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LINEHAUL TRUCKING SYSTEMS DECARBONIZATION ANALYSIS

Master's Practicum

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CENTER FOR
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UNIVERSITY OF MICHIGAN

Linehaul Trucking Systems Decarbonization Analysis

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Professor Gregory Keoleian

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Executive Summary

Greenhouse gases (e.g., carbon dioxide, methane, and nitrous oxide) emitted by human activities are inarguably contributing to a changing climate. The transportation sector – which relies heavily on combusting fossil fuels such as gasoline and diesel and has long been a dominant contributor to greenhouse gas emissions – must be part of the solution to reduce emissions. This report explores the ways in which linehaul (heavy truck freight traveling long distances) can decarbonize. Both short-haul (commercial trips less than 250 miles from start to finish) and long-haul (trips over 250 miles) trucking are evaluated. The report focuses on three diesel truck alternatives: renewable natural gas (upgraded biogas) trucks, battery electric trucks, and hydrogen gas-powered fuel cell electric trucks.

This report analyzes the opportunities and challenges that multiple alternative powertrains present and addresses how each powertrain could be used to advance decarbonization and zero-emissions initiatives, depending on the priorities of linehaul owners. It seeks to guide further research and investments so that the linehaul transportation industry can move past technical limitations into a position where trucking decarbonization can be a reality.

Research insight was based on an extensive literature review, the Argonne National Laboratory's transportation emissions and economic modeling tools, academic and fuel-vendor interviews, and a summer internship on Amazon's Transportation Sustainability team. The Argonne models used were the 2019 versions of Greenhouse gases, Regulated Emissions and Energy in Transportation (GREET) and Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET).

Five criteria were determined to influence the fit of alternative powertrains for linehaul trucking: greenhouse gas reduction potential, vehicle availability, vehicle functionality, cost, and scalability. Ability to meet zero-emissions vehicle targets is a consideration within the greenhouse gas reduction criterion. Alternative transportation systems become competitive when their total cost of operations are near diesel parity, their carbon footprints from well-to-wheel (across the fuel supply chain, including fuel use) are lower than the diesel vehicle status-quo – especially if they approach zero emissions, and if they are scalable. All three powertrains can, under the right conditions, improve upon the emissions scenario of business-as-usual diesel dependence. All alternative powertrains require a facilitative market and policy environment.

Analysis and Results

Summarized below are the findings from the literature review and independent analysis for this report. Each diesel alternative was evaluated against the five criteria outlined as determinants of a successful, sustainable linehaul decarbonization transition.

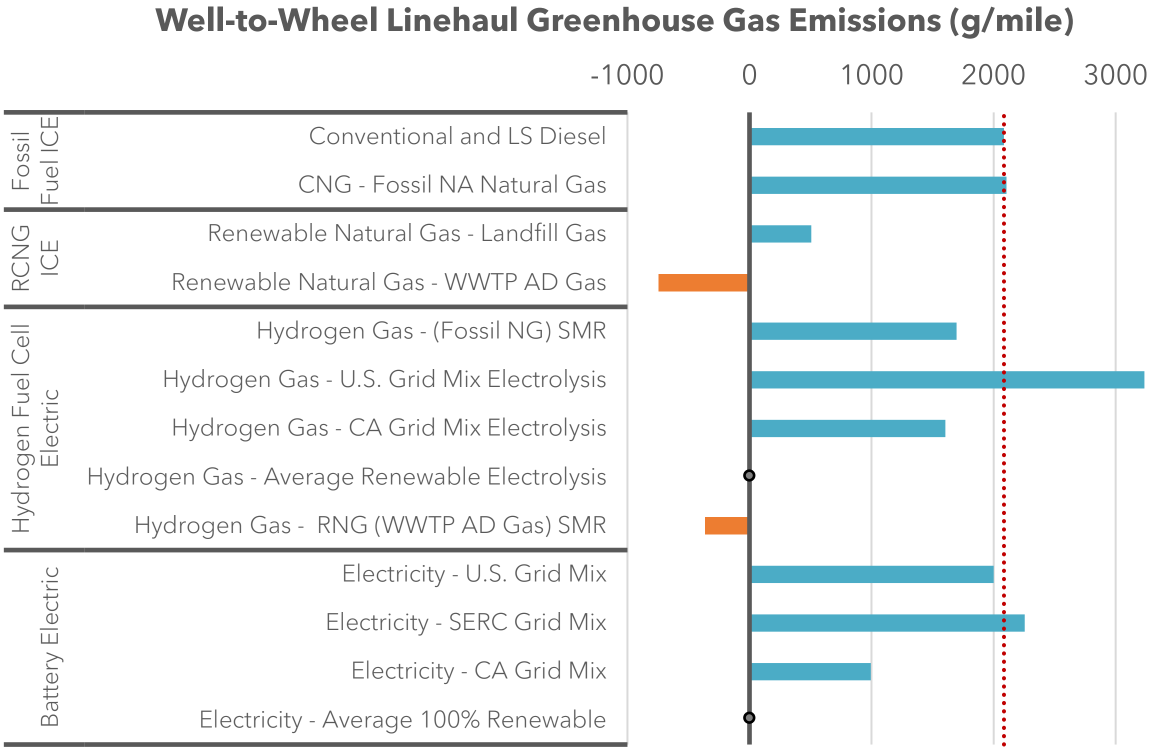
Greenhouse Gas Reduction Potential

Natural gas vehicles emit tailpipe emissions so they cannot be "zero-emissions vehicles" but electric powertrains – both battery electric and hydrogen fuel cell electric – qualify as zero-emissions vehicles because they emit no harmful tailpipe emissions.

It was determined that anaerobic waste-to-energy production pathways for renewable natural gas offer the greatest net greenhouse gas emissions reductions from diesel of any biogas production process – in some cases more reductions than any other powertrain can offer. Repurposing waste biogas resources and processing them for combustion in renewable compressed natural gas vehicles (RCNGVs) can offset more emissions than are released from the vehicles' tailpipes (making them net-carbon-negative), or at least reduce emissions about 75% from a diesel baseline. Liquefying natural gas or hydrogen resources results in higher well-to-wheel greenhouse gas emissions than when the fuels are used in their compressed gaseous forms. Consequently, gaseous fuel is recommended for natural gas and hydrogen fuel cell electric trucks.

Hydrogen production in today's market is largely reliant on fossil fuels (Alternative Fuels Data Center, 2020c). Efficiency losses are a consistent challenge across hydrogen production pathways. As a result, the most sustainable approach to hydrogen production is renewable electricity water electrolysis. Though renewable natural gas could be used to create electricity or hydrogen and transfer some of its carbon-reduction benefits to electric powertrains, its greenhouse gas reduction potential would diminish due to process efficiency losses. Biogas resources are limited and better suited to natural gas vehicles or other sectors, given that renewable electricity from resources like wind and solar is plentiful and offers another transportation decarbonization route.

Renewable electricity yields zero fuel cycle emissions from battery and hydrogen fuel cell electric vehicles (BEVs and FCEVs). The low-carbon appeal of renewable electricity is countered by its intermittency. Grid networks, in contrast, are more reliable but not yet fully renewable. Though grid-powered electric vehicles qualify as zero-tailpipe-emissions vehicles and offer localized air quality improvements from diesel vehicles, their environmental impacts can be worse than diesel vehicles on a fuel cycle basis. Greener electricity sources in grid portfolios yield electric vehicles with lower fuel cycle emissions; not all grids yield electric powertrains with well-to-wheel emissions above diesel trucks. As the electricity sector moves to decarbonize as well, the footprint of grid-powered battery and fuel cell electric vehicles will improve.



E.S. Figure 1. Fuel Cycle Emissions from Linehaul Alternative Powertrains. Red dashed line is the diesel linehaul emission baseline. A list of abbreviations can be found in the body of the report.

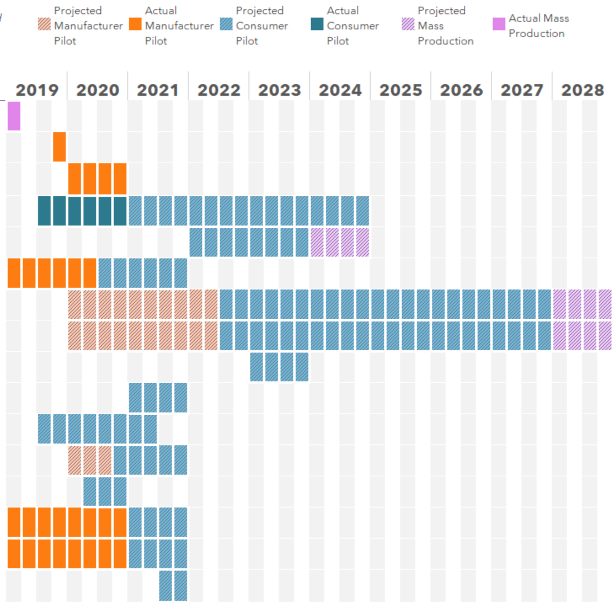
Vehicle Availability

Refueling station access is indicative of linehaul market prevalence. Whereas diesel and natural gas trucks made by various manufacturers have been in use for years and there are many stations to support them, heavy-duty electric trucks are trailing the development of their electric light-duty counterparts. There are, however, many new players in the battery and fuel cell electric truck markets competing for investments.

TIMELINE

Manufacturer operation specifics are confidential. This timeline is based upon publicly available information and should not be considered a complete projection. Any projections for past/present quarters not confirmed to have occured are not considered "actualized." Further, in light of COVID-19, these dates - which were projected before the pandemic - are subject to change.

MANUFACTURER	VEHICLE TYPE	PROTOTYPE BUILT	PILOT VEHICLE READY FOR CONSUMER TRIAL	MASS PRODUCTION
Cummins Westport *(OEM + Manufacturer)*	CNGV Engine for Multiple Vehicles	Yes	Yes	Yes
	Class 8 Hydrogen Fuel Cell Day Cab	Yes	No	No
Kenworth/ Toyota	Class 8 Hydrogen Fuel Cell Day Cab	Yes, NA only.	No	No
Hyundai	Class 8 Hydrogen Fuel Cell Rigid Truck	Yes	Yes, for EU deployment, not NA.	
	Class 8 Hydrogen Fuel Cell Day Cab	No, but tractor design released.	No	No
Nikola	Class 8 Hydrogen Fuel Cell Sleeper	Yes, NA only. First Nikola semi-truck prototype.	No, planned for late 2020.	No
	Class 8 Hydrogen Fuel Cell Day Cab	Yes, NA only.	No	No
	Class 8 Electric Day Cab	Yes, NA only.	No	No
	Class 8 Hydrogen Fuel Cell Cabover	No, but design released. EU, Asia, and Australia.	No	No
	Class 8 Electric Cabover	No, but design released. EU, Asia, and Australia.	No	No
BYD Motors	Class 8 Electric Day Cab	Yes, NA only.	Yes	No
Volvo	Class 8 Electric Drayage Truck	Yes	No	No
Lion Electric	Class 8 Electric Urban Truck	Yes	No, planned for summer 2020.	No
Tesla	Class 8 Electric Day Cab, Shorter Range	Yes	No	No
	Class 8 Electric Day Cab, Mid-Range	Yes	No	No
Daimler Trucks/ Freightliner	Class 8 Electric Day Cab	Yes, NA only.	No	No



E.S. Figure 2. Tracking Developments in the Market for Alternative Powertrains.

Vehicle Functionality

Diesel fueling infrastructure is more prevalent than that of any of the powertrain alternatives, though natural gas freight vehicle fueling stations support an already large network of fossil natural gas vehicles and could be supplied with renewable natural gas – either via credit accounting or direct fuel delivery. Alternative linehaul trucks are not able to use all available fueling stations; many stations are configured to only accommodate light-duty vehicles – particularly the stations made for novel electric powertrains. Limited refueling infrastructure access feeds into the range limitations of each powertrain. Natural gas vehicle ranges can approach long diesel truck ranges, but battery electric vehicles cannot easily compete due to battery constraints. Battery electric trucks usually also repower slower than the other powertrains evaluated in this report. Meanwhile, hydrogen fuel cell electric vehicles have the potential to drive long ranges, but available technology has not proven this capability. Confidence in a vehicle's ability to traverse a desired range impacts consumer acceptance of alternative powertrains. Greater heavy-duty vehicle compatible fast fueling/charging infrastructure access along freight corridors will benefit every powertrain evaluated in this study, especially hydrogen fuel cell electric and battery electric trucks. Battery electric trucks are most range-limited and there are far fewer hydrogen fueling stations than natural gas, diesel or charging stations. Station development must be coordinated with vehicle fuel demand to avoid the high costs of low station utilization. Investments into more efficient fuel and renewable electricity production as well as higher vehicle energy economies would help to offset capital expenses and mitigate range concerns.

Cost

Compressed natural gas trucks are more expensive than their diesel counterparts but are far lower in price than novel electric powertrains. Prices for battery and fuel cell electric trucks will decrease from their anticipated starting points if electric linehaul achieves market acceptance. The renewable natural gas of interest in this report is produced in geographic pockets where the anaerobic digestion of organic waste is financially viable and logistically convenient to distribute. Coordinating fuel production in this way yields high fuel costs that dominate the total cost of operating a renewable natural gas truck. Without incentives, renewable natural gas trucks were consistently the most expensive systems modeled in AFLEET. Their costs were reduced significantly by federal and state fuel and vehicle incentives, after which, operating the powertrain was estimated to be cheaper than conventional diesel systems. Current incentives are structured as artificial commodities that drive the quantity of alternative fuels available on the market.

Across vehicle vocation types (delivery, long- or short-haul truck), battery electric vehicle costs came closest to diesel parity before incentives. Under state alternative fuel and vehicle incentives, the BEV powertrain offered total cost-reduction opportunities from a diesel baseline. Importantly, current Californian Low Carbon Fuel Standard incentives may overvalue credit offerings tied to the carbon reductions from energy used in battery (and possibly also fuel cell) electric linehaul, due to optimistic estimates of fuel economy relative to diesel trucks. Cost models conducted in AFLEET demonstrated that one difference in the regulatory scheme's BEV fuel economy metrics could shift the total cost after incentives of operating a battery electric truck by hundreds of thousands of dollars. As a result, electric linehaul adopters could leverage a financial bargain with California's Fuel Standard that overestimates their trucks' environmental benefits. Further investigation is encouraged to ensure that credit evaluations align with the energy efficiency and true environmental impacts of battery electric linehaul.

A shift towards renewable hydrogen production is necessary for fuel cell electric vehicles to offer net environmental benefits. Reliance on renewable electrolysis implies higher fuel prices than those of conventional hydrogen supplies. The total cost of conventional fossil-produced hydrogen fuel cell electric vehicle systems is already above parity with diesel because transportation applications of hydrogen have not reached economies of scale. Fuel cell electric vehicle applications of hydrogen from grid-powered electrolysis modeled in AFLEET consistently increased total cost of operations from a diesel baseline, regardless of state incentives. If transportation hydrogen applications grow to propel electrolyzer economies of scale and renewable electricity costs decrease, clean hydrogen fuel cell electric vehicles could become more financially feasible. Of all diesel short-haul truck alternatives in California evaluated in this report, fuel cell electric short-haul was the most expensive after incentives were applied.

Scalability

The appeal of natural gas vehicle and fueling station availability and functionality is countered by renewable natural gas production limitations. Renewable natural supplies will not scale to replace all diesel. RCNGVs' inability to qualify for zero-emissions vehicle targets further segments their applications in the linehaul market. Their market penetration also depends on alternative fuel vehicle incentives.

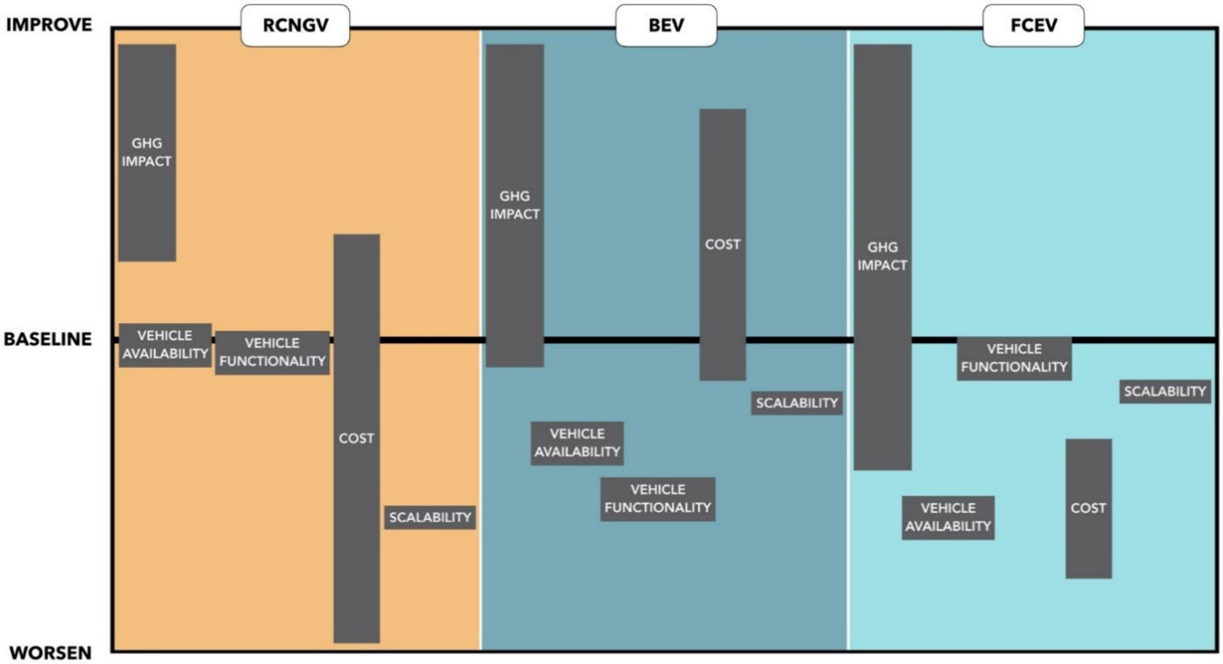
Electric powertrains are attractive zero-emissions linehaul alternatives and are eligible for zero-emissions vehicle incentives. However, renewable electricity and hydrogen supplies lag those of fossil fuels. Battery electric systems may be ahead of fuel cell electric but are unlikely to replace long-haul diesel trucks due to battery scaling limitations. FCEVs, in contrast, could serve as short- or long-haul diesel truck alternatives. Neither electric powertrain has proven ranges as long as those of diesel long-haul trucks. More research is needed to understand the resource implications of heavy-duty vehicle dependence on batteries.

Grid backups may be required for renewable production operations that lack storage or that operate on smaller scales, at the detriment to overall carbon intensity. Grid operators will need to manage the added demand of battery electric vehicle charging and hydrogen production/fueling. Further, while electric powertrains have been cited in literature for their potential grid smoothing and renewable energy storage properties, the schedules of linehaul networks may be more challenging than those of passenger vehicles to coordinate. Though linehaul driving patterns are more predictable than those of passenger vehicles, cost-effective freight delivery must be aligned with fueling schedules. Incentives could help linehaul networks and grid operators capture these benefits and ease an electric linehaul transition. Hydrogen production – which can be conducted without vehicles present – may be a more convenient form of storage than charging vehicles directly. Though battery swapping could afford similar fueling flexibility to BEVs, the approach is not yet the focus of battery electric linehaul manufacturers.

Comparison and Recommendations

Following a comparative analysis, this report draws conclusions to guide linehaul market segmentation. Between resource limitations, distribution constraints, and competition in biogas demand, there is not enough renewable natural gas for a complete linehaul transition in the United States and likely elsewhere. Renewable natural gas systems are impractically expensive diesel alternatives without incentives. Yet, renewable natural gas trucks can be attractive for some fleets with certain priorities: potential for carbon negativity; easy, rapid adoption; widespread fuel infrastructure access; and long mileage (fewer range concerns). Depending on how strongly linehaul managers favor these characteristics and how large a fleet they intend to operate, they may or may not want to fully commit to renewable natural gas. It offers a bridge to full decarbonization but may never approach diesel cost parity without fuel incentives and will not meet zero-emissions vehicle targets. Combustion of renewable natural gas onboard trucks still has detrimental impacts to air and water quality.

The zero-emissions battery electric powertrain is best aligned with short-haul trucking. Short-haul battery electric trucks perform better than long-haul versions and better than fuel cell electric short-haul trucks on a well-to-wheel emissions basis. Battery electric linehaul efficiency is range-limited to short-haul. Unconventional battery electric charging technologies like wireless power transfer or battery swapping could be convenient ways to expedite charging and alleviate the range anxiety of battery electric linehaul operators, but investment into these technologies for linehaul is minimal at present. Battery technology is evolving rapidly, so battery environmental and cost implications create some uncertainty in this assessment of electric linehaul. Battery electric trucks may be widely available on the market faster than fuel cell electric trucks, and their charging networks certainly have a head start over hydrogen fueling. Adopting BEVs was also shown to be consistently cheaper on a total cost of operations basis than a fuel cell electric truck transition from diesel. Linehaul operators intent on zero-emissions truck targets who plan to drive long-haul or who need especially fast refueling will be best served by fuel cell electric vehicles that can leverage higher hydrogen gas energy density than what pure battery electric systems offer. Fuel cell electric truck total operating costs are significantly higher than diesel. By the time that fuel cell electric truck manufacturers establish their designs on the market and seek economies of scale, long-haul trucking may be a niche market; the hub-and-spoke trucking model that constrains freight routes to short-haul is logistically attractive and is becoming more widespread (Penske, 2020). Thus, as linehaul shifts toward regional haul, it is probable that battery electric vehicles will dominate the sector’s demand for zero-emissions vehicles, especially if fast charging station access increases.



