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Decarbonizing Freight Transport: Mobile Carbon Capture from Heavy Duty Vehicles

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Abstract— **The future of passenger transportation lies in electrification. Freight transportation however has size and weight limitations that make electrification challenging, such that the continued emission of carbon dioxide from the combustion exhaust of heavy-duty vehicles is likely. A carbon capture strategy to intercept CO_2 from mobile emission sources, analogous to stationary capture systems for power plants, is therefore attractive to reduce CO_2 emissions from freight shipping. The economic and environmental implications of a conceptual technology, utilizing a porous adsorbent bed to selectively remove CO_2 from tailpipe exhaust, are examined herein. In the economic evaluation, the hypothetical abatement cost for mobile carbon capture is found to be competitive with stationary capture and with vehicle electrification at about $100 per ton of avoided CO_2 emissions. Based on the market potential of land freight shipping, 0.12 to 0.15 °C of avoided warming through the end of the century is achievable by the implementation of mobile carbon capture for long-haul freight vehicles. Collectively, carbon capture from heavy-duty vehicles could provide a practical, cost-competitive, and sustainable contribution to mitigating global greenhouse gas emissions.**

Keywords—carbon dioxide, separation, economics

I. INTRODUCTION

Decarbonization of the global economy is required to avoid the worst consequences of anthropogenic climate change. Decarbonization strategies to reduce CO_2 emissions can be broadly categorized into three approaches: a switch to carbon-free fuels; the addition of a post-combustion carbon capture and storage (CCS) process that removes carbon dioxide from an exhaust stream before it is emitted to the atmosphere; or the removal of CO_2 directly from the atmosphere, also known as direct air CCS or DACCS. Renewable energy resources such as solar and wind have been harvested at increasing scale for electricity production, and these power sources may provide a path forward for reducing emissions from light-duty vehicles by fleet electrification. In other transportation sectors, including those involving aircraft, marine vessels, or heavy-duty land vehicles, avoidance of carbon emissions through electrification is more challenging on account of the larger vehicle mass [1].

Here, we focus on decarbonization of freight shipping from heavy-duty vehicles (HDV). Heavy-duty vehicles are used primarily for long-haul freight shipping and have a disproportionately high environmental impact compared to their share of use. For example, only 10% of the existing vehicle fleet is HDV while their respective share of CO_2 emissions equals nearly 50%. Whereas more than twenty nations have implemented light-duty vehicle fuel economy standards, such as the Corporate Average Fuel Economy (CAFE) standards in the United States, only four nations (U.S., Canada, China, and Japan) have HDV fuel economy standards [2]. Implementation of existing HDV standards will reduce CO_2 emissions by only 10% through 2040, compared to a projected rise of 153% in CO_2 from HDVs in the same period [3].

Herein we describe a system to capture carbon dioxide emissions from HDVs used in land-based freight transport. We assess the environmental and economic impacts of this carbon capture technology by (1) establishing the market potential of HDV freight through the end of the century; (2) relating possible emissions reductions to the avoided temperature increase; (3) building a hypothetical program to develop a baseline cost estimate; and (4) comparing the carbon abatement cost for HDV carbon capture (HDVCC) against other decarbonization strategies.

A. *Growth of Transport Emissions*

At present, the transportation sector accounts for about 20% of global anthropogenic CO_2 emissions. This is expected to increase to over 40% by the end of the century, as renewable energy installations and efficiency gains in the electric utility sector reduce CO_2 emissions arising from power generation. Within transportation, the predominant share of emissions are from road transport, which includes passenger vehicles, buses, and trucks. On-road emissions are split about half HDV and half passenger cars and trucks.

The share of CO_2 emissions from the transportation sector is projected to increase from 16% in 2015 to 39% by 2100, while the fraction of transportation emissions from road-based sources is projected to remain relatively constant (74% in 2015; 68% in 2100). Sector-based carbon emissions are taken from the Shared Socioeconomic Pathway SSP2 [4], with 2015 and 2100 emissions of 10.7 and 2.6 GtC/yr, respectively. Transportation mode changes are based off business-as-usual scenario predictions [5]. To reach 2050 emission reduction goals set forth in the Paris Agreement [6], rapid decarbonization of road transportation must begin by 2025 at the latest [7].

