Fuels Institute

The Easiest and Hardest Commercial Vehicles to Decarbonize

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Guidehouse INSIGHTS

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Executive Summary

The Easiest and Hardest Commercial Vehicles to Decarbonize

Global leaders have set decarbonizing energy consumption as a top priority for public policy and financial investment criteria. The road-transportation sector, being a major energy consumer and therein greenhouse gas (GHG) emissions source, is a focus.

To date, the primary approach for decreasing emissions has been through regulations on vehicle and fuel suppliers to improve vehicle energy efficiency and fuel carbon intensity, respectively. These regulations have mostly been developed for light-duty vehicle markets and technologies. However, the success of these policies in the light-duty vehicle market is prompting replication for the medium- and heavy-duty vehicle (MHDV) market.

While some have embraced this approach, the MHDV market policies, targets, and expectations cannot be the same as those for light-duty vehicles because the MHDV market is vastly more complex. Vehicle types and sizes are diverse, customization is frequent, and operating conditions present myriad and nuanced challenges for various decarbonization solutions. Legislators, regulators, and corporations need to understand this complexity as they set targets for policy and design incentive mechanisms for market suppliers.

To inform the broad community of stakeholders (vehicle suppliers, fuel providers, owners and operators, corporations, policymakers, and regulators) on the nuances of MHDV decarbonization, the Fuels Institute collaborated with Guidehouse Insights to highlight the complexity of the market. To do so, Guidehouse Insights identified the top five and bottom five applications for MHDV decarbonization as a function of technology readiness and quantified each market's impact on the overall U.S. MHDV market and contribution to U.S. MHDV GHG emissions.

The results of the analysis indicate that the top five MHDV applications affect nearly 50% of the market and are responsible for 42% of emissions. Meanwhile the bottom five affect 20% of the market but are responsible for 45% of emissions. While applications within the top and bottom five have attributes conducive to or challenging for decarbonization, each has nuance. This variance makes scaling of any one decarbonization solution a challenge, reinforcing the need for policies to be open to, and enabling of, a variety of solutions.

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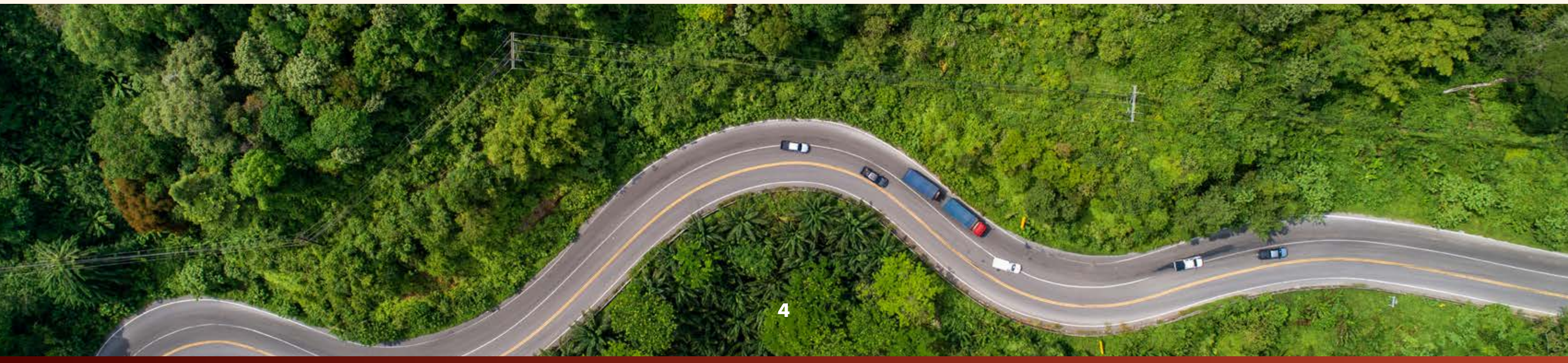
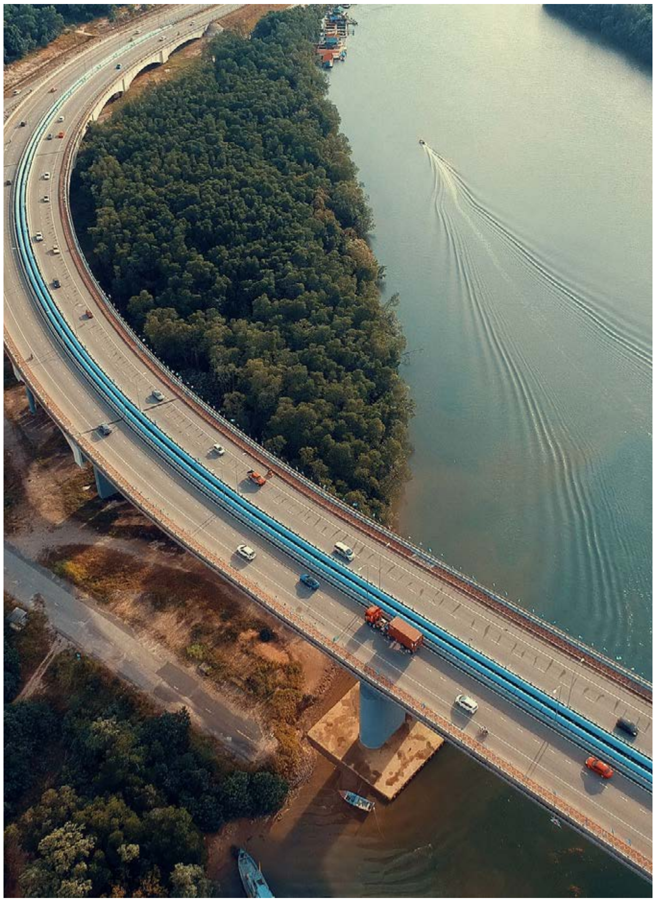


Introduction

Global attention to climate science, most notably the Sixth Assessment Report of the International Panel on Climate Change,[1] has increased world leaders' focus to reducing carbon emissions across all sectors with specific attention being directed at transportation.



The road-transportation sector is a major source of GHG emissions, estimated to account for around 18% of global emissions and 24% of U.S. emissions.[2] As such, pressure is mounting from governments and corporate customers for vehicle manufacturers and fleets to decarbonize and provide zero-emissions solutions. This has led to the introduction of electric vehicle (EV) and fuel cell vehicle (FCV) technologies, the development of a suite of renewable liquid and gaseous fuels, and gradual efficiency improvements to the internal combustion engine responsible for powering a vast majority of the global vehicle fleet.

The pressure has fallen sharply on light-duty vehicles, which account for over 70% of road GHG emissions in the U.S. Government policies are increasingly being adopted to push suppliers toward zero-emission solutions. As such, EV technologies have had marked success achieving 3.7% of global sales in 2020. Guidehouse Insights expects the success to continue with a tipping point due later in the decade that leads to one of every three new light-duty vehicles, sold globally, being either fully electric or a plug-in hybrid by 2030.[3]

Government pressure for zero-emission technologies and decarbonization of MHDVs has not been as strong as with the light-duty vehicle market. This is because introducing decarbonization technologies to this market is far more difficult.

1 Intergovernmental Panel on Climate Change, "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis (contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change)*, eds. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (Cambridge, U.K.: Cambridge University Press, forthcoming). Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf.

2 "Transport: Improving the Sustainability of Passenger and Freight Transport," International Energy Agency, August 22nd 2021, https://www.iea.org/topics/transport; "Fast Facts on Transportation Greenhouse Gas Emissions," U.S. Environmental Protection Agency, August 22nd 2021, https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions.

3 "Market Data: Light Duty EVs," Guidehouse Insights, second quarter 2021, https://guidehouseinsights.com/reports/market-data-light-duty-evs.

The MHDV market is not like the light-duty vehicle market.

It serves a much more diverse set of customer needs and also has smaller unit volumes and much more customization.