E.S. Figure 3. Possible Performance of Each Powertrain Against the Five Criteria, Relative to a Diesel Baseline. The vertical length of each grey bar denotes the range in potential outcomes, depending on different conditions (change in feedstock energy, presence of incentives, etc.). Further, the best-case GHG impact scenarios are shown to be equivalent across the three alternatives, even though it is not so simple; their relative improvements upon diesel depend on priorities: zero-emissions vehicle potential, avoiding fossil fuel combustion, or net-carbon negativity. This chart is meant as a visual aid to summarize report findings but is not to scale.

There are multiple ways to facilitate market penetration of alternative fuel vehicles. Sometimes, eliminating one barrier to adoption appears to hinge upon the elimination of another. A multipronged set of initiatives engaging stakeholders, guiding researchers, and developing policy at regional, national and international levels would accelerate alternative fuel vehicle development.

Acknowledgements

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

- ANL: Argonne National Laboratory
  - AFLEET: Alternative Fuel Life-Cycle Environmental and Economic Transportation (ANL tool)
  - CIDI: Compression-ignition direct-injection
  - FCV: ANL uses this to abbreviate “fuel cell (electric) vehicle” – not used elsewhere in report
  - GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation (ANL tool)
  - G.H2: ANL uses this to abbreviate “gaseous hydrogen” – not used elsewhere in report
  - L.H2: ANL uses this to abbreviate “liquid hydrogen” – not used elsewhere in report
  - SI: Spark-ignition
- BFL: Biofuel
- BEV/EV: Battery electric vehicle/ electric vehicle
- CA: California
- CARB: California Air Resources Board
  - EER: Energy Economy Ratio
  - HVIP: Hybrid and Zero-Emission Truck and Bus Voucher Inventive Project
  - LCFS: Low Carbon Fuel Standard
- CI: Carbon intensity
- DGE: Diesel gallon equivalents
- DOE: United States Department of Energy
  - AFDC: Alternative Fuels Data Center (in DOE Office of Energy Efficiency & Renewable Energy)
- EDF: Environmental Defense Fund
- EIA: United States Energy Information Administration
- EISA: Energy Independence and Security Act
- EPA: United States Environmental Protection Agency
  - GHGI: Inventory of U.S. Greenhouse Gas Emissions and Sinks
  - RFS: Renewable Fuel Standard
    - OP: Obligated Party
    - RIN: Renewable Identification Number
    - RVO: Renewable Volume Obligations
- EU: European Union
- FCEV: Fuel cell electric vehicle
- GHG: Greenhouse gas
- GVWR: Gross Vehicle Weight Rating
- HDV: Heavy-duty vehicle

- ICE: Internal combustion engine
- IEA: International Energy Agency
- IPCC: Intergovernmental Panel on Climate Change
  - AR5: IPCC's Fifth Assessment Report
  - GWP: Global warming potential
- LCOE: Levelized cost of electricity
- LDV: Light-duty vehicle
- NA: North American
- NG: Natural gas
  - NGV: Natural gas vehicle
  - CNG: Compressed natural gas
  - LNG: Liquified natural gas
  - RNG: Renewable natural gas (biomethane)
    - AD: Anaerobic digestor
    - LFG: Landfill gas
      - MSW: Municipal solid waste
    - WWTP: Wastewater treatment plant
- NREL: National Renewable Energy Laboratory
- PEM: Polymer electrolyte membrane
- PHEV/HEV: Plug-in hybrid/ hybrid electric vehicles
- P2G: Power-to-gas
- PV: Photovoltaic (solar power)
- REC: Renewable energy credit
- R&D: Research and development
- SERC: SERC Reliability Corporation
- SMR: Steam methane reformation
- TCO: Total cost of ownership
- ULS/LS: Ultra-low sulfur/ low sulfur
- U.S.: United States
- WECC: Western Electricity Coordinating Council
- ZEV: Zero-emissions vehicle

I. Introduction

In 2018, researchers from the Institute of Energy and Climate Research, citing insight from the European Commission, noted that "while total emissions of European countries have decreased by 17% in the last 25 years, the transportation sector has been the only one that saw its emissions increase by 22% during the same period," (Directorate-General for Mobility and Transport (European Commission), 2015; Lahnaoui, Wulf, Heinrichs, Paristech, & Mar, 2018). The transportation sector is also the largest source of greenhouse gas emissions in the United States (U.S. Environmental Protection Agency, 2020g). Further, according to the U.S. Department of Transportation, trucking is the largest contributor to national freight-related air pollution. In fact, truck freight greenhouse gas emissions have increased five times faster than passenger travel emissions in the U.S. since 1990 (U.S. Department of Transportation, 2015). As U.S. truck freight movements are expected to increase ~45% between 2015-2045, linehaul systems must be considered for decarbonized sustainable development (U.S. Department of Transportation, 2015).

Performance improvements to conventional diesel trucks like aerodynamic drag reduction will not meet emissions-reduction targets. The trucking industry must transition away from diesel. Alternatives to fossil fuel-powered light-duty vehicles (LDVs) in short-distance transport are developing more rapidly than those for heavy-duty[1] vehicle (HDV) powertrains, but there are diesel alternatives for short- and long-haul trucks.

1.1 Purpose

Amazon Worldwide Sustainability proposed a suite of carbon reduction goals in conjunction with the public release of Amazon's carbon footprint in the fall of 2019. Shipment Zero was Amazon's initial public goal to make 50% of all shipments net-zero-carbon by 2030. Later, informed by its carbon footprint assessment, Amazon announced The Climate Pledge, its commitment to reaching net-zero-carbon across all of Amazon by 2040. The company has moved to electrify its last-mile fleet with a purchase of 100,000 electric delivery vans, set to deploy in 2021 (Coyle, 2020). Amazon is still developing its strategic approach to decarbonizing linehaul trucking. Carbon reductions can be achieved by reducing the well-to-wheel emissions of vehicle operations, while zero-emissions targets specifically require vehicles with zero tailpipe emissions. This research evaluated the potential of renewable natural gas, hydrogen fuel cell electric, and battery electric vehicles to reduce the carbon footprint of heavy-duty diesel linehaul trucking. This report makes recommendations for decarbonizing linehaul trucking activities in order to contribute to Shipment Zero and other net-zero-carbon goals.

1.2 Context

This report explores three existing and developing powertrain technologies to help plan low-carbon linehaul transitions. The first, renewable natural gas (RNG), is fuel derived from waste, repurposing decomposing resources that would otherwise release greenhouse gases directly to the atmosphere. RNG can be used in place of fossil NG in standard natural gas trucks. Because natural gas vehicles (NGVs) emit tailpipe emissions, RNG use does not meet zero-emissions vehicle standards, but could help its consumers meet net-zero-carbon targets. Meanwhile, two types of electric powertrains have potential as zero-emissions vehicles: battery electric vehicles (BEVs) and hydrogen-powered fuel cell electric vehicles (FCEVs). Electric powertrains are less mature than combustion engines but evolving quickly, so this report's literature review dedicates significant analysis to BEVs and FCEVs in order to encapsulate the opportunities and challenges ahead of these two developing technologies. Together, RNGVs, BEVs, and

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[1] U.S. Federal Highway Administration Class 7 and Class 8 vehicles; Gross Vehicle Weight Rating (GVWR; combined weight of passengers, the vehicle, fluids, and cargo) > 26,000 pounds (Alternative Fuels Data Center, 2020d).

FCEVs provide varying paths forward for a sustainable linehaul trucking sector. The basis for excluding other fuels and powertrains from this study can be found in Appendix A – Alternative Powertrains.

1.3 Policy Driving Zero-Emissions Vehicles

Across the world, as regions confront climate change and address pollution, there is a growing interest in increasing the adoption of zero-emissions vehicles. Policies targeting air quality improvements or greenhouse gas reduction are championing the potential of zero-emissions vehicles (ZEVs). ZEVs are so labeled because they create no tailpipe emissions. California has long been a leader in the transportation emissions regulatory space, recognizing the contribution of tailpipes to air quality since the '50s and '60s, and formally regulating ZEVs as of 1990, through its Low Emission Vehicle policy ("Zero-Emission Vehicle Program," 2019). Since then, California's Zero Emission Vehicle Regulation has been updated and worked into a broader set of standards labeled the Advanced Clean Cars Package. California aims to have 1.5 million ZEVs on the road by 2025 (Levinson & West, 2018). This ZEV mandate in California is focused on ZEVs as a volume percentage of LDVs on the road (not HDVs), but it signals a broader market interest in hydrogen fuel cell and battery electric vehicles. The ZEV mandate is in place through a waiver of the Clean Air Act:[2] California can set more stringent emissions standards than those of the U.S. Environmental Protection Agency, and other states may adopt California's regulatory approach if they deem the federal regulations insufficient (Barboza & Phillips, 2019). Consequently, Colorado, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont have adopted California's ZEV rules to date (Walton, 2019). Hawaii, Michigan, Nevada, and Ohio are also considering incentives for electric fleets (Karkaria, 2019).

Also in California, in 2018, the California Public Utilities Commission supported multiple utilities' transportation electrification proposals, amounting to $768 million that will, among other things, fund "installations for 15,000 medium- and heavy-duty vehicles across Northern and Southern California" (Karkaria, 2019). Regarding HDVs, the California Air Resources Board (CARB) is drafting an Advanced Clean Truck regulation, which if approved "will require medium- and heavy-duty vehicle manufacturers, that sell 500 or more vehicles in California annually, to produce and sell ZEVs as a percentage of their annual sales volume" as soon as 2024 (Neandross, 2019). California also passed a bill in 2017 targeted at HDVs purchased by its state agencies, requiring that "at least 15%" be ZEVs starting in 2025 and beginning in 2030, at least 30% of their HDVs be ZEVs (AB-739 State vehicle fleet: purchases., 2017).

In 2017, China modeled a "New Energy Vehicle" mandate for light-duty passenger vehicles, including FCEVs, off of California's ZEV policy (Cui, 2018). The European Union also made decarbonization targets for the transportation sector to "reduce oil dependency in transportation by 70% by 2050 compared to its 2008 level" (European Comission, 2011 via Lahnaoui et al., 2018). The EU does not have formal ZEV mandates, but created voluntary ZEV targets with compliance credits to help manufacturers meet corporate average CO_2 standards (The International Council on Clean Transportation, 2019). Though Canada does not have national ZEV policies, British Columbia passed its own ZEV mandate in 2019 that entails ZEV-percentage requirements for new vehicle sales for 2025 and 2030, leading up to 100% by 2040 (ZEVA Regulations Team - Clean Transportation Branch, 2019). Across the globe, it is likely that actors at the regional and national levels will modify and add to their emissions and vehicle targets as the work to combat climate change continues and leadership cycles.

Electric vehicles – both battery and fuel cell – are the two main powertrains considered by the International Energy Agency to be zero-emissions vehicles (Teter et al., 2019a). While battery electric vehicles use external electricity sources to charge, whereas power is generated onboard FCEVs, "both the BEV and the FCEV rely upon an electric powertrain, and thus the remainder of the vehicle can effectively be

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[2] Currently under dispute. See Policy Considerations - Future of Alternative Fuel Policy.

identical" (Offer, Howey, Contestabile, Clague, & Brandon, 2010). Both technologies have zero harmful tailpipe emissions; battery-powered EVs and FCEVs running on colorless, odorless, naturally abundant, and nontoxic hydrogen do not yield the same localized air quality or acid rain concerns as some conventional fuels in combustion engines (Suleman, Dincer, & Agelin-Chaab, 2015). Fuel cell electric and battery electric trucks present emissions reduction opportunities (compared to diesel) across their entire life cycles, though the amount depends on electricity source. ZEV requirements specify tailpipe impacts and do not inherently mean no emissions at all; non-renewable energy resources could yield significant upstream emissions. By capitalizing upon renewable electricity resources, the linehaul industry can use electric powertrains to reach zero-carbon targets across the entire fuel cycle (well-to-wheel, WTW).

Even regenerative braking – a common feature in BEVs and FCEVs – offers emissions reductions, given that the particulate matter emissions from diesel vehicles are largely a consequence of tire and brake wear (Lee, Elgowainy, Kotz, Vijayagopal, & Marcinkoski, 2018). It is worth noting that gross vehicle weight rating (GVWR) and usage patterns impact vehicle efficiency and thus the relative benefits of alternative powertrains. A simulation conducted by Lee et al. found that fuel cell electric tractor-trailers, which spend a larger share of driving time on highways over urban roads compared to other vehicle vocations, yield a smaller reduction in particulate matter emissions from regenerative braking than fuel cell electric drayage trucks from their respective diesel counterparts. Drayage trucks have the same vehicle build as tractor-trailers but concentrated vocational driving activity in urban areas, (where FCEVs demonstrate a greater margin of efficiency improvement over diesel) (Lee et al., 2018). The analysis included in this report demonstrates how different situations can play to a powertrain's strengths or exacerbate its limitations.

II. Methods

A thorough literature review informed much of the insight within this report. Scientific studies, economic and governmental reports, and industry perspectives informed the critiques of existing and future policy and technology development projections. Government reports from the U.S. and abroad were repeatedly consulted for emissions standards, vehicle and fuel infrastructure market characterization and innovation targets, as well as climate impact metrics.

For each of the criteria listed below, the key parameters and models used are outlined. Further explanation of the calculation methods and assumptions for the quantitative analyses conducted for Criteria (i) and (iv) are provided in their associated Appendices B and D, respectively.

2.1 Criteria for the Successful Adoption of Alternative Linehaul Systems

Five measures were used to evaluate the potential fit of alternative transportation systems for linehaul operators: greenhouse gas reduction potential, vehicle availability, vehicle functionality, cost, and scalability.

i. Greenhouse Gas Reduction Potential

Fuel cycle WTW emissions refer to emissions from well to pump (WTP, energy source to fueling station) and pump-to-wheel emissions (PTW, emissions tied to operating the vehicle). The greenhouse gas (GHG) reduction potential of a powertrain is characterized using a few common measures. Reference values of the global warming potentials of greenhouse gases, relative to carbon dioxide, were sourced from the Intergovernmental Panel on Climate Change. Total GHG emissions of an entire trip, vehicle (over its lifetime), or an entire business unit, can be summarized in one metric, carbon dioxide equivalents (CO_2e), based on various gases' potential to trap heat in the atmosphere relative to an equal mass of CO_2. Carbon intensity (CI, measured as gCO_2e/MJ fuel energy) is a measure of the life cycle greenhouse gas emissions per unit of transportation fuel, encompassing extraction, processing (refining), distribution, and use.

Carbon intensity per unit of fuel energy is commonly used in regulatory schemes, but the metric does not incorporate efficiency, so it is not completely representative of a vehicle's emissions benefit. Fuel economy must also be addressed. Dimensionless fuel economy ratios were used to reflect a fuel system's energy efficiency compared to a diesel powertrain baseline – see section 2.2 Approach to Energy Equivalencies, below. These ratios allow analysts to compare the change in GHG emissions relative to the amount of fuel energy needed to travel the same distance in comparable vehicle models using different powertrains. California's Low Carbon Fuel Standard (LCFS) is built around formally registering the carbon intensities of different transportation energy sources in the state, as well as certifying reference fuel economy ratios. The California average ultra-low sulfur diesel has a CI of 100.45 gCO_2e/MJ according to CARB (California Air Resources Board, 2020b). Therefore, alternative linehaul fuels must have lower vehicle-energy-efficiency-adjusted CIs to reduce emissions. A full table of efficiency-adjusted California Air Resources Board-certified CI scores for various fuel alternatives is shown in Appendix C.

While California is the American epicenter of alternative transportation developments, CARB's regulatory approach to registering existing fuel pathways was not the focus of this report's GHG calculations. It is useful to measure the carbon reduction potential of a fuel system normalized to distance traveled, gCO_2e/mile, in order to account for the fuel economy of the vehicle when using each fuel. A comparison of available powertrains using this measurement, as well as a haul-oriented gCO_2e/ton-mile metric, is in Appendix B. Appendix B's values come from modeling of GHG reduction potential conducted using Argonne National Laboratory's Greenhouse gases, Regulated Emissions and Energy in Transportation (GREET) 2019 model. Calculation methods and assumptions are explained further in Appendix B: Greenhouse Gas Footprint Models.

ii. Vehicle Availability

Vehicle development timelines (both for pilots and mass production) are a hurdle to fleet transitions. Internal combustion engine (ICE) vehicles are more mature than alternative technologies, and alternative powertrain developments have moved faster for light-duty (LDVs) than heavy-duty vehicles (HDVs). RNG and its associated vehicles are readily available today, whereas hydrogen fuel cell electric linehaul vehicles and battery electric linehaul vehicles are still in pilot stages. Estimates of alternative truck availability were based on light-duty vehicle development patterns; the relative rate of LDV powertrain deployments was assumed to carry over to the HDV market. Estimates are based on industry press releases and statements from companies and industry leaders quoted in market publications. These projections are inherently uncertain. It is not yet known how the COVID-19 pandemic's impacts on people and the economy across the planet will affect vehicle availability in the long term.

iii. Vehicle Functionality

Truck powertrains offer different power and range capabilities. Amazon and other linehaul operators have both short-haul trucks (which travel less than 250 miles/trip) and long-haul trucks (which travel routes greater than 250 miles) eligible for decarbonization. Each vehicle technology has a different range between fueling, which affects its suitability and economics for short- and long-haul. Vehicle functionality is also influenced by fueling infrastructure access. This section also addresses the different safety considerations each powertrain requires.

iv. Cost

The total cost of ownership (TCO) normalized to dollar per mile varies based on fueling and vehicle technology maturity and economies of scale. National and some state fuel standards include credit structures that reduce the cost of registered fuel alternatives. Alternative power sources like RNG, electricity, and hydrogen are more competitive with conventional fuel where there are policy incentives. Existing alternative fueling infrastructure is concentrated in areas where fuel is economically viable. Adopting alternative fleets will be easiest in regions with supportive policy. The costs to own and operate each powertrain were calculated using Argonne National Laboratory's Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) 2019 tool. Fuel and vehicle price data was supplemented using market insight from vehicle market publications and data from research publications, the U.S. Department of Energy and its Alternative Fuels Data Center, and the U.S. Energy Information Administration. Rough estimates of the value of incentives (subject to fluctuations in the alternative fuel credit market and the credit-sharing negotiations specific to each fuel supply contract) were informed by the California Air Resources Board's registered carbon intensities of diesel alternatives and by manipulating the 2019 version (1.3) of their Credit Price Calculator. A full explanation of cost parameters and methods used, as well as the resultant TCO estimates, can be found in Appendix D.

v. Scalability

Adoption of alternative fuel vehicles is impacted by concerns over deployment factors such as supply limitations and refueling-site access, which constrain vehicles' actualized driving range. Alternative fueling development will depend on incentives that drive low-carbon fuel and vehicle production, plus certainty in consumer demand for these fuels and vehicles that will drive alternative fueling station development. Even still, each powertrain has different limits on its capacity to support widescale linehaul vehicle transitions.

2.2 Approach to Energy Equivalencies

For gaseous fuels that are compressible, pressure and temperature ought to be noted if discussing gas volumes. To circumvent this problem, fuel is often measured in terms of Diesel or Gasoline Gallon Equivalents (DGE/GGE) to specify an amount of alternative fuel equivalent in energy to a gallon of conventional fuel. However, if considering use-cases for fuel (either when specifying demand quantities or when comparing vehicle carbon intensities) one cannot simply convert between fuels based on fuel energy content per unit mass. Energy efficiency varies across powertrains, meaning that one diesel gallon equivalent of energy will translate differently to an electric vehicle than it will to a CNG vehicle. Fuel economy ratios allow analysts to compare "expected energy use and associated greenhouse gas… emissions between different vehicles technologies and fuel types" (California Air Resources Board, 2018a). These values, which compare the utility of alternative energy sources relative to conventional fuel baselines, are evaluated and periodically revised based on vehicle performance metrics. Miles per diesel gallon equivalent of energy is a straightforward metric and is used often for HDVs.

Fuel economy ratios are estimates of emerging powertrains' fuel economies. Depending on the data referenced, some ratios are more/less conservative estimates of performance than others. The California Air Resources Board determines and certifies a set of Energy Economy Ratios (EER) for light- and heavy-duty gasoline and diesel alternatives. To establish these numbers, ideally identical vehicle models using two energy sources are compared, but in the event that perfect matches are not made, fuel consumption test data in different driving conditions for vehicles of similar size, weight, and function can be compared (California Air Resources Board, 2018a). After analyzing the data and observing patterns, analysts ascertain EER values to represent the efficiency of a type of alternative fuel vehicle across driving cycles and manufacturers; the EER is a ratio of an alternative vehicle's fuel economy relative to that of a conventionally fueled equivalent vehicle. For novel technologies like FCEVs, EERs are slightly uncertain and can change as technology advances.

This report defers to fuel economy relationships determined by Argonne National Laboratory (ANL) for greenhouse gas accounting (as shown in Appendix B) and fuel usage estimates for the cost models in Appendix D, but recognizes that the EERs determined by the California Air Resources Board are used on the market to quantify the energy use/emissions offset afforded by diesel alternatives when doling out low-carbon fuel incentives. Thus, EERs are used in the credit calculations included in Appendix D's cost models, and for reference, CARB's EER-scaled certified carbon intensities are shared in Appendix C. CARB's EER values were not needed to convert the GREET and AFLEET model outputs that quantified the overall environmental and cost implications of vehicles.