Drastic increases in vehicle efficiency and simultaneous reductions in fuel carbon content will not be enough to achieve a reduction of 50-80% in greenhouse gas emissions; long-term and higher-cost interventions are necessary to achieve global climate goals [8]. To this end, electric vehicles would need to replace internal combustion engines between 2035 and 2050 [2] to remain under 2 ºC peak warming. Vehicle electrification, combined with widespread renewable energy, will vastly reduce emissions from passenger cars. Unfortunately, the large size and weight of HDV makes them especially challenging to electrify.

Economic growth is dependent on the movement of freight; as gross domestic product increases, so does truck and rail ton-miles, along with freight tonnage and diesel fuel consumption [9]. All freight measurements, save rail, are realized in HDV emissions. The growth of the global economy ensures that HDV emissions will continue to increase. This problem is exacerbated for developing nations: rapid economic growth spurs rapid increases in freight movement; in an unregulated HDV market, the corresponding emissions from heavy-duty trucks and buses will rise unconstrained.

Projections for freight miles travelled vastly increase in the coming decades [10], surpassing passenger vehicle emissions [11] and doubling the global fleet [12] by 2030. Emissions from road freight transport will likely increase two- to three-fold by 2050 [12,13]. As a result, the share of carbon emissions from HDV will increase to a vast majority by 2100. This increase, combined with their low fuel economy and limited existing regulations [14,15], makes HDV freight transport a vital target for decarbonization.

While the future of carbon-free passenger transport lies in vehicle electrification, the same cannot be said for freight transport, where the heavier vehicles need significant torque to operate. Recent efforts by Tesla and Daimler, however, have illustrated prototype all-electric freight trucks, which have spurred public concerns regarding range, cost, charging time, and cargo limitations [16]. Specifically, the significantly larger battery size of the Tesla Semi, which comes with range of 500 miles, means that the battery itself will cost nearly the same as the price of a traditional diesel class 8 HDV. The battery is so large, in fact, that Tesla had to design and build a new megacharger grid, with each charger able to supply several times as much electricity as a Supercharger [17].

Alternative means of HDV electrification include overhead catenary power lines or in-road inductive charging, but this would require substantial capital investments over decades to build a standardized, nationwide travel network prior to deployment. This prerequisite means a delay in market growth, with estimates of only 15% of sales in 2050 for catenary electric [18]. The delay in growth equates to decades of continued carbon emissions from traditional HDV, ensuring that emissions reduction targets for 2050 are not met.

B. *Mobile Carbon Capture for Heavy Duty Vehicles*

An alternative opportunity exists to decarbonize the HDV fleet: carbon capture using porous solid adsorbents that selectively remove carbon dioxide gas from vehicle exhaust, where the CO_2 concentration is 12-14% by volume. In a HDVCC program, illustrated in Fig. 1, exhaust from a diesel-powered HDV would exit the tailpipe under normal vehicle operation and then enter a vessel packed with adsorbent, where the CO_2 would be captured within the adsorbent.

Periodically and ideally while refueling, the saturated adsorbent bed will be regenerated using a steam displacement purge over approximately 20 minutes. The regeneration product is a CO_2 and H_2O mixture. After condensing out the captured water vapor, on-site pumps can compress the CO_2 for transport via pipeline to an injection well, where is will either be stored underground in a geological formation or utilized in enhanced oil recovery (EOR). After regenerating, the adsorption cycle can be repeated.

Carbon capture from vehicles has been discounted in previous studies due to the feasibility challenges and presumed high costs [19-21]. The oft-used reasoning is that the on-board capture system would be detrimental to vehicle performance and the infrastructure investment would be costly, rendering the system impractical and uneconomical. While this might be a valid argument for light-duty vehicles, where the smaller size and mass make an on-board system cost-prohibitive, it is not reasonable to discount all vehicles.

We argue here that carbon capture for HDV mitigates these issues based on unique characteristics of the HDV fleet. For example, compared to an average vehicle lifetime of 8 years for passenger cars, HDV are typically driven over 20 years [14]. In addition, many HDV fleets have a central hub, whereas most passenger vehicles are parked at homes. These distinctive differences between heavy and light-duty vehicles, combined with anticipated increases in road freight shipping, means that even widespread electrification of passenger vehicles after 2020 would not reduce transportation sector CO_2 emissions significantly by 2050 [18]. By retrofitting existing HDV, this technology could spur rapid decarbonization before 2050.