However, EV success with light-duty vehicles is prompting translation of policies designed for the light-duty-vehicle market to the MHDV market. For example, California announced the implementation of a zero-emission vehicle, or ZEV, mandate for MHDV trucks similar to its mandate for light-duty vehicles.[4] Also, Europe has begun a GHG emissions efficiency regulation analogous to its standards for passenger cars and light commercial vehicles.[5]

The MHDV market is not like the light-duty vehicle market. It serves a much more diverse set of customer needs and also has smaller unit volumes and much more customization. This creates a highly varied market with relatively limited opportunities for scale. So, in translating policies that have worked for the light-duty vehicle market, policymakers and regulators need to approach this market differently, be wise to its nuances and challenges, and be open to a wide range of zero-emission and decarbonization solutions.

The purpose of this white paper is to inform a broad community of fuel providers, fleet managers, corporations, and policymakers on the complex problems decarbonization presents for the MHDV market. To do so, this white paper provides an overview of the key decarbonization solutions, an inventory of the MHDV market by application, and an evaluation of the five strongest and most challenging applications for decarbonization.

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4 Claire Buysse and Ben Sharpe, *California's Advanced Clean Trucks Regulation: Sales Requirements for Zero-Emission Heavy-Duty Trucks, policy update (International Council on Clean Transportation, July 2020)*. Available at https://theicct.org/sites/default/files/publications/CA-HDV-EV-policy-update-jul212020.pdf.

5 "Reducing CO2 Emissions from Heavy-Duty Vehicles," EU Action, European Commission, European Union, September 7th 2021, https://ec.europa.eu/clima/policies/transport/vehicles/heavy_en.

The Key Decarbonization Solutions

The key decarbonization solutions for the MHDV market are electricity, hydrogen, and a variety of renewable fuels that can power internal combustion engines via natural gas, liquified petroleum gas, conventional diesel, or gasoline infrastructure systems. The following sections provide brief overviews of the commercial readiness of each alternative for the MHDV market.

ELECTRICITY

Decarbonization through electrification is promising but requires significant infrastructure investments. Renewable electricity generation from wind, solar, geothermal, and other resources is on the rise and has prompted many U.S. state governments to push for zero-emissions electricity targets in the next 10 to 20 years.[6] The rise of these resources, specifically solar and wind, creates issues for grid operators because production depends on the weather and is hence difficult to align with consumer demands. Energy storage is critical here; as such, the batteries of EVs themselves may be useful assets in solar and wind integration.

While the grid pushes forward with decarbonization, it must simultaneously improve grid reliability against cyber and environmental threats and prepare to power large portions of the road-transportation sector. The investments needed include a panoply of strategies and technologies such as EV smart-charging, distributed energy resources, and micro-grids as well as traditional capacity upgrades through transformers, lines, and substations.

To date, the preparations required for EVs have been manageable. However, EVs only represent marginal percentages of overall road-transport demand. Looking ahead, increased EV charging speed and greater EV numbers are likely to escalate demands for grid upgrades. On top of this, enabling long-range travel for electric MHDVs (growing beyond the current "hub-and-spoke" model for electric MHDVs) will require entirely new grid infrastructure systems. These systems will require significant capacity expansions that will likely take many years to build and be expensive.

While the infrastructure investment requirements for EVs is high, the momentum for investment in EV

6 "100% Clean Energy Collaborative — Table of 100% Clean Energy States," Clean Energy States Alliance, August 22nd 2021, https://www.cesa.org/projects/100-clean-energy-collaborative/guide/table-of-100-clean-energy-states/.

technologies is equally high. Innovations in battery chemistries, formats, and architectures are occurring at a rapid pace. Meanwhile industry collaborations on charging infrastructure systems are on the verge of demonstrating power capacities over 1 MW.[7] The innovations are fostering a burgeoning market for electric MHDVs with fleets and stakeholders interested not only in GHG savings but also reducing local air pollutants, noise, and, in some instances, total ownership costs. The trends are encouraging for an expanding EV market; however, significant developments need to be achieved before EVs can feasibly replace major portions of the market.

HYDROGEN

Decarbonization through hydrogen has potential but also a series of challenges throughout the supply chain. The first challenge is in scaling renewable hydrogen production. Potential renewable production pathways include steam reformation of bio-based feedstocks and electrolysis of water using solar or wind generation. Another pathway that is not renewable but has interesting environmental implications is the gasification of waste plastics. Production of hydrogen through all of these pathways is, however, limited. Most hydrogen production currently comes from the reformation of fossil-based natural gas, which produces a more carbon-intense fuel than diesel.[8] However, because fuel cell powertrains are around twice as energy efficient as diesel-fueled powertrains, Guidehouse Insights has calculated the GHG reduction potential of fossil-based hydrogen to range from between 8% to 50% when used in MHDVs.[9]

A second challenge for hydrogen is distribution infrastructure. An efficient means of distributing hydrogen would be via pipeline from centralized production facilities, however, very little pipeline infrastructure exists. Therefore, hydrogen must be distributed by truck, which poses problems for efficiency, venting, and costs, or produced in a distributed model, closer to where it is consumed. This is possible as distributed hydrogen production equipment could leverage natural-gas or electricity infrastructure, which is well developed in major markets. A distributed production model does, however, contribute to higher fuel costs.[10]

As of July 2021, a limited sampling of hydrogen prices in the US indicates average costs are over $16 per gasoline gallon equivalent ($18 per diesel gallon equivalent[11]).[12] While FCV powertrain energy efficiency gains over the internal combustion engine cut into the hydrogen fuel premium, the fuel is still significantly more expensive than diesel on a per mile basis. While discouraging, costs can come down with scale, but stakeholders will need to make significant investments as FCV adoption and hydrogen site development remains nascent across the major global markets. Regardless of these challenges, interest and investment in hydrogen and FCVs continues as the competitiveness of EVs in some MHDV applications, such as long-haul trucking, remains questionable.

7 "NREL-Hosted Event Supports Industry Development of Megawatt Charging System Connectors," National Renewable Energy Laboratory, published Oct. 12, 2020, https://www.nrel.gov/news/program/2020/nrel-hosted-event-supports-industry-development-megawatt-charging-system-connectors.html.

8 "Hydrogen Production: Natural Gas Reforming," Hydrogen and Fuel Cell Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, August 22nd 2021, https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

9 "LCFS Pathway Certified Carbon Intensities," California Air Resources Board, California Environmental Protection Agency, September 14th 2021, https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities; Colin Murphy, "Medium and Heavy Duty Vehicles Under California's LCFS" (presentation, Mapping Standards for Low- and Zero-Emission Electric Heavy Duty Vehicles Expert Workshop, International Transport Forum, Paris, France, February 17-18, 2020), published by the Policy Institute for Energy, Environment, and the Economy, University of California, Davis, available at https://policyinstitute.ucdavis.edu/wp-content/uploads/Murphy-ITF-LCFS-in-MDHD-Transitions.pdf.

10 T. Ramsden, M. Ruth, V. Diakov, M. Laffen, and T.A. Timbario, *Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios* (Golden, CO: National Renewable Energy Laboratory, March 2013), https://www.nrel.gov/docs/fy14osti/60528.pdf.

11 Calculated assuming 1 gasoline gallon is equal to 0.88 diesel gallons in terms of energy equivalence.

12 "Clean Cities Alternative Fuel Price Report," U.S. Department of Energy, July 2021, https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_july_2021.pdf.

RENEWABLE FUELS

Decarbonization through renewable fuels is highly attractive in specific cases but has issues with scale that are limiting for the mass market. Renewable fuels include any fuel that can be consumed in conventional fossil-based fuel (diesel, gasoline, natural gas, and propane autogas) vehicle and infrastructure systems. These include ethanol, biodiesel, renewable diesel, renewable natural gas, and renewable propane autogas.