Heavy-Duty/Off-Road Applications ***(Fuels used as diesel replacement)***	
Fuel/Vehicle Combination	**CARB's EER Values Relative to Diesel**
Diesel Fuel or Biomass-based diesel blends	1.0
CNG or LNG (Spark-Ignition Engines)	0.9
CNG or LNG (Compression-Ignition Engines)	1.0
Electricity/BEV or PHEV Truck or Bus	5.0 **See Footnote 3*
H_2/FCEV	1.9

*Table 1. EERs specified by Low Carbon Fuel Standard Regulations from CARB as of January 2019. *The BEV EER of 5.0 may not be representative of linehaul[3] (California Air Resources Board, 2019a, 2019b).*

To account for different vehicle efficiencies when comparing emissions to a diesel baseline (gCO_2e per MJ of conventional fuel displaced), CARB divides its certified fuel CI by the dimensionless Energy Economy Ratio for the appropriate fuel-vehicle. Understanding fuel demand allows for an applied discussion of emissions released by different powertrains performing the same transportation function, relative to diesel for the purposes of this report. For example, heavy-duty hydrogen FCEVs have an EER of 1.9 relative to diesel according to CARB, meaning CARB expects that these FCEVs can do almost twice as much work with a unit of energy compared to heavy-duty diesel internal combustion engines. Thus, the fuel price could be twice as much per unit of hydrogen energy and still approach diesel TCO parity, because less energy is needed in the more efficient vehicle.

Comparing CARB's EER values to the fuel economy relationships built into Argonne's GREET and AFLEET models showed that Argonne is more conservative in its estimate of electric powertrains' fuel efficiencies relative to diesel baselines. Their linehaul CNGV fuel economy ratios (90% relative to diesel) match, likely because NGV technology is more mature, and thus its performance is better understood and standardized (Argonne National Laboratory, 2019b, 2019a). AFLEET's single unit long-haul model (a delivery straight truck) showed fuel economy values like CARB's HDV EERs, but the electric combination linehaul vehicles in Argonne's models had lower fuel economy ratios than CARB's EERs (see Tables 6 and 10 in the Appendix, compared to Table 1); Argonne's fuel economy ratios are between one and two for BEV and FCEV combination diesel vehicle alternatives (Argonne National Laboratory, 2019a, 2019b). ANL's models sourced their data on different vehicles' fuel economies from vehicle operations studies and Argonne's Autonomie vehicle energy consumption simulation tool (Argonne National Laboratory, 2019a). Meanwhile, CARB has one EER metric (5.0) for almost all types of heavy-duty battery electric trucks and gives the same simplified EER treatment to heavy-duty fuel cell electric trucks (California Air

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[3] CARB's initial battery electric truck EER (circa 2007) of 2.7 compared to diesel was updated to 5.0 in 2018, due to greater data availability. Analyzing the data from multiple studies showed that slow-moving battery electric trucks across GVWRs and classes have a higher EER (5-7 when at low speed duty cycles) than trucks moving at higher average speeds (EER of ~3.5 at highway speeds) (California Air Resources Board, 2018b). Then, because CARB anticipated that low speed applications of HDV BEVs would dominate in the next decade due to battery costs and range constraints, they selected an EER of five to be representative (California Air Resources Board, 2018b). However, because this paper is interested in linehaul, a lower number like 3.5 was deemed more appropriate for electric linehaul's EER relative to diesel trucks.

Resources Board, 2019b). This report recognizes that CARB's certified EER values may be oversimplifications of fuel economy ratios. It is likely that battery electric vehicles driving a larger proportion of their mileage at higher speeds would have lower EER values. This logic explains why the delivery straight truck more closely resembled CARB's data in GREET than the combination vehicles and is consistent with insight shared in July, 2020 by Argonne National Laboratory Energy Systems division researcher Xinyu Liu who worked on GREET's 2019 HDV model (California Air Resources Board, 2018a). It is for this reason that CARB's EER values were not relied upon to estimate fuel use for emissions accounting or cost estimates, only applied where they would be on the market – in LCFS credit calculations. Because fuel economy ratios are meant to aggregate the relative efficiencies of available powertrain alternatives compared to diesel, the values depend on what information was available about different automaker's trucks when the values were calculated and change over time as innovations improve vehicle efficiency. For the most part, the changes between sources do not substantially impact overarching decisions about powertrain viability.

III. Results: Alternative Powertrains of Interest

The following discussion of three powertrains is the first of two results sections in this report. It explains how each energy source could serve alternative linehaul – how supply could be orchestrated and how each powertrain would align with current approaches to heavy-duty linehaul. Each powertrain faces different limitations, so this results section also evaluates some potential workarounds that have been proposed by researchers.

3.1 Renewable Natural Gas

How can natural gas fuel linehaul trucks?

There are two types of natural gas vehicles: those that run on compressed natural gas (CNG) and those that utilize liquefied natural gas (LNG). Due to liquefied natural gas vehicles' larger environmental footprints (see below – Natural Gas Production Approaches and Resource Sustainability), compressed natural gas vehicles (CNGVs) are recommended. Compressed natural gas vehicles run on spark-ignited internal combustion engines. The gas (from either fossil or organic sources) is stored at high pressure in an onboard tank. To power the vehicle, the fuel pressure is reduced before it is "introduced into the intake manifold or combustion chamber" to mix with air using a fuel injection system before the mixture is compressed and then ignited (Alternative Fuels Data Center, 2020b). NGVs release tailpipe emissions through this process. Ultimately, they operate much like other conventional internal combustion engine vehicles.

Natural Gas Production Approaches and Resource Sustainability

Natural gas (NG), primarily composed of methane, is a fuel used in many sectors for heat, electricity, and vehicle operations (see Figure 2a) (U.S. Energy Information Administration, 2020b). It has been framed as an attractive transitional bridge fuel to a sustainable energy future due to its lower carbon dioxide (CO_2) combustion emissions per unit of energy: roughly 42% less than coal and 27% less than diesel (U.S. Energy Information Administration, 2019b). Natural gas could be an environmental improvement upon conventional fuels, but "potential climate benefits could be reduced or even delayed for decades or centuries, depending on the magnitude of methane (CH_4) loss from the natural gas supply chain," (Camuzeaux, Alvarez, Brooks, Browne, & Sterner, 2015). Natural gas is primarily methane, which has a global warming potential 28 times that of carbon dioxide on a 100-year time horizon (U.S. Environmental Protection Agency, 2020d).[4] Thus, on a unit-mass basis, methane is a significantly greater threat to climate change than is carbon dioxide. High methane leakage across the oil/ natural gas supply chain will reduce the carbon-reduction potential from conventional natural gas; NGVs using fossil natural gas present a

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[4] See Appendix B for a further explanation of global warming potentials.

potential well-to-wheel greenhouse gas emissions increase over diesel long-haul (see Appendices A and B). Many trucking sustainability projections exclude fossil-fueled NGVs from consideration (International Energy Agency, 2017; McKinnon, 2018). Consequently, fossil natural gas is not a low-carbon transportation solution evaluated further in this report; a detailed explanation of the decision to omit fossil natural gas vehicles can be found in Appendix A.

Alternatively, renewable natural gas can be used, which is chemically equivalent to fossil natural gas but produced from organic matter (Kovacs & European Biogas Association, 2013). RNG is compatible with existing natural gas networks and vehicles. There are two key production pathways for RNG. Organic waste streams can be processed via anaerobic digestion (AD) into a biofuel known as biogas. Specifically, biogas comes from decomposing municipal solid waste (MSW) underground in landfills and from AD of animal waste, wastewater biosolids, or other organic materials like agricultural crop residues (Argonne National Laboratory, 2019b). Biogas (a mix of CH_4, CO_2, N_2 and H_2, that is typically between 45% to 75% methane by-volume content) must then be upgraded to biomethane, so that the upgraded gas has a (generally 96% or higher) methane content sufficient to meet natural gas quality standards (Badurek, 2019; European Biogas Association, 2013; International Energy Agency, 2020). Only biomethane, otherwise known as renewable natural gas, is suitable for transportation. Besides upgrading biogas, the other RNG production pathway makes biomethane directly in a biomass gasification/methanation process (Alternative Fuels Data Center, 2020g). Feedstocks for gasification include woody biomass in addition to crop residues and municipal solid waste (International Energy Agency, 2020).

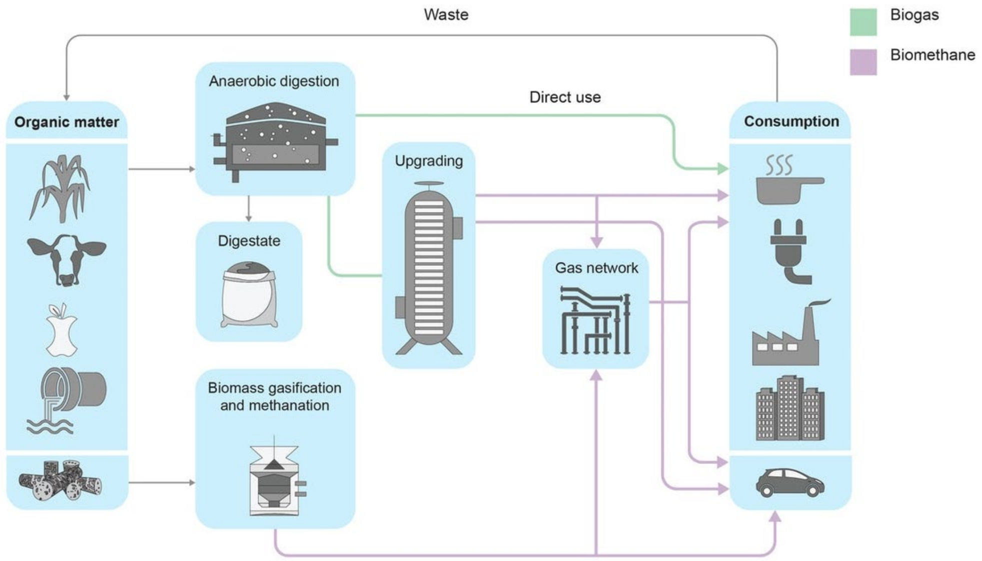

Figure 1. Biogas and Biomethane Supply Chain – Source: IEA (2020), Outlook for biogas and biomethane: Prospects for organic growth (International Energy Agency, 2020).

Most RNG in production today comes from upgraded biogas, and though biomethane resource studies project large potential supplies from biomass gasification, using dedicated energy crops for RNG presents many of the same concerns about upstream impacts that ruled out first-generation biofuels such as biodiesel from this study (see Appendix A) (International Energy Agency, 2020). This report excludes energy crop feedstocks for biomethane from analysis on the basis that energy crops require inputs (fertilizer, etc.) that crop residues and other waste streams do not. Consequently, biomass gasification for RNG is not considered in this report, much like it was excluded from the International Energy Agency's (IEA) 2020 outlook of sustainable prospects for biomethane (International Energy Agency, 2020). Better than growing biofuel crops like corn, using waste for fuel repurposes decomposing resources that would otherwise release greenhouse gases directly to the atmosphere (McKinnon, 2018). To illustrate, as of 2018, landfills released 15.1% of all anthropogenic methane emissions in the United States, making them the third-largest source (U.S. Environmental Protection Agency, 2020b). Reclaiming waste gas eliminates extraction and production well-to-pump (WTP) emissions (biogenic carbon at the Earth's surface is recycled rather than pulling more carbon from underground). Combining these carbon credits with the greenhouse gas advantage of methane combustion's lower carbon footprint and the convenience of an established natural gas distribution network, RNG may present the viable pathway for "increased adoption of NG as a HD transportation fuel" in place of diesel, but it still faces challenges (Clark, Johnson, et al., 2017; U.S. Energy Information Administration, 2019b). Biomethane is still subject to processing, distribution, transmission and vehicular leaks through the natural gas supply chain.

While the overall sustainability of modern commercial agricultural and waste disposal practices is questionable, the scope of biogas life cycle environmental assessments focuses on gas upgrading and use; the RNG industry utilizes other industries' waste, so the negative environmental impacts of the upstream processes are attributed to those agricultural, wastewater treatment, and landfill industries, not to RNG. Thus, RNG's fuel cycle emissions are significantly lower than those of conventional fuels. Background GREET modeling and a literature review conducted for this report also confirmed that liquefaction energy inputs yield higher WTW emissions for LNG compared to CNG-powered systems (Ou & Zhang, 2013; Ozbilen, Dincer, & Hosseini, 2018; Tong, Jaramillo, & Azevedo, 2015). Consequently, this report only evaluated RNG in CNG vehicles for future sustainable linehaul investments. The GREET 2019 model estimated an RCNG linehaul greenhouse gas emissions reduction of 75-135% from diesel vehicles (see Appendix B). Anaerobic digestion of manure and wastewater sludge yields the biogas that can provide the greatest carbon reductions from conventional fuels. The European Biogas Association noted an extra environmental benefit of anaerobic digestion of agricultural residues: "crop rotation and recycling of the nutrients and organic matter through digestate… improve the overall productivity of farms," (European Biogas Association, 2013). Note that organic matter gathered for anaerobic digestion at the detriment to sensitive wildlife/ecological zones is not sustainable. Exact RNG fuel cycle emissions reductions from diesel depend on the fuel feedstock; different farms, landfills, etc. may have a different set of crops or MSW composition. Consequently, individual suppliers' RNG may vary slightly in reported carbon intensity through certification schemes like California's Low Carbon Fuel Standard-registered fuel pathways.

RNG is often distributed through the same pipelines as conventional (fossil) natural gas. RNG flows are a small portion of the NG supply chain, but RNG financial investments indirectly support the environmentally unsustainable broader NG market and the shared leaking distribution infrastructure responsible for $2 billion-worth of methane leaks annually (Hausman & Raimi, 2019). Those interested in NGVs must recognize that any acquired fossil NG as a supplement to their RNG supply would severely diminish the environmental benefits of their investment. From a logistical standpoint, utilizing biogas for vehicles is better than wasting the gas by flaring it or releasing it directly to the atmosphere, but researchers at UC Davis found that distributing gas via pipelines can increase landfill gas (LFG) emissions by as much as 67%, compared to using it at its source. Essentially, it is not advisable to push biogas producers who already have a use for their gas to switch to supplying gas for transport if pipelines are required (Myers Jaffe et al., 2016). Ultimately, the value proposition for RNG as a transportation fuel is strongest when the supply chain capitalizes on an otherwise unused resource to provide fleet operators with a gas that mimics familiar fossil fuels.

Renewable Natural Gas Market – Availability and Logistics

Resource Availability

The volume of biogas supply and spread of collection and processing infrastructure requires further research and may be inadequate for large-scale linehaul networks. The National Renewable Energy

Laboratory (NREL) estimated the "U.S. total methane potential in raw biogas [to be] about 16 million tonnes, but the net availability [as] 6.2 million tonnes" as of 2014 (Saur & Milbrandt, 2014). This American biogas potential is equivalent to 6.39 billion diesel gallons per year, but as of 2014, only about 40% of those resources (2.49 billion DGEs) were available for use annually (see Table 2). NREL's assessment of availability was based on competing demands for the fuels (like existing combined heat and power plants using WWTP biogas) and the feasibility of building digesters or landfill gas recovery systems (Saur & Milbrandt, 2014).

NREL U.S. Biogas Assessment	**Total Methane Potential**	**Methane Available as of 2014**	**Total RNG Potential**	**RNG Available as of 2014**
	million DGE/yr	*million DGE/yr*	*Bcf/yr*	*Bcf/yr*
WWTP	935	770	122	101
Landfills	4232	981	553	128
Animal Manure	762	736	100	96
IIC* Organic Waste	463	0	60	0
Total	6392	2488	835	325

*Table 2. RNG Resources in the U.S., Modified from Saur and Milbrandt, 2014.[5] *IIC: industrial, institutional, and commercial sources like grocery stores (Saur & Milbrandt, 2014).*

Other studies published in the last decade on total U.S. biomethane potential – including RNG from biomass gasification – estimate enough RNG to supply about 10% of annual U.S. natural gas consumption; for context, the United States' total natural gas consumption in 2019 amounted to 31,014.3 billion cubic feet (Gas Technology Institute, 2011; M.J. Bradley & Associates, 2019; U.S. Energy Information Administration, 2020c). California's transportation sector alone used over 40 billion cubic feet of natural gas in just the third quarter of 2018 and 70% (over 30 million DGE) of it was biomethane (U.S. Energy Information Administration, 2019a). California was an early adopter of low-carbon transportation solutions and consumes more RNG than states without a strong emphasis on decarbonizing transportation. California is also one of the U.S.'s largest vehicle fuel consumers overall (Federal Highway Administration - Office of Highway Policy Information, 2014). At their rate of consumption, the amount of biomethane available nationwide (according to NREL's estimate, as seen in Table 2) would be enough to supply all of California's annual natural gas transportation needs, with leftover RNG for many other states. Further, the U.S. Energy Information Administration (EIA) has projected a Supplemental Natural Gas[6] production magnitude of just 60 billion cubic feet annually for the next 30 years (see Figure 2a) (U.S. Energy Information Administration, 2020b). The EIA anticipated insignificant growth in unconventional NG supplies like biomass gas, which is not a guarantee; the other studies of biomethane potential indicate that the biogas market can increase supply from current levels if presented with interested buyers. 60 Bcf of Supplemental NG is lower than the other studies' estimates of biogas availability, but all estimates of biogas supplies are consistently below nationwide transportation NG which has a projected demand around one trillion cubic feet annually (U.S. Energy Information Administration, 2020b).

The amount of diesel to be offset by RNG is much greater than the amount of fossil NG used in transportation. In fact, "the five states consuming the most diesel fuel [for vehicles in 2009] – California,

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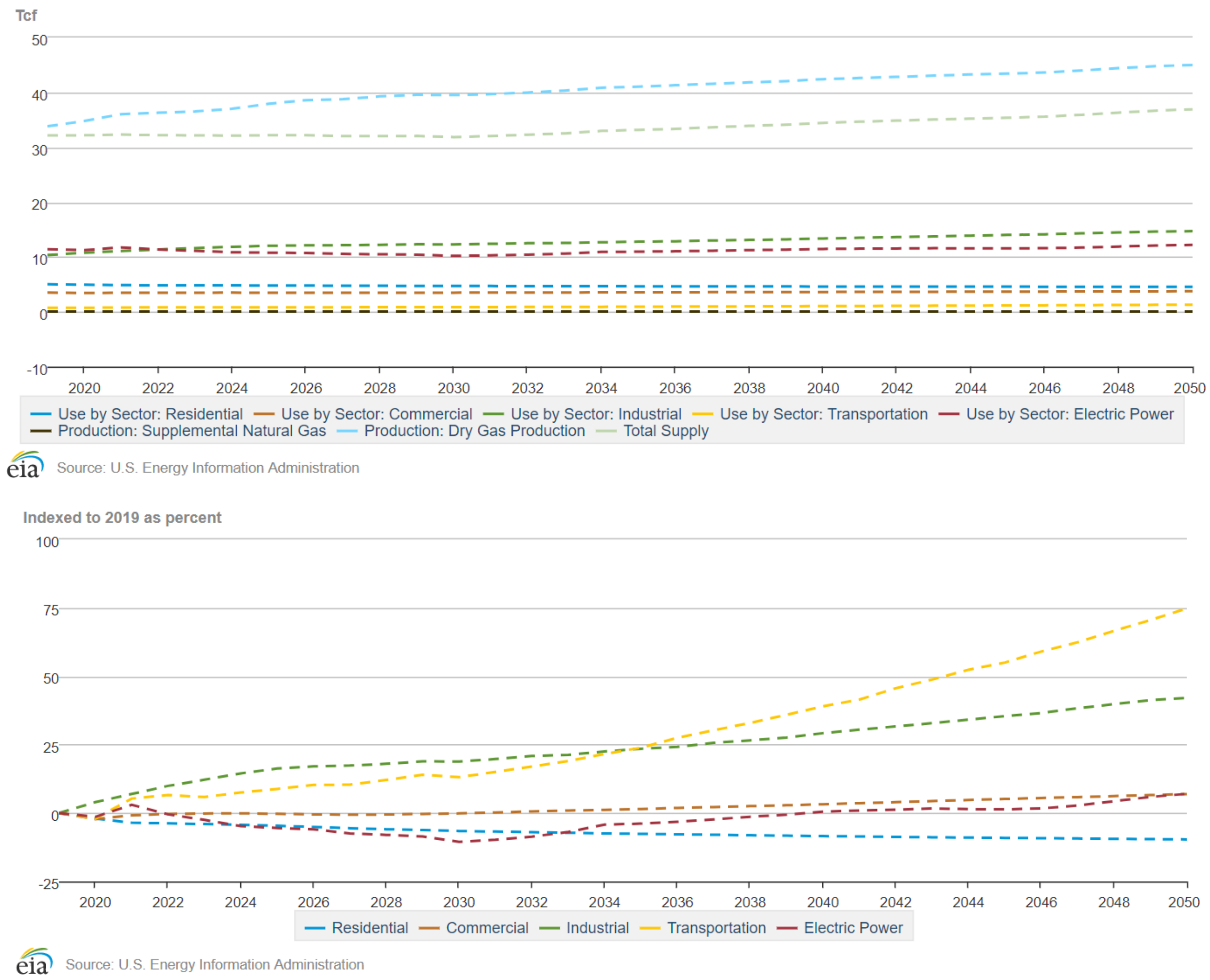
[5] Varying units provided for both energy and sales contexts, found using lower heating values (LHV) of conventional U.S. diesel (128450 Btu/gal), methane (962 Btu/cf), and NG (983 Btu/cf) at standard temperature and pressure from GREET 2019 and NREL's assumed methane density of 0.0413 lb/cf (Argonne National Laboratory, 2019).

[6] "Supplemental Natural Gas" includes biomass gas, among other unconventional NG production methods (U.S. Energy Information Administration, 2020b).

Illinois, New York, Pennsylvania, and Texas – [consumed] 11 billion gallons," which was only 30% of the diesel consumed by vehicles nationwide that year (Federal Highway Administration - Office of Highway Policy Information, 2014). Looking just at Class 8 trucks, which each consume 10,683 diesel gallon equivalents each year on average, America's 2,745,265 registered truck tractors (as of 2018) would need over 29 billion DGEs of fuel per year (Alternative Fuels Data Center, 2020i; Federal Highway Administration - Office of Highway Policy Information, 2019). The projected U.S. biogas supply is inadequate to replace all linehaul diesel vehicles in America with renewable NGVs.

