active railyard.

#### 6.4 Capacity Specifications / Minimum Functional Objectives

Capacity specifications are controlled primarily by the pipe size and the maximum allowable operating pressure (MAOP) and the classification of the area. The pipeline is assumed to be constructed out of Schedule 80 pipe (Table 14). Capacity calculations have been calculated, according to Bernoulli's Principle, for each pipeline segment, assuming they operate at MAOP as well as accounting for average pressure loss.

Table 14. Schedule 80 pipe specifications, including the MAOP for different classification areas<sup>(a)</sup> (The Engineering ToolBox, 2003).

Pipe Size (in)	Diameter (in)		Nominal Thickness (in)	Volume (ft <sup>3</sup> /ft)	Weight		No. of threads/in. of Screw	MAOP (psi)			
	Ex-ternal	In-ternal			lb/ft	kg/m		Class 1 0.72	Class 2 0.6	Class 3 0.5	Class 4 0.4
4	4.5	3.83	0.34	0.08	14.9	22.17	8	3,808	3,173	2,644	2,116
6	6.63	5.76	0.43	0.181	28.6	42.56	8	3,269	2,724	2,270	1,816
8	8.63	7.63	0.5	0.3171	43.4	64.59	8	2,920	2,433	2,028	1,622
12	12.75	11.38	0.69	0.7058	88.6	131.85		2,728	2,273	1,894	1,515
16	16	14.31	0.84	1.117	137	203.88		2,646	2,205	1,838	1,470
24	24	21.56	1.22	2.536	297	441.99		2,562	2,135	1,779	1,423

Notes: a. Classification area design factors are found in 49 CFR §192.111. Area classifications are found in 45 CFR §192.5. Areas listed as High Population Areas are assumed to be Class 4 areas (preponderance of four-story or larger buildings for human occupancy). Areas listed as Other Populated Areas are assumed to be Class 3 areas (46 or more buildings for human occupancy per unit area or within 100 yards of defined outdoor area). All other areas are assumed to be Class 1 areas (less than 10 buildings per unit area for human occupancy).

#### 6.5 Reliability and Maintainability

The Reliability and Maintainability is commented on for the Railyard 1 Hub Area. This includes the uptime targets, safety and compliance, and sustainability and environmental impact of the area. In addition, assumptions for uptime targets and the notes on the sustainability and environmental impact for the other nodes in the Conceptual Scenarios are detailed.

**Uptime Targets: Railyard 1 Hub Area uptime targets:** Annual planned maintenance for the system includes the following: patrolling (49 CFR §192.702), leakage surveys (49 CFR §192.706), required external corrosion control monitoring and remediation (49 CFR §192.465), repair requirements (49 CFR §192.711-720), and records retention (49 CFR §192.709). In addition, other component inspections and maintenance will be followed, such as pressure regulation devices, valves, vaults, and compressors. The cadence and impact of these activities on facility uptime targets will be defined in future phases of the project.

**Conceptual scenarios uptime targets:** The system has been designed assuming a 90% uptime for each node within the network. The flow into the Railyard 1 Hub Area is estimated assuming randomly assigned system should be able to downtime dates that are repeated quarterly. This simulates the expected variations of flow into the Railyard 1 Hub Node.

**Safety and Compliance: Pipeline design:** Pipeline designed will follow the requirements set forth in 49 CFR §192.101-205 and DNV (2010).

*Valves:* Block valves should be placed based on the area's legal requirements. Block valves can reduce volume of released product in containment failures, increase maintainability by allowing sectioning during depressurization. The effectiveness of these valves relies heavily on a robust leak detection system. Check valves can also be added to reduce volume of leaked CO<sub>2</sub> in the event of accidental release.

*Vent stations:* Vent stations generally should be pointing at a 45-degree angle away from the direction of highest consequence. Design of vent stations should take into account dominant wind and topography, and should be robust enough for worst case foreseeable CO<sub>2</sub> release and weather conditions.

*Routing:* Routes should be determined based upon population density according to ISO 13623. The route should be documented with respect to length of pipeline in each population density zone.

*Stream composition:* With a co-mingling system an analysis should be done to ensure that the mixing of different streams do not cause water-dropout, other intended chemical reactions, or other miscellaneous condensation. For shorter pipeline sections where sufficient de-watering cannot occur, polyethylene liners may be considered for corrosion control.

