CHAPTER 5

CO_2 and Biomass Transportation

SUMMARY

Some CO_2-removal pathways, such as direct air capture with storage (DACS) or biomass with carbon removal and storage (BiCRS), involve several steps that may not all occur at the same location. This necessitates transportation of CO_2 and/or biomass between different sites. In the future, CO_2 transportation infrastructure will be most efficient if pipelines are available. To enhance flexibility in capacity and routing, alternative transportation modes like trucking, rail, and barges are also viable options. Developing these transportation options can contribute to job creation and retention. However, routing necessitates careful consideration and strategic actions to avoid perpetuating historical inequities. Equitable distribution of CO_2 and biomass transportation routes is essential to avoid further burdening disadvantaged communities.

Key Findings

- Pipelines are efficient but are not essential for CO_2 transportation; other modes, such as rail, trucking, and barges, are viable alternatives with a minimal cost increase.
- If available nearby, large trunk pipelines and barges are the most cost-effective options for transporting CO_2, with costs of \$0.07 and \$0.012/tonne-km, respectively. However, pipeline construction requires multi-billion-dollar investments, and barges have upfront loading costs of \$14–\$18/tonne before leaving the port.
- Trunk pipelines, rail, and barges often require secondary transportation networks with higher transportation costs to gather CO_2 and/or biomass from multiple sources.
- For distances under 400 km, trucking is more economical than rail for a “round-trip, no back-hauling” option, at \$0.11 and \$0.10/tonne-km for CO_2 and biomass, respectively, and a flat rate of \$9/tonne CO_2 for the process of compressing CO_2.
- Multimodal configurations will require transloading facilities (where cargo is shifted between two different transport modes) with adequate infrastructure to properly handle CO_2 and biomass shipments, including temporary storage and reconditioning capabilities for CO_2 when modal shipping conditions differ.
- Achieving long-term, sustainable CO_2 transportation involves decarbonizing the rail and trucking sectors, prioritizing public health, and fostering job creation through local hiring commitments.
- The infrastructure capacity required to transport biomass and CO_2 (for BiCRS) is of a similar magnitude to what the United States currently uses for transport of corn-ethanol plus pulp and paper industry products, or hazardous class II liquids.

CHAPTER SCOPE

This chapter analyzes four modes of transportation for CO_2 and biomass: pipelines, rail, trucking, and barge. It presents key takeaways surrounding the cost, operation, and execution of these modes, including:

- Most economical mode or combination of modes for a given capacity and transportation distance
- Commodities that are cheaper to transport
- Transportation costs for potential BiCRS and DACS routes
- Social and environmental considerations
- Recommendations to limit negative impacts and explore potential co-benefits to local communities

Introduction

CO_2-removal methods, such as BiCRS and DACS, capture and store CO_2 in several steps. Under ideal conditions, these steps are co-located, which helps minimize transportation infrastructure and cost. However, ideal conditions for CO_2 capture do not always geographically overlap with ideal conditions for geologic CO_2 storage (**Figure 5-1**), and the scale of CO_2-removal needed for a net-zero future requires that we consider many options. Hence, transporting CO_2 and/or biomass will likely be a critical element of ongoing carbon-management logistics.

As commodities, biomass and CO_2 are already transported in the United States, though at a small scale when compared to the volumes that will be required to reach net-zero CO_2 emissions. Biomass is currently transported by train and/or truck, depending on the route, distance, and availability of infrastructure, while CO_2 is moved by pipeline, rail, or truck. In 2022, about 230.1 million tonnes of corn was transported to produce ethanol (assuming 25.4 kg/bushel) [6]. Also, about 207.5 million dry tonnes of biomass is transported annually for pulp and paper (assuming 83 million dry tonnes of pulp produced annually and 2.5 dry tonnes of biomass needed to produce one tonne of pulp product) [7, 8]. Together, the total transported volume of these two feedstocks corresponds to between one half and the total amount of the biomass transportation needs identified in **Chapter 6 – BiCRS,** depending on the scenario. In 2007, about 227 million tonnes of hazardous class II liquids (non-flammable gases, including CO_2) was transported in the United States [9]. This is also of a similar order of magnitude to the volume of CO_2 transportation needed, as identified in **Chapter 6 – BiCRS**.

Transportation of CO_2 in the future is often envisioned to occur through an extensive pipeline network across the United States, well beyond the roughly 9600 km of pipelines currently dedicated to supplying CO_2 to oil and gas fields for enhanced oil recovery. Building pipelines takes time [1, 10, 11] and can be hindered by the negative reputational risks

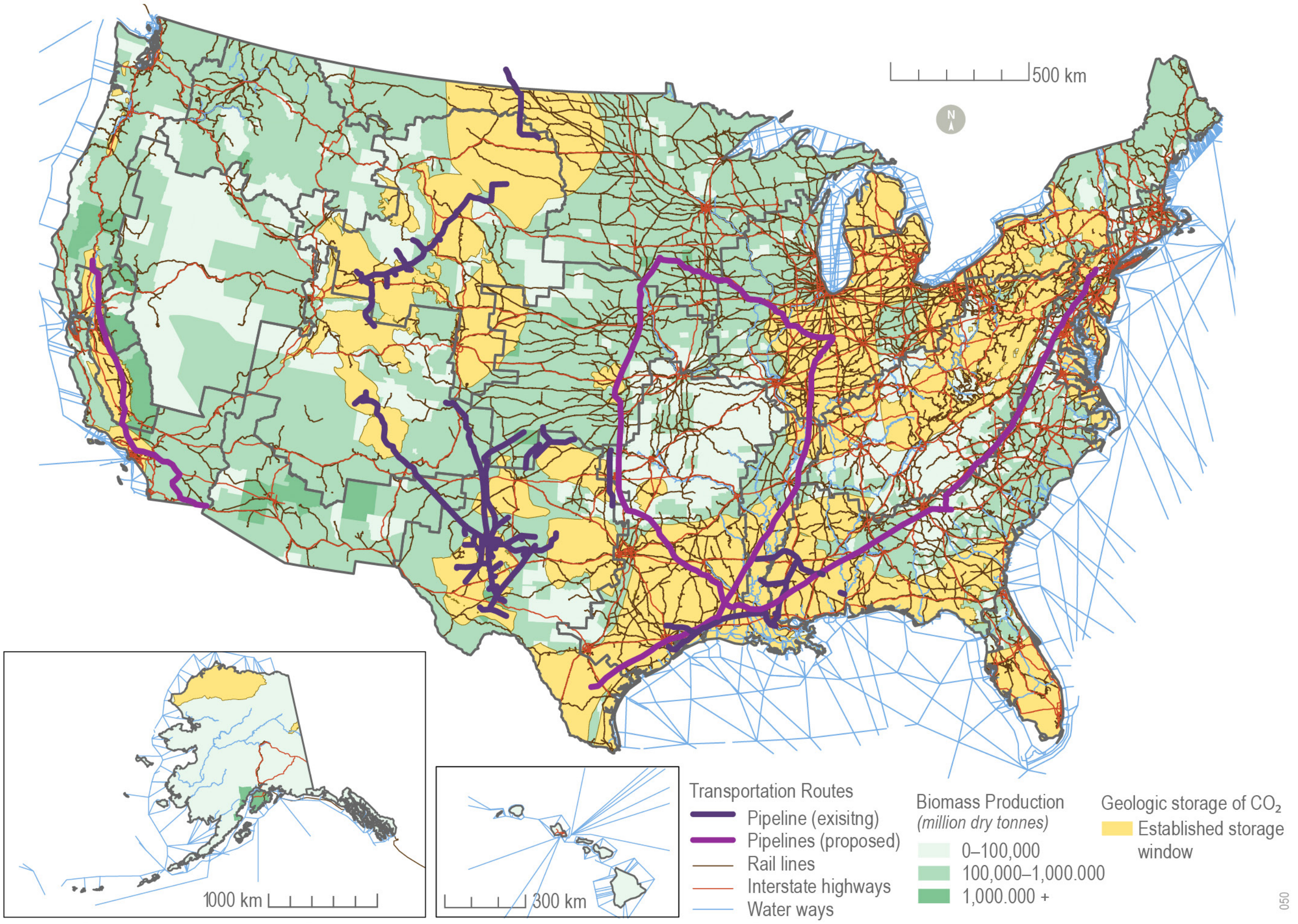

Figure 5-1. *Map of transportation networks for transporting biomass and CO_2, along with CO_2 storage and biomass production [1-5]. This map outlines areas where CO_2 and/or biomass transportation might be needed, namely regions with no established storage window and larger amounts of biomass. Note that the data for geologic storage of CO_2 are overlapping and hiding the biomass-production data. The biomass production data depict the "zero-cropland-change" scenario from **Chapter 6 – BiCRS**.*

Table 5-1. *Fuel used and carbon intensity for each transportation mode.*

Transportation Mode	Fuel Used	Carbon Intensity[a] (gCO_2e/tonne-km) [12]
Rail	Conventional diesel	15
Trucking	Conventional diesel	83
Barge	Marine diesel oil (0.5% sulfur)	4.1
Pipeline	Natural gas (boosting stations)	<1

[a] Carbon intensity is calculated as the sum of greenhouse gases (GHGs) emitted to the atmosphere per unit transported (tonne-km) from source to sink. These figures do not include emissions encountered on the sink-to-source return trip. If that return trip does not carry an additional commodity (known as back-hauling), the actual emissions may be approximately twice that reported here.

of such infrastructure related to historical incidents (e.g., on oil and gas pipelines and more recently with CO_2), in addition to issues with right-of-way acquisitioning. Reliance on CO_2-pipeline construction as the predominant means of transportation could yield undesirable effects on timely technological development of CO_2-removal pathways. One solution is to avoid transporting CO_2 altogether by placing DACS and BiCRS facilities above geologic formations that are suitable for CO_2 storage. Another solution is to use existing infrastructure with established networks (Figure 5-1), such as rail, trucking, barges, or some multimodal combination **(Box 5-1) .**

This chapter presents key takeaways surrounding the cost, operation, and execution of transportation within the context of CO_2 removal. In this context, transportation is multivariate, involving multiple types of transportation (rail, trucking, barges, and pipelines) and multiple types of cargo (CO_2 and biomass feedstocks) with different handling requirements. Our transportation model takes a conservative approach for fuel use (**Table 5-1**), using diesel fuel for trucking and rail; however, tailpipe emissions from moving CO_2 and biomass could be reduced by electrifying transportation modes. Our analysis also limits the number of proposed trunk pipelines and does not include spur pipelines. To use trunk-pipeline services, new DACS and BiCRS facilities would have to be built next to them. We combine our transportation cost model (**Figure 5-2**) and the transportation network for each mode (Figure 5-1) with the Biocarbon Infrastructure, Logistics, and Transportation (BILT) model (see **Chapter 6 – BiCRS**) to understand which mode or combination of modes would be most economical for a given route. We also discuss the variety of social and environmental considerations for each mode of transportation as an aspect of determining the best route for transporting either CO_2 or biomass.

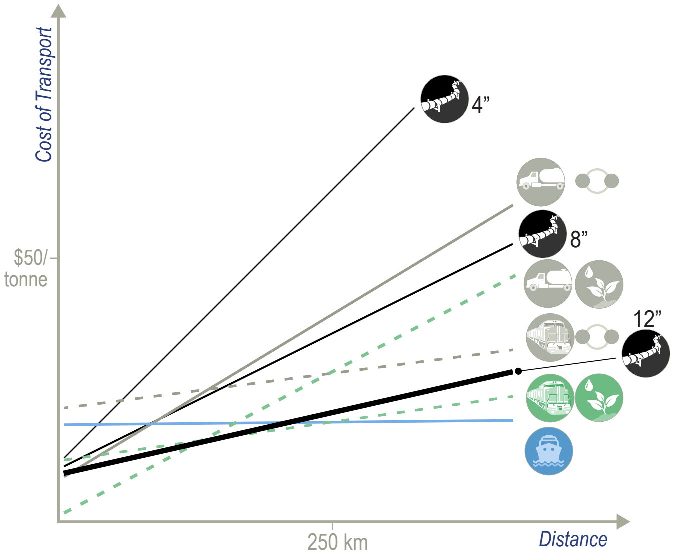

Figure 5-2. *Cost of CO_2 and biomass transportation using various modes or combinations of modes. Biomass is modeled here as transported biomass (solid).*

BOX 5-1

Terminology Around Transport

In this chapter, the term “multimodal” refers to combining several modes of transportation to accomplish a trip from the origin to the destination. For CO_2, these modes include rail, trucking, barges, and pipeline, while biomass can be transported with rail, trucking, and barges. Shifting from one transportation mode to another for CO_2 may require a reconditioning process.