Notably, some fossil-based fuels (natural gas and propane autogas) can generate a GHG reduction benefit up to roughly 20% over diesel and gasoline.[13] For reference, life cycle analyses by the California Air Resources Board (CARB) and Environmental Protection Agency (EPA) indicate diesel and gasoline carbon intensity ratings between 97 and 100 grams/MJ.[14] While these gaseous fuels are not renewable, they do play a role in the overall reduction of road-transport decarbonization. Further, in the case of natural gas, expanded vehicle and infrastructure capacity for this fuel specifically could enable increased direct consumption of extremely beneficial renewable resources, such as renewable natural gas (RNG) produced from cow manure. Life-cycle analyses of the carbon intensity of RNG have resulted in values as low as -532 grams/MJ.[15]

Renewable fuel can be produced from a wide variety of resources, which are mainly bio-based. The best, in terms of GHG emission reductions and other sustainability issues, are waste streams such as cow manure, used cooking oil, sewage, and so on. Renewable fuels could also be produced through solar and wind. Here, renewable electricity powers electrolysis of water to produce hydrogen, which is then paired with carbon or nitrogen to produce a variety of different liquid or gaseous fuels, sometimes called e-fuels.

While intriguing, the process is highly inefficient relative to simply using electricity or hydrogen directly. As such, production of these fuels is likely directed toward energy demands where EVs and FCVs are less competitive, such as aviation and marine.

For bio-based resources, the total addressable resource base is often limited or other sustainability issues such as land-use-change limit expansions to the resource base. As such, bio-based resources can only satisfy a portion of road-transport demand. While renewable fuels may not be able to provide for the entire MHDV market, they can be viable and attractive solutions to decarbonize specific fleets in specific markets.

13 Carbon-intensity comparison of fossil-based natural gas and propane autogas pathways against default values for diesel and gasoline in “LCFS Pathway Certified Carbon Intensities,” California Air Resources Board.

14 “LCFS Pathway Certified Carbon Intensities,” California Air Resources Board; “Lifecycle Greenhouse Gas Results” United States Environmental Protection Agency, October 26th 2021, https://www.epa.gov/fuels-registration-reporting-and-compliance-help/lifecycle-greenhouse-gas-results.

15 “LCFS Pathway Certified Carbon Intensities,” California Air Resources Board

The Complex MHDV Market

The MHDV market is composed of highway-capable vehicles with a gross vehicle-weight rating over 10,000 lbs. In the U.S., this rating system is equivalent to Classes 3 to 8. There are a variety of vehicle types throughout the classes (Table 1).

Generally, different vehicle types will share a similar chassis that is then upfit with a body designed for a specific application. For example, step-vans, which typically provide delivery services, are built on what is known as a stripped chassis. Meanwhile, numerous other vehicle types—ambulances, shuttle buses, bucket trucks, and so on—are built on a cab chassis.

Slightly less than two-thirds of the U.S. market is composed of what is often considered the medium-duty vehicle classes (3 through 6) with the remainder being heavy duty (7 and 8). Market share is not analogous to energy consumption, as energy efficiency declines and vehicle travel alongside other energy demands increases in heavier vehicle-weight classes. While there is some commonality within vehicle types regarding efficiency and use, these attributes are highly sensitive to the application vehicles are deployed to. Hence the analysis of this whitepaper focuses on applications. Application is not only a strong indicator of common energy consumption and emission calculation attributes but also of common challenges and opportunities for decarbonization.

TABLE 1: MHDV TYPES

VEHICLE TYPE	CLASSES	PRIMARY APPLICATIONS	MARKET SHARE
Van	3-4	Last-mile cargo, emergency, shuttle	30%
Pickup	3-5	Light construction, agriculture, towing, electric utilities, telecommunications, government, emergency, shuttle	30%
Low cab forward	3-5	Last-mile cargo, government	<3%
Step-van	4-6	Last-mile cargo	<1%
Rigid truck	6-8	Regional cargo, construction, refuse, oil and gas, school busing, shuttle	19%
Bus	7-8	Public transit, motorcoach	<1%
Tractor	8	Regional cargo, long-haul cargo, logging, oil and gas	16%

Source: Guidehouse Insights

Market share is not analogous to energy consumption, as energy efficiency declines and vehicle travel alongside other energy demands increases in heavier vehicle-weight classes.

Guidehouse Insights has identified 17 applications (Table 2). This inventory is not comprehensive, and Guidehouse Insights estimates it accounts for 91% of the U.S. MHDV market and 94% of U.S. MHDV emissions. Each application is described by common vehicle types (Table 1) and key decarbonization considerations. The considerations are the major challenge or driver regarding decarbonization. For example, the key consideration for some applications is the *challenge or opportunity of duty cycle*. In this regard, a challenging duty cycle would require long distances on highways between refueling stops, whereas a duty cycle opportunity would include routes in urban areas with many stops.

Per each application, industry and government reports and databases were analyzed to approximate new vehicle market share, average annual travel, and energy efficiency.[16] The estimates of market share are assumed to translate to the share of vehicles in use per application. This implicitly assumes that (1) vehicles remain active in applications until they are scrapped and (2) vehicle longevity is similar across applications.

16 Alongside a number of other industry reports and databases focusing on specific applications or vehicle types such as school buses, refuse trucks, cement trucks and so on, critical sources of this analysis include: Stacy C. Davis and Robert G. Boundy, Transportation Energy Data Book, 39th ed., (Oak Ridge, TN: Oak Ridge National Laboratory, 2020), https://doi.org/10.2172/1767864; Office of Highway Policy Information, *Highway Statistics Series* (Washington, DC: Federal Highway Administration, U.S. Department of Transportation, 1970-2019), available at https://www.fhwa.dot.gov/policyinformation/statistics.cfm; "Alternative Fuels Data Center," Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, https://afdc.energy.gov/; U.S. General Services Administration and U.S. Department of Energy, Federal Fleet Report, 2020, datasets available at https://www.gsa.gov/policy-regulations/policy/vehicle-management-policy/federal-fleet-report; American Transportation Research Institute (website), https://truckingresearch.org/.

TABLE 2: MHDV APPLICATIONS RANKED BY GHG SHARE

APPLICATION	VEHICLE TYPES	KEY CONSIDERATIONS	ANNUAL TRAVEL (THOUSAND MILES)	MARKET SHARE	SHARE OF GHG
Long-haul cargo	Tractors	Challenge: public infrastructure network	75–100	14%	40%
Regional cargo	Class 6–8 trucks and tractors	Driver: stakeholder's sensitivity	30–50	12%	19%
Last-mile cargo	Class 3–6 trucks and vans	Driver: stakeholder's sensitivity	12–20	31%	17%
School busing	Class 6 buses	Driver: duty cycle	10–15	5%	2%
Heavy construction	Class 6–8 trucks with superstructures (cement, dump, drilling, etc.)	Challenge: auxiliary loads	12–20	2%	2%
Refuse trucking	Class 6–8 trucks with refuse superstructure	Driver: duty cycle	20–30	1%	2%
Oil and gas	Class 6–8 tanker trucks and tractors	Challenge: public infrastructure network	25–35	1%	2%
Public transit	Class 7–8 buses	Driver: stakeholder's sensitivity	40–50	1%	2%
Light construction	Class 3–5 trucks	Challenge: public infrastructure network	5–10	8%	1%
Government	Class 3–8 trucks	Challenge: on-call services	5–10	6%	1%
Utilities	Class 3–6 trucks with boom superstructures	Challenge: on-call services	5–10	5%	1%
Agriculture	Class 3–8 trucks and tractors	Challenge: public infrastructure network	12–20	2%	1%
Tow trucking	Class 3–8 trucks	Challenge: on-call services	12–20	2%	1%
Private coach	Class 8 buses	Challenge: duty cycle	75–100	<1%	<1%
Moving	Class 3–8 trucks	Challenge: public infrastructure network	12–20	1%	<1%
Logging	Class 8 tractors	Challenge: public infrastructure network	25–35	<1%	<1%
Emergency	Class 3–8 trucks and vans	Challenge: on-call services	5–10	<1%	<1%