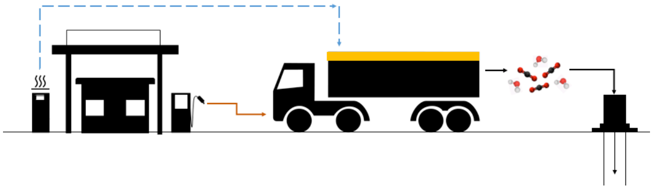

Fig. 1. Schematic of HDVCC. Steam and diesel fuel are supplied at a refueling station, CO_2 is captured in an on-board adsorption vessel (yellow box), the CO_2/H_2O mixture is utilized or stored permanently underground, and the system is periodically regenerated using a steam purge (dotted blue line)

II. Economic Evaluation

In an HDVCC program, the capture unit, weighing just over 2000 kg, would be installed along the top or bottom of the trailer. Operation would continue normally. After a predetermined distance of approximately 250 miles, the driver would connect their capture unit to a regeneration unit while refueling. The CO_2 would be siphoned out of the capture unit, and an alert would inform the driver when his vehicle was again ready for operation. The siphoned CO_2 would then be compressed and transported via pipeline to a storage or utilization site.

The components used to make a baseline cost estimate fall under three categories: CO_2 capture (covering gas separation, material regeneration, and fuel penalty), transport and storage (including compression and potential utilization), and capital cost expenditures [22]. Using HDV (Class 7/8 in the U.S.), the average payload is ~20,000 kg (Sharpe et al, 2016) and the fleet-wide fuel economy is 6.8 miles per gallon [23]. Diesel fuel emits ~10 kg CO_2 for every gallon combusted and is expected to cost \$3.15/gallon [24] in the near future. Differences in diesel fuel prices have a minimal impact on overall carbon abatement cost; every 10% change in fuel cost results in a corresponding \$1 change in the carbon abatement cost.

A. Carbon Dioxide Capture

In our hypothetical HDVCC system, a porous solid material selectively removes CO_2 from vehicle exhaust post-tailpipe. Commercially available materials have CO_2 adsorption capacities similar to liquid absorbents at 50-200 grams per kilogram (kg) of material [25]. Using a typical zeolite under expected operating conditions, a capacity of 20 weight % (1 kg of CO_2 captured per 5 kg of zeolite) is assumed [26].

Thermodynamic minimum work requirements for gas separation are based on the difference in Gibbs free energy between the initial and final states. In the simplified case of ideal gas streams in an isothermal and isobaric process, the minimum work per unit mass of CO_2 (kJ/kg) assuming 100% capture, reduces to:

$$w_{min} = -(RT/yM_{CO2})\,[y\ln(y) + (1-y)\ln(1-y)] \qquad (1)$$

where R is the ideal gas constant (8.314 J/mol-K), T is temperature (K), y is the mole fraction of CO_2 in the feed stream, and M_{CO2} is molecular weight (44 g/mol) [27].

As the CO_2 concentration in the feed gas decreases, the minimum work requirement increases. For HDVCC from diesel exhaust at 12% CO_2, the minimum work requirement is equal to 172 kJ/kg CO_2 removed, approximately equal to stationary capture from a coal-fired power plant. Capture directly from ambient air, where the CO_2 concentration has been diluted to 0.04%, would require almost triple the energy (497 kJ/kg).

Actual work is governed by the second-law efficiency, which compares theoretical to actual power consumption and is 5-40% [28] for a combined separation and compression process, with an average for stationary capture at 24% for separation alone [29]. Assuming a high efficiency system and/or future technological advancements, the second law efficiency is set at 40%. For every 10% reduction in efficiency, the corresponding cost estimate increases by approximately 11%.

Periodically, the adsorbent will reach saturation and the captured CO_2 will need to be purged and the material regenerated for another cycle. For long-haul freight shipping, HDV are driven up to 11 hours per day at an average highway speed of 55 miles per hour, giving a conservative average daily commute of around 500 miles [30]. To minimize the volume and mass sacrificed for the capture system, along with the inconvenience to the driver, regeneration should occur twice a day, at around 250 miles per trip (consistent with the need to refuel based on an 6.8 mpg fuel economy for HDV). Since the effect of added mass from captured CO2 is detrimental to vehicle performance, the fuel economy is reduced by approximately 3% for HDV for every 10% increase in payload mass [31]. Parasitic mass is computed at full capacity, which is necessary as any commute beyond the intended range will involve a saturated adsorbent bed. Under these conditions, the parasitic mass is 2200 kg, effectively reducing fuel economy to 6.5 mpg.