When cargo is moved between two different modes, it is referred to as “transloading,” and this operation typically takes place at transloading facilities.

Backhauling refers to the practice of using the return journey of a vehicle to transport cargo from the destination point back to the origin. This practice is challenging to implement for CO_2 bulk-liquid transportation, as this commodity requires specific containers.

Modes of Transportation

CO_2 Pipeline Transportation

CO_2 can be moved in large volumes through pipeline networks. Typically, CO_2 is moved as a dense liquid under high pressure (100–150 bar), which is advantageous for subsurface storage, as high pressures are required for injecting CO_2 into suitable reservoirs. For longer pipelines, pressure-boosting pumps are spaced along the route to compensate for transit-related pressure drops. CO_2 is typically transported at purities greater than 95 mol%, though it is more important to keep the stream free of water as water can expedite corrosion of the steel-alloy lining of the pipeline.

Currently in the United States, about 8500 km of CO_2 pipelines transport 80 million tonnes of CO_2 per year, primarily servicing enhanced oil-recovery operations [1]. These pipelines are carrying CO_2 mainly to the Permian Basin in Texas and New Mexico, along the Gulf Coast, and through Wyoming. The larger pipelines used to transport CO_2 today are 30 inches in diameter and have an estimated flow capacity of about 24.7 million tonnes of CO_2 per year [13].

Multiple studies have modeled possible deployment of CO_2 pipelines in the United States. In each of these studies, pipeline developments take place over a long period of time due to the extensive steps required for new pipeline planning, approval, and construction. The U.S. Department of Transportation’s (DOT’s) Pipeline and Hazardous Materials Safety Administration (PHMSA) outlines the steps involved in developing a pipeline in its Phases of Pipeline Construction [14]:

1. **Route Selection:** Various routes for pipeline placement are assessed. This process includes assessing communities needing to be served by the pipeline delivery, natural resources that might be impacted, environmental and population areas that might be intersected, and any other infrastructure systems that lie alone the route, among other considerations. Local governments and agencies are consulted, environmental and land-use assessments are completed, and mitigation plans are generated for various deployment scenarios.

2. **Regulatory Process:** The Federal Energy Regulatory Commission (FERC) handles the regulatory process for pipeline projects crossing state lines and federal lands and coordinates with federal, state, and local agencies to ensure compliance with all regulations [15]. (This commission is not involved in authorizing the construction and operation of intrastate pipelines, for which the regulatory process varies by location [15].) FERC examines the primary route and location for the proposed pipeline and suggests alternate routes or locations to avoid or minimize impacts to the environment, buildings, fences, crops, water supplies, soil, vegetation, wildlife, air quality, noise, safety, landowner interests, and more. FERC also looks for opportunities to co-locate new pipeline routes with existing pipeline, power line, highway, or railroad right-of-way. For projects that are determined to have a significant environmental impact, an in-depth environmental-impact statement illustrating mitigation efforts must be submitted prior to moving forward.

3. **Design:** Pipeline design consists of designing pipe geometry and materials, including pipe size, thickness, bulk material, and coating material; these properties are often dictated by soil conditions, geographic features, and population characteristics of the pipeline route. Other components of pipeline system design may include compressor and pump stations, breakout-tank locations, storage facilities, valves, and other auxiliary equipment. Longer pipelines often have more system components than shorter lines.
4. **Pipe Fabrication:** Pipe sections are fabricated to meet government and industry design and safety standards in 40–80 ft (12–24 m) lengths.
5. **Site Preparation:** Sites for pipeline route and construction work (included equipment-passage routes) are cleared. Construction right-of-way is surveyed to identify areas for further clearing and grading to allow for safe equipment passage and to locate potentially impacted utilities to prevent damage during pipeline construction.
6. **Pipe Stringing:** Sections of pipe are laid out along the right-of-way, as per the pipeline design plan.
7. **Trenching:** Trenches are dug to specification or drilling or blasting is used to clear rock obstructions along the right-of-way.
8. **Bending:** Individual sections of pipe are bent so the pipeline route will conform to existing topology.
9. **Welding and Weld Inspection:** Individual sections of pipe are welded together and inspected using visual inspection, destructive testing, and non-destructive testing, such as radiographs and ultrasound testing.
10. **Field Coating:** Coating material is applied to the ends of the individual pipe sections.
11. **Lowering and Backfilling:** Pipeline is lowered into the trench, and the trench is backfilled with removed dirt or clean fill dirt.
12. **Pressure Testing:** Pipeline is tested using water, pressurized air, or other gas to ensure it can sustain operation at maximum operating pressure.
13. **Site Restoration:** Adhering to practices that prevent erosion, stabilize soils, and retain habitats, construction right-of-way is restored as closely as possible to its original condition, which may include (among other methods) replacing topsoil, repairing irrigation systems, and applying grass seed.

The timeframe for pipeline development and construction may experience bottlenecks at any of the outlined stages, and potential public pushback (**Box 5-2**. Public Perception of Pipelines), which may result in longer lead times for pipeline deployment. The approval process for a new pipeline route may be expedited if it can be laid in areas with existing rights-of-way, such as along the same path as other

BOX 5-2

Public Perception of Pipelines

While the first US pipeline for CO_2 was constructed in 1970 [16], transporting CO_2 is still perceived by the public as a "first of its kind" practice, which understandably invokes skepticism and concerns about risk that can be either magnified or lessened by a community's relationship with and trust in an individual project developer [17].

In rural areas where CO_2 pipelines may be built, concerns have emerged among communities regarding potential negative impacts on their livelihood, environment, and safety, often with limited perceived benefits [18]. Consequently, even in traditionally conservative regions seeking economic growth, pipelines may not be welcomed. This situation can result in carbon-management projects facing a "double unseeing." On one hand, experts may overlook local priorities and knowledge, while on the other hand, local residents may not fully understand the intentions and plans of carbon-management developers. The disconnect between these two groups, coupled with limited options for local communities to voice their concerns and influence project decisions, can lead to heightened resistance to the construction of CO_2 pipelines [18]. Enhancing public trust may involve—early in the planning process—engaging communities in areas where CO_2 pipelines may be constructed and granting them a more significant role in decision-making, including veto power. Additionally, carbon-management developers could present these communities with alternative CO_2 transportation options, as detailed in this chapter.

pipelines or underground powerlines. Once pipeline plans have been approved, many kilometers of pipeline can be laid and put into operation over the course of a year, barring technical bottlenecks. Some technical bottlenecks that may arise include (but are not limited to) supply-chain issues with materials for pipeline fabrication, site preparation and trenching, and challenges conforming pipelines to topology. In the United States, an average of nearly 8000 km of new pipeline was built from 2006 to 2022 and was used for gas distribution or transmission or hazardous liquids and CO_2 [19].

Studies that have investigated how pipelines could be deployed have considered various approaches, the extremes being the hub approach and the cluster approach. The hub approach (**Figure 5-3,** left) is based on very large "highway" pipelines that connect regions located very far apart and can move CO_2 over very long distances, as in the Princeton Net-Zero America study [1]. This study envisioned building 13,000 miles (21,000 km) of new trunk pipelines that would transport a billion tonnes of CO_2 every year. This plan would require very large pipelines, with pipeline capacities up to 490 million tonnes of CO_2 per year [1]. The largest pipeline designs would have an internal diameter of 45.5 inches and could carry an average of 94.2 million tonnes of CO_2 per year with a maximum mass flow rate of 110.8 million tonnes of CO_2 per year [20]. The largest capacities proposed by the Princeton Net-Zero America study would thus likely require multiple parallel pipelines. Further, the study reported that \$13 billion in stakeholder engagement, characterization, appraisal, and permitting would be needed by 2035 to allow for a rapid expansion of the CO_2 pipeline network. Further, Princeton study estimated that, during the 2021–2025 period, \$70 billion of capital would be needed, rising progressively to \$170–\$220 billion for the 2046–2050 period, with a flow of 929–1361 million tonnes of CO_2 per year and an aggregated pipeline length of 106,000–111,000 km [1]. This hub approach, connecting many sources to many sinks, could allow for greater flexibility for matching sources to sinks but would require longer pipelines and more building materials.

The cluster approach (**Figure 5-3**, right) would identify regions with multiple sources and sinks of CO_2 and deploy local networks of pipelines, with the goal of pairing CO_2 sources with nearby CO_2 sinks. The Great Plains Institute has proposed an approach close to the cluster approach with more modest infrastructure that would require maximum pipeline capacities of 33 million tonnes of CO_2 per year and a maximum pipeline diameter of 30 inches [21]. Their report presented several scenarios, with the most extensive network looking at the midcentury horizon with a 29,923-mile (48,146-km) network and 669.1 million tonnes of CO_2 per year in capacity. They estimated that deploying this infrastructure would require \$19.3 billion in capital investments, \$15.3 billion in project labor costs, and \$253.7 million of annual operating and maintenance costs. Several local studies have also explored the cluster approach [22], with a specific interest in the Midwest, where corn-ethanol plants produce high-grade CO_2 from their fermentation process [23-25]. With this cluster approach, CO_2 would be moved over shorter distances, which requires building smaller and shorter pipelines and infers lower capital costs.

These CO_2 pipeline networks were modeled based on existing CO_2 point sources, such as fossil-fuel-based power plants and industries Also, some of these studies included potential future sources of CO_2 from BiCRS facilities, based

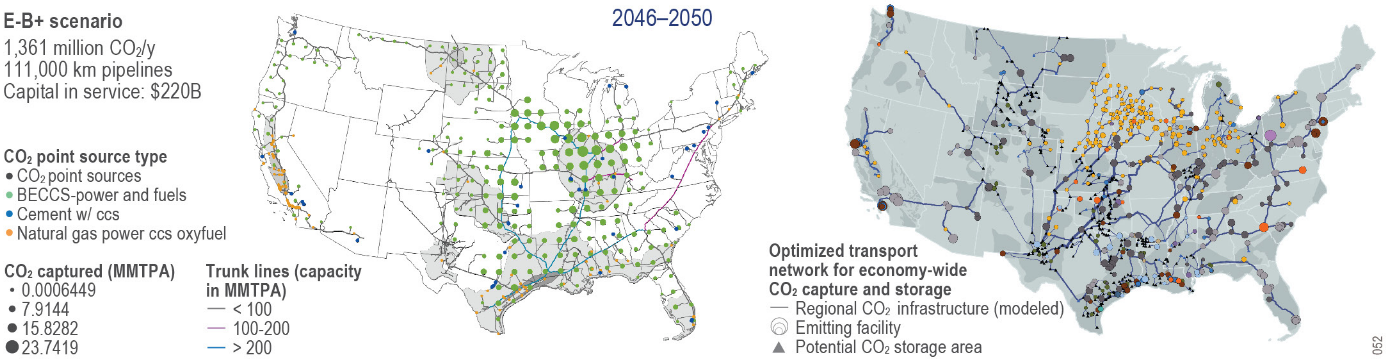

Figure 5-3. *Maps of existing and proposed pipeline networks showing the difference the difference between a hub approach (left [1]) and an approach closer to a cluster approach (right [21]). These approaches are explained in details in the text above.*

on biomass availability [1]. However, none of them included potential future DACS facilities in their modeling, which raises a question about the interaction between DACS and the CO_2 transportation network: will DACS adapt and be placed near CO_2 storage or pipelines, or will extra pipelines be built to accommodate new DACS plants that would be placed in optimum locations for DACS but far from CO_2 storage or pipelines? If the pipeline network is shaped around BiCRS facilities, DACS plants could be hosted on nearby non-arable lands to benefit from the CO_2 transportation network and infrastructure of the BiCRS facility. Routing of the pipelines was also greatly influenced by the CO_2 storage basins that a given study considered. For instance, the Princeton Net-Zero America study considered very few storage options in the western United States compared to the Great Plains Institute 2020 study, which significantly reduced the number of proposed pipelines inland and increased the length of the pipelines in coastal states.

Rail Transportation

The United States has an extensive rail network that is classified by the DOT's Surface Transportation Board (STB) into three categories, based on their annual revenue (**Figure 5-4**) [2]. Six Class I carriers operate the main tracks, which cover over 140,000 miles (225,000 km). They represent 83%–95% of the rail industry workforce and make an annual revenue of over $504 million. Class II and III carriers operate shorter lines, often providing the additional tracks to connect the origin and/or the destination of the freight trip to the main rail network. The threshold between Class II and III is set at $42 million.