Source: Guidehouse Insights

The Top Five Markets to Decarbonize

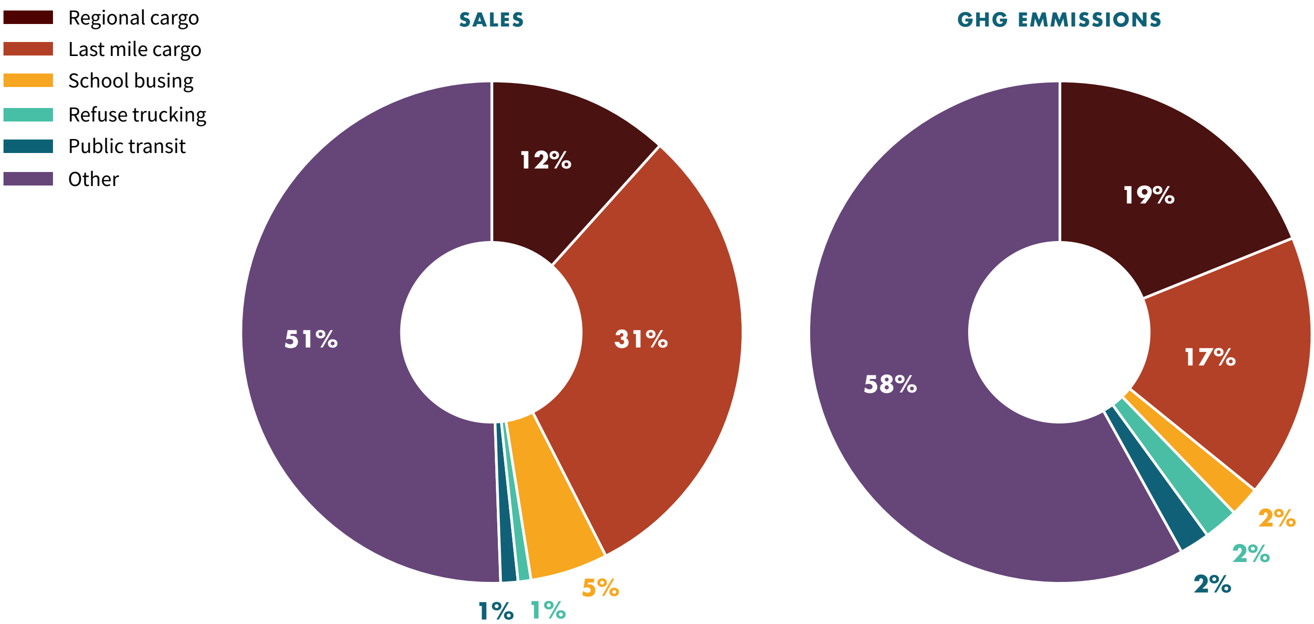
Several of the MHDV applications identified above are particularly attractive for decarbonization. These applications are distinguished by the following five attributes:

- **Stakeholder sensitivity:** A major driver of decarbonization is government and consumer pressure. Some applications will be more sensitive than others to pressure based on the industries or geographies served. Another factor is the distribution of services provided by large fleets rather than by small owners/operators. Generally, larger fleets are considered better positioned to invest in decarbonization than small owners/operators. Hence stakeholder sensitivity will likely be amplified for large fleets.
- **Ownership periods:** The probability that fleets will make a return on their alternative fuel investment depends greatly on how long they own and operate their vehicles. The longer the ownership period, the more likely alternative fuels will result in total-ownership-cost savings.
- **Return-to-base routes:** Third-party-owned infrastructure typically does not provide electricity, hydrogen, or renewable fuels; therefore, early-adopting fleets will most likely need to rely on developing access to these fuels at fleet or client properties.

- **Urban operations:** Some decarbonization solutions present environmental or operational advantages beyond just GHG emissions reduction. The oft-congested urban operating environment is a focus for many of these advantages, including reduced local air pollution, reduced noise, and energy-efficiency improvements through high utilization of regenerative braking systems.
- **Low energy-density requirements:** A significant challenge of many decarbonization solutions is energy density. Where MHDVs have moderate motive or auxiliary energy demands between refueling opportunities, the solution proposition will be stronger.

Using the above criteria, Guidehouse Insights identified the five strongest applications for decarbonization. In descending order these are: regional cargo, last-mile cargo, refuse trucking, public transit, and school busing. Combined, these markets are estimated to account for nearly 50% of new sales and 42% of GHG emissions in the U.S. (Figure 1)

FIGURE 1: TOP FIVE MARKETS TO DECARBONIZE: SHARE OF U.S. NEW MHDV SALES AND GHG EMISSIONS



Source: Guidehouse Insights

Combined, these markets are estimated to account for nearly 50% of new sales and 42% of GHG emissions in the U.S.

TOP MARKET 5: REGIONAL CARGO

Regional cargo deliveries, consisting mainly of consumer goods, are typically supported by Class 6 through 8 vehicles rigid trucks and Class 8 tractors. Guidehouse Insights estimates this is the second largest of the top five markets accounting for near 12% of sales. However, given a relatively high annual average travel, regional cargo is estimated to account for the largest share of GHG emissions among the top five at 19%.

The opportunity to decarbonize regional cargo is high, but so are the challenges. This market has strong stakeholder support and return-to-base routes, but it is likely that demands of the duty cycle require deployment of publicly accessible refueling infrastructure in multiple cases (Table 3). As such, EV and FCV adoption in the near-term is limited, but other renewable fuels can be impactful. For example, Amazon has ordered over 700 natural-gas trucks as part of its effort to achieve carbon neutrality by 2040.[17] Similarly UPS announced in 2019 its plans to buy over 6,000 natural-gas-powered trucks by 2022 while increasing its RNG purchases.[18]

TABLE 3: REGIONAL CARGO ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivity	Advantage	High rates of vehicle ownership by large and/or private fleets serving industries vulnerable to consumer sustainability sensitivities.
Ownership periods	Neutral	Trade cycle is around the average for MHDVs.
Return-to-base routes	Neutral	Many fleets will be able to deploy infrastructure along routes (warehouses and distribution centers), but development of publicly accessible infrastructure for other fleets will be needed.
Urban operations	Impediment	Operations tend to focus on highway corridors where other technology benefits are diminished. Some fleets operating around ports will realize these benefits.
Low energy-density requirements	Neutral	Some challenges for routes with long distances between end points.

Source: Guidehouse Insights

17 Laura Sanicola, "Exclusive: Amazon Orders Hundreds of Trucks that Run On Natural Gas," *Reuters*, February 5, 2021, https://www.reuters.com/article/us-amazon-engines-natural-gas-exclusive/exclusive-amazon-orders-hundreds-of-trucks-that-run-on-natural-gas-idUSKBN2A52ML.

18 UPS, "Renewed Emphasis: Renewable Natural Gas (RNG) Turns Waste Into Fuel," company announcement, January 27, 2021, https://about.ups.com/us/en/our-stories/innovation-driven/renewable-natural-gas-is-an-important-part-of-ups-strategy-to-in.html.