During regeneration, a change in pressure or temperature releases captured CO_2. In this model, a steam displacement purge (water vapor heated to ~130 ºC) is used. Steam consumption is assumed at 0.3 kg/kg CO_2 [27]. Low-carbon or CO_2-free electricity, generated through the use of wind turbines or solar panels, provide the energy needed for steam generation. The assumed cost is \$0.13 per kilowatt-hour (kWh), in the range of actual costs of \$0.10 to \$0.20/kWh [28].

B. Compression, Transport, Storage, & Utilization

Once the captured CO_2 has been successfully purged from the adsorbent bed, it must be compressed and transported to another location for utilization or storage. The industry standard for pipeline transport requires CO_2 at supercritical phase, at a pressure of 110 bar. HDVCC infrastructure for CO_2 compression would mimic power plants, where the average cost is estimated at \$6-8/tonne CO_2 [32]. Estimates for transportation of CO_2 via pipeline and injection into deep geological storage are on average \$10-\$15 per tonne of CO_2 avoided [33-35] and differ based on pipeline length, basin range, and storage volume. In the U.S., cost per ton for pipeline transport ranges from \$1.03 to \$2.63 [36]. Pipeline transport of CO_2 is assumed to cost \$2/tonne (under 150 kilometers) and storage is an additional \$10/tonne.

Instead of storage, captured CO_2 would ideally be utilized for EOR, which refers to various techniques that increase crude oil extraction. The use of EOR allows a shift from a parasitic and indefinite storage cost to a marketable end product. In addition to the cost benefit, this also allows the narrative surrounding CO_2 to switch from the cause of climate change to a usable product. As carbon capture projects grow, captured CO_2 is expected to provide 43% of EOR needs by 2020 [37]. The Global CCS Institute [38] estimates a delivered cost for CO_2 at EOR sites of \$40-\$45/tonne of CO_2 (tCO_2) if oil prices remain above \$100 per barrel. With average oil prices currently at half this amount, the estimated return for CO_2-EOR is \$20/tCO_2.

C. Capital Costs

HDVCC capital costs are difficult to assess in a hypothetical system, so cost estimates rely on assumptions from literature on post-combustion capture at power plants, where capital costs are twice operation and maintenance (O&M) costs (2:1 ratio), and direct air capture, where capital costs are half of O&M (0.5:1 ratio) [39]. A need for significant infrastructure means greater capital costs, while the synergies between existing stationary carbon capture and EOR sites would decrease the capital investments needed for a nationwide HDVCC program [40].

With evidence that modular technologies have faster learning rates and thus lower costs [41], the future capital costs for HDVCC are likely around 1:1 capital cost to O&M costs, as the capture and regeneration units could be mass-manufactured. A range of capital costs ratios, ranging from 0.5:1 to 3:1, are included to test sensitivity.

D. Summary

In the estimates shown in Fig. 2, a \$25/tCO_2 contingency cost has been added to cover any potentially missing or misunderstood information for this new, transformative technology. The abatement costs for separation, compression, regeneration, and transport, which serve as the baseline for capital costs, total \$27/tCO_2, with a corresponding range of \$14-\$82/tCO_2 for 0.5-3:1 capital to O&M cost ratios. At a likely capital: O&M ratio of 1:1, the carbon abatement cost is \$100/tCO_2 (column B in Fig. 2) and rises to \$155 (column A) for a ratio of 3:1. If captured CO_2

can be utilized via EOR, the cost drops to \$80/tCO_2 (column C).

In addition to CO_2 utilization via EOR, future technological advancements would decrease the expected total carbon abatement cost. Modular retrofit technology would permit mass production, next-generation adsorbents would achieve higher weight percent capture which would vastly lower the parasitic mass, and technology advancements would permit gradual cost decreases over time. Moreover, tax rebates for carbon capture technology or a carbon tax on fossil fuel generation would serve to further lower this estimate. As Fig. 2 illustrates, the total carbon abatement cost from HDV is competitive with stationary carbon capture and passenger vehicle electrification.