Transporting CO_2 by Rail

Liquefied CO_2 is classified as a hazardous material and therefore is subject to regulation by the Federal Rail Administration (FRA) and the PHMSA. Specifically, the United Nations Sub-Committee of Experts on the Transportation of Dangerous Goods (UN TGD Sub-Committee) classifies CO_2 as

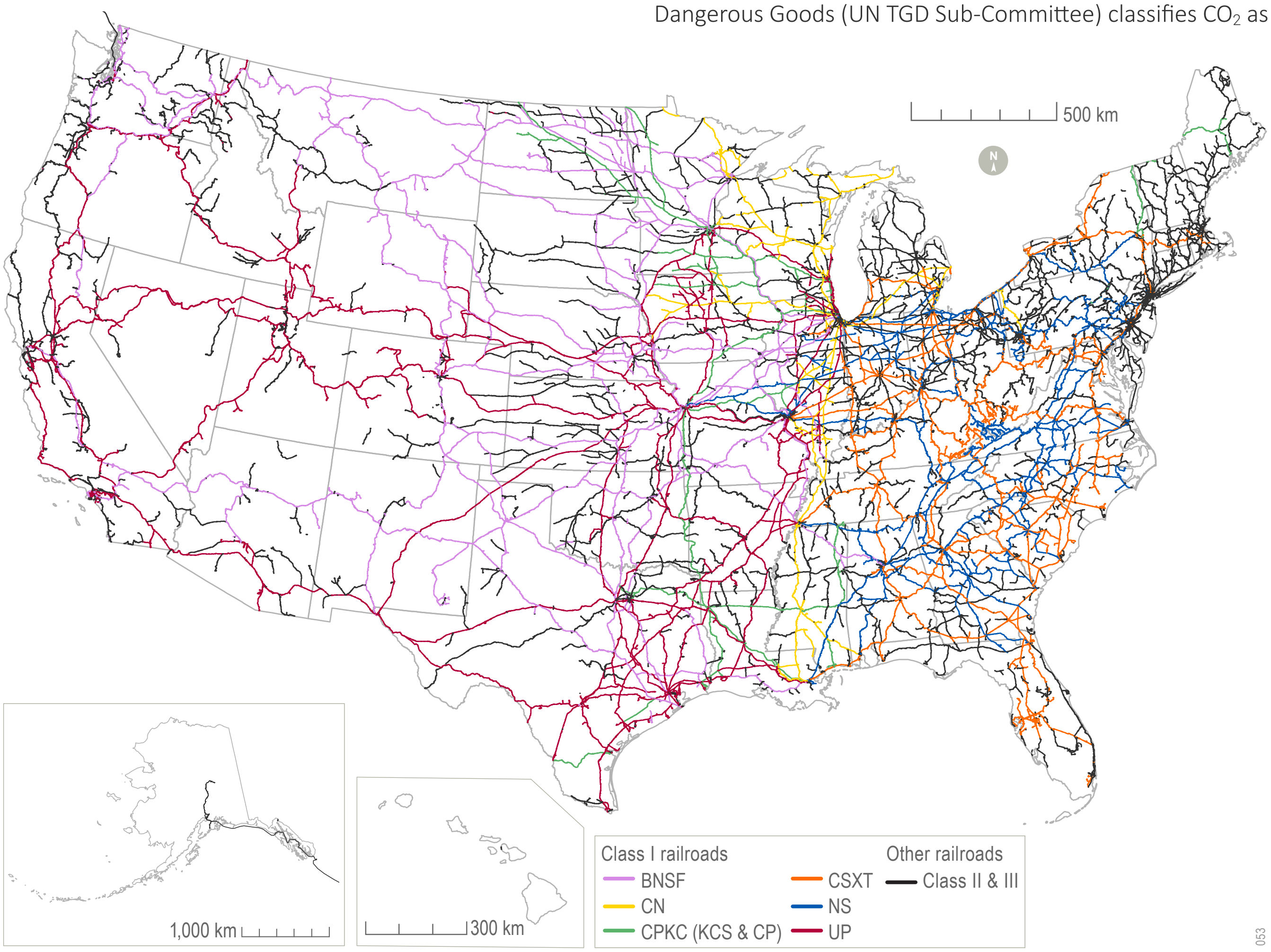

Figure 5-4. *Map of the railroads operated by Class I, II, and III carriers in the United States [2]. BNSF = Burlington Northern and Santa Fe Railway, CN = Canadian National Railway Company, CPKC = Canadian Pacific Kansas City (a recent combination of KCS = Kansas City Southern Railway Company and CP = Canadian Pacific Railway), CSTX = Chessie System Railway and Seaboard Coast Line Railroad Transportation, NS = Norfolk Southern Railway, UP = Union Pacific Railroad.*

Figure 5-5. (left) *The Trinity DOT 105 tank car for transporting liquid* CO_2 *and* **(right)** *a covered gravity hopper (> 5000 cubic feet) for transporting bulk-waste biomass.*

an inhalation hazard—under the description United Nations number UN 1013, Class 2.2 (non-toxic, non-flammable)—but does not list it as an environmental hazard. This classification requires CO_2 to be moved in DOT 105 CO_2-specified tankers (**Figure 5-5**), pressurized at 20 bar (2 MPa) and refrigerated at -20°C [26]. These tankers have a capacity of 21,964 gallons (83,143 L or 83.1 m^3) and hold a maximum weight of 100 tonnes of liquefied CO_2. Rail cars carrying CO_2 must also be separated by a buffer car from the locomotive or from cars carrying other types of goods. In 2022, all the CO_2 moved by rail—1.0 million tonnes of food-grade CO_2 (International Society of Beverage Technologists (ISBT) grade is >99.9% purity)—was moved in DOT 105 tankers [27], with an average shipping distance of 1120 km. Further, this CO_2 is transported under the Standard Transportation Commodity Code (STCC) 2813320 – *carbon dioxide gas, liquefied or carbonic gas*. In 2022, 10,472 carloads of CO_2 were shipped under this STCC identifier. In the future, there will likely need to be a new STCC code established to differentiate product CO_2 from industrial byproduct or ambiently captured CO_2, which could be classified as a waste or byproduct.

DOT 105 containers are appropriate for rail but are too big to be hauled by a truck due to gross vehicle weight (GVW) restrictions. Alternatively, several smaller containers could be stacked on a rail flatcar to allow for easier transloading. International intermodal (or ISO) containers specifically designed for carrying CO_2 can carry about 19.6 tonnes of CO_2 with a maximum pressure of 22 bars (2.2 MPa) and a temperature allowance ranging from-196 to +50°C [28]. A full unit train with two locomotives is expected to haul about 10,000 tonnes of commodities, equivalent to about 100 DOT 105 containers or 500 ISO containers.

Transporting biomass by rail

Biomass is moved in many forms, though the STCC code 24177 – *fuelwood, hog fuel, or cord wood* is considered the closest to describing the bulk transportation of wood from unconventional sources (e.g., chips, mill waste, branches, etc.) for use in heating applications. In 2022, 3.2 million tonnes of commodities were transported under this classification with an average shipping distance of 260 km, almost exclusively in covered gravity hoppers with volumes in excess of 5000 cubic feet (140 m^3) (Figure 5-5). These units transported on average 80 tonnes of biomass material per car, corresponding to about 125 cars per unit train.

Costs associated with rail-based transportation

Rail economics are influenced by ownership of equipment, rail rates, and fuel-surcharge rates. For CO_2 and biomass rail-based transportation, the cars are most commonly privately owned (99.7% and 93% for CO_2 and biomass, respectively). Leasing rates for privately owned cars vary by type and can typically range from $400 to $1000 per car per month. In exchange, customers receive discounted rates from the rail carrier. Another factor influencing cost is whether a single carrier can accommodate the transit (e.g., it is within the serviceable areas of one of the six major Class I carriers) or if multiple carriers are required, the latter of which carries an incremental cost of approximately 25% over single-carrier rates.

Trucking Transportation

Despite the efficiencies of rail for bulk transportation, trucking remains the dominant mode for transporting freight in the United States, owning roughly 72.2% of all movement [29].

In 2017, trucks carried about 6.7 million tonnes of CO_2, and a combination of truck and rail carried another 1.0 million tonnes [27].

Smaller local shipments of CO_2 are likely transported most economically via truck. Liquefied CO_2 is transported in insulated tanker trailers, for which the DOT 80,000-pound GVW limit restricts the maximum CO_2 payload to around 20 tonnes (when considering the additional weight of the tank and the tractor pulling it). Because CO_2 is classified as a hazardous material, routes are subject to hazardous-material regulations and drivers require licenses with tanker and hazmat endorsements.

To ensure drivers can execute a full round-trip in one day, including wait times at loading and unloading stations, trucks routes are recommended to be under 400 km one-way. Reducing overnight transportation has the potential to reduce trucking costs. While bulk-liquid transporters are typically required to visit a tank-washing station post-delivery, this step can be obviated if the fleet operates exclusively between origin and destination and does not change the commodity being transported. Nevertheless, this restriction means that each return trip to the origin (CO_2 source) occurs with an empty tank, commonly referred to in the industry as "deadhead mileage." It is more common to "back-haul" a commodity (**Box 5-3**), in essence making use of the truck to transport an additional commodity on the return trip. Because this is an inaccessible feature for CO_2 bulk-liquid transportation, CO_2 trucking costs must consider both transportation to the destination and return to the origin.

Hauling of biomass occurs in many different types of vehicles and depends on form (e.g., loose fill vs dried bricks), as well as logistical setups at the origin and destination. The wood and lumber industry have the highest reliance on trucking for ground transportation, with over 90% of all movement occurring via this mode [30]. Self-unloading trucks can "end-tip" or bottom load directly into receiving hoppers, which can allow for quicker unloading times. While these trucks are more capable of back-hauling commodities than CO_2 tankers, for our study we assumed that back-hauling remains non-viable for biomass, since biomass locations are not expected to be co-located with regions that have other commodity needs. Hence, both CO_2 and biomass trucking occurs via the same logistics: a fully loaded cargo transiting from origin to destination, and an empty cargo transiting back to the origin for additional loading.

We modeled trucking as a complementary mode to pipelines for lower volume and shorter distance CO_2 transportation [31]. The crossover point below which trucking becomes more economical than pipeline occurs somewhere between 500,000 and 700,000 tonnes of CO_2 per year because these volumes represent the minimum operable nominal diameter for pipeline at which point diminishing flow rates lead to exponentially increasing unit costs for pipeline. However, a very large fleet is required to reach this capacity given that each trucking payload can move at maximum 20 tonnes. According to the American Trucking Association, 4.06 million Class VIII trucks (GVW of 33,001 lbs or more) were in circulation in 2021, and 3.5 million truck drivers were employed [29, 32]. This includes 1.92 million US motor carriers, though less than 1% of carriers had vehicle fleets greater than 100 trucks. Full utilization of a 100-truck fleet size would correspond to roughly 700,000 tonnes of CO_2 moved per year but may result in unintended consequences

BOX 5-3

Terminology Around Transloading Facilities

Multiple terms are used to designate transloading facilities and are often used interchangeably in practice. RSI Logistics, Inc. defines three terms: **intermodal terminal, transload facility, and terminal** [46].

Intermodal terminals are facilities designed specifically to handle loading and/or unloading of trailers on flat cars/containers on flat cars (TOFC/COFC), where intermodal shipping itself is classified as shipping in which the product remains in the container regardless of the mode of transportation to which it gets transferred.

Transloading facilities Transloading facilities are designated for transferring shipments from truck to rail and vice versa.

Terminal is the broadest term, with multiple definitions. The most relevant definition in this case is a railroad facility used for handling freight and the receiving, classifying, and assembling and dispatching of trains.

associated with tail-pipe emissions and increased (and constant) trucking traffic to and from the origin and destination. We discuss these impacts later in the chapter.

Trucking freight rates depend on many of the same factors as rail, including labor wages and benefits, fuel costs, and equipment leasing, as well as repair and maintenance costs, truck insurance premiums, permits and special licenses, and tolls where applicable. According to the American Transport Research Institute (ATRI), the average marginal cost per mile increased from $1.646 in 2020 to $1.855 in 2021, a 15-year high [33]. Fuel and labor costs remained the largest contributors, at roughly 23% and 34%, respectively.

Despite advocacy for a multimodal transportation network for moving CO_2 to storage, multiple sources have concluded that trucking is only a viable option in the carbon capture and storage process for small quantities and over small distances [34, 35]. Today, some companies use trucks to transport captured CO_2 to nearby storage facilities [35]. Likewise, trucking is expected to handle first-kilometer/last-kilometer logistics of other higher throughput modes, for example, in getting CO_2 from the origin to the nearest transloading facility or port, as well as delivering it to the final destination.