TOP MARKET 4: LAST-MILE CARGO

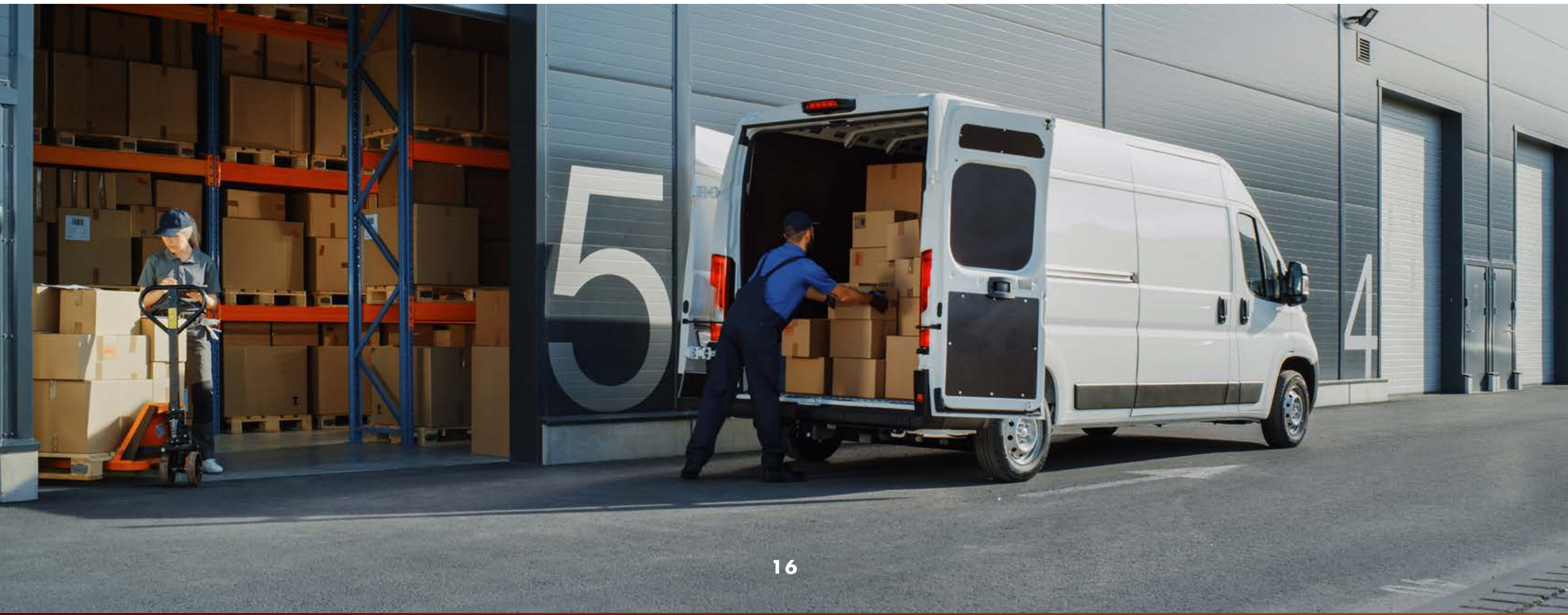
Largely composed of vehicles in Class 3 through 6, the last-mile cargo application provides goods to consumers, retailers, and other commercial properties. It is the largest of the top five markets, estimated to account for 31% of sales. However, given relatively low annual travel compared to regional cargo, it is estimated to have the second largest GHG emissions share of the top five with 17%.

Due to increasing levels of e-commerce, last-mile cargo is likely to grow relative to other MHDV applications. It is also likely to be quick to decarbonize because it has high scores for three of the five attributes for decarbonization (Table 4). Of the decarbonization solutions, electrification is the focus, driven primarily by major investments from Amazon, UPS, DHL, and FedEx. Some likely challenges are observed in food and beverage services, where reefer (refrigeration) trucks are needed. The additional energy demands of refrigeration may delay decarbonization through electrification for some fleets serving food and beverage demands.

TABLE 4: LAST-MILE CARGO ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivity	Advantage	Industries served are highly vulnerable to consumer sustainability sensitivities.
Ownership periods	Neutral	Trade cycle is around the average for MHDVs.
Return-to-base routes	Advantage	Many fleets will be able to access private infrastructure warehouses and distribution centers. Public infrastructure needs will be limited.
Urban operations	Advantage	Operations require many stops, often in urban areas, presenting additional benefits for local air quality and energy efficiency.
Low energy-density requirements	Neutral	Refrigeration demands are on the rise with the emergence of grocery e-commerce. For some fleets, this challenge may be offset by the urban duty cycle.

Source: Guidehouse Insights



TOP MARKET 3: REFUSE TRUCKING

This market typically uses Class 6 to 8 rigid trucks with an upfitted refuse collection superstructure. It is the second smallest of the top five, estimated to account for nearly 1% of sales. Due to very low energy efficiency, the market is estimated to have an outsized impact on GHG emissions, accounting for 2%.

Decarbonization of refuse trucking is attractive with high scores for four of the five attributes for decarbonization (Table 5). Over 17,000 refuse trucks are reported to run on natural gas in the U.S., and roughly 60% of new orders are powered by natural gas.[19] Use of natural-gas vehicles presents an intriguing opportunity to tap renewable natural gas produced from landfills. This approach could create a closed-loop decarbonization scheme whereby refuse trucks are powered by the waste they collect. While intriguing, suppliers indicate fleets are also becoming interested in electrification; for example, Los Angeles Sanitation and Environment (within the City of Los Angeles Department of Public Works) pledged to electrify its entire fleet of 750 refuse trucks by 2035.[20]

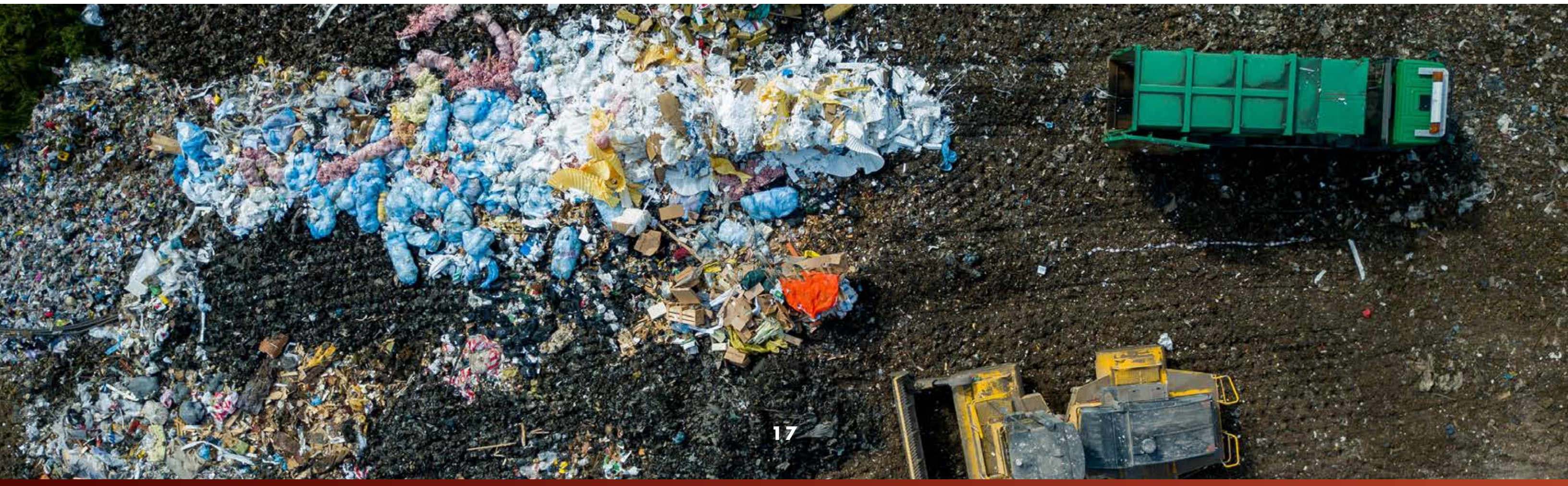
TABLE 5: REFUSE TRUCKING ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivity	Advantage	Fleets operate close to stakeholders in residential and urban environments, which hightens sensitivities.
Ownership periods	Advantage	Vehicles tend to be used by purchasers until they are retired.
Return-to-base routes	Advantage	Vehicles return to facilities and depots, creating opportunities for centralized alternative-fuels infrastructure.
Urban operations	Advantage	Operations require frequent stops in residential areas, presenting significant environmental/public health benefits.
Low energy-density requirements	Neutral	Refuse superstructure is an additional non-insignficant load. Challenge is likely offset by the urban duty cycle for many fleets.

Source: Guidehouse Insights

19 "Refuse," "Vehicles," Natural Gas Vehicles for America, August 22nd 2021, https://ngvamerica.org/vehicles/refuse/.

20 Waste360 staff, "LA Sanitation Commits to 100% Electric Refuse Truck Fleet," *Waste360*, January 24, 2020, https://www.waste360.com/trucks/la-sanitation-commits-100-electric-refuse-truck-fleet.



TOP MARKET 2: PUBLIC TRANSIT

Transit buses are typically Class 7 to 8 vehicles and provide both inter- and intra-city services. The U.S. public transit market is the smallest of the top five markets, estimated to represent less than 1% of sales. Due to relatively high annual travel and low energy efficiency, transit buses have an outsized impact on GHG emissions, accounting for 2%.

Decarbonization solutions are attractive in public transit with high scores for four of the five attributes for decarbonization (Table 6). Historically, the market has been an early adopter of decarbonization technologies. Lately, however, the trend has been towards electrification. A growing number of transit authorities in major cities across the U.S., including New York, Los Angeles, San Francisco, Chicago, Seattle, Minneapolis, and others, have committed to 100% electric bus fleets by 2040 or earlier.[21] FCVs are also of interest, although the technology remains in pre-commercialization phase due to high implementation costs relative to EVs.