Europe, by comparison, has approximately 918 billion cubic feet of biomethane potential from anaerobic digestion of wet biomass residues, in addition to larger potential biomass gasification feedstocks (Kovacs & European Biogas Association, 2013). The International Energy Agency noted that Europe dominates biogas production, citing European Biogas Association measurements that over 450 biomethane plants were in operation by the end of 2015 (International Energy Agency, 2017). While approximately half of their biogas production was used for heating in 2015, over 5.6 billion cubic feet of biomethane fueled European transportation that year, making Europe the leader in RNG for transport as well (Scarlat, Dallemand, & Fahl, 2018). As of 2016, Germany, Sweden, Switzerland, the U.K., and the U.S. were the top producers of biogas for transport (International Renewable Energy Agency, 2018). Global biogas production amounted to 1.33 exajoules in 2017 (World Bioenergy Association, 2019). China's government recently expressed interest in developing biomethane for transport and already produces a large amount of biogas, but about 70% of its current installed capacity comes from household-scale digesters for in-home use (International Energy Agency, 2020). Similarly, biogas is produced in many other parts of the world but is not necessarily meant to be upgraded for vehicle use, nor are all operations constructed to facilitate widescale collection and distribution.

There are multiple factors that will determine the gas's success as a transportation fuel. Biofuel production overall is not on par with the International Energy Agency's Sustainable Development Scenario targets (Teter et al., 2019b). Competition with other sectors for natural gas supplies mean that the full production volume potential will not be realized for the transportation sector. In fact, less than 10% of biogas produced in 2018 across the globe was upgraded to biomethane for transportation use (International Energy Agency, 2020). The EIA's speculation on future NG demand in the U.S. can be seen in Figure 2a&b; note that EIA projections have inherent uncertainty on large time scales. NG consumption is spread across residential, commercial, industrial, transportation and electric sectors, and there will be competition for the limited quantities of RNG, especially as other sectors (like electricity) also attempt to decarbonize. Who claims low-carbon-intensity RNG will likely depend on respective market incentives. Incentives for low-carbon fuels make RNG collection and distribution financially viable; without them, the full potential of renewable natural gas supplies is unlikely to develop. Assuming the cost to produce RNG decreases and demand for low-carbon transportation fuel increases over time, the availability of RNG for transport will grow.



Source: U.S. Energy Information Administration

Source: U.S. Energy Information Administration

Figure 2a&b. Natural Gas – Reference Case Future Projections; Projected Percent Changes in Natural Gas Use by Sector – Reference Case. "Total Supply" reflects the production of U.S. natural gas supplies, accounting for imports and exports. Produced using U.S. EIA Annual Energy Outlook 2020 Table 13 (U.S. Energy Information Administration, 2020b).

Noteworthy in the EIA's outlook on natural gas is the anticipated growth of natural gas demand for electricity, reflected in the Electric Power sector as well as the Industrial sector uses in Figure 2b – in which the EIA accounted for energy generation from combined heat and power plants (U.S. Energy Information Administration, 2020b). Pursuant of low-carbon energy policies like the Clean Power Plan, the electricity sector is eyeing natural gas as a reliable, cost-effective stepping stone away from coal combustion that is more than twice as CO_2-emissive per kWh (Ozbilen et al., 2018; United States Energy Information Administration, 2020). NG trucks (pickup, refuse, etc.), transit buses, and combination freight vehicles are all projected to expand their HDV market shares (H. Cai, Burnham, Wang, Hang, & Vyas, 2015). If NG HDV adoption outpaces the development of RNG resources, the transportation network would remain partially reliant on conventional fossil NG resources, which is suboptimal. Thus, if RNG will be insufficient to fuel future linehaul NGV fleets, fleet operators looking to decarbonize would be better served by other powertrains. In that event, the gas may be better used for "greening" the electricity grid. A lower-carbon grid is key for electric vehicles to be considered sustainable.

Logistics

Biogas resources are scattered around the country. In regions of concentrated agricultural operations, biogas resources are especially prevalent. In their assessment of biogas potential (for hydrogen production), NREL mapped the United States' resources, as seen in Figure 3. LFG resource potential is largest and its collection dominates U.S. biogas production, though the carbon intensity of biomethane from AD of agricultural and WWTP byproducts is lower than that of landfill gas. As of March 2020, the U.S. Environmental Protection Agency (EPA) reported 564 landfill gas collection projects in operation (U.S. Environmental Protection Agency, 2020f). As of 2017, there are also 1,269 wastewater treatment plants that have anaerobic digesters in the U.S., but very few industrial organic waste collection projects (Tanigawa, 2017). Additionally, there were roughly 250 anaerobic digestor systems running on manure from commercial livestock facilities in America in 2017 (AgSTAR, 2018). These reports of biogas production do not encompass how many sites are already using their gas onsite versus upgrading it for commercial vehicle fuel use. For example, about 860 of the American WWTP sites with digesters already use their biogas onsite – the rest have no use for the biomethane and flare it, releasing carbon dioxide instead (Tanigawa, 2017).

Generally, landfills that hold 2.5 million metric tons of waste or more are also mandated by the Clean Air Act to have LFG control systems, regardless of their intent to sell the gas for RNG (U.S. Environmental Protection Agency, 1996). This policy may be a factor in the large number of landfill biogas collection operations. Another possible reason for the fewer (by comparison) manure AD sites is the difference in capital investment required compared to gas payoff. Agricultural and industrial sources of organic waste require large capital investments in specialized anaerobic digestion systems, whereas the relatively simpler biogas collection and upgrading technology adjustments at landfills and wastewater treatment plants make biomethane from the latter sources cheaper to produce (Myers Jaffe et al., 2016). To that end, distribution costs limit biogas availability for the transportation sector. If farms or other remote biogas producers are not near natural gas pipeline access points, and onsite storage capital costs preclude trucking biomethane to offsite consumers, then a potential biogas project may not come to fruition without financial incentives (Krich et al., 2005). Economies of scale also favor landfills. Only the large (high animal head-count) dairy and swine farms create sufficient manure to justify investment, and manure still yields less methane than other decomposing organic sources (AgSTAR, 2018; Myers Jaffe et al., 2016). Higher investment would be needed to provide the same amount of RNG as a single landfill.

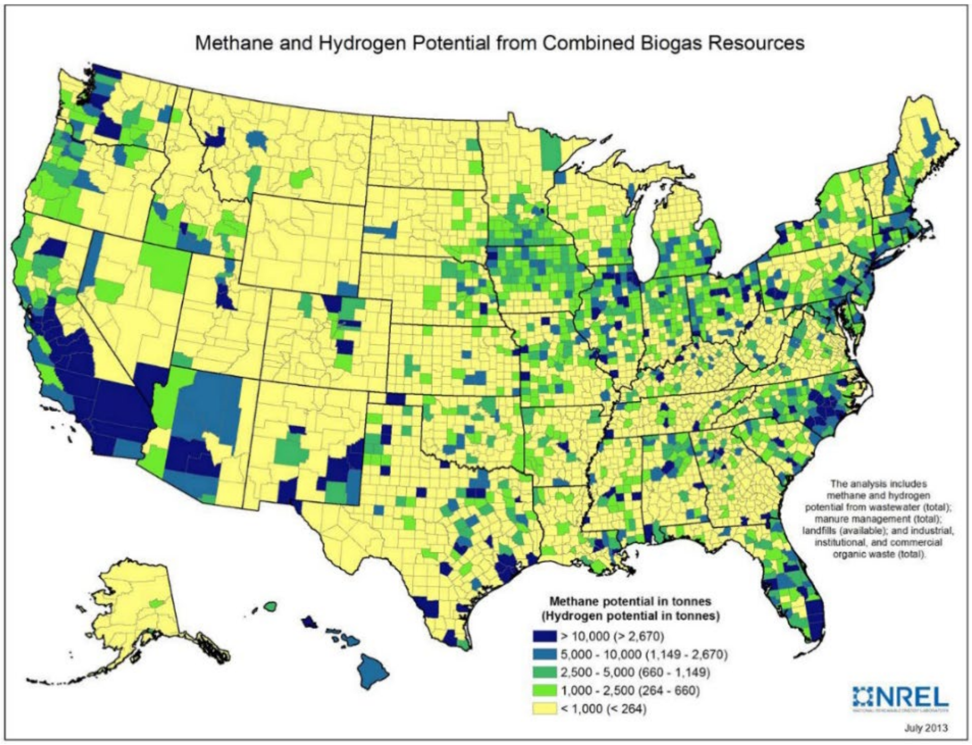


Figure 3. Representation of Regional Biogas Potential, Reprinted from Saur and Milbrandt. Original study evaluated this biogas potential for subsequent conversion to hydrogen (Saur & Milbrandt, 2014).

Due to North America's highly developed natural gas distribution infrastructure, consumers of gas are not limited to the biogas sources in their state. A linehaul operator can coordinate RNG deals that guarantee a supply of biogas enters natural gas pipelines. Whether or not the purchased biogas is the same set of methane molecules the consumer collects at a natural gas station is less relevant as far as carbon accounting and fuel-credit allocation is concerned; RNG consumers support the presence of biogas in the NG supply chain and are usually considered for their contributions to carbon emission reductions much like consumers of Renewable Energy Credits in the electricity sector. One caveat is that states and other incentive-providers may restrict where consumers of RNG source their fuel in order to be eligible for low-carbon fuel credits. Oregon, for example, could require that RNG come from farms and landfills within the state, perhaps to bolster local biogas production industries. If desired, natural gas can even be transported from producer to consumer via storage tanks on trucks. But in general – U.S. or elsewhere, natural gas distribution networks disperse gas from many sources to many consumers – certain "greener" supplies of gas are not physically going to specific consumers. Unless biomethane is used at the same site at which it is produced or it is shipped directly to a customer, tracing the gas becomes complicated, hence the carbon accounting approach.

Fueling Types

NGV fueling stations also reflect renewable natural gas access. Compressed natural gas stations offer either slow time-fill or fast-fill refueling. The two types vary in their approach to compressing an NG supply for vehicle use: in real-time, or in advance with compressed storage onsite, respectively (International Energy Agency, 2017). Multi-hour time-fill is compatible with fleets that can refuel overnight, while more expensive fast-fill stations can restore an NGV's supply in minutes, making fast-fill better for retail (Gorrie, 2014). Approximately 738 publicly accessible refueling stations are compatible with heavy-duty compressed natural gas vehicles in North America, as seen in Figure 4 (Alternative Fuels Data Center, 2020f). There are more than 80 times as many diesel stations in the U.S., leading some freight operators to lament a comparative lack of natural gas refueling stations (Diesel Technology Forum, 2020; Wagner & U.S. Census Bureau, 2020). While there may be fewer options for drivers to stop and refuel, there are many stretches of the country with sufficient station access to accommodate the onboard fuel capacity of CNGVs; operators using fixed routes in regions with high natural gas fueling station concentrations ought not to be concerned with nationwide station numbers. Instead, operators should focus on the availability of stations en route with the right fueling speeds to accommodate their specific travel plans. Station presence will inevitably increase with the rise in natural gas for transportation predicted by the EIA. Furthermore, fleet operators have significant flexibility thanks to the range capabilities of modern natural gas linehaul vehicles.

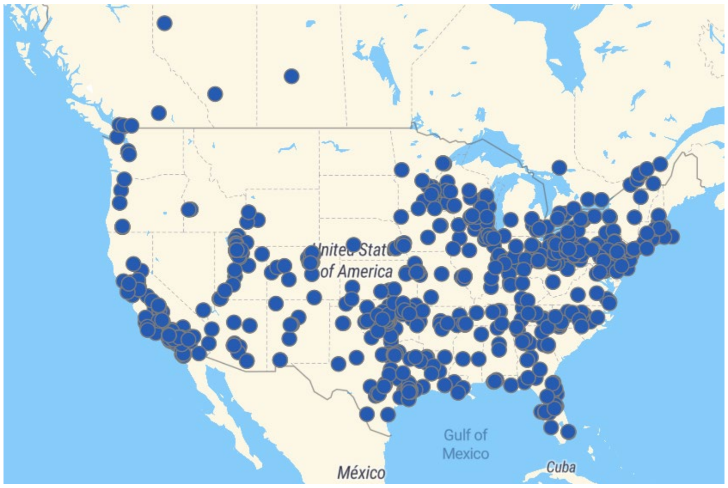


Figure 4. Public HDV-compatible CNG fueling stations in North America (Alternative Fuels Data Center, 2020f).

Vehicle Functionality

Safety

Chemical odorants are added to natural gas, which is otherwise colorless and odorless (Alternative Fuels Data Center, 2020e). The associated sulfur smell can warn of natural gas leaks and mitigate the risk of the gas igniting outside of NGVs. Flammability is not a concern unique to NG – diesel, hydrogen, and gasoline vehicles carry their own explosion risks. However, the high compression of gas in CNG cylinders requires extra precautions (Alternative Fuels Data Center, 2020e). As a well-established transportation fuel, NG is subject to fuel management safety codes which would ease an NGV transition.

Range

LNG vehicles have a higher range than CNGVs – because liquid fuel has a higher energy density – and have historically been promoted for long-haul over CNG. CNGVs have consistently been capable of short-haul demands. To add range to CNGVs, more onboard gas tank storage is required, which adds weight and consumes space. However, the range of CNGVs and LNGVs are converging as CNG storage becomes more efficient (Jensen, 2015). CNG vehicle storage configurations are now able to provide 1,000-mile ranges if desired, making them competitive with diesel vehicles for both short- and long-haul (Park, 2014). Fleet managers interested in the longest ranges for CNGVs must be willing to compromise some freight capacity for increased fuel capacity onboard. It is a common tradeoff for freight vehicles – designers of other powertrains in this report also grapple with fitting enough power to efficiently deliver cargo over long ranges. If HDV CNG fueling station access grows, concerns over range limitations will also diminish.

Vehicle Market

Natural gas linehaul vehicles are mass produced by many vehicle manufacturers. Cummins Westport serves as an original equipment manufacturer (OEM) of a heavy-duty low-NO_x engine for many of these providers. Renewable CNGVs are available for short- and long-haul adopters. LNG fueling is more capital-intensive, so now that CNGVs can reach over 600 miles of range, they dominate vehicle sales (Berg, 2016; International Energy Agency, 2017). Vehicle specifications vary by manufacturer and can be tailored to the design requests of a consumer.

Summary

PROS	CONS
GHG Impact	ZEV Viability
Vehicle Availability	Cost - Worst Case
Vehicle Functionality	Scalability
Cost - Best Case	

RNG's compatibility with existing natural gas infrastructure and CNG vehicles means it is ready for adoption today, in contrast to other diesel linehaul alternatives. Unfortunately, natural gas vehicles release tailpipe emissions from internal gas combustion. However, agricultural and wastewater treatment plant renewable natural gas feedstocks yield net-carbon-negative transportation fuel, while landfill gas affords substantial carbon reductions from diesel. RCNG vehicles could facilitate significant decarbonization of certain fleets that aim to take immediate action to reduce their greenhouse gas emissions while they await zero-emissions technology developments aligned with emissions targets with more distant deadlines.

Some of the lowest-CI fuel may prove to be the most expensive to develop for biogas collection and upgrading. The RNG vehicle fuel market supply will need fuel incentive and consumer-base certainty to grow to its hypothetical resource potential, though transportation will consistently compete with other sectors for the renewable natural gas supply. Biomethane facilities already exist, and financial commitment to including biogas in their low-carbon plans will allow fleet managers to coordinate deals for RNG. Fleet managers ought to self-determine willingness to commit to RCNGV and NG fueling station ownership; some may prefer to simply lease vehicles and utilize public fueling infrastructure. The decision should be based on the firm's prioritization of carbon neutrality versus zero-emissions vehicle targets.

3.2 Battery Electric

How can batteries power linehaul trucks?

Electric vehicles in the light- and heavy-duty spaces operate under the same premise: an external electricity source is plugged into a vehicle to charge an onboard battery, which powers an electric motor. There are three main types of batteries used in electric vehicles: lithium-ion, nickel-metal hydride, and lead-acid (Alternative Fuels Data Center, 2020a). Lithium-ion batteries are the most common in electric vehicles, because they can hold high charge per unit mass and volume (they have higher energy densities, also known as "specific energy," than nickel-metal hydride and lead-acid batteries), are relatively low maintenance, and have low self-discharge rates (Clean Energy Institute, 2020). Batteries run on "direct current" (DC) power, but can utilize onboard chargers to convert any "alternating current" (AC) power that may come from the grid to DC (Team ChargePoint, 2019). Electric vehicles also use regenerative braking to extend battery charge on the road. Regenerative braking recovers the kinetic energy that would otherwise be lost as the vehicle slows by converting it back into stored energy in the battery.

In the interest of a zero-emissions vehicle future, this paper focuses on battery electric vehicles (labeled BEVs or simply EVs). Though plug-in hybrid and hybrid electric vehicles do rely on battery electric power in tandem with liquid fuels, they are not the subject of this report. Hybrids create tailpipe emissions when they combust fuel and are generally dependent on fossil fuels. Pure, all-electric BEVs, on the other hand, do not combust fuels onboard and can thus qualify as zero-emissions vehicles.

Electricity and Battery Production Approaches and Resource Sustainability

Batteries

This evaluation of BEVs as the potential future of linehaul does not critique battery sustainability in depth, in part because other powertrains like FCEVs also require batteries, and because the vehicle life cycle is not the focus of this report. In the developing space of alternative vehicles, battery innovation is occurring exceptionally quickly; energy-storage patent filings – dominated by lithium-ion technologies – in the U.S., Western Europe, China, and Japan rose 26% annually between 2005 and 2008 (Dinger et al., 2010; Safoutin, 2017). This rapid battery development increases uncertainty in how the resources used in the future will affect vehicle carbon footprint once EVs are ready for adoption at scale. There are environmental and human rights concerns tied to the underregulated battery supply chain – particularly those related to extracting and disposing of rare earth elements like lithium and cobalt – that disproportionately impact people in the developing world (Frankel, 2016; Lombrana, 2019). Cristina Dorador, a biologist in Chile where lithium is mined, reflected that it is foolish to call current practices "sustainable and green mining," because they damage ecosystems, deplete water resources, and threaten local communities (Lombrana, 2019). While EV battery recycling would reduce the resource impacts of battery consumption, its market will naturally lag that of EVs; significant quantities of batteries need to reach end-of-life to drive an EV battery recycling industry. Responsible end-of-life solutions must also evolve to keep up with innovations in batteries. Promisingly, Tesla and BMW are already pursuing battery recycling for their LDVs (Matousek, 2019; Warren, 2020). Battery life cycle environmental and social sustainability is an area of ongoing research.

Battery degradation – losing storage capacity and the ability to efficiently power a motor over the vehicle lifetime – is a concern. A model of 30% capacity loss on an LDV's 24 kWh lithium-manganese-oxide–graphite battery demonstrated a "11.5–16.2% increase in energy consumption and GHG emissions per km driven" (Yang, Xie, Deng, & Yuan, 2018). Degradation can be caused by constant discharge/recharge cycling, aging, and other factors (National Renewable Energy Laboratory, 2020). Substantial degradation could necessitate battery replacement over the operational lifetime of an EV. Multiple studies on heavy-duty electric vehicles model one battery replacement across a 10-year vehicle lifetime (Sen, Ercan, Tatari, & Zheng, 2019). Because battery costs drive the total EV system cost, battery replacements pose a limitation to EV market success (Yang et al., 2018). Further, rare metals consumption is a resource challenge that would be compounded by high penetrations of battery electric vehicles with short useful lives and poor disposal practices. Battery charging needs to be optimized to ensure longevity so that the batteries reliably deliver power over the whole vehicle operational lifetime. While batteries could be oversized to ensure satisfactory performance even after degradation, this would increase vehicle weight (reducing energy efficiency) and increase total EV costs (Dinger et al., 2010). A common battery warranty for electric LDVs is eight years, with expectations that batteries would last approximately ten years (Dinger et al., 2010; Warren, 2020). Thus far, passenger "electric vehicle battery degradation has not been a widespread problem, even among Tesla vehicles with high travel activity, and there is no evidence to suggest that a [battery] replacement is typical within [a 150,000 km assumed car lifetime]" (Hall & Lutsey, 2018). LDV battery performance may not translate to linehaul EVs. As linehaul electric vehicles develop, OEMs will take varying approaches to batteries' chemistry, energy capacity, size, and ownership structure (leasing, warranties, etc.). Battery replacement schemes allow for smaller batteries and let vehicle owners to trade-in for the latest, most efficient battery technologies before retiring their entire BEV, but consuming many batteries diminishes an EV's environmental benefits. Time will tell if HDV batteries perform sufficiently in practice or necessitate replacement as conservative academic models have predicted.

A 2018 literature review on vehicle battery manufacturing emissions conducted by the International Council on Clean Transportation (ICCT) concluded that "battery production is associated with 56 to 494 kilograms of carbon dioxide per kilowatt-hour of battery capacity (kg CO_2/kWh) for electric vehicles." The authors explained the wide range in estimated footprints by the high degree of uncertainty in battery life cycle assessments and range of characteristics of vehicle battery technologies studied (Hall & Lutsey, 2018). Battery production emissions are not included in this report's emissions calculations of fuel cell nor battery electric vehicles. The ICCT researchers noted that electricity inputs to battery manufacturing account for half of battery production emissions, and postulated that cleaner electricity supplies in the future will lower EV battery footprints (Hall & Lutsey, 2018). The study concluded that, at least in the context of passenger vehicles, the carbon emissions from manufacturing batteries do not outweigh the life cycle emissions reductions that BEVs provide, but noted that larger batteries for long-range vehicles could detract more from the benefit of an EV (Hall & Lutsey, 2018). This is an area of the linehaul electric vehicle field that demands further research.