Barge Transportation

In addition to truck and rail, CO_2 could also be transported by barge. CO_2 is currently transported by ships on a small-scale (2000 tonnes or less) for merchant purposes [19, 36]. However, no large-scale barge transportation of CO_2 currently exists in the United States. Here, commodities similar to CO_2 can be used as a proxy to understand the cost, operation, and execution of CO_2 transportation via barge. Specifically, CO_2 can be shipped in the low-pressure, low-temperature state (6.5 to 8.7 bar, -45 °C to -41 °C) [36] used for semi-refrigerated liquified petroleum gas (7 bar, -50 °C, 22,000 m^3) [16] or in the medium-pressure, low-temperature state used today for transporting liquefied natural gas (17.2 bar, -40 °C) [37].

Little to no barge transportation of liquefied natural gas occurs within the United States, which is attributed to Jones Act restrictions; CO_2 transportation on barges is likely to face similar restrictions. To date, no operational liquefied-natural-gas barges adhere to Jones Act's requirements. However, one Jones-Act-abiding liquefied-natural-gas ship is currently being built and is set to be ready for use in 2024. Specifically, the act states that any ship that travels domestically between two US ports must be American-made and-owned and operated by a group made up of at least 75% American citizens or permanent residents [38]. The Jones Act has been recognized as a barrier for transporting commodities within the United States. Some notable exceptions have been made to this Act in response to emergencies in oil and energy supply in the aftermath of natural disasters, such as the Jones Act waiver granted under the Biden administration in October 2022 after Hurricane Fiona battered Puerto Rico [39].

Today, other parts of the world have proven more advanced in CO_2 barge transportation than the United States. For example, several initiatives in northern Europe aim to collect CO_2 and then send it to various storage sites in the North Sea or Iceland [40, 41]. Although there is no indication that Europe is currently transporting CO_2 via barge, many projects for creating this infrastructure have been greenlighted and are well underway, with some projects set to send out their first fleet by the end of 2023 [40]. Results from CO_2 barge-transportation efforts in Europe and other parts of the world could serve as inspiration for the United States.

Multimodal Transportation

As an alternative to pipelines, transportation modes using existing infrastructure, such as rail, trucking, and barges can also be used to transport CO_2 and biomass. Their varied capacity and networks bring flexibility to transporting CO_2 and biomass. Rail, trucking, and barges can be configured as either stand-alone or multimodal options, as they typically transport CO_2 at similar physical conditions (temperature and pressure). This conditioning is commonly referred to as the "cold liquid" state, with the CO_2 being liquified at moderate pressure and low temperatures and transported in insulated containers. By contrast, pipelines transport CO_2 in the "dense liquid" state at much higher pressures, typically between 100 and 150 bar. This discrepancy means that multimodal configurations between pipeline and other modes require reconditioning of the CO_2 and are thus not considered pragmatic options for transporting CO_2. This also means that the "cold dense" modes must recondition (pressurize) CO_2 at the site of subsurface injection.

Interaction of Transportation Modes

Combining several transportation modes can leverage the various capacities and networks of each mode and lower transportation costs while preserving flexibility in routing. This approach requires facilities with adequate infrastructure for transferring biomass and/or CO_2. While there is a growing market for transporting biomass, there is little to no literature about existing transloading facilities dedicated specifically to biomass—only that transporting biomass often requires a multimodal form [42]. There is discussion about which combinations of transportation mode are most efficient depending on the route used for transporting biomass. For example, a combination of tractor-trailer and bulk van is said to be the most cost-efficient mode of transporting woody biomass in the southern United States [43]. Whereas, tractor-trailer/container-trailer combinations are convenient for transitioning from truck transportation to rail or boat due to the fact that the biomass containers used in trucking can be transferred directly to trains or boats [43].

While transloading facilities are increasing in number for transporting warehouse products [44] and hydrocarbons (such as liquified petroleum gas and natural-gas liquids [45]), little to no discussion has occurred regarding building facilities dedicated to transloading CO_2. However, transloading facilities are built where they are needed, so transloading facilities able to handle CO_2 are likely to be built to accommodate the rising CO_2 industry.

When selecting a transloading facility to handle product transportation, many factors should be considered—the most basic is having the right equipment for the product(s) being transloaded. Typical transloading facilities need pumps, mechanical conveyance, pneumatic conveyance, lifting equipment, a steam boiler, grounded tracks, and additional storage [46]. However, additional equipment is needed to manage liquid CO_2. Various forms of conveyance, as well as the pumps, are all dependent on the material to be transferred. Pumps are better for liquids and are a less-involved process than conveying, whereas mechanical conveying is favorable for heavy and wet materials and pneumatic conveying is favorable for fine, dry, and granular materials [47]. Other considerations for equipment and facilities when transloading a material include recognizing the material's hazard class and, if applicable, what facilities are equipped to handle materials of that type. CO_2 is classified as a class 2.2 hazardous material (which categorizes materials of this nature as non-flammable and non-toxic) and is also an asphyxiant that has to be handled in well-ventilated areas [48].

Cost Modeling and Rules for Decision Making

Cost Assumptions and Model Description

Pipelines

The National Energy and Technology Laboratory (NETL), in partnership with the Office of Fossil Energy and Carbon Management (FECM), has released a tool [49] that can predict the cost at which no net debts or profits occur over the entire project lifetime (i.e., the "breakeven" cost) for pipelines of varying length and capacity. These costs are highly dependent on the chosen capacity—which dictates the pipeline diameter—and have slight regional variations (e.g., to account for elevation changes). They account for the costs of materials, labor, obtaining right-of-way and allowances for damages, and other miscellaneous costs (e.g., surveying, engineering, supervision, contingencies, telecommunications equipment, freight, tax allowances for funds used during construction, administration and overhead, and regulatory filing fees).

It is useful to compare transportation costs in the units of cost per tonne-km, or the cost to move one tonne of commodity by one kilometer. The often-cited economies of scale associated with pipeline transportation are observed at large volumes, typically above 1 million tonnes of CO_2 per year. For smaller volumes, this cost increases exponentially (**Figure 5-6**). The crossover point (where trucking becomes more economical than pipelines) occurs between 0.5 and 0.6 million tonnes of CO_2 per year.

Recent analyses suggest the opportunity for ultra-large-capacity trunk pipelines, placed strategically throughout the United States, to connect disparate CO_2 sources with viable sink locations. These trunk pipelines could carry CO_2 at a capacity of 100 million tonnes per year, leading to even lower costs (~$0.007 per tonne-km). However, these trunk lines would cost many billions of dollars in infrastructural investment, and their large scale implies that they will likely carry CO_2 from many different and perhaps unrelated sources.

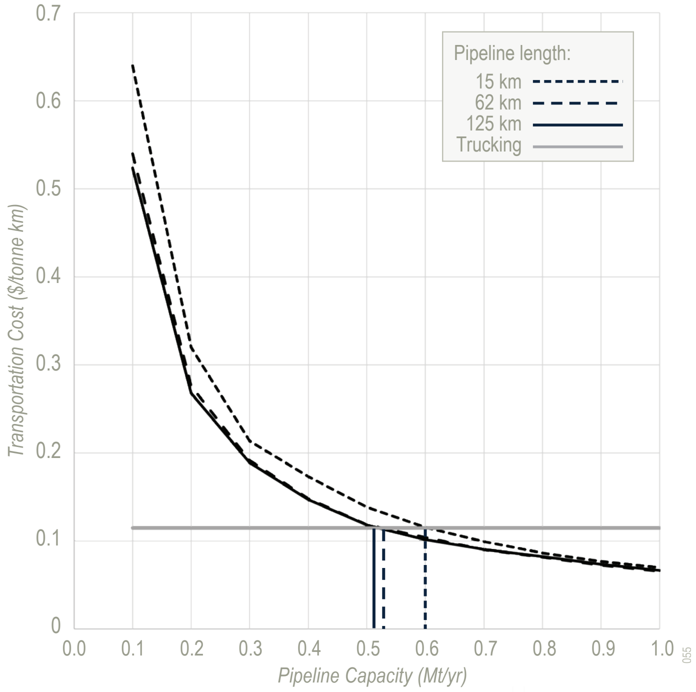

Figure 5-6. *The cost to move 1 tonne of CO_2 by 1 km increases exponentially with smaller-capacity pipelines and enters cost parity with trucking at a capacity of between 0.5 to 0.6 million tonnes of CO_2 per year.*

Further complicating this issue is that many scenarios suggest that these interstate pipelines could span >1600 km, implicating that a source linked to the pipeline in the final 100-km stretch before the destination will use a different fraction of the pipeline length than a source located at the origin, akin to how public shared toll roads often charge based on distance traveled (calculated from point of entry to point of exit) rather than by one flat rate.

While the business case of trunk pipelines has not been fully developed, in our analysis, we considered a “pay-by-segment” approach, whereby sources are charged a flat rate for each 161-km segment used. As an example, take a 1609-km trunk pipeline with the capacity to move 100 million tonnes of CO_2 per year. According to the model above, such a pipeline would command nearly \$2 billion in annual operating revenue and have an internal rate of return of 15%. Trunk-pipeline costs can be estimated using the following equation:

$$\textbf{Trunk pipeline cost} = [d/160] * CB_L$$

where the trunk-pipeline cost is reported in \$/tonne CO_2, *d* represents distance in km, and CB_L reflects the equal distribution of cost burden over the pipeline length, which is approximately \$3.50/tonne CO_2 for a 160-km segment. We rounded the ratio of *d/160* up to the nearest integer to represent discrete pricing segments over the pipeline length (analogous to fixed tolls on a turnpike based on exit segments).

While these economics make trunk pipelines the lowest-cost option for sources already proximal to the trunk pipeline (or sited intentionally nearby), the lack of regional flexibility and reach make trunk pipelines unlikely to be the *only* option for transporting CO_2 in bulk. Much like our interstate highway systems, a secondary complementary network of smaller-capacity transportation corridors will be necessary to meet the logistical demands of net-zero.

Multimodal Transport

Unlike pipelines, the unit costs for rail and trucking are largely agnostic to capacity, and barges are assumed to transport a fixed volume of around 10,000 tonnes per trip, similar to a fully loaded unit-train of CO_2. However, bulk modes like rail and barge incur larger “fixed costs” associated with loading and unloading. These costs are invariant to the distance traveled (unless multiple carriers are required) and instead pay off in the full levelized cost when the distance transported is maximized. Such fixed costs make short-haul transit via rail and barge less economical than trucking. Importantly, the actual rates paid are a complicated function of market dynamics, negotiations, and levers such as fuel-surcharge costs. For the sake of comparison, the rates presented below are simply representative, though they carry enough certainty to make generalizable observations.

In our model, transporting CO_2 via truck costs \$0.11/tonne-km, with an additional flat rate of \$9/tonne for liquefaction costs. These same liquefaction costs apply to rail and barge—as they all transport under similar conditions—which enables intermodal configurability. Trucking hauls are ideally constrained to less than 400 km, so that a driver can complete a round-trip in a single day. Our model assumed no back-hauling of commodity (meaning the levelized cost included the return trip of the empty truck). In our model, transporting biomass via truck costs slightly less at \$0.10/tonne-km. This disparity is attributed to several factors, including different equipment and leasing costs, no need for product compression, and more costly insurance and licenses required for transporting CO_2 as a hazardous material.