**Federal, State, and Local Regulations:** Required federal, state, and local regulations and permits have been defined in Section 3 of this report. RY1 Hub Area is in Washington County, Pennsylvania. Thus, identified permits for Washington County, the Commonwealth of Pennsylvania, and the United States apply.

## 6.6 Sustainability and Environmental Impact

To minimize the impact of the intermodal hub's construction and operation on the environment and optimize the net CO<sub>2</sub> transported and stored by the hub, a life cycle assessment (LCA) was completed for conceptual Scenarios 1 and 2. The analysis was performed using openLCA (version 2.4.1) software coupled with the ecoinvent (version 3.9.1) database and will quantify key impact categories such as climate change, water and land usage, and acidification to understand the sustainability and environmental impact of the hub. ReCiPe 2016 v 1.03 midpoint (H) was used as the impact assessment method, and inputs for the LCA model was generated by the pre-FEED study. Additionally, the hub's primary waste streams was identified in the pre-FEED study and reviewed to determine the appropriate regulatory response for compliance.

The LCA will also include a sensitivity analysis that compares sub-scenarios, such as using different materials of construction, electricity generation technologies, and transportation methods, to understand their effect on the overall LCA results. Primarily, however, the LCA was used to assess the intermodal hub's global warming potential (GWP) in terms of kilograms of CO<sub>2</sub>-equivalents generated per kilogram of CO<sub>2</sub> transported/stored. This value was used to calculate the net CO<sub>2</sub> transported and stored by the hub, which will then be optimized by weighing different environmental impact and economic factors.

## 6.7 Economic Considerations

The economic assessment of the system is presented in Section 4 of this report.

## 6.8 Feed Stock Properties

Feed stock properties for power generation and CO<sub>2</sub> inlet properties are defined for the RY1 Hub Area below.

**Power Generation:** Power requirements will be satisfied by the local grid. Power requirements will be defined in later phases of the project. The site is located within the Allegheny Power Systems Zone of the PJM Interconnection (2023). Current (2024 annual) industrial power rates in Pennsylvania at 7.84 cents per kilowatt-hour (EIA, 2025c).

**CO<sub>2</sub> Inlet:** CO<sub>2</sub> will arrive at the RY1 Hub Rally Point from four different sources in both scenarios. These are outlined in Section 2. In both scenarios, the rally point will have to receive and store supercritical and liquefied CO<sub>2</sub> and transport via pipeline supercritical CO<sub>2</sub> to the storage area.

## 6.9 Products

Expected products are defined for the RY1 Hub Area. This includes the amount, state, and purity of the CO<sub>2</sub> resulting from the RY1 Hub Area.

## 6.10 Integration Requirements

Integration Requirements are considered for the RY1 Hub Area. These include system integration with existing utilities and offsite systems, quality assurance, and user requirements.

**Quality Assurance:** *Standards and procedures to ensure the quality of the design and construction:* Pipeline designs will follow the regulatory requirements detailed in 49 CFR §192 and the standards set forth by DNV (2010).

*Includes testing protocols, certifications, and quality control measures:* DNV (2010) sets for requirements for flow assurances:

- Modeling should be done to analyze the effect of temperature and pressure of the CO<sub>2</sub> on the flow capacity in the pipeline; care should also be taken to negate hydrate formations, which may cause blockages in flow.
- Models should also be developed to analyze water drop-out, pressure surges, controlled and accidental release, shut-in and start-up operations, depressurization and heat transfer to surroundings.
- Hydrate formation should be prevented to avoid the risk of blockages. Sufficient dewatering of the CO<sub>2</sub> stream should be done prior to transport and should be monitored and controlled.

**User Requirements:** *Considerations for the end-users of the system or product:* For the end-user to be able to use the transport network, the network must be 1) cost-effective, 2) applicable to the size of the user's CO<sub>2</sub> source, and 3) operational within a reasonable distance of the user's CO<sub>2</sub> source. These considerations will be further developed and defined as part of future tasks, particularly through the completion of the techno-economic assessment / BCA and LCA. Information obtained through these assessments will be used to understand the feasibility of integrating the transport network with various sizes and locations of CO<sub>2</sub> sources and to ensure applicability of the network to relevant sources in the area. Additionally, other user requirements for the transport network will be identified as applicable as the project progresses.