Emissions

The well-to-wheel emissions of electric vehicles depend on the power source (Williams et al., 2012). All else held constant, the cleaner the electricity, the cleaner the EV. California's Low Carbon Fuel Standard has registered renewable solar and wind electricity supplies at a carbon intensity of zero gCO_2e/MJ (California Air Resources Board, 2020a). Few regional grid energy supplies yield EVs with clean carbon footprints due to the pervasiveness of entrenched fossil electricity sources like coal in the American grid (as well as grids abroad). The U.S. average megajoule of grid electricity has a carbon intensity of 120.06 gCO_2e/MJ according to the EPA, whereas GREET models the U.S. electricity mix at 136 grams of GHGs per MJ (Argonne National Laboratory, 2019b; U.S. Environmental Protection Agency, 2020e). According to CARB, California ultra-low sulfur diesel has a CI of 100.45 gCO_2e/MJ (California Air Resources Board, 2018c). GREET's carbon intensity metric for low sulfur diesel is about 91.5 gCO_2e/MJ (Argonne National Laboratory, 2019b).[7] This report defers to GREET values where possible. Accounting for driving patterns and relative efficiencies, GREET modeling estimates a g/mile reduction of 9% for grid-powered electric combination short-haul, but a marginal increase in emissions for a combination long-haul vehicle using the same electricity, presumably due to vehicle design (and subsequent energy efficiency) differences (see Appendix B).

An important caveat is that grids vary regionally. In some areas, the carbon intensity of the grid may be lower or higher than average, depending on fluctuations in regional grid mix. Consequently, a BEV may increase the environmental footprint of linehaul from a diesel baseline in some areas but decrease it in others (see Figure 6 and Appendix B). Over time, as portfolio managers integrate renewables, replace coal with lower-carbon natural gas, or retire fossil plants altogether, grid electricity will decrease in carbon intensity and the environmental value of BEVs will improve. Economists Holland et al. demonstrated temporal and regional changes in the environmental footprint of electric vehicles through two studies on the annual environmental benefits of electric passenger vehicles running on grid electricity compared to gasoline LDVs – conducted in 2016 and 2018. As annual air pollution damages from U.S. power plant emissions fell from $245 billion to $133 billion between 2010 and 2017, the environmental benefit of electric vehicles increased (Holland, Mansur, Muller, & Yates, 2018). Their work mapping the comparative impacts of an electric vehicle transition across the United States against a gasoline baseline suggests that linehaul EVs connected to regional grids with varying portfolios will also display a range in environmental impacts when compared to diesel.

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[7] These carbon intensities factor in high methane leakage across the oil/natural gas supply chain by referencing the "EDF 2019" CH_4 leakage metrics built into GREET; see Appendix B.

A 2019 attempt to optimize sustainable heavy-duty truck fleets found that the total vehicle, fuel, and charging infrastructure life cycle GHG emissions reductions from a fleet of electric Class 8 53’ tractor-trailers each equipped with a 400 kWh battery charged by the U.S. grid only reduced emissions 10% from a conventional ICE heavy-duty truck baseline. They concluded that unsustainable electricity generation practices and vehicle fuel economies were to blame (Sen et al., 2019). Notably, Sen et al. included one battery replacement during the 10-year truck lifetime but excluded end-of-life impacts from their model. The environmental benefit of a linehaul network relying on grid electricity depends on a rapidly decarbonizing electricity sector/ access to renewable-energy charging stations, improvements in the specific energy and power of battery technologies, and a sustainable supply chain for battery resources.

Electricity Market – Availability and Logistics

Resource Availability

An EV charged solely with electricity from renewables is a zero-fuel-cycle-emissions vehicle. Many renewable electricity sources are variable,[8] meaning that their availability fluctuates temporally. Solar and wind, for example, fluctuate hourly, daily, and seasonally. Renewable electricity’s variability hinders consumers from relying strictly on renewable resources. If demand cannot be perfectly aligned with supply, consumers of renewable electricity may be left without electricity or excess renewable supply could be curtailed – intentionally reduced. Energy storage could absorb excess green electricity during low demand periods, but additional considerations must be made to ensure enough electricity is available for consumers in times when demand exceeds renewable production.

Siting distributed renewable energy projects near charging points would help ensure a zero-emissions energy pathway for BEV fleets. Large projects of complimentary wind and solar, coupled with onsite storage, could sustainably meet the electricity needs of some fleets with little dependence on the grid. Or contracts could be structured to allow BEVs to connect to preexisting renewable generation projects (either utility-scale or non-EV-dedicated distributed resources) and capture some of their otherwise-curtailed clean energy. The feasibility of a renewable-oriented approach to electric vehicles generally depends on a driver’s amenability to energy-optimized charging schedules. For instance, solar resources that peak midday encourage daytime charging, and wind resources normally peak at night, which could encourage overnight charging (Office of Energy Efficiency & Renewable Energy, 2017; Taylor, 2009). A pilot conducted by Pacific Gas & Electric and automaker BMW attempted to optimize electric BMW passenger vehicle charging by coordinating it with renewable electricity generation, using targeted messaging and incentives for customers. Their “ChargeForward” pilot successfully shifted load into daytime hours of peak solar generation – grid balancing that benefited the utility while reducing the EVs’ environmental footprint (Pyper, 2018). There is a lot of market interest in leveraging this multifunctional vehicle-grid integration. EVs could be used as a portable energy storage solution, conserving electricity that would otherwise be curtailed and reducing grid operating costs (Szinai, Sheppard, Abhyankar, & Gopal, 2020).

With linehaul vehicles, charging time may be less flexible, especially for shipping operations running on time-sensitive, expedited delivery schedules. While some individuals can be incentivized to charge their cars during the day at a charging station in their office parking lot (instead of at home in the evening after work), commercial fleet operators must ensure efficient transportation logistics – generally meaning that vehicles are driving during daytime work hours. Drivers’ working hour regulations vary across the world, but in the U.S. the Federal Motor Carrier Safety Administration requires that commercial motor vehicle drivers may only drive 11 cumulative hours within in a 14-hour period, after which at least ten consecutive rest hours are mandatory (Federal Motor Carrier Safety Administration, 2005). Refueling times will have

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[8] Power generation from a solar panel or wind turbine, etc. as dictated by the sun shining or wind blowing is intermittent, in contrast to fixed power supplies like geothermal or coal.

to work into the driver's downtime (likely at night). If two drivers take shifts on the same truck (known as team driving), the charging schedule flexibility may be further constrained. In isolation, fleet managers would coordinate refueling between driving shifts, but "commercial fleet customers are especially susceptible to pricey demand charges [and] companies must balance their fleets' charging schedule to minimize demand charges" (Karkaria, 2019). Businesses using fleets of linehaul electric vehicles with strict driving schedules may need higher demand charges than passenger-BEV owners to motivate charging behavior that offsets curtailment and facilitates grid-balancing.

If a BEV fleet is not connected to a dedicated solar or wind farm large or reliable enough to meet all its needs, grid backups can supplement renewables. Alternatively, EV charging stations can be entirely grid-reliant, which is the norm for America's current EV-charging network. Relying on the grid for electricity rather than investing in renewables is a tradeoff between cost, carbon footprint, and convenience. It is hard to guarantee consistent zero-emissions electricity supplies unless a vehicle consistently makes round trips or follows fixed routes between renewable-powered charging sites. Grid-electric vehicles' sustainability will vary depending on the grid portfolio in any given region, and this will change over time as grid operators transition away from coal to natural gas and renewables. Meanwhile, grid connections yield reliability in electricity supplies.

Grid Impacts

One of the concerns about the proliferation of electric vehicles is their potential to put demand pressure on electricity grid loads. Current levels of EV penetration are not substantial enough to disrupt grid operations (Hardman et al., 2018). However, future increases in electric load due to EV charging could create problems. There is consensus that EV charging during peak grid demand times (generally the early evening) in the future will strain the grid (Hardman et al., 2018; Heid, Hensley, Knupfer, & Tschiesner, 2017; U.S. Energy Information Administration (EIA), 2011). Researchers evaluating public charging infrastructure in Switzerland found that the country's 20%-EV-penetration-by-2030 target could lead to up to 78% increased grid loads at some transformers, and an average city-wide increase in load of 6% (Pagani, Korosec, Chokani, & Abhari, 2019). Sustainable Technology senior manager, Kellen Schefter, at utility trade association Edison Electric Institute told reporters at *Automotive News* that commercial electric fleets would increase U.S. electricity demand by 10% (Karkaria, 2019). Stressors on the grid require demand management – otherwise grid operators and charging station owners must implement accommodating electrical upgrades. Researchers believe that economic incentives will help. McKinsey analysts found that electricity grids "in leading economies can cope with the additional demand posed by [electric trucks] in off-peak times, which remains below one percent of total electricity consumption by 2030" (Heid et al., 2017). Pricing strategies like time-of-use electricity rates or smart (automated) charging can move charging demand to off-peak times (Hardman et al., 2018). Smart charging would also boost EV utility as an energy storage option, and potentially facilitate renewables' grid penetration. Coupling distributed generation and EV charging stations can simultaneously reduce the carbon footprint of electric vehicles and ease grid load (Meyer, Choi, & Wang, 2015). As discussed above, load shifting could also align EV charging with renewable energy grid supplies. These approaches will help utility operators and fleet managers to ease the electrical burden of electric vehicles.

Again, it is important to recognize that linehaul fleets may not follow the same charging schedule flexibility as other EVs and may require higher incentives to shift demand to off-peak hours. When drivers return from a day shift, the vehicle either needs to charge immediately (likely early evening peak hours) if a night shift driver intends to use the vehicle, or sometime overnight before the truck is used the next day. Team driving complicates driving and charging schedules further. Trucks with fewer operating hours or more flexible operating schedules will be most amenable to peak-shifting their charging times.

Charging Types

Limited charging infrastructure availability compounds the range anxiety that battery limitations present. Until charging infrastructure is ubiquitous and accessible for HDVs, haul routes will be limited to available stations. This will reduce overall trip efficiency as emissions/mile reductions are traded off for extra miles driven out of the way to reach a charging point. To expand charging infrastructure access, there are three charging types available: AC Level 1, AC Level 2 and DC Level 3. Level 1, essentially a standard U.S. wall outlet (110-120 volts), has the slowest recharge rate at about 1.4 kW, five miles of range added per hour (Meyer et al., 2015; Valderrama, Boloor, Statler, & Garcia, 2019). It is not practical to expect fleets of heavy-duty vehicles to rely on Level 1 chargers. Level 2 chargers range from 208-240 V and charge at a rate of 3.6-7.2 kW (25 miles of range per hour, at best, or about eight miles added per hour at worst: charging speeds depend on vehicle specifications and charging equipment) (Bao, Li, & Zheng, 2012; Hardman et al., 2018; Meyer et al., 2015). Level 2 chargers using "J1772" connectors are often installed at charging stations and, conveniently, "in Europe, Australia, most of Asia, and most of South America, Level 2 charging is [already] the standard level from domestic plug sockets," (Hardman et al., 2018). Still, Level 2 charging times are not compatible with all heavy-duty trucking business demands, such as a freight operation that revolves around driving shifts and quick vehicle refueling. Especially for vehicles planning long-distance travel, Level 2 charging is likely impractical: at best, 250 miles of range would take the whole night to accumulate. 480 volt Level 3 DC fast charging is far faster than AC because the equipment converts AC to DC power at the station and then supplies DC power directly to the vehicle battery, rather than requiring onboard conversion (Bao et al., 2012; Team ChargePoint, 2019). It restores a battery to full power at a rate of 50-60 kW (up to 150 miles of range added per hour spent charging) which is far more attractive for linehaul purposes (Valderrama et al., 2019). Tesla's DC Superchargers work at a rate of 120 kW, and ultra-fast 150-350 kW DC chargers are finding their way onto the market as well: "at present [ultra-fast chargers] can only charge vehicles up to 150 kW, but have the potential to charge at 350 kW when vehicle and battery technology can take this level of power" (Hardman et al., 2018; Levinson & West, 2018). High-powered fast charging requires cooling equipment and may expedite battery degradation (Team ChargePoint, 2019; Tillemann & McCormick, 2018). DC fast charging stations have different connectors, either "SAE Combo (CCS1 in the U.S. and CCS2 in Europe), CHAdeMO or Tesla (as well as GB/T in China)" (Team ChargePoint, 2019). Drivers must ensure that the station they visit will have connectors compatible with their vehicle. Not all EVs are equipped to handle DC charging, but OEMs in the HDV space will likely prioritize fast charging compatibility.

Linehaul electric vehicles' reliance on fast charging and BEVs' value for energy storage rides on charging schedule flexibility unless battery swapping systems (trading fully charged batteries for empty ones at stations) are developed for linehaul. Under a swapping setup, charging is no longer tied temporally to vehicle presence at a charging station. Batteries' power could be replenished with slower, less expensive chargers and their charging could be optimally aligned with cheaper electricity at off-peak hours or periods of higher renewable electricity generation. Thus, battery swapping would facilitate greater renewable electricity usage, reduce the strain of fast charging on both batteries and the grid, and cut down refueling times to just a few minutes of battery trading (Tillemann & McCormick, 2018). Recharging times would factor less into range anxiety. However, battery swapping systems – offered by companies including Tesla and the famed, bankrupt startup Better Place – have failed on the market for LDVs due to high capital costs, low utilization, and a steep business-model learning curve (Chafkin, 2014). The concept struggles with consumer acceptance, but is still being attempted by some in the EV industry like Chinese car company Nio (Tillemann & McCormick, 2018). Swapping is not getting traction in the HDV sector at present. The need for more batteries than vehicles in a swapping system also raises concerns, given that batteries factor largely into EV cost and environmental impacts (Hall & Lutsey, 2018; Yang et al., 2018). Perhaps in the future, battery swapping could be used to further renewable electricity penetration in the HDV space encourage BEV adoption. Battery designs would need to be standardized for swapping to work well at public stations (Berman, 2020). Fleets may prove to be a strong use-case; operators could charge batteries on company property and then swap batteries while loading and unloading freight on their electric HDVs. Private fleets of linehaul vehicles all produced by one automaker would circumvent battery standardization concerns.

Another technology on the horizon is wireless power transfer. It uses inductive charging to power an EV. An electromagnetic field is created in the space between coil transmitters installed on the vehicle chassis and in a charging pad on the ground, which transfers electricity to the vehicle (Bi, 2018; Office of Energy Efficiency & Renewable Energy, n.d.). Power sources for current wireless charging pads range between 220-240 volts, on the order of Level 2 chargers (Garsten, 2019). EVs could recharge while parked over a charging pad (static charging). Or, even better, without the constraint of plug-in charging EVs could dynamically repower while driving on miles of wireless-charging road lanes. In turn, this would reduce the burden of sizing the large, heavy batteries that plug-in vehicles need to facilitate long-distance travel, ultimately alleviating range anxiety and improving energy efficiency. Wireless charging in-transit could also eliminate charging wait-times and thus expedite commercial fleet operations. In the case of freight, building out designated charging lanes in shipping corridors could ensure cost-effective high utilization of wireless infrastructure. Of course, this hypothetically convenient wireless method requires miles of charging lane infrastructure and the availability of wireless charging vehicles. University of Michigan researcher Zicheng Bi recently published a unique dissertation on a comprehensive life cycle environmental and cost model for wireless charging. He found that wireless charging entails a higher upfront capital cost for chargers than plug-in charging, but lower operational and battery costs such that a bus fleet using static wireless charging had lower life cycle costs (Bi, 2018). Dynamic charging, which requires whole stretches of road with charging pads, may not be cost-competitive with plug-in charging for HDVs; more research is needed. In his life cycle cost model of an electric transit bus fleet using stationary wireless charging, Bi also found that the lightweighting[9]-related energy efficiency benefits of wireless EVs were offset by a reduced charging efficiency compared to plug-in EVs (85% vs. 90% assumed) such that "the difference found in final electricity costs between the plug-in and wireless systems is small," (2018). There is significant uncertainty in these cost projections, as the technology is in development and assessments are speculative. Bi noted that battery price and sensitivity to time-of-use electricity rates are the driving factors in life cycle cost differences between plug-in and wireless EV buses – insight that would likely hold for other HDV transit (2018). Researchers like Bi argue that the life cycle carbon emissions of wireless vehicles would be lower than plug-ins, hybrids, and conventional diesel vehicles, due to the lightweighting benefits; in fact, Limb et al. found that transitioning Class 8 trucks from ICE engines to wireless power transfer could reduce GHG emissions by 72.4% on average across the U.S. (Bi, 2018; Limb et al., 2019). Environmental impacts can be lowered if distributed renewable generation is positioned strategically along charging lanes. However, at least in the case of roadside solar plus battery storage, the financial burdens would be significant: "a breakeven year for solar charging benefits to pay back the [dynamic wireless charging] infrastructure burdens can be less than 20 years for GHG and energy burdens but longer than 20 years for costs" (Bi, 2018). While wireless BEVs hold significant potential, the vehicles and their associated infrastructure are lagging that of plug-in battery electric vehicles and their charging stations at both LDV and HDV levels.

Charging Approaches

Batteries follow charging curves, which are specific to each battery/vehicle make and model. They charge slower as they reach full capacity, regardless of charging type: listed charging rates reflect the speed at which a battery can reach approximately 80% charge, after which, charging slows down significantly (Team ChargePoint, 2019). Charging beyond 80% of capacity can also expedite battery degradation.

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[9] Lightweighting reduces the weight of a vehicle to improve its efficiency, generally through component material replacement.

Extremes in ambient air temperature and battery temperature (particularly cold) also limit charging levels, such that the range of passenger BEVs was reduced between 25-30% in winter in a study done by Idaho National Laboratory (Office of Energy Efficiency & Renewable Energy, 2020; Yi & Shirk, 2018). Cold temperatures slow battery charging rates, and any temperatures that prompt drivers to engage comfort-accessories like air conditioning reduce the battery economy of EVs – more than the fuel economy would decrease in other powertrains (Office of Energy Efficiency & Renewable Energy, 2020). It is advisable to build in a factor of safety into linehaul scheduling of BEV logistics, either to anticipate constrained range if drivers only refuel up to 80% of capacity, or to add buffer time to listed charging rates.

The European Union has over 170,000 public charging points to date, and just over 10% were fast chargers that supply over 22 kW (approximately 24 public fast charging points per 100 km of highway) (European Union, 2020). Across the Atlantic, the U.S. Department of Energy (DOE) built more than 17,000 charging stations in the two-year period of 2011-2013 through the EV Project and ChargePoint America programs (Levinson & West, 2018). Then in 2016, the Obama Administration created a coalition to expand EV charging infrastructure access and grow EV adoption directed by the *Guiding Principles to Promote Electric Vehicles and Charging Infrastructure* (Levinson & West, 2018; The White House Office of the Press Secretary, 2016). Southern California Edison committed to a "$356-million Charge Ready Transport program supporting 8,490 medium- and heavy-duty vehicles at 870 commercial charging sites," by the middle of the decade (Adler, 2019). As of May 2019, the U.S. has over 20,000 charging stations with approximately 68,000 outlets: 84% are Level 2 and 16% (approximately 10,860) are DC fast charging units (Vehicle Technologies Office, 2019). Because electric HDVs are still in development, and public fast chargers for electric vehicles are "hardly profitable at low EV adoption rates" most stations to date have been constructed for light-duty vehicle use, which dominates the electric vehicles on the road today (Schroeder & Traber, 2012). Therefore, the siting of individual chargers may not be conducive to heavy-duty vehicles with larger turning radii or vehicle footprint areas. Consequently, many charging stations may require upgrades to be compatible with HDV fleet operations, and the number of Level 2 and DC chargers will not entirely reflect the true availability of charge points for linehaul.

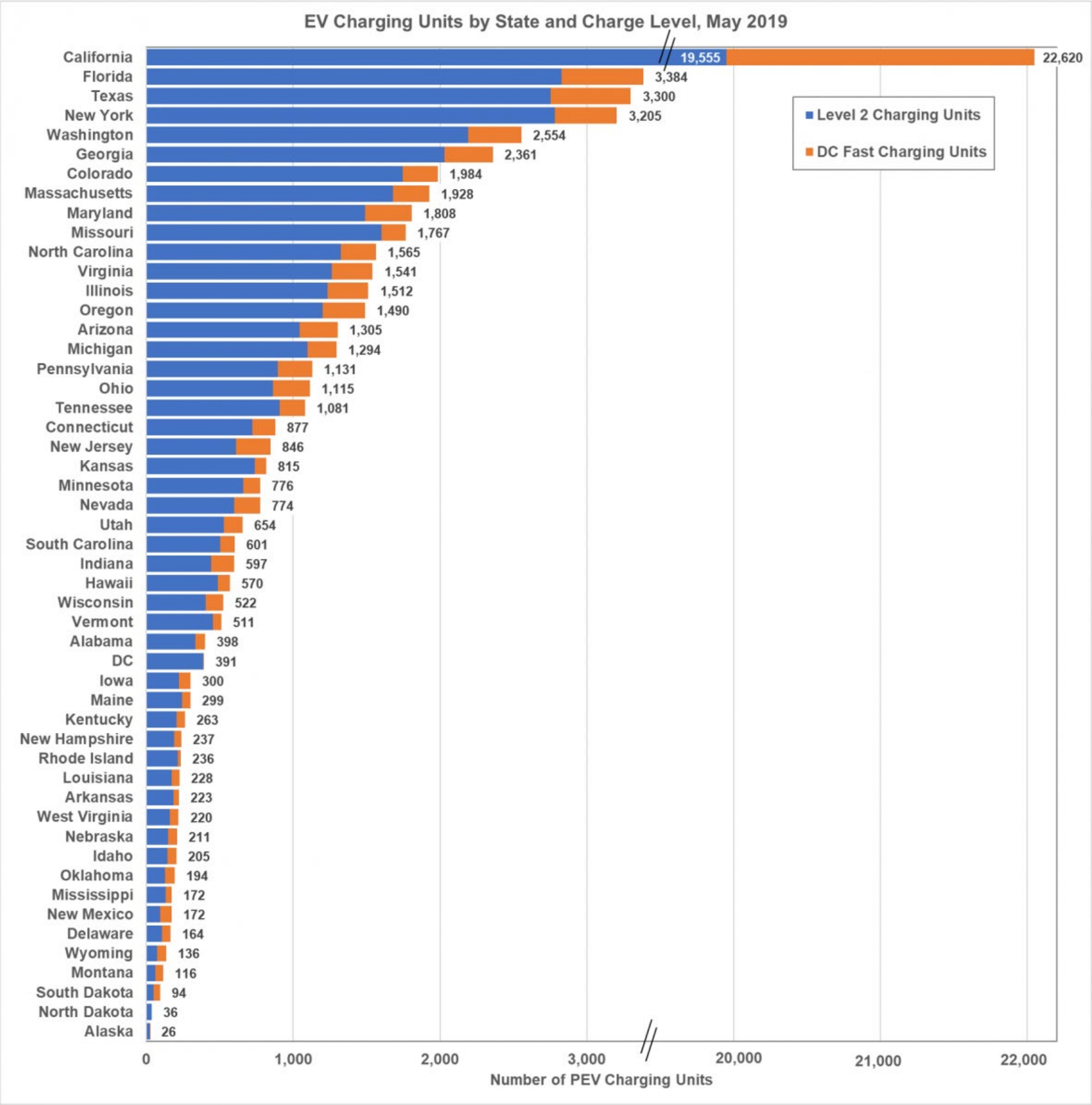

Figure 5. State of EV Charging Infrastructure in the United States (Vehicle Technologies Office, 2019).