TABLE 6: PUBLIC TRANSIT ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivity	Advantage	Fleets serve stakeholders in urban environments and are particularly sensitive to local governments.
Ownership periods	Advantage	Vehicles tend to be used by purchasers until they are retired.
Return-to-base routes	Advantage	Vehicles return to terminals and depots and have highly regimented routes and stops at public properties. This creates multiple opportunities for dedicted infrastructure development.
Urban operations	Advantage	Operations require many stops in urban areas and, in providing services to people specifically, can realize significant benefits for local air-quality improvements.
Low energy-density requirements	Neutral	Long daily duty cycles pose challenges for intra-city services.

Source: Guidehouse Insights

21 Paola Massoli, "The Road To Net-Zero Is Paved By Electric Buses," *Green Energy Consumers Alliance*, May 19, 2020, https://blog.greenenergyconsumers.org/blog/why-electric-buses-make-sense-now.

TOP MARKET 1: SCHOOL BUSING

The school-bus market, unique to North America, consists mainly of Class 6 vehicles. The market is the third largest of the top five, accounting for over 5% of sales. Due to relatively low annual travel relative to fleet size, its impact on GHG emissions is smaller, estimated to account for 2%.

School buses are the most attractive market for decarbonization with high scores in all five criteria. Historically, propane autogas has been the most popular alternative to diesel. As of 2020, over 20,000 (roughly 4%) school buses were reportedly powered by propane autogas.[22] Natural gas also powers approximately 5,500 (over 1%) school buses.[23] However, looking ahead electrification has garnered significant attention.

Beyond the five attributes for decarbonization (Table 7), the duty cycle of school buses presents a unique opportunity for EVs and vehicle-to-grid technologies. Because school buses are stationary for much of the day and have highly predictable usage patterns with long downtimes, the energy storage potential of the school-bus battery can be tapped for revenue-generating grid-balancing services. This revenue stream can help pay back the investment cost of school-bus electrification. As such, Dominion Energy, an electric utility in Virginia, is launching an initiative to lease and manage the energy demands of over 1,000 vehicle-to-grid-capable electric school buses by 2025.[24]

TABLE 7: SCHOOL BUSING ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivity	Advantage	Fleets serve a particularly vulnerable population and are therefore highly sensitive to government interests.
Ownership periods	Advantage	Vehicles tend to be used by purchasers until they are retired.
Return-to-base routes	Advantage	Vehicles return to depots and have long downtime periods.
Urban operations	Advantage	School-bus operations are more dispersed than many of the top five markets. These operations present the same opportunities of local air-quality and energy-efficiency benefits.
Low energy-density requirements	Advantage	Duty cycles are manageable, and vehicles typically have lengthy non-utilization periods, so much so that vehicle energy flexibility can be used in non-motive purposes.

Source: Guidehouse Insights

22 Ryan Gray, "Record-High 20,000 Propane Autogas School Buses Transporting Students This School Year," *School Transportation News*, November 10, 2020, https://stnonline.com/industry-releases/record-high-20000-propane-autogas-school-buses-transporting-students-this-school-year/.

23 "Schools" Natural Gas Vehicles for America, February 9th, 2022, https://ngvamerica.org/vehicles/schools/.

24 "V2G Hits the Big Time with Dominion Electric School Bus Project," *PJM Inside Lines*, October 10, 2019, https://insidelines.pjm.com/dominion-to-roll-out-largest-electric-school-bus-deployment-in-u-s/.

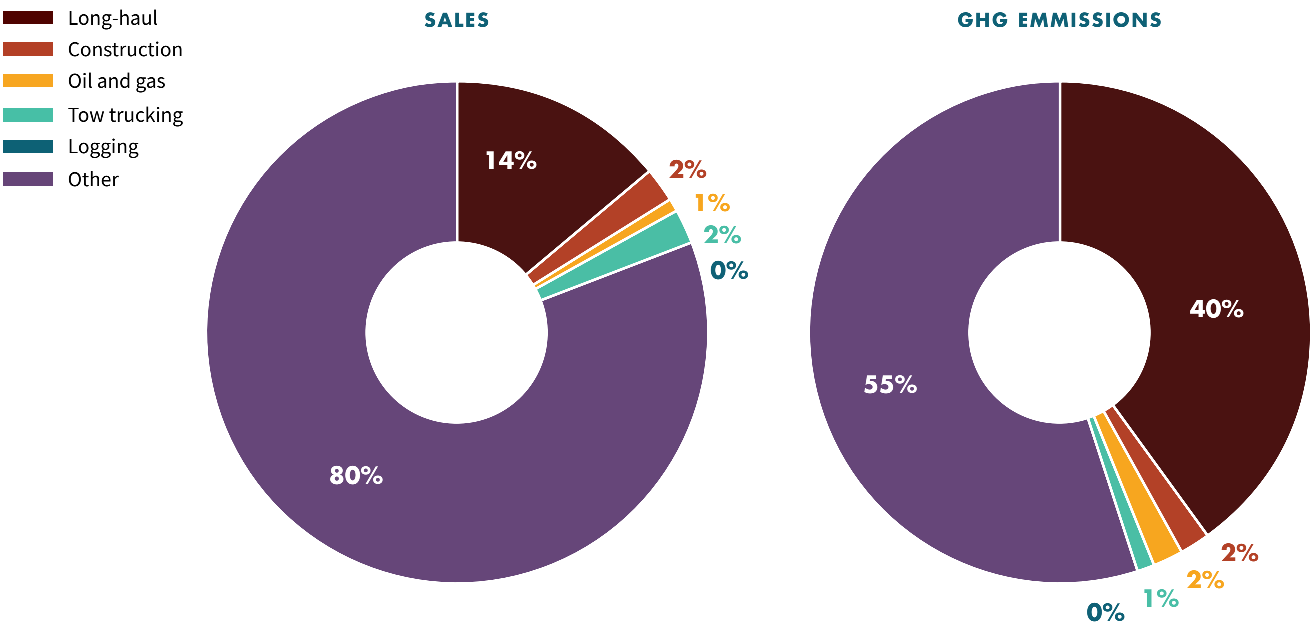
The Bottom Five Markets to Decarbonize

Several MHDV applications are particularly challenging to decarbonize. These are distinguished by the following five attributes:

- **Stakeholder sensitivity:** Fleets serving industrial or commodity-based markets are likely less exposed to client climate concerns. Additionally, applications with high rates of small owners/operators are more difficult to influence because investment risks for decarbonization are much greater than applications with greater rates of vehicle ownership by large fleets.
- **Ownership periods:** Fleets with high turnover rates present challenges for new decarbonization technology ownership in two ways:
    1. Depreciation is likely worse for decarbonization technologies than for conventional vehicles because resale markets will be limited to select secondhand buyers until familiarity and feasibility of the technology is more common.
    2. Increased upfront capital expenditures on more costly decarbonization technologies can result in reduced annual vehicle acquisitions. This disruption to fleet turnover has cascading impacts on fleet operational practices, such as managing maintenance and driver satisfaction, among others.
- **Publicly accessible refueling needs:** Infrastructure for electricity, hydrogen, and many renewable fuels is typically not accessible publicly and will take time to build out. Fleets that rely on refueling infrastructure networks will find adoption challenging, if not infeasible, in the near-term.
- **Rural operations:** Vehicle operations outside cities are generally more energy efficient and impacts on local air quality and public health are substantially decreased. This diminishes the non-climate environmental benefits that often accompany decarbonization solutions.
- **Non-motive auxiliary loads:** Transitioning motive power requirements to electricity or hydrogen is a challenge in any market. Adding other power requirements, such as truck hoteling or cement mixing, amplifies the challenge.

Considering the above criteria, Guidehouse Insights has identified the five most challenging applications for decarbonization. In descending order these are: tow trucking, logging, heavy construction, oil and gas, and long-haul. Combined, these markets are estimated to account for 20% of sales and 45% of GHG emissions (Figure 2).