Rail costs are more challenging to describe for two reasons: (1) the cost per tonne-km varies with haul length and (2) the costs reported for rail often only consider the rail rates incurred to move a commodity from origin to destination (which correspond with transloading stations) and neglect the first/last-kilometer costs to complete the source-sink haul via trucking. Both concerns become less problematic for hauls of greater than 800 km, where the costs per tonne-km begin to converge and the first/last kilometer trucking charges represent a diminishing portion of the total costs. **Figure 5-7** shows rail costs as a function of rail transportation distance and front-end/back-end trucking distance. In a pure,

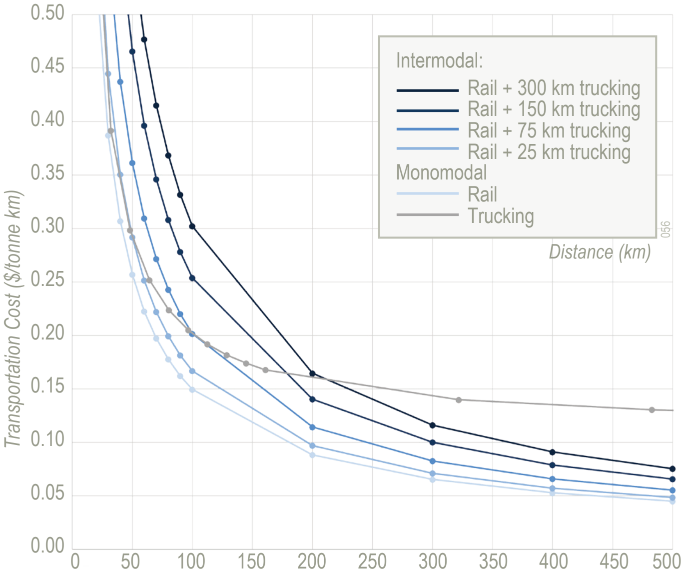

Figure 5-7. *Levelized costs of intermodal rail with varying degrees of first/last kilometer trucking; the cost-parity crossover point increases with increasing trucking requirement.*

monomodal comparison, rail can effectively reach cost parity with trucking at less than 100 km, where the economies of rail "in motion" begin to dominate and the flat loading and unloading costs become increasingly less important. However, most realistic scenarios will require intermodal movement, with trucking serving the first/last kilometer of delivery. Thus, it is important to consider these additional costs when evaluating the true cost of rail in transportation logistics. These effects are captured in the remaining curves (Figure 5-7), where increasing needs for first/last kilometer trucking increase the cost-parity crossover point between monomodal trucking and intermodal rail.

Barge costs exhibit a similar trend when considering short hauls, commanding a similar loading/unloading fee for each tonne of commodity (between \$14 and \$18/tonne) before the ship even leaves port. The levelized cost of commodity drops much faster than in rail, meaning that shorter-haul transits (<320 km) could be economically rational, particularly in cases where other options may be logistically prohibitive (e.g., offshore storage that can only be reached by waterway). The levelized cost also converges to a lower value than that observed for rail, reaching \$0.012 per tonne-km at >1600 km, a figure that is not too different from the aforementioned "best-in-class" trunk-pipeline economics. It is important to consider—as was the case for rail—the first/last kilometer costs associated with getting CO_2 to port, with access to transloading locations representing a more near-term infrastructural constraint than with rail.

Generalized Rules for Decision Making

Given the number of options, variability in levelized costs, and ability (and need) to run multimodal configurations, we developed generalizable guidance for how to approach modal selection. This section discusses this guidance within the context of technoeconomic considerations alone, but any configuration should meet best practices and principles for responsible deployment, particularly when solving for routing (see below for more discussion on socially and environmentally responsible aspects of transportation routing).

Modal selection is relatively straightforward when both source and sink are proximal to large-scale, low-cost transportation modes like trunk pipeline or barge: these will invariably represent the lowest-cost option for most cases. But challenges arise when the source and/or sink are not co-located with these options or when large-scale biomass transportation is required. An additional challenge exists in deciding which *commodity* to transport when there is more than one option available, as is true for most biomass-conversion technologies, which must decide where to site their conversion facility (i.e., near where the biomass is collected or near where the CO_2 is to be stored).

Stolaroff et al. (2021) [50] suggests that moving one commodity—rather than both—is always best. That is, always site with either the biomass collection or the CO_2 storage, never in between. Further, they introduced the CO_2-storage factor, which represents the mass ratio of CO_2 generated per biomass. Thus, to minimize transportation costs, moving the lesser quantity is advisable, as expressed in the following equation:

$$\frac{C_b m_b}{C_{CO_2} m_{CO_2}} = r$$

where C_b is the minimum unit cost of transporting biomass, m_b is the mass of biomass, C_{CO_2} is the minimum unit cost of transporting CO_2, m_{CO_2} is the mass of CO_2, and r is the ratio between the two. When $r > 1$ the cost of moving biomass is higher than the cost of moving CO_2, making CO_2 the preferred commodity to transport. The same logic can be extended in the flip case toward biomass. This equation can be rearranged into the following:

$$\frac{C_b}{C_{CO_2}} = r\frac{m_{CO_2}}{m_b}$$

where the right-hand side represents the aforementioned *storage factor* and the ratio on the left-hand side is defined as the *cost factor*. The storage factors are unique to each conversion technology and are defined in **Chapter 6 – BiCRS**. The cost factor is built as the ratio of the least expensive unit cost for each commodity (e.g., the cheaper of trucking or rail for biomass and CO_2, respectively), represented visually in **Figure 5-8**. The blue line on the left panel represents the relatively constant cost-factor line for rail/trucking and sits at a value of ~0.90 (derived from the slightly lower unit costs of moving biomass over CO_2). Exceptions occur at relatively short distances, as CO_2 liquefaction costs inflate the economics for CO_2 over short distances, making movement of biomass the lowest-cost option in most cases.

Because of competitive economic factors, the majority of configuration space— both in technology choice and in haul distance—is covered by trunk-pipeline movement. This suggests that when trunk pipeline is an available option, it is almost always the lowest-cost option, regardless of conversion technology. The exception occurs for very long-distance transportation of biomass for high storage-factor technologies.

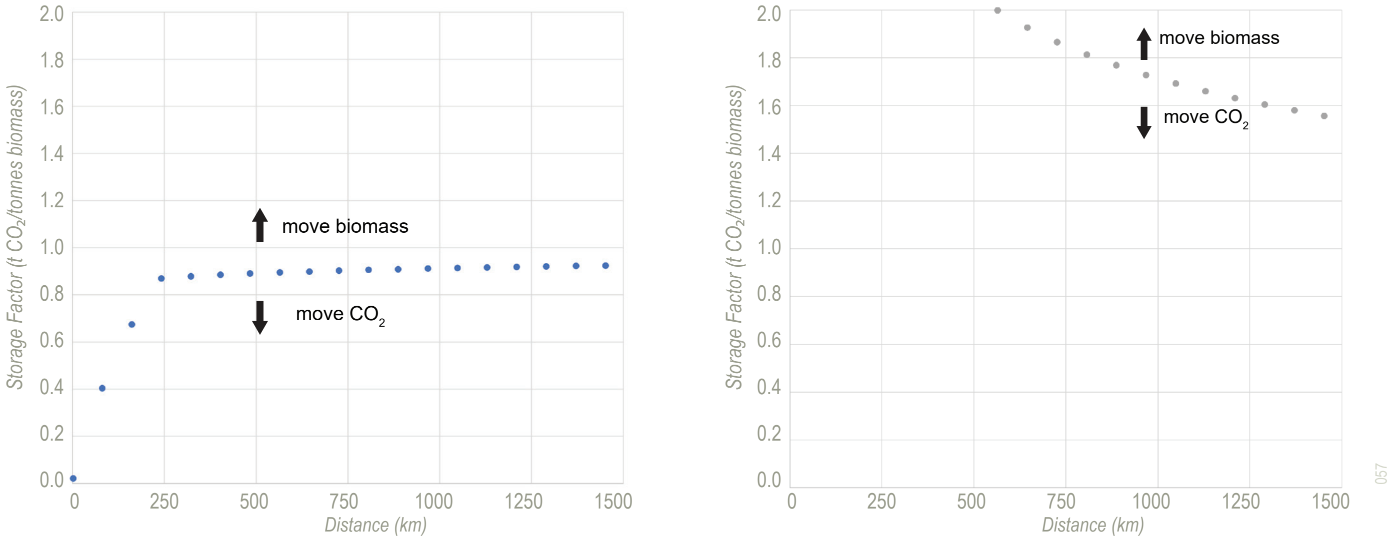

Figure 5-8. *General rules for transportation configurations for biomass-conversion technologies with different storage factors (vertical axis). To interpret the dotted ‘CO_2 versus biomass’ cutoff line: when the conversion storage factor is less than 0.90, the CO_2 should be moved. Otherwise, the biomass should be moved. The grey cost factor line on the right panel introduces the economics of trunk pipeline transportation. The left panel suggests that when the technology storage factor is less than 0.92, one should move CO_2; otherwise move biomass. When trunk lines are available (right panel), moving CO_2 is almost always cheaper, with the exception of transporting biomass long distances in the case of high storage-factor technologies.*

Here, the unit economics of long-distance rail begin to play “catch-up” with trunk lines, and moving biomass becomes the preferred option. Note that this only applies for technologies that generate significant CO_2 (storage factor of 1.5 or greater).

Once the commodity to move is decided, and if trunk pipelines are not available, it is necessary to decide whether to truck the commodity or configure intermodal transportation. For long distances (greater than 350–400 km), moving via intermodal truck/rail or truck/barge connections will generally be most economical. For shorter range distances, and to configure in the first/last-kilometer trucking costs, the following relationships may be applied (represented schematically in **Figure 5-9**).

The breakeven point for moving CO_2 occurs when the difference between distance z and distance y (where y is the sum of segments y1 and y2) is equal to $150.88x^{0.178}$, where x is the rail distance in kilometers.

$$\mathbf{z-y = 150.88x^{0.178}}$$

When the right-hand-side of the equation is greater, trucking directly is more economical. A similar relationship exists for transporting biomass:

$$\mathbf{z–y = 47.27x^{0.293}}$$

Though barge transport is not included in the generalized rules above (due to current regulatory restrictions and less prevalent logistical alignment), similar relationships can be

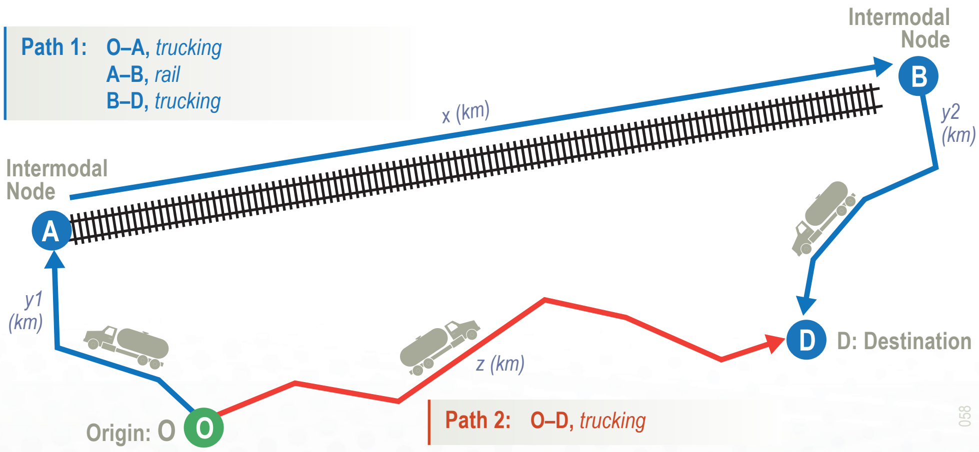

Figure 5-9. *When the difference between the direct trucking distance (z) and the total distance of intermodal trucking (y1+ y2 = y) is less than $150.88x^{0.178}$ for CO_2 or $47.27x^{0.293}$ for biomass, it is more economical to forego the rail leg and truck directly (Path 2).*

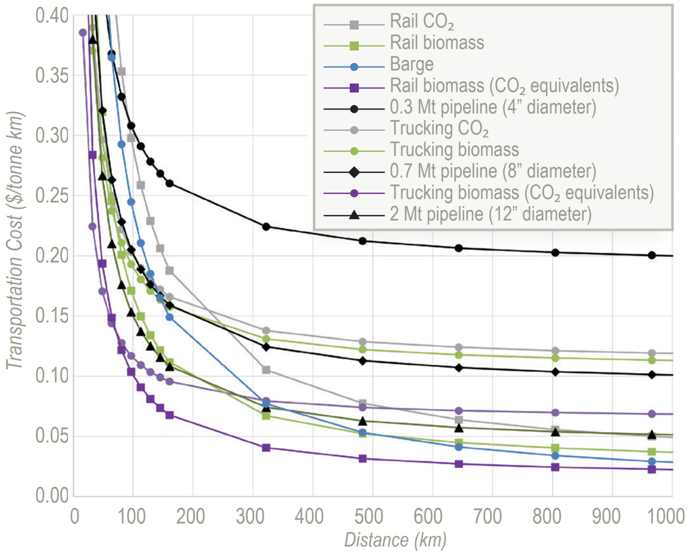

Figure 5-10. *A summary comparison of various transportation modes as a function of haul distance. General crossovers can be derived, including between low-volume spur lines and trucking or rail. The advantage of barge at relatively short distances is also apparent. Mt = million tonne; CO_2e = CO_2 equivalents.*

derived. Importantly, barge costs are calculated for open water (coastal) transportation and do not consider additional costs for traversing inland waterways. Similarly, while we excluded spur lines from our modeling, they can bring an additional level of nuance to transportation planning if permitting and public acceptance present great barriers to deployment. A general comparison of these transportation modes is provided in Figures 5-2 and **5-10**; these figures allow the reader to evaluate the economic viability and cross-over points as a function of distance. Importantly, we added two additional cases to this comparison where trucking and rail transportation of biomass are converted into their CO_2 equivalents (CO_2e). This conversion assumes that the biomass is 45% carbon by mass and uses the simple 44/12 factor (molecular mass of CO_2/atomic mass of carbon) to determine the effective CO_2 transported.