In 2014, Neubauer et al. used the National Renewable Energy Laboratory's Battery Lifetime Analysis and Simulation Tool for Vehicles to build scenarios of BEV utility based on varying charging infrastructure and degrees of range anxiety. Range anxiety, they found, reduces the number of "achieved" miles travelled in a BEV. A driver may undertake a conservative fraction (i.e. 80-90% of the capacity) of her battery range in order to leave a buffer to complete the trip. For example, a driver might limit herself to a 110-mile trip even though her vehicle has a 130-mile range. Not surprisingly, the NREL authors determined that the battery utility effects of range anxiety were alleviated by better access to charging infrastructure, even for high mileage drivers (Neubauer & Wood, 2014). Linehaul vehicles could travel longer distances with expanded charging access. Researchers at Sandia National Laboratories found that "for large deployments of public chargers, DC fast chargers are more effective than Level 2 chargers at increasing BEV sales, increasing electrified mileage, and lowering GHG emissions, even if only one DC fast charging station can be built for every ten Level 2 charging stations" (Levinson & West, 2018). While Levinson and West's study was on LDVs, heavy-duty linehaul vehicles with high charging demands would also benefit from extended DC fast charging more than from slow AC chargers. Nie et al. found that greater access to Level 3 charging facilities would lower social costs (tied to consumer expenditures, range anxiety, and charging times) more effectively than expanding Level 2 charging and be of more service to long-distance drivers (Nie & Ghamami, 2013). In sum, Level 3 DC chargers would likely have greater utility for linehaul applications of battery electric vehicles than AC chargers.

Analysis of charging infrastructure has also led to consensus that charging-corridor development is more valuable than bolstering charging access in population-dense areas; the optimal charging station would be placed along a highly-trafficked lane to attract the maximum flow of charging consumers (He, Yang, Tang, & Huang, 2018; Nie & Ghamami, 2013). Optimal station location and scale (number of charging points) depends on the anticipated vehicle range of the flow of drivers in the corridor and accounts for the potential queuing delays of charging station congestion (He et al., 2018; Nie & Ghamami, 2013). Hypothetically, the optimal charging station development would facilitate the least amount of construction for the largest range extension. In a coordinated effort among long-distance freight operators, or by one large fleet operator, the ideal station would segment the entire route of interest into the greatest common denominator of the vehicles' ranges, where station utilization is highest (e.g. 400 miles of travel bisected with one charging station to accommodate a 250-mile-capacity battery). Charging stations are expensive to construct, but with sufficient utilization "it is always beneficial to provide recharging facilities," (Nie & Ghamami, 2013). Commercial fleets with high localized demand for EV charging could also financially justify onsite charging equipment because they can guarantee high technology utilization. A 2018 GreenBiz survey of corporations found that "inadequate on-site charging infrastructure is the second biggest barrier to electrification of corporate fleets" and that corporations were intimidated by the burden of facility upgrades and utility coordination required to boost power supply/electrical capacity for EVs onsite (Karkaria, 2019). Access to onsite charging would add business flexibility and alleviate range anxiety for corporate fleet logistics but is a significant undertaking best left to fleets undergoing high EV adoption.

Vehicle Functionality

Safety

There are some safety considerations to be made when transitioning from conventional ICE linehaul to battery electric. Some battery materials require safe handling and proper disposal to avoid environmental contamination. For example, lead-acid and nickel-cadmium batteries contain toxic metals (lead and cadmium) (Clean Energy Institute, 2020). In the case of lithium-ion batteries, Li is flammable. Safety components to manage voltage, temperature and pressure are used in EVs to prevent Li-ion thermal runaway, and the transport and disposal of Li-ion batteries require proper handling procedures (Clean Energy Institute, 2020; Warren, 2020). Overall, undertaking safety precautions during battery production and disposal and following electric vehicle safety codes should circumvent most EV safety concerns.

As mentioned previously, there are upstream concerns about the safety of current mining practices. Miners' working conditions are not well-regulated, and the wellbeing of miners and mining district communities is not often prioritized (Frankel, 2016; Lombrana, 2019). Linehaul fleet managers ought to consider the upstream impacts of investing in alternative powertrains to ensure environmentally and socially sustainable supply chains, rather than focusing exclusively on the use-phase impacts of EVs.

Range

Electric vehicles are relatively familiar to consumers. EVs became prominent in the alternate-light-duty-vehicle market for the last decade, with breakout brands like Tesla acquiring a lot of press coverage for their electric passenger vehicles while many veteran automakers were building their own EV models to compete. Electric vehicle technology maturity means that heavy-duty BEVs are closer on the market horizon than are heavy-duty FCEVs for linehaul. Technology familiarity is also important - consumer perception influences alternate-vehicle market penetration. Perhaps the most significant barrier EVs face at present is range anxiety; driver apprehension of being stranded with an empty battery due to limited charging points en route and inadequate battery capacity. Batteries can scale sufficiently for most passenger vehicle trips, which in 2018 averaged 31 miles traveled per day in the U.S. (Alternative Fuels Data Center & Federal Highway Administration, 2018). LDV charging stations are also becoming more widespread. Though BEVs serve as an attractive passenger/private vehicle replacement, heavy-duty BEVs face unique challenges.

In 2018, the average Class 8 truck in America traveled 187 miles per day (Alternative Fuels Data Center & Federal Highway Administration, 2018). Designated long-haul trucks require an even longer driving range. Moving weighty vehicles longer distances in freight means that heavy-duty vehicles need a large battery capacity. Batteries are far less energy-dense than liquid fuels like gasoline and diesel (Clean Energy Institute, 2020). Consequently, scaling batteries to accommodate haul has tradeoffs: a larger battery demands more onboard volume and adds to vehicle mass, limiting its efficiency. Further, "each extra kg of battery weight to increase range requires extra structural weight, heavier brakes, a larger traction motor, and in turn more batteries to carry around this extra mass" – a problem referred to as mass compounding (Thomas, 2014). Li-ion batteries also need safety mechanisms to prevent damages via overheating/ combustion and high voltages (Clean Energy Institute, 2020). These mechanisms add to vehicle weight. Shipping efficiency is sacrificed if fewer packages can fit in the smaller storage volume (raising the emissions footprint per package delivered). Energy efficiency ("fuel" economy) is also reduced because more power is needed to move the heavier truck one mile (Vehicle Technologies Office, 2020). While CNGV developers found a way to accommodate large gas tanks onboard to achieve high (diesel-competitive) vehicle ranges, BEV ranges may be more constrained due to heavy batteries.

EV OEMs can take measures to accommodate the added battery weight, like lightweighting the truck body. For example, by building trucks with aluminum, high-strength steel, or fiber-reinforced composites – lighter than other vehicle body metal options like heavy steel – manufacturers can reduce component weight by 10-60% and allow for a heavier, higher capacity battery (Bull, 2009; Vehicle Technologies Office, 2020). These measures help to extend the range of an electric vehicle, but it is probable that HDV EVs will hit a cap on economically and energetically efficient designs. Batteries are expensive, and a truck body cannot be indefinitely lightweighted without diminishing design integrity and safety characteristics. Further, mass reductions also reduce the energy savings value of regenerative braking, which is a function of vehicle mass (Lewis, Kelly, & Keoleian, 2014). As such, currently available EV trucking technology has not surpassed a 300-mile battery capacity. The niche for battery electric linehaul vehicles may be short-haul trucks and other HDVs like yard hostlers.

Vehicle Market

The electric vehicle market has seen a boom in recent years. Globally, it is projected to reach about 360 billion U.S. dollars by 2025 (Valuates Reports via PR Newswire, 2019).[10] Much of this value is and will be due to passenger vehicles; automakers already have light-duty versions of electric vehicles on the road in droves. It is altogether promising for the future of electric linehaul. BEV trucks' marketing claims include "half the noise pollution" of diesel and CNG engines, fewer components needing maintenance, and lower fuel costs (BYD USA, 2018; The Lion Electric Co., 2019). All Class 8 fully electric trucks that are already on the road or in development have ranges in that classify as short-haul/middle-mile (200-300 miles). In fact, only Tesla, Inc. has announced a battery electric semi-truck with a range over 300 miles, yet the company is experiencing growing pains, layoffs, and challenges with leadership ("in the last three years, Tesla has missed several of the ambitious goals [CEO Elon] Musk has set") so their long-haul 500 mile truck did not go into production in 2019 or 2020 as promised (Boudette, 2019). In late April 2020, Tesla Semis'

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[10] The market observations for all powertrains included in this report were developed before the global onset of COVID-19 and are subject to change.

production and delivery was postponed again – until 2021 (Kolodny, 2020). In general, Class 8 linehaul vehicles in development by various manufacturers will not be ready for buyers until late 2020 at best. HDV designs discussed in this report are for plug-in charging, not wireless, which will be developed in the more remote future.

BYD Motors, Inc. offers multiple electric vehicles. Among them are the Class 8 BYD 8TT day cab (435 kWh battery, 124-mile range, three hour AC charge or 1.5 hour 300 kW DC fast charge) and BYD 8Y terminal tractor (BYD, 2019; BYD USA, 2018). Anheuser-Busch bought 21 of BYD's Class 8 battery electric trucks to deploy and test between the end of 2019 and early 2021 in Southern California – the largest battery electric truck deployment in North America (Field, 2019). The project is funded in part by the California Air Resources Board and will be partially powered by a 958.5 kW solar array (Field, 2019). The California South Coast Air Quality Management District has partnered with Volvo Trucks North America and 14 other industry partners in the Volvo Low Impact Green Heavy Transport Solutions (LIGHTS) program, also funded in large part by CARB (Davic Cullen, 2019; Volvo Group North America, 2019). The project aims to test charging infrastructure, EV warehouse logistics, and battery electric trucks. Volvo showed its first EVNR Class 8 short-haul drayage truck prototypes at the end of 2019 and plans to trial 23 of the BEVs in 2020 (Hirsch, 2019c; Volvo Group North America, 2019). Through this program, Volvo announced plans to sell its EVNR by the end of 2020, beginning in "California, Oregon, Washington, Texas and a few northeast states" (Adler, 2019; Davic Cullen, 2019). Established vehicle manufacturers are making big investments in the EV space.

The Lion Electric Co. got its start in 2017 with electric school buses, which have consistent operating times and small operating regions that make charging logistics straightforward. It has an agreement with CN – Canadian National Railway Company to pilot its LION8 in 2020, which it began producing in late 2019 (Abecassis, 2019; Ridden, 2019). The Class 8 truck has lithium-ion batteries with storage up to 480 kWh (up to 250 miles of range) which could charge in 5-16 hours at a Level 2 station or between 1.5 and five hours at a Level 3 charging station (The Lion Electric Co., 2019). Perhaps the most recognizable EV manufacturer is Tesla. After establishing themselves in the LDV electric vehicle space, the company announced plans to produce the Tesla Semi in 2021 (originally planned for 2019) (Downing, 2020; Kolodny, 2020). Two Tesla Semi types are in pilot stage and available for reservation, with either 300- or 500-mile ranges at "less than 2 kWh per mile" (Tesla, 2020). The company also plans to establish a "Megacharger" station network at truck stops and at client facilities – Anheuser-Busch, PepsiCo and UPS have pre-ordered so far – similar to their 1100 existing LDV "Supercharger" stations (Johnson, 2018). Tesla claims their trucks could recharge 400 miles of range in 30 minutes (Tesla, 2020). Meanwhile, hydrogen FCEV startup Nikola has plans to also provide battery electric versions of its Nikola Two and Tre semi-truck models in American and European markets, respectively (Kane, 2019; Nikola Motor Company, 2020). Finally, HDV trucking leader Daimler Trucks, working with Freightliner, plans to begin production of their Class 8 eCascadia regional 18-wheeler with a 250-mile range in late 2021 (Downing, 2020). There are many other companies trying to break into the EV market, like startup Xos Trucks, which offers a Class 8 truck with a 100-mile range called ET-One (Xos Trucks Inc., 2019). In addition, some EV manufacturers may engage in the linehaul market in the future, like Rivian (in which Amazon has invested), Workhorse, and Chanje – all EV startups that currently offer medium-duty vans and/or trucks – and Orange EV, which has a popular electric Class 8 terminal tractor (Downing, 2020; Orange EV, 2020). Essentially, many existing and prospective automakers are interested in what they see as a profitable electric vehicle market.

Summary

PROS	CONS
ZEV Viability	GHG Impact - Worst Case
GHG Impact - Best Case	Vehicle Availability
Cost	Vehicle Functionality
Scalability	

In the last decade, accelerating adoptions of light-duty electric vehicles spurred charging infrastructure development. Some of these charging stations are compatible with the fast charging needs of battery electric linehaul vehicles, which are just hitting the market. Light-duty penetration of EV technology gives heavy-duty BEVs an edge over more nascent diesel linehaul alternatives like fuel cell electric vehicles. However, current HDV batteries cannot efficiently scale for long ranges. The existing DC fast charging network needs investment to expand access points and account for battery shortfalls. Swapping and wireless alternatives to conventional charging are promising but not the initial investment focus of battery electric linehaul manufacturers. Until charging infrastructure improves, range limitations mean that battery electric linehaul is only compatible with short-haul transport.

Battery electric vehicles qualify as ZEVs and have the potential to have zero fuel cycle emissions when combined with renewable power sources. As electricity grids decarbonize, the average WTW carbon footprint of a grid-connected BEV will decrease.

3.3 Hydrogen Fuel Cell Electric

How can hydrogen fuel linehaul trucks?

In a fuel cell electric vehicle, hydrogen (H_2) is streamed quickly into onboard gas tanks as an energy carrier, akin to fueling a vehicle with an internal combustion engine. Like NGVs, FCEVs can run on either liquid or gaseous H_2. This report focuses on FCEVs that use gaseous H_2 for a similar rationale that NGVs focused on CNG – see Hydrogen Production Approaches and Resource Sustainability. Hydrogen gas is compressible, meaning that significant quantities of the energy resource can be stored in a tank onboard without demanding much space so that the vehicle can drive far between refuels. Fuel cells – polymer electrolyte membrane (PEM) fuel cells are most common – in the vehicle collect electrons from the gaseous hydrogen to power an onboard battery, hence the "electric vehicle" label (Alternative Fuels Data Center, n.d.-a). The cells also make use of oxygen from the air in the process, and together molecules are released as water (H_2O) steam from the FCEV's tailpipe. Hydrogen fuel cell electric vehicles are consequently attractive as ZEVs because their tailpipes only emit warm air, water vapor and a marginal amount of NO_x (Suleman et al., 2015).

Essentially, FCEV powertrains use high-voltage batteries and a fuel cell system, composed of air and hydrogen modules with a fuel cell stack, to operate an electric motor that moves the vehicle (Mohrdieck, Venturi, & Breitru, 2014). Like battery electric vehicles, FCEVs can make use of regenerative braking for added power. There are two approaches to FCEV technology: battery-dominant, which "rely on a relatively large-capacity battery charged with electricity drawn from the power grid, for which onboard hydrogen energy system serves as a range extender" and fuel cell-dominant vehicles, that "carry a smaller battery and are primarily powered by electricity from the hydrogen fuel cells," (Lee et al., 2018). A battery-dominant FCEV essentially works like a plug-in hybrid electric vehicle, but these designs have, so far, received less focus during research and development (R&D) than pure fuel cell-dominant vehicles (Alternative Fuels Data Center, n.d.-b). Lee et al. note that the two types of FCEVs are not always differentiated between in literature, and as such, this discussion will focus on the idea of fuel cell-dominant FCEVs (2018).

Hydrogen Production Approaches and Resource Sustainability

While tailpipe emissions from FCEVs are negligible, hydrogen fuel cell electric vehicles can still have high carbon footprints from well-to-wheel. An FCEV's footprint and life cycle energy efficiency depend heavily on the energy feedstocks as well as the production and delivery methods of its hydrogen. Thermal, electrical, biochemical and photonic energies can each be used to extract hydrogen from organic molecules – usually from water, fossil fuels, like petroleum and natural gas, biomass, or hydrogen sulfide (Dincer, 2011). Electrolysis, for example, uses electricity (from fossil or renewable sources) to split water into hydrogen and oxygen. Many production methods exist, but most operate in research, not industry. At the moment, about half of H_2 is produced by mixing natural gas and steam at high temperatures, a process called steam methane reformation (SMR) (Muradov & Veziroä, 2005).

Life cycle assessments of FCEVs using hydrogen made via fossil natural gas reformation found that the upstream SMR process is responsible for the majority of these vehicles' greenhouse gas emissions, whereas tailpipe GHG emissions dominate diesel trucks' footprints (Lee et al., 2018). On a life cycle basis, hydrogen produced by steam methane reformation of fossil natural gas often has the worst environmental impact of all hydrogen fuel pathways in use in industry today. Though it presents an average 13.53% GHG emissions reduction per mile from diesel (see Appendix B), when compared to all other hydrogen fuel pathways, SMR of fossil NG is generally most harmful in terms of human and ecosystem health, global warming potential, acidification, and ozone layer depletion, among other impacts (Suleman et al., 2015). However, hydrogen from electrolysis can potentially have higher (as much as double the amount of) greenhouse gas emissions per vehicle-km driven than SMR H_2, if the electricity portfolio (like the average U.S. grid mix) used is heavily reliant on fossil fuels (Bhandari, Trudewind, & Zapp, 2014; Rumpke, 2010). This high-emissions scenario occurs because converting fossil fuels to electricity to then power electrolysis is an inefficient two-step process, instead of using fossil natural gas directly to make H_2. It is hard to generalize the impacts of electrolytic hydrogen from grid electricity because grid portfolios vary in carbon intensity. In general, efficiency losses are a big contributor to the net environmental impact of hydrogen regardless of H_2 production pathway – converting energy to gas, only to use the gas to make energy later, is bound to have losses.

Presented with this challenge, renewable electricity inputs like wind or solar stand out because they can suffer conversion losses and still demonstrate meaningful WTW carbon reductions relative to the H_2 energy output. Comparative life cycle assessments found that electrolysis with wind energy is the best hydrogen production method from a human health, ecosystem quality, and resource protection standpoint; solar electrolysis is second-best, and SMR using renewable natural gas is third (Suleman et al., 2015). Researchers Lee et al. published "Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks" in 2018. They found that even when running on H_2 made from SMR of fossil natural gas, FCEVs generally present well-to-wheel emissions reductions of criteria air pollutants – VOCs, CO, NOx, and particulate matter smaller than 2.5 and ten μm (PM 2.5 and PM 10) compared to conventional diesel vehicles (Lee et al., 2018). However the same study showed that SMR hydrogen increases SO_x emissions of trucks from a diesel baseline, "mostly due to the emissions associated with electricity required for hydrogen compression or liquefaction," (Lee et al., 2018). That aside, H_2 made from water using renewable energy-powered electrolysis yields "the largest reduction of WTW fossil fuel consumption and air emissions associated with hydrogen use in fuel cell electric vehicles, including [trucks]" (Lee et al., 2018). SMR of biogas could yield net-GHG-negative FCEVs on a well-to-wheel basis, but renewable electrolysis is more beneficial overall environmentally. Further, fleet managers interested in RNG for its carbon-accounting appeal will realize that the H_2 production losses deplete the carbon negativity per mile (see Figure 6 and Appendix B).

The environment in which a fuel cell electric vehicle operates influences its improvement potential compared to a conventional internal combustion engine vehicle. Beyond hydrogen source, driving patterns and geographical location of the FCEV impact its emissions. Lee et al. found that GVWR Class 8b[11] fuel cell electric short-haul combination drayage trucks demonstrate greater emissions reductions than Class 8b fuel cell electric day cab tractor-trailers compared to their diesel counterparts, due to dissimilar driving patterns; day cabs spend equal amounts driving on highways as in urban areas, whereas short-haul drayage trucks are generally driven around urban areas (2018). The efficiency gain of an FCEV over diesel is lower on highways than in cities, so a larger share of highway driving yields less fossil fuel reduction (Lee et al., 2018). The relationship described is consistent with analysis provided by CARB about the connection between battery electric truck driving patterns and fuel economy discussed in Footnote 3 (California Air Resources Board, 2018b). GREET, currently, only has the capability to model short-haul FCEVs and could not directly confirm the Lee et al. findings for Appendix B.