FIGURE 2: BOTTOM 5 MARKETS TO DECARBONIZE: SHARE OF NEW VEHICLE SALES AND GHG EMISSIONS



Source: Guidehouse Insights

Combined, these markets are estimated to account for 20% of sales and 45% of GHG emissions.

BOTTOM MARKET 5: TOW TRUCKING

Tow trucks are found in all classes and come in a variety of configurations designed for different towing needs. It is a relatively small application, estimated to account for 2% of sales. Due to low annual travel relative to fleet size, the tow truck market's impact on GHG emissions is estimated to account for less than 1%.

Tow trucking is a challenge for alternative fuels in part because many vehicles are operated by small fleets and operators, but more so because the operations of these vehicles are less predictable than most markets (Table 8). Many operators provide services on call and need fast and flexible refueling solutions to ensure trucks are ready for the next call. This, of course, has negative implications for alternative fuels.

TABLE 8: TOW TRUCKING ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivity	Impediment	Due to high rates of small owners/operators, sensitivity is likely muted in this market.
Ownership periods	Neutral	Trade cycle is around the average for MHDVs.
Publicly accessible refueling needs	Impediment	Due to small owner/operator rate and on-demand duty cycle requirements, near-term adoption will likely require fast and flexible solutions.
Rural operations	Advantage	High rate of urban operations relative to the bottom five markets.
Non-motive auxiliary loads	Advantage	Some non-motive energy demands, but not significant relative to other applications.

Source: Guidehouse Insights

BOTTOM MARKET 4: LOGGING TRUCKS

Logging trucks are typically Class 8 tractors. Some use specialized equipment to cut, trim, and place timber in trailers, but this is also often satisfied by heavy commercial off-road vehicles. This is the smallest of the bottom five markets with an estimated less than 1% of sales. Vehicle operations are regional, primarily focused to transporting rural timber harvests to mills, all of which is typically based in a rural setting. Guidehouse Insights estimates this market accounts for 1% of GHG emissions.

Logging is a challenge for decarbonization due primarily to public refueling infrastructure needs and rural operations (Table 9). Logging trucks also have nuanced challenges with weight, so much so that fully loaded logging trucks are currently prohibited from using interstates.[25] These weight issues are likely to increase concerns with using EVs or FCVs that are heavier than diesel-powered counterparts.

While there are challenges, there may also be nuanced opportunities. For example, a logging fleet on Vancouver Island, Canada, is looking to test EVs in its operations.[26] A basis for the test is that the regenerative braking capability of EVs may be highly attractive for displacing trucks that drive uphill empty and downhill fully loaded. The pattern presents an intriguing opportunity for charging EV batteries.

TABLE 9: LOGGING TRUCK ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivity	Neutral	Some industry and regional stakeholders may present pressure.
Ownership periods	Neutral	Trade cycle is around the average for MHDVs.
Publicly accessible refueling needs	Neutral	Common delivery points and mills present opportunities for alternative-fuels infrastructure.
Rural operations	Impediment	Operating environment is focused to rural areas, diminishing local air-quality and energy-efficiency benefits.
Non-motive uxiliary loads	Advantage	While some trucks operate equipment in the field, most energy requirements are focused to motive.

Source: Guidehouse Insights

25 The Safe Routes Act is currently being deliberated at the federal level to open access of interstates to logging trucks: H.R.2213—Safe Routes Act of 2021 (introduced March 26, 2021), available at https://www.congress.gov/bill/117th-congress/house-bill/2213/amendments?r=1&s=1.

26 Marc Kitteringham, "Electric logging trucks to be tested on Island," *Victoria News*, April 16, 2021, https://www.vicnews.com/autos/electric-logging-trucks-to-be-tested-on-island/.

BOTTOM MARKET 3: HEAVY CONSTRUCTION

Several vehicle types are included within the heavy construction market, including cement mixing, dump, excavation, mining, and drilling, among others. These vehicles are typically Class 6 through 8 and must haul and power superstructures relevant to their application. The market is the second largest of the bottom five, estimated to account for 2% of sales. With energy-efficiency losses tied to work-site energy needs, it is estimated to account for 2% of GHG emissions.

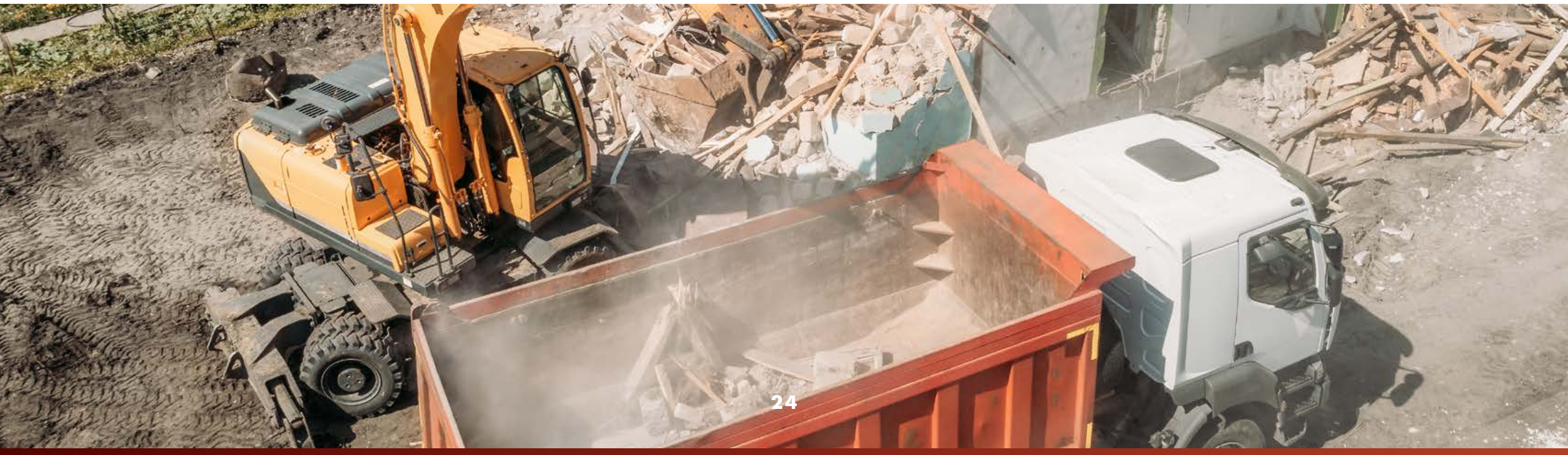
The market is a challenge for decarbonization due primarily to auxiliary load requirements (Table 10). The requirement varies by vehicle type and presents challenges that go beyond the energy-density disadvantages for decarbonization solutions. For example, concrete mixing has timing considerations for refueling since deliveries typically need to take place soon after cement is loaded in the truck. This could present risks for electrification as increased downtime for charging could reduce fleet flexibility. While there are challenges, some suppliers are developing zero-emission solutions. For example, Swiss construction firm Liebherr released its first all-electric cement mixer in April 2020.[27]

TABLE 10: HEAVY CONSTRUCTION ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivity	Impediment	Due to high rates of small owners/operators, sensitivity is likely muted in this market.
Ownership periods	Neutral	Trade cycle for vehicles is around the average for MHDVs.
Publicly accessible refueling needs	Neutral	Common work sites and/or fleet properties do present some opportunities for alternative fuels.
Rural operations	Neutral	Operations are mixed between urban and rural. Fleets in urban areas will likely see more pressure for alternative fuels.
Non-motive auxiliary loads	Impediment	Substantial power requirements are needed in environments where energy-density and refueling-network disadvantages may prove complicated.

Source: Guidehouse Insights

27 Jo Borrás, "Liebherr Releases First All-Electric Cement Mixer," *CleanTechnica*, April 2, 2020, https://cleantechnica.com/2020/04/02/liebherr-releases-first-all-electric-cement-mixer/.



BOTTOM MARKET 2: OIL AND GAS TRUCKING

Oil and gas trucking consists of moving liquids and gases to and from oil fields and more so delivering refined fuels to refueling sites. Vehicles in this application are Class 6 through 8, with a high proportion being Class 8 tractors. It is the second smallest of the bottom five, estimated to account for just over 1% of sales. Given relatively high annual travel with few non-motive energy needs, it is estimated to account for 2% of GHG emissions.