Transporting CO_2 and Biomass in the United States: Assumptions and Rationale

In our analysis of biomass and CO_2 transport, we considered two snapshots in time: 2025 and 2050. Our assessment did not include any CO_2 pipelines in 2025 and used only the existing infrastructure for rail and trucking to transport biomass and CO_2 to and from BiCRS refineries; we assumed DACS plants would be located only above storage and thus would not require transportation. Our model considered any location where storage costs are less than $53/tonne of CO_2 (see **Chapter 4 – Geologic Storage**) to be a viable option.

Figure 5-11 shows the modes and combinations of modes we assumed for BiCRS and DACS transport configurations in 2050. Our study followed a conservative approach and assumed that only trunk pipelines would be built and operating by that time. Some factors may preclude building an extensive pipeline network: the large capital investments required, potential public pushback due to prior negative experiences with hydrocarbon pipelines, and challenges reaching agreement on rights of way. Future pipelines we considered follow the routes the Princeton Net-Zero America report determined for the year 2030 [1] (**Figure 5-12**; [1-5]). We assumed that the BiCRS facilities using pipelines would be restricted to an area within 80 km of these proposed pipelines and that the DACS facilities would be restricted to the counties with proposed pipelines. Due to potential negative public perception of pipelines (see Box 5-2), we did not include any spur lines. The locations of these BiCRS and DACS facilities would likely be adjusted according to the actual routing of future pipelines.

In the BiCRS configuration, CO_2 and biomass can also be transported by truck, rail, or a combination of both. The maximum transport distance for biomass is 1600 km, and

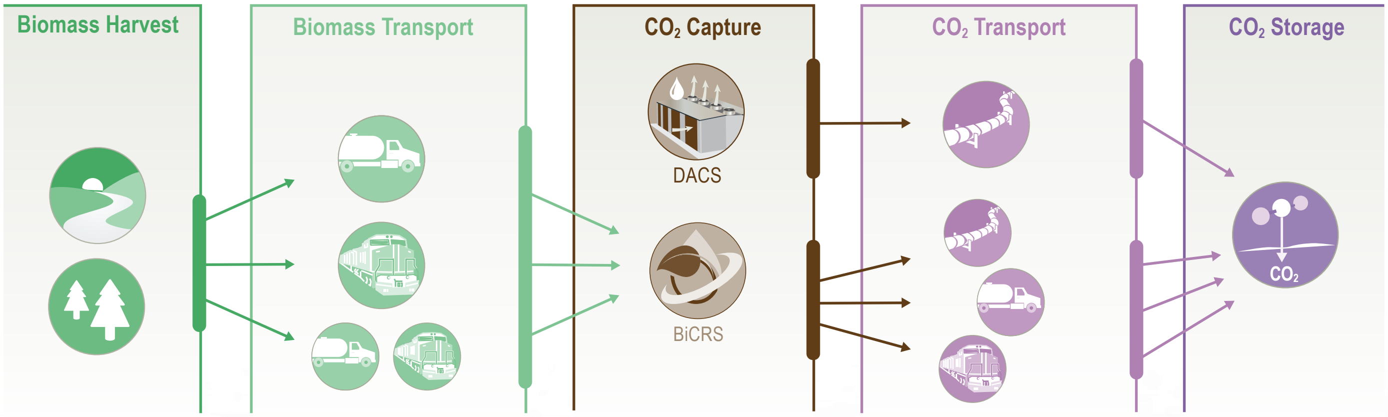

Figure 5-11. *Modes and combinations of modes used to transport CO_2 and biomass in the proposed DACS and BiCRS configurations. Other modes or combinations of modes could also be considered for transporting CO_2.*

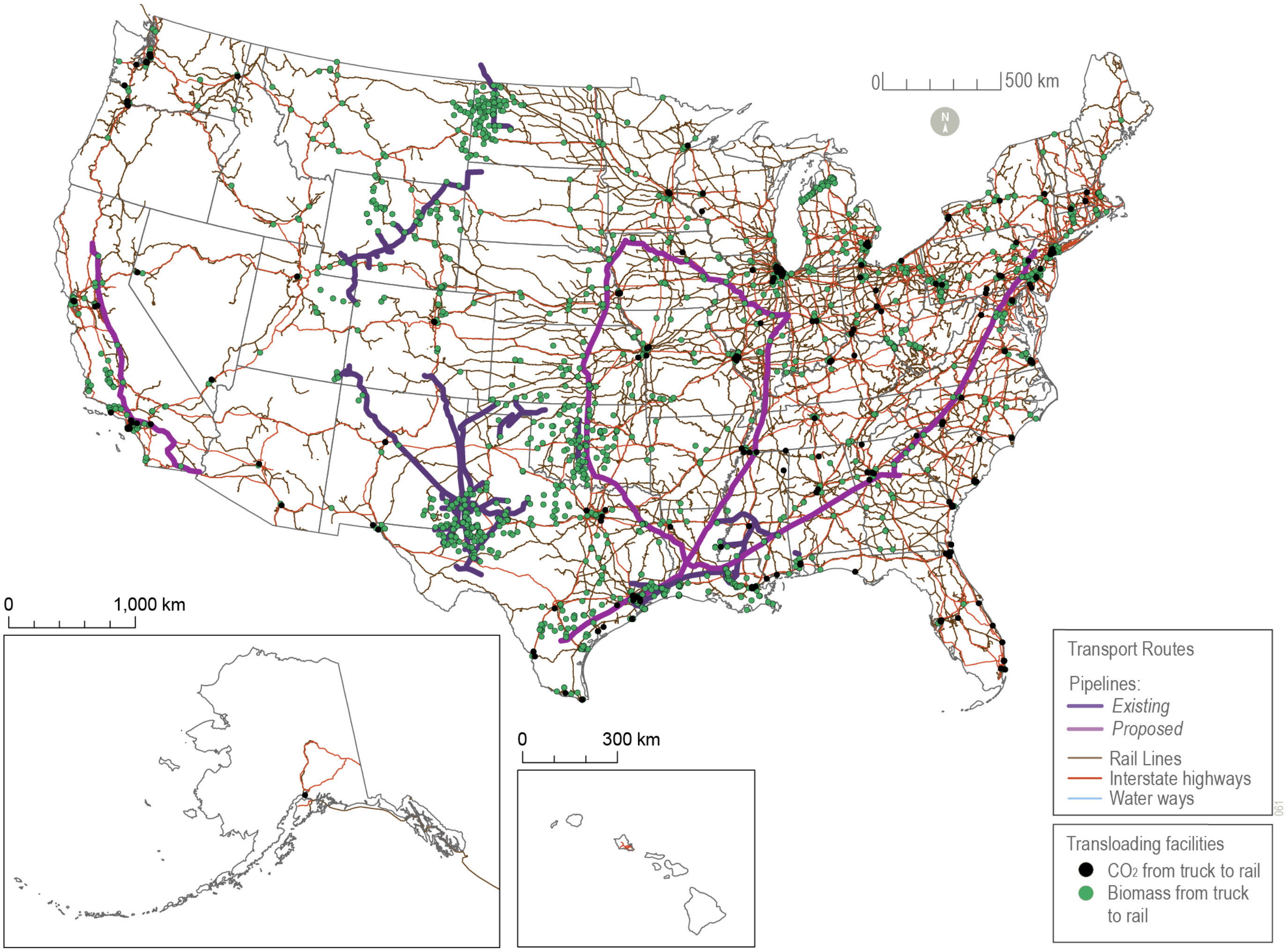

Figure 5-12. *Transportation networks and transloading facilities in the United States ([1-5]). Bulk transfer locations from the Freight and Fuel Transportation Optimization Tool are used as a proxy for biomass transloading, and trailer-on-flatcar transfer locations are used as a proxy for CO_2 transloading. To ensure readability, only interstate highways are shown.*

the maximum transport distance for biomass and CO_2 by truck is 320 km, as per our results detailed in the section "Generalized Rules for Decision Making," showing that, above this threshold, truck transportation becomes cost prohibitive compared to other modes (Figure 5-10). Transferring biomass or CO_2 from truck to rail can happen only at specific terminals that have the appropriate infrastructure. For biomass, our model used the Freight and Fuel Transportation Optimization Tool transfer stations; for CO_2, it assumed transfers would occur at trailer-on-flatcar transfer stations (Figure 5-12). Even though our model used existing facilities, we recognize that new terminals will be built where they are needed to accommodate transfers between modes ("Interaction of Modes" in section "Modes of Transport"). The BILT model, which we used to optimize the locations of BiCRS refineries (**Chapter 6 – BiCRS**), used our cost model for transporting biomass and CO_2 ("Generalized Rules for Decision Making" section, Figure 5-10). The BILT model used the same emissions factors for 2050 as for 2025 for the various transportation modes (Table 5-1) and did not account for CO_2 leakage during transportation (see "Comparing Modes from a Social and Environmental Perspective" below).

For DACS, only our 2050 scenario involves transporting CO_2. In that scenario, DACS facilities would be located close enough to existing and future pipelines to require only pipeline transportation. Where DACS was not co-located with storage, we estimated pipeline transportation costs to the nearest potential CO_2 storage site by first calculating distances using a network analysis performed with the ArcGIS software and then using the pipeline cost model described above to calculate the costs. These results are detailed in **Chapter 7 – DACS.**

Comparing Modes from a Social and Environmental Perspective

Each method of transporting CO_2 has advantages and disadvantages concerning CO_2 volume, cost, and maximum transport distance. Considerations also extend to the socioeconomic and environmental impacts associated with these transportation methods. Consequently, there is no "one size fits all" approach for a CO_2 transportation method that is generally perceived as safe, beneficial, and equitably distributed. Nonetheless, the available literature and data offer valuable guiding principles for designing a CO_2 transportation strategy (**Tables 5-2, 5-3,** and **5-4** in the following subsections).

Pipeline

Risks. Pipelines are the most efficient option for transporting large quantities of CO_2; once constructed, they are the most energy- and labor-efficient method of transporting CO_2. Despite the relatively low frequency of incidents, averaging 4.3 per year over the past two decades, pipelines remain responsible for the most substantial CO_2 spills, releasing an average of 976 m^3 of CO_2 annually. The leading causes of the top 15% of pipeline incidents are failures related to valves and pressure-relief equipment. The largest incident occurred in February 2020 on the Denbury pipeline in Mississippi, resulting in the release of 1515 m^3 of CO_2. This incident led to the evacuation of 200 residents, and 45 people were hospitalized due to CO_2 poisoning [51]. These events underscore the need to carefully route pipelines to minimize risks to nearby populations. Historically, smaller diameter pipelines, carrying any commodity, have tended to exhibit a higher rate of incidents. However, larger diameter pipelines can lead to much larger spills.

Environmental Impacts. Historically in the United States, placement of fossil fuel transmission pipelines has disproportionately impacted vulnerable communities, perpetuating inequitable siting burdens and environmental injustices related to construction and leakage events [52]. Therefore, it is of the utmost importance that the United States CO_2 transportation industry not solely rely upon historical right-of-way agreements, which could further entrench past injustices. Instead, given that the nationwide CO_2 transportation industry is still in early development, there is potential to start with a "communities first" approach. In such an approach, variables identified as instrumental for gaining the social license for pipelines to operate would guide the nuances of siting pipeline routes. These variables include trust in individual project developers [17], mutually acceptable buffer zones between pipelines and residences to help build trust in the industry, and involvement of environmental organizations in assessing safety and environmental compatibility [53].

Socioeconomic Impacts. The post-construction jobs that exist for pipeline are likely to be long-term positions because they are likely deemed necessary to adhere to PHMSA regulations. It is estimated that ~0.9 long-term, post-construction jobs are created for every $1 million invested in a pipeline transportation project [54], which presents opportunities to re-employ or maintain employment for skilled pipeline-transportation employees in the fossil-fuel sector. The pipeline-transportation sector was, prior to 2020, experiencing a national growth of ~2% per year; however, post-2020, the pipeline-transportation industry has experienced a decline of similar magnitude (~1.8%) nationwide (**Figure 5-13**; [55]). While these increases and decreases have been experienced differently in counties across the United States (**Figure 5-14**; [55]), this underemployed skilled workforce might welcome the economic revitalization of the industry, if the relative safety of CO_2 transportation (compared to oil and gas) were communicated clearly and in collaboration with trusted sources. Furthermore, displaced fossil-fuel and fossil-fuel-powered power-plant employees in counties whose identities and economic prosperity are tightly tied to the fossil-fuel industry, may not find renewable-energy generation alone to be a fulfilling commercial opportunity for their county [56]. In these counties, transporting CO_2 may be viewed as a more acceptable, complementary industry, given its practical and aesthetic similarities to traditional fossil-fuel transportation [56]. These benefits, however, will not be realized without purposeful prioritization of job creation and equitable, local workforce development.