As mentioned above, the region in which hydrogen is produced impacts the WTW environmental impacts of an FCEV. Energy is consumed during hydrogen production regardless of method, though electricity supply most significantly impacts the overall H_2 environmental footprint in electrolysis. Large amounts of electricity are also consumed while compressing or liquifying hydrogen for distribution and vehicle use (Lee et al., 2018). The liquid hydrogen life cycle emits more air quality pollutants and is approximately 23% worse from a carbon intensity standpoint than gaseous hydrogen for FCEVs because of additional (~+30%) process energy needs (see Appendix B) (Argonne National Laboratory, 2019b; Lee et al., 2018). Unfortunately, the liquefying process is so energy-intensive that liquid H_2 often has higher WTW GHG emissions than diesel (Lee et al., 2018). Gaseous H_2 is encouraged as a result. Essentially, regional grid mix variation, facility energy efficiency differences, and different operational practices yield life cycle environmental impact asymmetry of FCEVs (Sun et al., 2019). For example, hydrogen produced from fossil natural gas steam methane reformation in California has a smaller GHG and climate air pollutant footprint (per MJ of hydrogen) than SMR H_2 from other parts of the U.S. (Sun et al., 2019). Similarly, like that of grid-powered BEVs, the net GHG impact of grid-electrolyzed H_2 for FCEVs will be better in California where grid electricity is less reliant on fossil fuels than in other parts of the country; the contrast in environmental impact based on grid mix can be seen in Figure 6 of this report.

Hydrogen Market – Availability and Logistics

Resource Availability

Current hydrogen production amounts to approximately ten million tonnes per year in the U.S. and 70 million tonnes globally (Fuel Cell Technologies Office, 2018; IEA, 2019). Its market demand is dominated by the chemical production (21%) and oil refining industries (68%); hydrogen's value is currently based upon its material properties rather than its potential as an energy carrier (Joseck, Nguyen, Klahr, & Talapatra, 2016; Sun et al., 2019). For example, H_2 is used to produce ammonia (NH_3) for fertilizer. Population growth suggests that the demand for hydrogen-sourced resources (fertilizer for food, etc.) will grow, even without new market demands for the element (Dincer, 2011). Considering its use in chemical processing for enduring industries in combination with the growing interest in hydrogen for light- and heavy-duty transport, the tight H_2 market will need to expand to meet transportation demand. Argonne National Laboratory projected total FCEV hydrogen demand in 2030 to be about 15 million tonnes (Singh, Moore, & Shadis, 2005). In the short- to mid-term, established fossil production methods of H_2 will likely retain their stronghold but may be ousted as the demand for green hydrogen in unconventional markets grows. Investing in sustainable sources and production methods for the inevitable capacity additions to hydrogen supplies could secure a cleaner transport future. While wind and solar electrolytic H_2 and biogas SMR hydrogen production capacities are lower than from other sources (coal gasification

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[11] Class 8b refers to trucks with a GVWR over 60,000 pounds, generally tractor trailer/combination trucks (Lee et al., 2018).

has a production capacity 20,000 times that of wind power), renewables still present resource potential to decarbonize hydrogen supplies for linehaul (Cetinkaya, Dincer, & Naterer, 2012; Suleman et al., 2015).

Because the market for hydrogen is dominated by the chemical and petroleum sectors, which do not prioritize environmental initiatives over cost factors, green hydrogen production mechanisms do not dominate the industry. Half of the United States' hydrogen comes from fossil SMR. Another third of the H_2 supply is made via petroleum refining, and coal gasification is the third-most-common pathway, at 18% of production. Only ~4% of current production is electrolysis of hydrogen-rich compounds like water (Muradov & Veziroä, 2005). Further, "production from electrolysis comprises only a small fraction of the global hydrogen market due to the high cost associated with expensive [electrolyzer capital]… and electricity consumption of the commercially available electrolysis systems," (U.S. Department of Energy, 2019). Capital investments to produce H_2 from fossil natural gas are lower than from coal or biomass gasification or wind and solar energies, so "the cost of wind- and solar-based electricity and hydrogen is substantially higher than that of natural gas," (Acar & Dincer, 2014; Granovskii, Dincer, & Rosen, 2007). Also, the petroleum refining and chemical industries' hegemony over today's hydrogen scene means that its market-clearing price (even for fossil NG SMR-sourced H_2) is set too high for H_2 to be financially competitive as a transportation fuel. In sum, current hydrogen supplies are already more costly than conventional fuels and would not be zero-emissions from well-to wheel, while renewable hydrogen supplies would be even more expensive.

Operating under the presumption that the most valuable decarbonization approach to linehaul is to not just incrementally lower carbon footprint, but bring it to zero-emissions, then renewable electrolysis or biogas SMR are the ways forward. The National Renewable Energy Laboratory found that while there is a significant potential supply of clean hydrogen from biogas SMR, the supply chain is not developed (Milbrandt, Bush, & Melaina, 2016). While the best-possible (most carbon-negative) biogas resources could yield carbon-negative hydrogen, the reality is that those biogas supplies will be in high future demand across sectors, and that the efficiency losses in SMR may not make H_2 production the best application of those limited resources. Though biogas is compatible with conventional SMR and its hydrogen production costs are in the same range as H_2 from other feedstocks, potentially high delivery expenses to transport H_2 from WWTPs, landfills and other biogas sources after the SMR process mean that only a fraction of renewable SMR hydrogen potential could be cost-competitive for transport use (Milbrandt et al., 2016). Valuable negative-CI dairy digester-sourced biogas for SMR is likely to cost even more.

The challenge, then, is to lower the cost of hydrogen from renewable energy water electrolysis. Reducing H_2 costs from renewable energy (like wind and solar) involve further reducing the levelized cost of electricity (LCOE) in large part by cutting the cost of photovoltaics, turbines, and related infrastructure. Onshore wind and solar became cost-competitive with the marginal cost of conventional energy years ago, and utility-scale solar and onshore wind costs have declined 13% and 7% annually, respectively, over the last five years, according to the annual LCOE analysis by financial advisory firm Lazard (2019). Regional variations in climate/resource availability will impact the financial viability of renewables and should be factored into H_2 feasibility assessments. Electrolyzer capital cost reductions would also be particularly beneficial to H_2 costs, given that expensive membrane, catalyst, and bipolar plate stack materials can make current electrolyzers cost-prohibitive (U.S. Department of Energy, 2019). Schmidt et al. studied how to reduce water electrolysis costs. They found that "increased R&D funding can reduce capital costs by 0-24%, while [electrolyzer] production scale-up alone has an impact of 17-30%" and that enhanced manufacturing methods like increased automation helped but efforts to improve efficiency did not affect costs (O. Schmidt et al., 2017). Highly variable renewable electricity resources can exacerbate expensive electrolyzer capital costs by resulting in low utilization rates and subsequent low H_2 productivity when electricity is used directly onsite (National Academy of Engineering, 2004).[12] This is another reason why high renewable energy capacity factors[13] and low electrolyzer costs are crucial; authors of *The Hydrogen Economy* argued that distributed solar photovoltaic electricity at grid-cost-parity that is only available 20% of the time for electrolysis will not yield hydrogen that is competitive with H_2 from conventional sources (National Academy of Engineering, 2004). Current U.S. average utility-scale capacity factors are 34.6% for wind and ~25% for solar and can improve with technological innovation and by siting renewables in regions with high resource availability (U.S. Energy Information Administration, 2019). Assuming 25-35% up-time for electrolysis is sub-optimal, hydrogen production can have a grid connection backup to mitigate capital underutilization and reduce costs, at the expense of a higher WTP carbon footprint of the hydrogen (National Academy of Engineering, 2004). Wholesale electricity bidding timed well to consider cost savings and low emissions will dampen the negative environmental effects of supplemental grid electricity. McDonagh et al. found that that if electrolysis only runs on grid electricity when the system marginal price is low, the resulting H_2 will have a lower carbon footprint, because "low-cost electricity should be analogous to more sustainable electricity" (McDonagh, Deane, Rajendran, & Murphy, 2019). This load-shifting strategy can also be applied to solely-grid-powered electrolysis operations.

Alternatively, the National Academy of Engineering found that a future dedicated wind-electrolysis plant could be "designed to be large enough that sufficient low-cost hydrogen can be generated and stored when the wind is blowing, without grid backup" (2004). Interestingly, the researchers found that a centralized large-scale system yielded a lower unit production cost for hydrogen than was achieved using a smaller wind-electrolyzer system dependent on a grid backup. Accounting for projected technological improvements like 40% capacity factors, their study, published in 2004, estimated that sometime between 2025 and 2050 "hydrogen produced [at a large plant] from wind without grid backup [would] cost \$2.86/kg H_2, while for a system with grid backup it [would cost] \$3.38/kg H_2 (all without financial incentives)" (National Academy of Engineering, 2004). Hydrogen production costs are not yet this low, but the insight remains. Large-scale H_2 operations could be entirely renewable. Production costs are not the only factor in H_2 gas retail prices: large centralized H_2 supplies would incur additional delivery costs that distributed generation could avoid.

In addition, optimizing electrolytic H_2 production to capitalize upon otherwise-curtailed renewable electricity has been cited as a potential way to reduce green H_2 costs while serving as a form of energy storage (National Academy of Engineering, 2004). One techno-economic study of H_2 production for FCEVs using curtailed wind electricity analyzed a wind farm in China with an installed capacity of 48 MW which experienced a curtailment rate around 32.7% (38,000 MWh) in 2014 (G. Cai & Kong, 2017). It is highly illustrative of electrolysis compatibility with curtailed electricity. High wind production on the farm meant that total curtailed electricity consistently exceeded the electricity needed for water electrolysis across three fuel cell electric vehicle H_2 load scenarios. Electrolyzer and hydrogen storage tank equipment costs scaled in proportion to kilograms of daily gas demand. Because wind power (and curtailment) fluctuates over time, the Chinese Society for Electrical Engineering researchers determined that the cost of necessary equipment for high H_2 demands overshadowed the economic benefit of variable cheap electricity; the higher the load level of electrolyzers on curtailed power, the worse the economic efficiency. The wind farm's curtailment power fluctuated over time, with greater availability in winter months. Though some low (under ten MW) levels of curtailed power were available almost year-round, larger supplies of

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[12] If an electrolyzer is powered by the grid, variability in renewable energy supplies instead affects the carbon footprint of a grid mix and subsequent H_2 produced (fewer renewable provisions are compensated by other – potentially fossil – fuels).

[13] Capacity factor: the ratio of actual power generated to the maximum possible power output (the installed capacity). Capacity factors are influenced by a technology's design and the resource (wind, etc.) availability.

curtailed power were more irregular. Consequently, electrolyzers experienced a tradeoff between increased capacity and decreased equipment utilization. The authors calculated that optimal profits could be found when H_2 production utilized between 16.9% (profitable in 2014) and 34% (most profitable by 2050 once electrolyzer and storage tank costs drop) of curtailed wind electricity (G. Cai & Kong, 2017). Further, they deemed scaling hydrogen production to use all curtailed electricity economically inefficient (2017). Thus, the scale of a renewable energy supply of interest compared to the intended hydrogen production load determines whether relying on curtailed electricity is cost-effective. If an electrolysis operation's hydrogen production plans exceed the economically efficient proportion of curtailed electricity, production would require supplemental grid connection to avoid capital underutilization. In a promising move, in January 2020, the world's first commercial-scale electrolytic hydrogen production operations powered solely by curtailed renewable electricity were announced for Belgian Hyport Oostende. A 50 MW demonstration plant will be built at the port, powered by surplus offshore wind power, with a commercial scale unit planned for 2025 operation (Collins, 2020).

Logistics

Hydrogen suppliers are not yet focused on the transportation sector, so most existing refueling stations rely on delivered-in hydrogen, either gaseous or liquid. Researchers found that using tube trailers to deliver compressed gaseous H_2 to small refueling stations "is an attractive economic option" in nascent FCEV markets with low demand (Lahnaoui et al., 2018; Krishna Reddi, Elgowainy, Rustagi, & Gupta, 2018). If hydrogen demand is greater or must be transported a long distance, liquefying (concentrating) the H_2 is convenient, but energy-intensive and expensive (Barbir, 2013; Lahnaoui et al., 2018; Suleman et al., 2015). In fact, because liquefaction consumes so much electricity, it is the second-greatest contributor to WTW GHG emissions for fuel cell electric trucks using liquid hydrogen (Lee et al., 2018). Liquefaction for fuel delivery ought to be avoided. For very large-scale demands of hydrogen like those of chemical refineries, gaseous hydrogen is distributed via H_2 pipelines – the U.S. has about 1600 miles of them; pipelines are convenient for established demand flows but high capital costs are a "major barrier" to constructing more between centralized producers and new consumers of hydrogen gas, according to the U.S. Department of Energy (Hydrogen and Fuel Cell Technologies Office, 2020). Considering that hydrogen demands are currently low in transport and low utilization would exacerbate high capital costs, delivery of H_2 gas for the near future will rely on tube trailers and existing pipelines.

Another option is to produce hydrogen at refueling stations. Production of H_2 at the point-of-fueling avoids delivery costs, which are also a major driver of final H_2 price (Krishna Reddi, Elgowainy, Rustagi, & Gupta, 2017). The book *The Hydrogen Economy* pointed out that electrolysis is well-suited to "early-stage fueling needs of a fuel cell vehicle market," citing that electrolyzers can scale down well with consistent efficiency, that their compact size is conducive to placement at or near fueling sites, and that running on electricity minimizes the need for new fueling station infrastructure (National Academy of Engineering, 2004). Some linehaul operators may be attracted to the idea of pairing electrolysis with private onsite fueling, which facilitates more control over the behind-the-meter power supply. However, private fueling presents space and financial constraints and implies longer-term commitment, which is why public refueling stations are attractive to others. The best approach towards low WTW footprints is through HDV fueling stations (private or public) fueled by onsite electrolysis production of hydrogen gas, powered by renewable energy. The economic success of these stations will ride on high-utilization, which is why delivered-in hydrogen to HDV-friendly stations will be more practical in the short term, until heavy-duty FCEV technology is more established to justify investments in station production. The United States had 39 public hydrogen refueling stations as of January 2018, with 35 in California due to its aggressive approach to alternative fuels (Sun et al., 2019). Transportation market penetration facilitates station development, and vice-versa: the majority of existing refueling stations cater to light-duty (Class 3 and below) vehicles that use 700 bar hydrogen in smaller quantities than HDVs would require. Today's station sizes range from 100-300 kg H_2/day, and many struggle to be profitable as a consequence of underutilization (Krishna Reddi et al., 2017; USDrive, 2013). Station development in the H_2 space is notably behind that of the other powertrains in this report.

Fueling Types

Uncertainty in the future development of the hydrogen FCEV space is also due in part to differing views on fuel pressure. There may be advantages of dispensing fuel at 350 bar (35 MPa) over 700 bar (70 MPa). 350 bar fueling is simpler because it demands less compression and cooling capacity, resulting in lower station capital, operating, and fuel costs. 350 bar fueling does not require as much cooling time built into fueling schedules. From the vehicle perspective though, higher gas pressure in a tank means more stored energy in the vehicle per unit of tank volume. The passenger LDV standard is 700 bar to compress more fuel into limited tank space (Mueller, 2016). Because fuel tanks on HDVs often have more room, 350 bar may provide enough daily range for buses or smaller trucks used for short-haul. As the technology advances, it is reasonable to presume that Class 8 long-haul vehicles will be developed with 700 bar pressure to add range while saving on space for shipping – storage space is important too. Day cab FCEV prototypes' H_2 tank pressures vary between 350 and 700 bar as providers angle themselves for different parts of the market. It is also possible to fuel a vehicle that has 700 bar capability with fuel at 350 bar pressure, so a linehaul operator would not be without fueling options if it committed to 700 bar vehicles. Alternatively, more 350 bar fuel tanks could yield the same range as a vehicle with fewer 700 bar tanks. This setup would offer lower fueling costs and the same ultimate range but demand more vehicle space. There is not universal agreement about pressure across the hydrogen vehicle fuel market at present.

Modern hydrogen fueling technology has demonstrated the potential for expedient refueling – on par with diesel and gasoline refueling times, and significantly faster (minutes, rather than hours) than BEV charging – even faster than DC "fast charging" setups (Nižetić, Barbir, & Djilali, 2019). This fast refueling is valuable. The longer a truck takes to refuel, the less flexible its travel logistics become, potentially translating into cost and distribution efficiency losses for a shipping network. Hydrogen fueling stations can operate using slow time-fill or fast-fill refueling approaches that – just like natural gas stations – can service vehicles at different rates depending on when the gas is compressed. Both 350 and 700 bar pressures can be supplied through either fueling speed setup, though there will be different compression and temperature control specifications required depending on the desired pressure (Gardiner, 2009). Akin to natural gas, time-fill is compatible for fueling single vehicles or fleets that can afford to fuel overnight, while fast-fill is convenient when multiple vehicles must be serviced in succession, such as at retail stations.

Vehicle Functionality

Safety

Hydrogen faces a public perception problem regarding safety. Its unusually wide range of flammable air concentrations and minimal spark energy needed to ignite (the gas can even be lit by static electricity under certain conditions), combined with a high flame speed have sparked concerns that the fuel carries higher risk than conventional resources (National Academy of Engineering, 2004). With any energy transition, there is a need for worker training and new safety standards to ensure good practice with an unfamiliar resource. For example, using fuel sight and smell as an indicator of risk does not transfer to colorless, odorless hydrogen. Odorants can interfere with fuel cell function and no odorants have been developed to be compatible with hydrogen fueling systems (Fuel Cell Technologies Program, 2011). Given H_2's widespread presence in other industries, the Committee on Alternatives and Strategies for Future Hydrogen Production and Use concluded that "the safety record of professionally managed hydrogen compares favorably with that of similar industrial processes, and that hydrogen can be manufactured and used by trained professionals under controlled conditions with acceptable safety" (National Academy of Engineering, 2004). Drivers, garage managers, and refueling station operators must be well versed in hydrogen's properties and how to manage the gas in closed spaces, because the strength of an explosion depends on the degree of confinement (Dagdougui, Sacile, Bersani, & Ouammi, 2018). The Society of Automotive Engineers established LDV fueling protocol (SAE J2601) in 2014 (K. Reddi, Mintz, Elgowainy, & Sutherland, 2016). DOE and NREL researchers are formulating hydrogen fueling safety codes. Leaders in the HDV realm must establish mandatory workplace training and safety guidelines for H_2 gas temperature and pressure during refueling, maintenance requirements for safe vehicle and gas storage tank management.

Range

On a unit mass basis, hydrogen holds 2-3 times more energy than gasoline, diesel, natural gas and other alternative fuels like ethanol and biodiesel (Suleman et al., 2015). As such, compressing many H_2 gas molecules in an FCEV's gas tank yields significant energy supplies and a high consequential vehicle range potential. This is a strong advantage of hydrogen fuel cell electric vehicles over pure battery electric vehicles, especially in long-haul. According to the International Energy Agency, under high compression (70 MPa), hydrogen has around six times the energy density per unit volume of an electric truck's battery (or about 300 times higher by weight) (International Energy Agency, 2017). BEVs struggle with the "relatively low energy density of batteries, which means that, for a reasonable range, they have to be large, heavy and expensive" because they do not have a compact, lightweight energy-generating resource onboard comparable to FCEVs (Offer et al., 2010). The weight and space contribution of the powertrain on a vehicle translates into energy efficiency impacts; for the same haul volume, a heavier vehicle will consume more energy per unit of haul than a lighter vehicle would (Pagerit, Sharer, & Rousseau, 2006). It is optimal to reduce vehicle mass while maximizing the payload/ storage volume of freight vehicles. Thus, hydrogen fuel cell electric vehicles, with competitive mass-vs.-storage capacity, range and fueling times compared to battery electric vehicles, are a more viable ZEV option for long-distance heavy-duty transport (Mohrdieck et al., 2014; Nižetić et al., 2019). Of course, hypothetical technological ability must be proven with linehaul ZEVs on the road.

An important caveat is that "even when compressed at high pressure (70 MPa), H_2 requires four times as much storage space as the equivalent amount of diesel fuel on a conventional truck" which can "encroach on the carrying capacity of vehicles," (McKinnon, 2018). Consequently, fuel cell electric heavy-duty truck designs still do not offer as much range as conventional diesel trucks. Whereas today's diesel HDVs can drive over 1,000 miles before refueling, even the most optimistic FCEV day cab range projections peak at approximately 700 miles (Molloy, 2019). Still, 700 miles is relatively long, and presents more of a routing-between-refueling-stations constraint than it interrupts daily driving patterns. Given that commercial truck drivers may only drive for up to 11 total hours per shift in the U.S., at a constant 65 miles per hour, drivers would empty their fuel supplies around when they would need to retire for the day (Federal Motor Carrier Safety Administration, 2005; Molloy, 2019). FCEV range may be more of a hindrance to the two-driver setup because the team may be forced to stop and refuel earlier than they would with a conventional vehicle. Regardless, to avoid the risk of a stranded vehicle, freight operators may choose to limit their drivers to less than the full vehicle range – either by requiring mid-trip refueling, which can happen quickly but depends on station accessibility, or by shortening routes.

Vehicle Market

Heavy-duty hydrogen fuel cell electric vehicles are still very much in the development stage. Toyota Motor Corp., which has experience in passenger FCEVs, was the first manufacturer to release a Class 8 FCEV in 2017 (Pocard, 2018). Toyota has a partnership with truck manufacturer Kenworth to build and operate ten Class 8, 300-mile range drayage "T680" trucks under a California Air Resources Board $41 million Zero and Near-Zero Emissions Freight Facilities (ZANZEFF) grant (Hirsch, 2019a; Molloy, 2019). The vehicles operate in and around the Port of Los Angeles and Port of Long Beach and are regularly used to move containers on 70-mile trips. Theirs is the most advanced pilot of linehaul FCEVs to-date. Of interest, the most advanced pilot does not test FCEVs for long-haul, where they have a theoretical advantage over BEVs.