Oil and gas trucking is a challenge for decarbonization due primarily to limited stakeholder sensitivity (Table 11). Given the industry's focus on delivering petroleum products, the adoption of vehicles not using such products, specifically EVs and FCVs, is unlikely to attract significant support. Renewable fuels, primarily biodiesel and renewable diesel, are better positioned to tap this market.

TABLE 11: OIL AND GAS TRUCKING ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivity	Impediment	It is unlikely industry stakeholders will present pressure.
Ownership periods	Neutral	Trade cycle for vehicles is around the average for MHDVs.
Publicly accessible refueling needs	Impediment	Infrastructure will be needed along routes.
Rural operations	Impediment	Operations tend to focus on highway corridors or in rural areas/oil fields, diminishing local air-quality and energy-efficiency benefits.
Non-motive auxiliary loads	Advantage	Energy requirements outside of motive power are limited.

Source: Guidehouse Insights

BOTTOM MARKET 1: LONG-HAUL CARGO

Long-haul cargo is the largest of the bottom five markets, estimated to account for nearly 14% of sales. It relies on Class 8 tractors designed to provide both motive power and driver comforts, as often drivers sleep in the tractor cab during trips. On average, a new long-haul truck travels around 100,000 miles annually, the most of any application. Due to the market's large size and high utilization, it is estimated to account for the largest share of GHG emissions at 40%.

Long-haul cargo attracts a great deal of attention for decarbonization because the share of GHG emissions is so significant. However, the challenges are equally significant (Table 12).

TABLE 12: LONG-HAUL CARGO ATTRIBUTES FOR DECARBONIZATION

ATTRIBUTE	SCORE	RATING EXPLANATION
Stakeholder sensitivities	Neutral	Significant focus is on decarbonization of this market, however a high rate of small owners/operators presents a challenge.
Ownership periods	Impediment	Vehicle trade cycles tend to be the shortest of all MHDV applications.
Publicly accessible refueling needs	Impediment	Long-haul trucks require development of alternative refueling networks.
Rural operations	Impediment	A vast majority of operations are on highways, diminishing the opportunities for energy efficiency and local air-quality improvements of alternative fuels.
Non-motive auxiliary loads	Impediment	Trucks must be able to provide hoteling functions for drivers, a significant additional load.

Source: Guidehouse Insights

While the challenges are significant, progress is being made for electricity, hydrogen, and renewable fuels—specifically: renewable natural gas, and renewable diesel. It is, however, unlikely that developments underway will have significant impacts on their application before 2030.

For electricity, many improvements in battery technology are required, including energy density and durability. Density improvements are required to make the tractor weight competitive with diesel. Excess weight diminishes ratio of cargo capacity to overall vehicle and cargo weight limits. Durability improvements are required to ensure reliable performance under significantly greater charging capacities than have been introduced in the EV market. Currently, major EV suppliers are developing charging systems capable of delivering power capacities of more than 1 MW designed specifically for long-haul trucking. Delivering such charging capacities to these systems will be a significant development effort in and of itself. It is likely that sites would need to be built to enable peak capacities from 10 to 100 MWs, requiring development of dedicated substations and significant energy resources behind the meter. Industry stakeholders indicate the costs will be high and the deployment timelines long.

The challenges for electricity open an opportunity for hydrogen. Tanks for hydrogen can be filled more quickly than batteries charged, presenting benefits for reducing downtime. Hydrogen tanks are also lighter than batteries, which decreases cargo-capacity concerns. Development of distribution via tanker truck and/or pipeline can also outpace the development of equivalent grid capacity. Development of renewable hydrogen relative to renewable electricity is however a concern. Additionally, FCVs and hydrogen do not have significant momentum coming from increased scale in other markets, such as EVs have with the light-duty market. This means market suppliers and stakeholders must make significant investments for extended periods to achieve scale.

Renewable fuels through liquid and gaseous infrastructure can be a partial solution, however, availability of renewables through the existing refueling infrastructure networks is a concern as third parties may not offer renewable options at refueling sites. Because such a gap exists, fuel retailers will need signals from customers and customers will need price signals from suppliers. Here, government policies to price renewable fuel benefits can aid in increasing availability among public network retailers.

Conclusions and Recommendations

In the U.S., MHDVs account for nearly 30% of road-transport emissions and 7% of overall GHG emissions. As a significant contributor to GHG emissions, the industry is being encouraged to move toward decarbonization quickly. To get there, massive investments need to be made across the supply chain to develop renewable resources, distribution infrastructure, and the enabling vehicle technologies. These investments need the support of governments and major corporations keen to see GHG emissions reduced.

A critical support mechanism for decarbonizing road-transport markets has been standards for vehicle efficiency and fuel carbon intensity. To date, these have primarily focused on the larger GHG emissions reduction opportunity: light-duty vehicles. While the regulations have produced successes, such as the introduction of and gradual growth of EVs, these regulations will not translate well directly to the MHDV market. This market is far more complex with infrastructure, technical, and adoption rigors far more challenging. As such, it is yet unclear which decarbonization pathway will fit best in many applications.

In designing the policies to decarbonize the MHDV market, the constraints of the many varied MHDV applications must be considered. As such, it is important that policies be open to a wide range of decarbonization solutions and that policy targets be feasible relative to the abatement difficulty of MHDV applications and government support guarantees. Critical components for future policies include:

- **Policy targets aligned to the viability of decarbonization by MHDV application, the feasible timelines for infrastructure development thereof, recognition of costs thereof, and financial mechanisms or commitments to reduce uncertainty regarding policy viability.**
- **Increased financial support mechanisms to spur renewable energy resource development and decrease carbon intensity of all transportation fuel pathways.**
- **Holistic accounting of emissions by considering vehicles and fuels as an integrated system rather than independent components to ensure fair competition between decarbonization solutions.**

As identified in this analysis, decarbonization technologies are best positioned to penetrate MHDV applications that account for nearly 50% of the market and 42% of GHG emissions; in contrast, 20% of the market is poorly positioned for decarbonization but accounts for 45% of GHG emissions. In between is roughly 30% of the market accounting for 13% of GHG emissions. Included in the in-between are a variety of markets including those vehicles serving electric utilities, telecommunications, governments, emergency services, and agriculture, among others. Each presents a variety of challenges and opportunities for decarbonization both similar and different to the top and bottom five markets. This underscores the complexity of the MHDV market and the difficulty that will come in decarbonizing.

As policymakers and corporations set targets for the MHDV industry, it is critical that more research be undertaken to inform decarbonization across all applications. This research needs to inform the near-term realization of decarbonization opportunities, such as what existing policy tools and financial mechanisms can be leveraged to accelerate fleet interest in decarbonization and what standards and practices need to be developed to expedite infrastructure development.

For the challenging, long-term applications, research needs to focus on innovation and evaluate how quickly innovation can diffuse across the many dimensions of the market. Funding for pilot studies and demonstrations is needed to gain real-world data, experience, and stakeholder confidence. The data from these activities can then be used to inform targets for MHDV decarbonization that are more feasible and therein more reliable, undergirding market supplier and investor confidence in decarbonization investments.

About the Fuels Institute

The Fuels Institute, founded by NACS in 2013, is a 501(c)(4) non-profit research-oriented think tank dedicated to evaluating the market issues related to vehicles and the fuels that power them. By bringing together diverse stakeholders of the transportation and fuels markets, the Institute helps to identify opportunities and challenges associated with new technologies and to facilitate industry coordination to help ensure that consumers derive the greatest benefit.

The Fuels Institute commissions and publishes comprehensive, fact-based research projects that address the interests of the affected stakeholders. Such publications will help to inform both business owners considering long-term investment decisions and policymakers considering legislation and regulations affecting the market. Research is independent and unbiased, designed to answer questions, not advocate a specific outcome. Participants in the Fuels Institute are dedicated to promoting facts and providing decision makers with the most credible information possible so that the market can deliver the best in vehicle and fueling options to the consumer.

For more about the Fuels Institute, visit fuelsinstitute.org

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