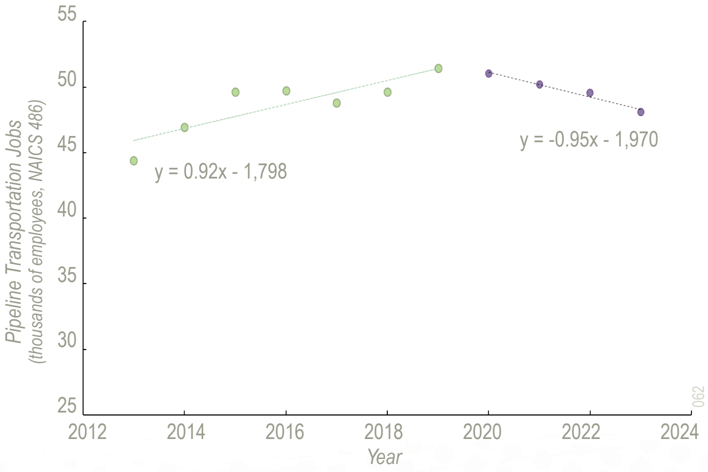

Figure 5-13. *Job-change trends in the pipeline industry from 2012 to 2022 [55].*

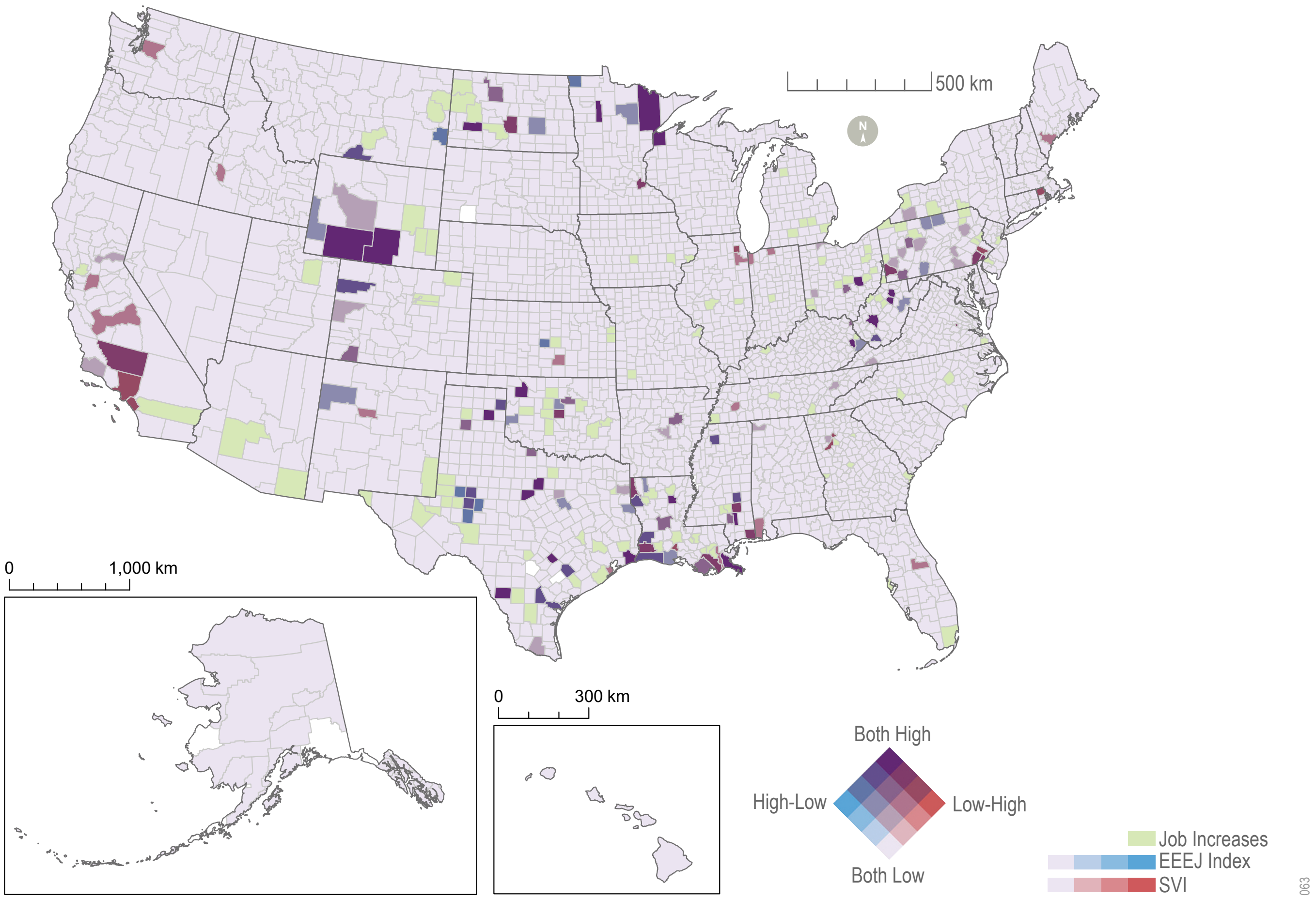

Figure 5-14. *Geographic distribution of employment losses and gains from the North American Industry Classification System (NAICS) industry code #486 (Pipeline Transportation subsector), 2015–2021. Data are from the United States Bureau of Labor and Statistics [55].*

Table 5-2. *Benefits and trade-offs of transporting CO_2 by pipelines.*

PIPELINE TRANSPORT	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Direct job creation and/or retention Focus on creating new, purpose-built CO_2 pipelines instead of repurposing existing pipelines for CO_2. Increase on-the-ground pipeline inspectors to ensure pipeline safety over the life of operations [57].	Hazards from pipeline leaks and failures Focus on creating new, purpose-built CO_2 pipelines instead of repurposing existing pipelines for CO_2 [58]. Increase on-the-ground pipeline inspectors to ensure pipeline safety over the life of operations.
Indirect job creation and/or retention Mirror the Build America, Buy America Act for non-federal projects to stimulate greater job growth in induced jobs and domestic manufacturing [20].	Construction impacts Make plans public and setup channels for the community to voice concerns well ahead of time to allow for project adjustments and prevent public backlash [59, 60].
Tax revenue Push for state and local policies, similar to those developed for renewable energy, that stipulate revenue sharing rates and mechanisms [61].	Loss of land value Historic access to land ownership is not equally distributed, and regional maps of land ownership demographics within regions of public support for CO_2 pipelines should be consulted to assess equitable distribution of pipeline-easement revenue [62, 63].
Infrastructure near pipelines Include community in discussions regarding infrastructure build-out and identify points for improvement that have the greatest shared benefit. Inclusion of a trusted social or environmental organization through the pipeline planning process has been shown to increase buy-in from some communities [53].	Exacerbation of inequality Enact changes to the pipeline regulatory system that look to undo existing patterns that have led to a disproportionate burden on vulnerable communities, and help balance power asymmetries between corporations, regulators, and vulnerable communities [52].
	Reduced employment relative to trucking and rail Focus on strengthening and expanding labor unions in the rail sector to protect wages and expand workforce [54, 64]. Consider regulations to reverse job losses due to Precision-Scheduled Railroading [65].
	Siting and routing Consider the challenge of eminent domain for communities and the state regulatory hurdles with respect to siting.

Table 5-3. *Benefits and trade-offs of transporting CO_2 and biomass by rail.*

RAIL TRANSPORT	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Direct job creation and/or retention Focus on repurposing fossil fuel-related freight rail infrastructure for transporting liquefied CO_2 [68].	Citizen concern from venting CO_2 for pressure regulation Replace traditional foam-insulated liquefied CO_2 transportation tankers with vacuum-jacketed, low-thermal-conductivity containers or update regulations to allow for liquefied CO_2 transportation in DOT 133 tank cars [69, 70].
Indirect job creation and/or retention Mirror the Build America, Buy America Act for non-federal projects to stimulate greater job growth in induced jobs and domestic manufacturing of rail-related items [20].	Higher air pollution than pipelines Utilize zero-emissions rail options along with open-source decarbonization-planning tools [71]. Focus efforts on highly-impacted areas [67].
	Reduced employment relative to trucking Focus on strengthening and expanding labor unions in the rail sector to protect wages and expand workforce [54, 64]. Consider regulations to reverse job losses due to precision-scheduled railroading [65].
	Increased incidents relative to pipelines Consider regulations to return rail operators to the worker, equipment, and logistical safety margins in place prior to adoption of precision-scheduled railroading [65].
	Increased energy consumption relative to pipelines Utilize electric rail options to increase transportation efficiency [72, 73]. Research options for supercritical CO_2 transportation options to reduce the energy of liquefaction and reconditioning [74].

Table 5-4. *Benefits and trade-offs of transporting CO_2 and biomass by truck.*

TRUCK TRANSPORT	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Direct job creation and/or retention Focus on requalifying liquid-fuel truck drivers—who are exposed to job loss from battery electric vehicle (EV) adoption—to transport liquefied CO_2 [76, 77].	Citizen concern from venting CO_2 for pressure regulation Replace traditional foam-insulated liquefied CO_2 transportation tankers with vacuum-jacketed, low-thermal-conductivity containers [69].
Indirect job creation and/or retention Mirror the Build America, Buy America Act for non-federal projects to stimulate greater job growth in induced jobs and domestic manufacturing in trucks and trucking-related items [20].	Higher air pollution than pipelines and rail Utilize zero-emissions trucking options and focus efforts on highly impacted areas [67].
State and federal tax revenue Increase tax rate to cover the chronic shortfall between transportation-related tax revenue and expenditures [78].	Increased incidents relative to pipelines and rail Set stricter fines, require speed limiters, further limit driving time, etc. for all motorists to reduce driver error—the main culprit of accidents involving freight trucks [79].
	Increased wear and congestion on public roads and bridges Optimize for routes through regions not identified as being unduly impacted by traffic [80]. Increase tax rate to cover the chronic shortfall between transportation-related tax revenue and expenditures [78, 81].
	Increased energy consumption relative to pipelines Utilize battery EV trucking options to increase transportation efficiency [82]. Research options for supercritical CO_2 transportation options to reduce the energy of liquefaction and reconditioning [74].

Rail

Risks. For modest quantities of CO_2 (e.g., a commercial CO_2 removal facility that is just starting up), rail may be adopted as a quick-to-implement and economically reasonable option. In comparison to pipelines and trucking, the rail industry has exhibited the lowest frequency of leakage incidents over the past two decades, with an average of 3.7 incidents per year. These rail incidents released a yearly average of 47.8 m^3 of CO_2, significantly less than what is observed in pipeline systems. Among the top 15% of incidents, over-pressurization and defective components (notably the failure of pressure-relief valves and frangible discs) emerge as the leading causes.

Environmental Impacts. Similar to the trucking industry, the rail industry is not yet decarbonized, leading to diesel-derived PM2.5 emissions, which negatively impact the air quality of communities near major rail networks and railyards [66]. High levels of PM2.5 lead to negative health impacts and premature deaths that can partly be prevented with stricter emissions control (**Figure 5-15**; [67]). Therefore, especially in counties with high rail-related PM2.5 emissions, opting for zero-emissions rail options will be important for reducing the negative impacts of transporting CO_2. The transportation modeling described in this chapter is conservative, using mostly diesel fuels (Table 5-1). However, fuels with lower emissions per tonne-km or electric options might be available in the future and would decrease the impact of CO_2 and biomass transportation in the life-cycle analyses (LCAs) of CO_2-removal systems, such as BiCRS and DACS.