**Accessibility:** The system will establish a tariff rate at the RY1 Hub Receiving Area. This rate, along with terms and conditions, will be made publicly available to ensure transparency and accessibility to the transport network. Economic information obtained from the pre-FEED study and the techno-economic assessment / BCA, along with publicly available literature, will be used to establish the rate and its associated terms and conditions.

## 7.0 Conclusions

The project accomplished several key outcomes. The project success criteria from the Project Management Plan and how each were satisfied are provided in Table 15.

Table 15. Project Success Criteria, established at the outset of the project, and the outcome from the work.

Success criteria	Task	Outcome
Collect datasets, files, metadata, map for CO <sub>2</sub> sources, sinks, pipelines, land use factors for a hub storage system	2.0	The project team developed maps that show the sources, sinks, anchor points for the hub, transport modes, and sensitive areas as part of the <i>project basis of design</i> and <i>risk assessment</i> , completed in Months 7 and 11 of the project, respectively.
Verification that the project can be permitted	3.0	The project team developed a permitting plan for the transport hub that included the federal, state, and local permitting requirements. This plan identified the permitting authority, application requirements, fees, public comment period, and potential lead time. This was completed in Month 10 of the project.
Provide evidence that project is economically feasible	4.0	A cost assessment and BCA were completed for each of the Scenarios considered in the project. The BCA found the following: In a moderate-growth scenario, CO <sub>2</sub> capture and transport infrastructure would expand incrementally, with early projects relying on truck and rail to move captured CO <sub>2</sub> to nearby injection wells, particularly in areas with limited pipeline access. This approach allows for flexible deployment while minimizing upfront capital costs. In a high-growth scenario, driven by aggressive climate policy, carbon markets, and industrial decarbonization mandates, the region could see the rapid buildout of a shared CO <sub>2</sub> pipeline network, similar to the development of natural gas infrastructure in the early 2000s This was completed in Month 9 of the project.
Reduce project risks and uncertainties	5.0	The project team completed a qualitative risk assessment of severity and likelihood of major risks, assessed the impact to specific receptors along the pipeline route (Impact Assessment), and completed Bow-Tie Assessment for each transportation mode. This was completed in Month 11 of the project.
Community Benefits Plan and SCI activities to evaluate public acceptance and community engagement	6.0	This section is deemed voluntary based upon the MEMORANDUM FOR ALL DEPARTMENT OF ENERGY ASSISTANCE AWARD with the Subject: Recission of the January 28th, 2025, Memorandum from the Department of Energy received on 3/14/25 by Battelle Memorial Institute.

In addition, the project team completed the following:

- Finish pre-FEED Design Product for RY1 Hub Area, including a basis of design (Sections 2.3 and 6.0), permitting plan (Section 3.0), economics assessment (Section 4.0), and risk assessment (Section 5.0).
- Complete process for temporal changes and regional interconnection, including modeling the impact of an expansion of the network to a hydrogen plant (Section 2.2) and demonstrating the addition of other existing sources and potential future sources (Section 2.4).
- Informed and briefed funding partners CNX, EQT, and Hope Gas through regular briefings and/or sharing of project deliverables.

- Linked our results to other DOE federal investments like the ARCH2 Hub, carbon storage projects, and other transport projects (See Section 2.4).

The project is well-positioned to continue to the FEED stage. Specific activities to be completed in the FEED study include the following:

- Identification and outreach to sources that are planning CO<sub>2</sub> capture projects as well as rail and trucking companies in the study area to supplement the interest and expertise of the funding partners for this project.
- Refinement of concepts and definition of specific equipment, piping, and construction requirements for the RY Hub 1 Area, including the development of process flow diagrams and instrumentation diagrams, layout drawings, and equipment specifications for the hub area.
- Outreach to regulatory and permitting entities to ensure compliance with permitting requirements and help establish relationships and expectations that would help facilitate permit processing.
- Refinement of project cost estimates using refined FEED study documentation and planning to obtain vendor quotes.
- Refinement of HAZID and ES&H requirements through plume release modeling; conversations with local emergency management leaders; and mitigation, recovery, and contingency planning.

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## **Appendix 1. Permitting/Regulatory Plan Analysis**

## **Appendix 2. Technoeconomic Assessment and Business Case Analysis**

## **Appendix 3. Hazard Identification (HAZID) Preliminary Summary**