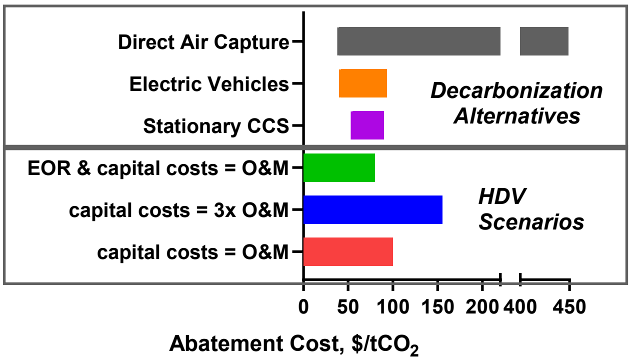

Fig. 2. Abatement cost estimates by cost category for HDVCC using geological storage or EOR, along with comparative decarbonization cost ranges from published literature for stationary CCS (\$55-90), electric vehicles (\$42-93), and direct air capture (\$40-449).

III. ENVIRONMENTAL IMPACT

A. *Climate Model Projections*

After establishing a pathway to HDV decarbonization and demonstrating its cost competitiveness compared to other options for carbon capture or vehicle electrification, we assess the potential environmental impacts based on avoided carbon. We base our estimates on the middle-of-the-road shared socioeconomic pathway (SSP2) since it represents a continuation of historical patterns regarding emissions intensity [42], decreasing at a rate of 1.2% globally [43].

In SSP2, global CO_2 emissions reach a relative plateau of 11-12 gigatonnes of carbon (GtC) between 2020 and 2060. Population peaks at 9.4 billion around 2070 [44]. After this, a lower energy demand and widespread shifts to carbon-free energy result in rapid reductions in global emissions through 2100 [43]. The prediction of future emissions prescribed by SSP2 does not assume any coordinated global climate change mitigation policy or new transformative technologies beyond the existing trends for passenger vehicle electrification.

Using SSP2, integrated assessment models (IAMs) predict a global temperature rise of 2°C by 2050 and ~3.8 °C by 2100 [45]. These temperature changes are inconsistent with the dangerous climate impact of 2 °C laid out in the Paris accord, but IAMs suggest that temperature increases could be limited to 2 ºC [43] if an additional ~330 GtC of emissions are avoided [46].

B. *Defining the Market Potential of HDVCC using SSP2*

Using SSP2 as the business-as-usual scenario for future emissions, Fig. 3 illustrates total global CO_2 emissions (blue) and transportation sector emissions (orange) based on data from phase 6 of the Coupled Model Intercomparison Project that uses a century-end radiative forcing of 4.5 watts per square meter [4]. Transportation sector emissions peak in 2050 and then decline at historic rates of 1.2% annually. By 2070, the transportation share of total emissions reaches a minimum around 20% before increasing to over 40% by 2100 [46]. The share of emissions for road freight (green) increases 2.5-fold from 2015 to 2050 [13], surpassing 50% of transportation sector emissions by mid-century. HDV freight is then assumed to remain at this share of transportation emissions through 2100.

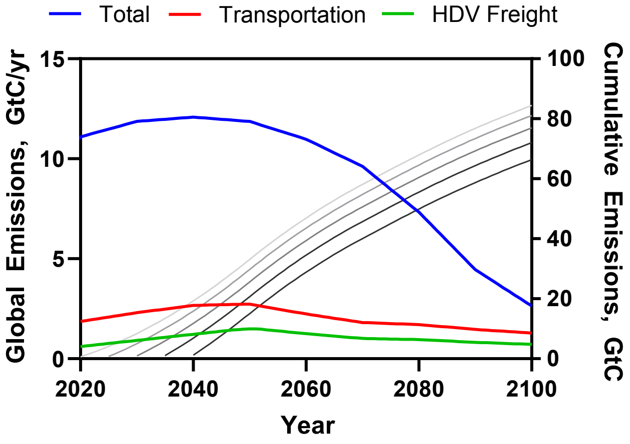

Fig. 3. Left axis: annual global CO_2 emissions for SSP2 (blue), the transportation sector (red), and HDV freight (green); Right axis: cumulative emissions from HDVCC (grey) starting at 5-year intervals between 2020 and 2040.

C. *Understanding the Climate Response using a Simple Climate Model*

An analysis of annualized HDV emissions from 2020 to 2100 (green line in Fig. 3) gives a baseline for total market potential of road freight decarbonization. The total market potential of HDV freight projected through 2100 (darkest grey line) is 84 GtC. Even with a delayed start for HDVCC in 2040, cumulative emissions reach 66 GtC in 2100. The remaining carbon budget to keep global warming under 2 °C is between 350 and 460 GtC [47,48] with IPCC estimates at 382 GtC (IPCC, 2018; Rogelj et al, 2019). This means that expected emissions from HDV freight represent 17-22% of the remaining allowable carbon emissions. For 1.5°C peak warming, the IPCC estimate for a remaining carbon budget drops to 131 GtC [1,49] and the HDV freight share increases to 50-64%.