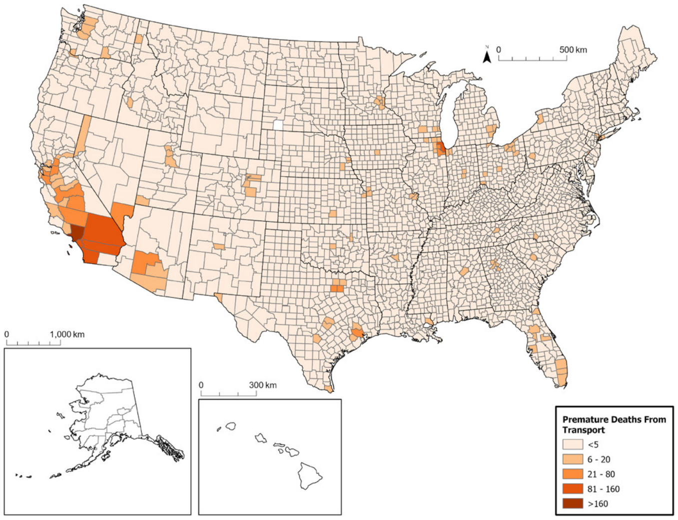

Figure 5-15. *Prevented premature deaths attributable to reducing diesel-derived PM2.5 in the trucking and rail sectors with the adoption of strict emissions controls, based on US Environmental Protection Agency (EPA) 2010 standards for heavy-duty vehicles. The CTR Case assumes stringent emission control policies. Reproduced from Pan et al. 2019 [67].*

Socioeconomic Impacts. Rail is less labor-intensive (i.e., long-term jobs per tonne of CO_2 transported) than trucking, so while there will be some jobs created, it is unlikely that the impact on local job inventory will be greater than that of trucking. However, the freight-rail industry does not appear to be automating as imminently as trucking, so it is possible rail-related jobs will remain longer-term. The US rail transportation workforce has decreased by approximately 3.4% year-over-year since 2013 (**Figure 5-16**; [55]). Therefore, regions that have experienced rail-job loss could be prioritized when building out the CO_2 rail-transportation network. The Bureau of Labor Statistics has reported very sparse data on job losses and gains in the rail industry at the county level, and more data would be needed to identify impacted counties.

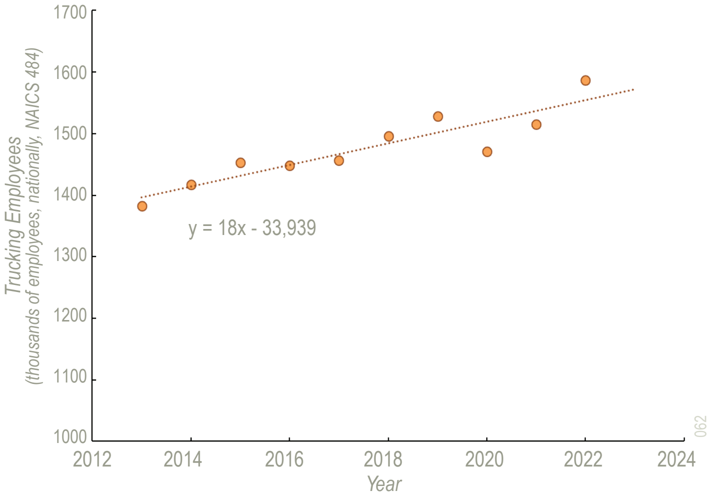

Figure 5-16. *Job-loss trends in the rail industry from 2012 to 2022 [55].*

Trucking

Risks. For very small quantities of CO_2 (e.g., a small, pilot-scale CO_2-removal facility), trucking is often the fastest method to implement at an economical scale. In comparison to other transportation modes, trucking of CO_2 displays the highest number of incidents, averaging 14.5 per year over the past two decades. However, the magnitude of these incidents is considerably lower, resulting in an average release of 13 m^3 of CO_2 per year. Among the top 15% of incidents, human error and defective components (e.g., incomplete valve closure and faulty pressure relief valves) emerge as the primary causes of failure.

Environmental Impacts. In addition to economic impacts, attention must be paid to the adverse health impacts associated with transportation-related air pollution. Because the trucking fleet contains almost no zero-emissions vehicles on the road, the internal combustion engines of the trucking industry negatively impact air quality and contribute to high levels of diesel-derived PM2.5 emissions along major highways [75]. This diesel-derived PM2.5 has been linked to respiratory and cardiovascular diseases that yield inequitably high premature-death rates, disproportionately affecting communities located near transportation corridors (Figure 5-15; [67]). Therefore, mitigating air pollution and prioritizing public health in counties with high diesel-derived PM2.5, through the exclusive implementation of zero-emissions vehicles, should be integral components of any strategy that involves transporting CO_2 via trucking (Figure 066; [67]). Similar to the rail industry, the use of lower-emission fuels than diesel (Table 5-1) in trucks would decrease the impact of CO_2 and biomass transportation in the LCAs of CO_2-removal systems, such as BiCRS and DACS.

Socioeconomic Impacts. The socioeconomic benefit of trucking is that it is relatively labor-intensive (i.e., long-term jobs per tonne of CO_2 transported), so there are opportunities to create jobs for the trucking workforce. The US trucking workforce has grown by ~1.3% year-over-year since 2013 (**Figure 5-17**; [55]); however, not all counties have experienced this sectoral growth (**Figure 5-18**; [55]). Due to the relative expense that trucking (as opposed to rail and pipelines) poses for CO_2 transportation, it may become cost prohibitive as CO_2-removal operations scale. This may indicate that the trucking jobs created might not persist in the same magnitude once there is ample volume of CO_2 to dictate alternative modes of transportation. Furthermore, the trucking workforce as a whole is facing an uncertain future amidst automated driving options that may decrease the potential long-term viability of these jobs [67]. The noise and pollution associated with large numbers of trucks driving through neighborhoods can face public pushback, while others are seeking to retain traffic to bring economic benefits from truck drivers stopping in their communities.

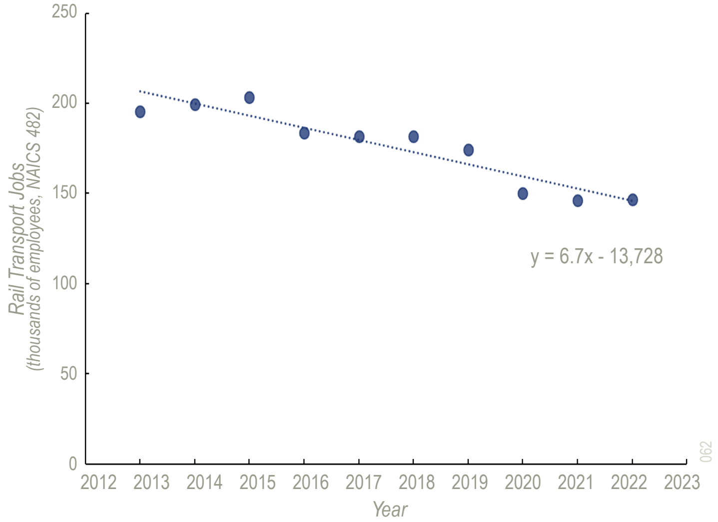

Figure 5-17. *Change in employment in the trucking industry nationally from 2012 to 2022 according to NAICS industry code #484 [55].*

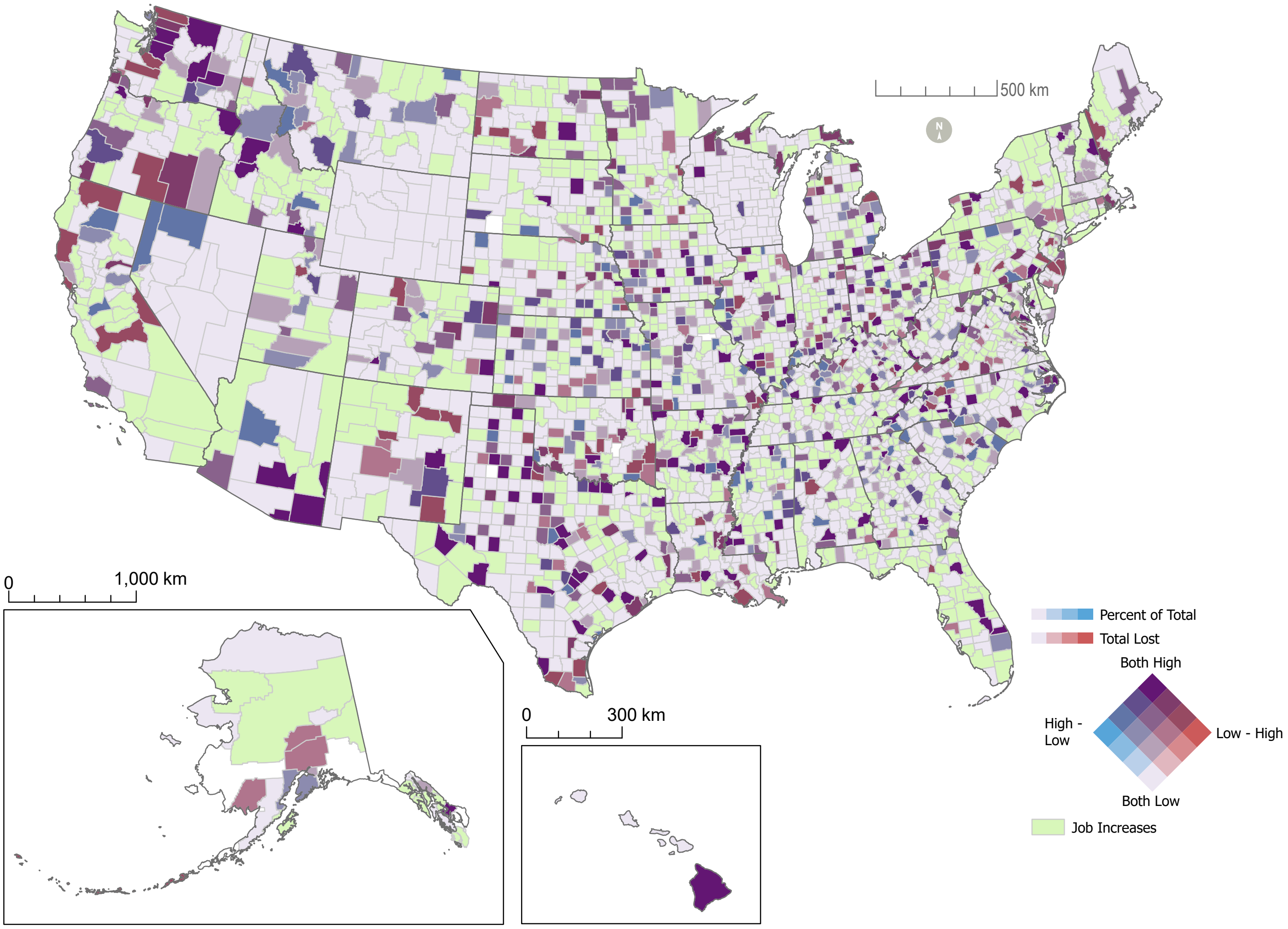

Figure 5-18. *Geographic distribution of employment losses and gains from NAICS industry code #484 (Truck Transportation subsector), 2015-2021. Data from United States Bureau of Labor and Statistics [55].*

Conclusions

This chapter compares four transportation modes for biomass and CO_2: pipelines, rail, trucking, and barges. Trunk pipelines emerge as the most cost-effective option for transporting CO_2 long distances; however, their implementation will demand significant multi-billion-dollar investments, overcoming regulatory hurdles, and essential community engagement. At sea, barges demonstrate low operating costs, but their cost-effectiveness diminishes for shorter distances due to substantial loading expenses. On land, rail serves as a viable and readily available alternative for CO_2 transportation, benefiting from an extensive network that is already in place across the United States.

Regardless of the chosen mode, pipelines, barges, and to a lesser extent, rail transportation might necessitate a secondary or tertiary transportation network to effectively gather CO_2 and biomass from diverse sources. Multimodal configurations demand transloading facilities with appropriate infrastructure to ensure proper handling of CO_2 and biomass shipments. These facilities must also include provisions for temporary storage and reconditioning of CO_2 to accommodate varying modal shipping conditions.

Looking ahead, as the carbon-management sector continues to expand, it will become imperative to develop a robust transportation model that effectively integrates all these considerations. Such a multimodal model should efficiently match sources and sinks of CO_2, provide reliable cost estimates, and minimize negative social and environmental consequences.

The energy equity and environmental justice (EEEJ) implications of transporting CO_2 via truck, rail, and pipeline necessitate careful consideration and strategic actions. To avoid perpetuating historical inequities, it is crucial to ensure equitable distribution of transportation routes that do not further burden disadvantaged communities [55]. Decarbonizing rail and trucking sectors, prioritizing public health, and fostering job creation with local hiring commitments are essential for long-term sustainable CO_2 transportation. By addressing these concerns and priorities, the transportation of CO_2 has the potential to contribute to a more equitable and environmentally sustainable future.

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