The climate response to cumulative CO_2 emissions, calculated from state-of-the-art climate and Earth system models, varies from 1.0-2.1ºC per 1000 GtC [50], and is insensitive to emissions timing or peak rate [51]. We use Hector, an open-source simple climate model developed by Pacific Northwest National Laboratory, to assess climate impacts of total global anthropogenic CO_2 emissions resulting from HDVCC. Hector uses a well-mixed globally averaged atmosphere, with annualized emissions of greenhouse gases, aerosols, and particulates used to force changes in climate [52]. For all scenarios, anthropogenic carbon emissions (1765-2017) follow records from the Global Carbon Project [53] while non-CO_2 forcings follow SSP2 (1765-2100).

D. Relating Cumulative Carbon Emissions and Peak Warming

Scenarios were run in Hector that reflect full market potential of HDV freight, at 5 year incremental start dates between 2020 and 2040. Across all scenarios, the average climate response to cumulative carbon emissions is approximately 1.8 °C per 1000 GtC of anthropogenic CO_2 emissions, giving a century-end temperature avoidance of 0.12 °C if HDVCC is implemented by 2040 and 0.15 ºC if implemented by 2025. If our current global temperature has increased 1 ºC and our peak warming target is 2 ºC, this avoidance is 12-15% of the remaining temperature budget. If our peak warming target is lowered to 1.5 ºC, this share rises to 24-30%. Warming is likely to reach 1.5 °C between 2030 and 2052 at its current rate of increase, resulting in sea level rise, lower agricultural yield, extreme heat waves, drought, flood, and species extinction [1]. The potential impact of pursuing HDVCC on global warming is too significant to ignore.

IV. CHALLENGES AND OPPORTUNITIES MOVING FORWARD

For the target capture distance and expected fuel economy of our HDVCC system, the adsorbent vessel would capture 380 kilograms of CO_2 per trip and occupy 6% of the gross vehicle weight for a class 8 truck, displacing 11% of the payload mass. This vessel would occupy roughly 7% of the trailer volume, placed along the top or bottom of the trailer bed to limit losses in cargo space. The use of a next-generation material instead of a commercial zeolite could potentially increase storage efficiency up to 240 weight % [54]; this would decrease the parasitic payload mass to under 3% and the volume to under 1%. These materials, called metal organic frameworks, have received substantial attention in chemistry research for their ability to separate CO_2 from complex gas streams under a wide array of pressures, temperatures, and humidity levels [55].

Compared to internal or external HDV electrification, there are several benefits to pursuing HDVCC: (1) the technology could be retrofit onto existing vehicles, bypassing the typical fleet turnover of over 20 years; (2) capital costs for infrastructure would be lower and the technology could be implemented progressively rather than requiring a nationwide network before implementation; and (3) regeneration infrastructure, placed alongside existing refueling stations, would encourage greater regional/geographic independence compared to the charging infrastructure or electricity supply lines needed for HDV electrification. The most significant barriers to widespread adoption of an HDVCC program are behavior change, since regeneration takes time and effort on the part of the driver, and regeneration infrastructure, which would require steam generation and gas compression equipment that is powered using carbon-free electricity.

Despite the slow growth of passenger vehicle electrification, global transformational shifts in transportation and freight have occurred on decadal time scales: automobiles replaced horses in 20 years [56], the U.S. Interstate Highway system was built in 35 years [57], and shipping containers replaced bulk cargo in 30 years [58]. Mobile carbon capture from heavy-duty freight shipping is a yet unexplored option for mitigating transportation sector emissions. Clean transportation initiatives like SmartWay and Green Freight have had success among freight shipping fleets [59], demonstrating the precedent for a transformational shift in our approach to freight shipping.

While the need for carbon emissions reductions may be apparent to the public, investments in carbon capture projects typically require prior federal policy or regulations [60] and estimates for the infrastructure investments needed to decarbonize road freight transport are approximately $150 billion USD for overhead catenary or inductive in-road charging [18]. HDVCC offers an effective complement to stationary CCS and passenger vehicle electrification and should be explored as a viable climate mitigation option before CO_2 removal techniques targeting net negative emissions.

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