Hyundai – who made the first commercially produced light-duty FCEV and have 1,000 rigid, 250-mile range (at 350 bar) fuel cell trucks in underway for a Swiss deployment – project that their Class 8 "HDC-6 Neptune" day cab fuel cell design will launch in 2022 and be ready for adoption by 2024 (Hirsch, 2019b, 2019a; Hyundai Motor, 2019; B. Schmidt, 2018). Their efforts also involve a partnership with H2 Energy to build out a clean supply of hydrogen in Europe (Hirsch, 2019a). Similarly, Nikola Motor Co. has made waves as a startup in the FCEV freight space, marketing themselves as a fully clean supply chain for FCEV freight: renewable-powered onsite electrolysis fueling stations and vehicles ("Process," 2020). Their business model includes deployment of "700 hydrogen stations across the United States by 2028" (Downing, 2020). Nikola plans to test their Class 8 day cab (with a 500-750-mile range) in 2020, begin full production by 2021, launch the truck in 2022, and have all 14,000 pre-ordered trucks on the road by 2028 (Downing, 2020; Hirsch, 2019a, 2019b). Anheuser-Busch has partnered with Nikola to test their truck for its long-haul delivery fleet, with intentions to lease up to 800 of the semi-tractors (Hirsch, 2019a). In October 2019, longstanding engine and component supplier Cummins also released a demonstration Class 8 6x4 day cab tractor with a PEM fuel cell from their subsidiary Hydrogenics and a range of 150-250 miles depending on fuel cell scale; the OEM's prototype is meant to market their technology potential to manufacturing partners (Lillian, 2019).

Producers claim that the Class 8 FCEV day cabs they are working on will run cleanly and quietly, with the same power and performance as their diesel counterparts, and be able to refuel quickly – Nikola claims their trucks will be able to refill in under 15 minutes (Downing, 2020; Hirsch, 2019a). As these manufacturers build out FCEVs and reach economies of scale, it is likely that the vehicles will improve in range and efficiency and decrease in cost. The DOE is investing efforts into improving the technology beyond business-as-usual development trajectories: reducing the total cost of operations of fuel cells for trucks past 2030, with FCEV TCO parity with Class 8 diesel trucks possibly feasible by 2050 (Vijayagopal & Rousseau, 2019). Hopefully the FCEV market will see a lot of innovation in coming years.

Summary

PROS	CONS
ZEV Viability	GHG Impact - Worst Case
GHG Impact - Best Case	Vehicle Availability
Vehicle Functionality	Cost
Scalability	

Many developers in the FCEV industry highlight the potential to reduce fossil fuel consumption, cut upstream emissions, and ultimately make the H_2 life cycle sustainable by producing the fuel from electrolysis using renewable energy. Fuel cell electric vehicles qualify as ZEVs and can have zero fuel cycle emissions when combined with renewable electricity. As electricity grids decarbonize, the average WTW carbon footprint of an FCEV powered by H_2 from grid electricity will decrease. High energy density can fit onboard FCEVs in less space/weight than a battery-only electric system requires, making FCEVs the superior zero-emissions technology for longer hauls. Like natural gas, hydrogen fueling also has the option of "fast-fill" fueling times (10-15 minutes for HDVs) whereas BEVs need hours.

However, linehaul FCEVs are not ready for the market. Their range appeal has yet to be proven at scale. BEVs also have a higher energy efficiency from well-to-wheel. Further complicating logistics, the majority of H_2 available today is made from fossil natural gas or conventional grid electricity in processes with low efficiencies such that hydrogen-powered trucks' GHG emissions could be as much as 50.26% higher (from WTW) than those of diesel trucks, based on GREET modeling; only nascent production methods using renewable feedstocks could actually decarbonize a linehaul fleet. Unproven renewable hydrogen production and vehicle manufacturing processes lead to high pricing uncertainty currently. In 2017, Transport and Mobility Leuven noted that it is too soon to predict the impact of H_2 on freight decarbonization, projecting that "high energy losses in the 'electrolysis-to-wheel' supply chain are likely to keep this contribution [to road freight decarbonization] relatively modest" (McKinnon, 2018).

IV. Results: Comparative Assessment Against Adoption Criteria

In this fourth section of the report, battery electric, hydrogen fuel cell electric, and renewable natural gas linehaul systems are evaluated against the five adoption criteria. The greenhouse gas accounting and total cost modeling are summarized here with supplemental information included in Appendices B and D.

4.1 Greenhouse Gas Reduction Potential

Each powertrain's emissions were evaluated on a fuel cycle (well-to-wheel) basis. Short- and long-haul[14] combination trucks were modeled in Argonne's 2019 version of their GREET 1 Series fuel cycle model, which is based on U.S. data. Results are tabulated in Appendix B and summarized in Figure 6, below. WTW emissions metrics relevant to GHG reduction in linehaul are grams per mile of greenhouse gases emitted, as well as grams of GHGs released per ton of freight moved one mile. Considering that medium- and heavy-duty trucks traveled 314,820 million miles in 2017, there is significant potential for GHG reduction (U.S. Environmental Protection Agency Office of Transportation and Air Quality, 2019). From upstream sourcing to downstream consumption, each phase in the fuel cycle contributes to a vehicle's WTW carbon footprint. Most often, the energy inputs to fuel processing and transport for use drive WTW emissions, but a deciding factor in a powertrain's greenhouse gas reduction potential is also its feedstock (Mohrdieck et al., 2014). The results indicate that each of the diesel truck alternatives of interest – RCNGVs, BEVs, and FCEVs – have the potential to decarbonize the linehaul sector. Both electric powertrains, however, operate within wide ranges of potential GHG impacts, depending on their feedstocks. Diesel and compressed fossil natural gas linehaul vehicles were also modeled to both provide a fossil baseline and to demonstrate that fossil NG does not offer an environmental improvement upon diesel vehicles.

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[14] Only FCEV short-haul truck emissions were modeled. The GREET model did not have enough data to model the emissions from a long-haul hydrogen fuel cell electric vehicle, presumably because long-haul fuel cell electric vehicles are still an emerging technology.

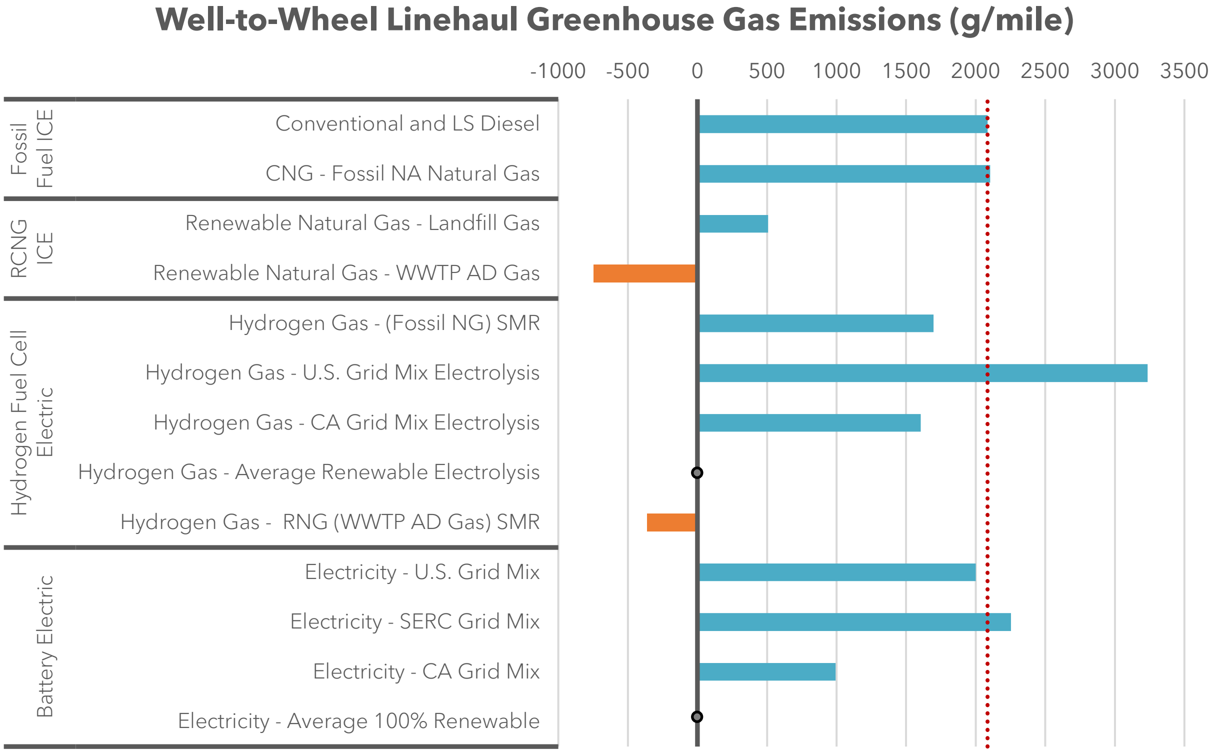

Figure 6. Summary of Results from GREET Modeling of the Well-to-Wheel Emissions Potentials of Various Powertrains Operating in the United States. Red dashed line is the diesel linehaul emission baseline.

Renewable Natural Gas

Depending on the waste feedstock (fuel source), the LCFS-certified carbon intensity of RNG is between 23% to potentially 266% lower than that of diesel, with some provisional[15] manure-AD gas production approaches claiming a CI reduction of over 500% (California Air Resources Board, 2020b). A negative carbon intensity score (and subsequent reduction from diesel >100%) signals using that fuel will "remove" greenhouse gases from the atmosphere. More specifically, consuming said fuel for transportation releases fewer emissions than if the fuel was not processed for use in vehicles.

RNG sources evaluated for WTW linehaul emissions in this report include landfill gas and biogas from anaerobic digestion of (a) sludge at wastewater treatment plants or (b) animal/agricultural waste or (c) municipal solid waste. Landfill gas is more greenhouse gas intensive than other RNG feedstocks, though all renewable natural gas is lower in carbon intensity than diesel and fossil natural gas. AD gas can have a negative carbon intensity, meaning trips running on dairy gas will be carbon negative (Argonne National Laboratory, 2019b). For some companies working towards decarbonization goals, the appeal would be to account for those trips as carbon neutral, with leftover carbon reductions to count towards making other company activities lower in carbon emissions. As of early May, 2020, the only LCFS-certified supplier pathways of RNG with negative carbon intensities come from animal waste, though LFG, WWTP and animal waste sources have all been registered with CARB (California Air Resources Board, 2020b).

Renewable natural gas presents greater decarbonization potential for linehaul than other available fuel alternatives. As seen in Appendix B, with reduced upstream fuel cycle emissions compared to fossil

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[15] These provisional pathways were not included in this report's GREET modeling of linehaul WTW footprints.

natural gas, RCNG linehaul poses a greenhouse gas reduction potential between 75%-136% per mile (on a 100-year time horizon in North America) compared to diesel. Transitioning an average diesel day cab running 75,000 miles/year (short-haul) to an RCNGV with fuel sourced from landfills would cut approximately 120,675 kg of CO_2-equivalent GHGs annually; 1,206,750 kg reduced in the vehicle's 10-year lifespan. Switching just one day cab from diesel instead to a carbon-negative animal waste supply of RNG could cut approximately 197,850 kg CO_2e/year (equivalent to taking 1.23 diesel day cabs off the road for that year). An important caveat is that while RNG reduces GHGs from well-to-wheel (WTW), its tailpipe emissions of NO_x and CO still negatively impact local and regional air quality, compared to zero-tailpipe-emissions vehicles. While RNG puts to use waste gas that would exist and pollute the environment regardless of transportation use, some opponents may take issue with calling burning methane in an engine and the subsequent tailpipe emissions carbon "negative."

Battery Electric

Electricity is generated with fossil, nuclear or renewable resources; in 2019, fossil fuels supplied 62.7% of utility-scale electricity generation in the U.S., while another 19.7% was sourced from nuclear and 17.5% came from renewables (U.S. Energy Information Administration (EIA), 2020). Adopting BEVs has been shown on average to reduce GHGs from the ICE baseline, but GHG impacts depend on electricity generation portfolio. Renewables like wind or solar with zero carbon intensities yield carbon-neutral vehicles, whereas fossil-powered electricity can worsen transportation emissions compared to diesel. When electricity is generated using carbon-negative renewable natural gas, the BEV that uses it[16] can have a carbon-negative footprint. Due to efficiency limitations on converting biogas to electricity for BEV-use, the EER-adjusted carbon intensity of this electricity is not as low as that of dairy-sourced RNG itself (California Air Resources Board, 2020b). GREET did not have this pathway built into its model, so the WTW emissions could not be calculated (as discussed in Appendix B). A BEV with RNG-sourced electricity will have no tailpipe emissions and may be net-carbon-negative but will still lead to combustion emissions that will impact local air quality wherever the NG power plant operates. Dedicated biogas-electricity BEVs are also not the most strategic application of limited biogas supplies, but the WTW emissions of grid-powered BEVs would certainly benefit from grids investing into biogas electricity supplies to offset fossil NG-electricity. Regional grid variations in feedstocks dictate that grid powered BEVs will demonstrate the highest environmental benefit in areas with the cleanest grid mixes; regional grid variations in WTW emissions are shown in Appendix B. One of the biggest takeaways from the GREET modeling is that short-haul BEVs perform better than long-haul BEVs on a WTW emissions basis, furthering the case that existing battery electric vehicles are not as well-suited for long-haul operations as they are for shorter trips.

Average U.S. grid electricity in battery electric linehaul vehicles yields a measly average 3.84% WTW GHG emissions-reduction from diesel (see Appendix B). Meanwhile, BEVs using renewable electricity will be both zero-tailpipe-emissions vehicles and have zero fuel cycle emissions. Transitioning one short-haul diesel day cab running 75,000 miles/year to a BEV running on wind electricity, for example, would eliminate all baseline WTW emissions – approximately 161,475 kg of CO_2-equivalent GHGs annually. Or, switching one short-haul day cab from diesel to a BEV using California's grid electricity could still cut nearly 88,575 kg CO_2e/year.

Hydrogen Fuel Cell Electric

Hydrogen can be produced in many ways. Feedstock, production method, and delivery method (gas or liquid) all impact the carbon intensity of hydrogen fuel. Its use can reduce GHGs from a diesel baseline but supplies rarely have negative carbon intensities, or even any carbon reduction potential – only in

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[16] Due to limitations in the GREET model, this report does not calculate the WTW emissions of an RNG-electricity-powered battery electric linehaul vehicle. The statement above is based on LCFS-registered CI-scores for electricity from dairy manure feedstocks (California Air Resources Board, 2020b).

circumstances with efficient renewable energy feedstocks, but that technology is not widespread. The most accessible source of H_2 – steam methane (from fossil natural gas) reformation – only provides an average 13.53% reduction in grams of greenhouse gases emitted per mile for short-haul vehicles (see Appendix B). Electrolysis – the pathway that many tout as a source for green hydrogen – is only environmentally beneficial if its feedstocks are renewable. Here, the difference is drastic; by switching from diesel truck to an FCEV, WTW emissions could be eliminated or increase immensely. Only refueling station electrolysis pathways of interest – and not also their centralized production equivalents – could be modeled in GREET, as discussed in Appendix B. Zero-carbon electricity yields an FCEV that has no tailpipe emissions and zero fuel cycle emissions, whereas a fossil-intensive grid engenders a fuel cell electric vehicle that should hardly be eligible for ZEV incentives. For example, SERC Reliability Corporation operates in the central/southeastern U.S. – an area of the country that consumes relatively high amounts of fossil fuels like coal (see Figure 12 and Table 7a) (U.S. Energy Information Administration, 2020a). A fuel cell electric combination short-haul truck operating on electrolyzed H_2 produced from SERC's grid would increase emissions from a diesel short-haul baseline by almost 70% (see Appendix B). While the same transition in California would decrease emissions ~25% from a diesel baseline, the average U.S. grid electricity yields hydrogen that would render a 50% WTW emissions increase over diesel, rendering the "ZEV" counterintuitive, unless the sole focus was on zero tailpipe emissions. Hydrogen produced using electrolysis with renewable energy or via SMR of biomethane are the only approaches that demonstrate meaningful greenhouse gas reductions.

Hydrogen serves as intermediary energy storage, and the efficiency of converting water or methane into hydrogen is a concern regardless of pathway. Energy is lost when a source of energy is used to produce hydrogen as an energy carrier, and again as fuel cells extract H_2 electrons for electricity. Energy is also used to compress or liquefy the gas for storage and transport. As previously mentioned, energy inputs during liquefaction of hydrogen increase the WTW carbon footprint of the fuel (as shown in Appendix B), and thus gaseous delivery and consumption methods are encouraged. Modeling of WTW emissions also showed that RNG may be wasted on FCEVs. Due to the many losses involved in hydrogen production and distribution, nearly all the negative-CI benefits of RNG are negated when it is used as an SMR feedstock. This suggests that the limited supplies of biomethane are best applied elsewhere.

Thus, renewable electrolysis is the greenest way forward for FCEVs. Based on the modeling summarized in Appendix B, FCEVs using H_2 from renewable electricity pose a greenhouse gas reduction from diesel of about 100%. Transitioning an average diesel day cab running 75,000 miles/year to this kind of FCEV would cut the same ~161,475 kg of CO_2-equivalent GHGs annually that a short-haul renewable-powered BEV could; both have approximately zero emissions over their fuel cycles. What is not immediately apparent when reading "zero" emissions for renewables is that more kilowatts of electricity inputs are needed to move a truck when hydrogen is created as an intermediary step. The energy efficiency losses in hydrogen production are more pronounced when comparing the environmental impact of grid electricity powered BEVs versus FCEVs, as seen in Figure 7 and Appendix B. This discrepancy in the impact of different feedstocks based on end powertrain use indicates that battery electric vehicles are more environmentally responsible from a greenhouse gas standpoint than fuel cell electric vehicles, at least for short-haul transport. Though the current iteration of the GREET model cannot calculate the emissions-reduction potential of future long-haul FCEV designs, it is possible that the emissions margin between BEVs and FCEVs seen in non-renewable production pathways would be smaller for long-haul than short, or even reversed. More research is needed to quantify these impacts.

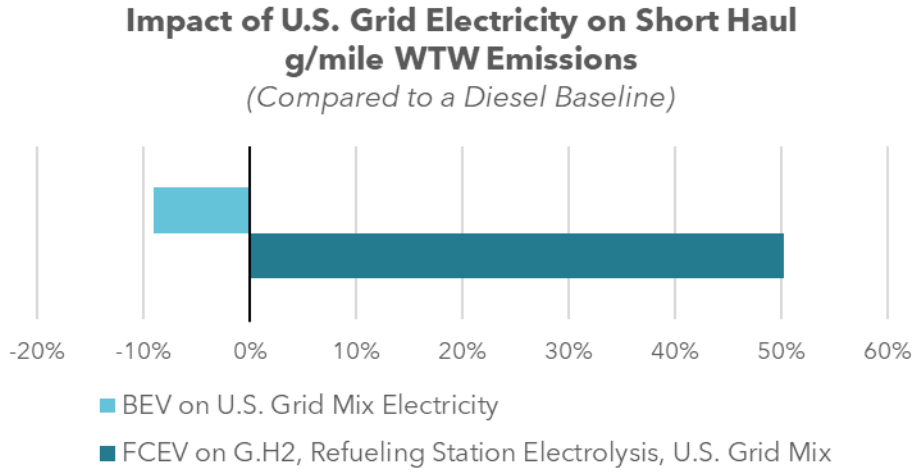

Figure 7. Effect of Efficiency Losses During Hydrogen Production When Using the Same Electricity Source. Losses yield a fuel cycle carbon footprint for an FCEV much higher than that of a comparable BEV using the same U.S. grid electricity source; FCEV ultimately increased emissions from a diesel baseline while BEV decreased emissions. Data from GREET modeling as shown in Appendix B.

4.2 Vehicle Availability

TIMELINE

Manufacturer operation specifics are confidential. This timeline is based upon publicly available information and should not be considered a complete projection. Any projections for past/present quarters not confirmed to have occured are not considered "actualized." Further, in light of COVID-19, these dates - which were projected before the pandemic - are subject to change.

MANUFACTURER	VEHICLE TYPE	PROTOTYPE BUILT	PILOT VEHICLE READY FOR CONSUMER TRIAL	MASS PRODUCTION
Cummins Westport *(OEM + Manufacturer)*	CNGV Engine for Multiple Vehicles	Yes	Yes	Yes
	Class 8 Hydrogen Fuel Cell Day Cab	Yes	No	No
Kenworth/ Toyota	Class 8 Hydrogen Fuel Cell Day Cab	Yes, NA only.	No	No
Hyundai	Class 8 Hydrogen Fuel Cell Rigid Truck	Yes	Yes, for EU deployment, not NA.	
	Class 8 Hydrogen Fuel Cell Day Cab	No, but tractor design released.	No	No
Nikola	Class 8 Hydrogen Fuel Cell Sleeper	Yes, NA only. First Nikola semi-truck prototype.	No, planned for late 2020.	No
	Class 8 Hydrogen Fuel Cell Day Cab	Yes, NA only.	No	No
	Class 8 Electric Day Cab	Yes, NA only.	No	No
	Class 8 Hydrogen Fuel Cell Cabover	No, but design released. EU, Asia, and Australia.	No	No
	Class 8 Electric Cabover	No, but design released. EU, Asia, and Australia.	No	No
BYD Motors	Class 8 Electric Day Cab	Yes, NA only.	Yes	No
Volvo	Class 8 Electric Drayage Truck	Yes	No	No
Lion Electric	Class 8 Electric Urban Truck	Yes	No, planned for summer 2020.	No
Tesla	Class 8 Electric Day Cab, Shorter Range	Yes	No	No
	Class 8 Electric Day Cab, Mid-Range	Yes	No	No
Daimler Trucks/ Freightliner	Class 8 Electric Day Cab	Yes, NA only.	No	No

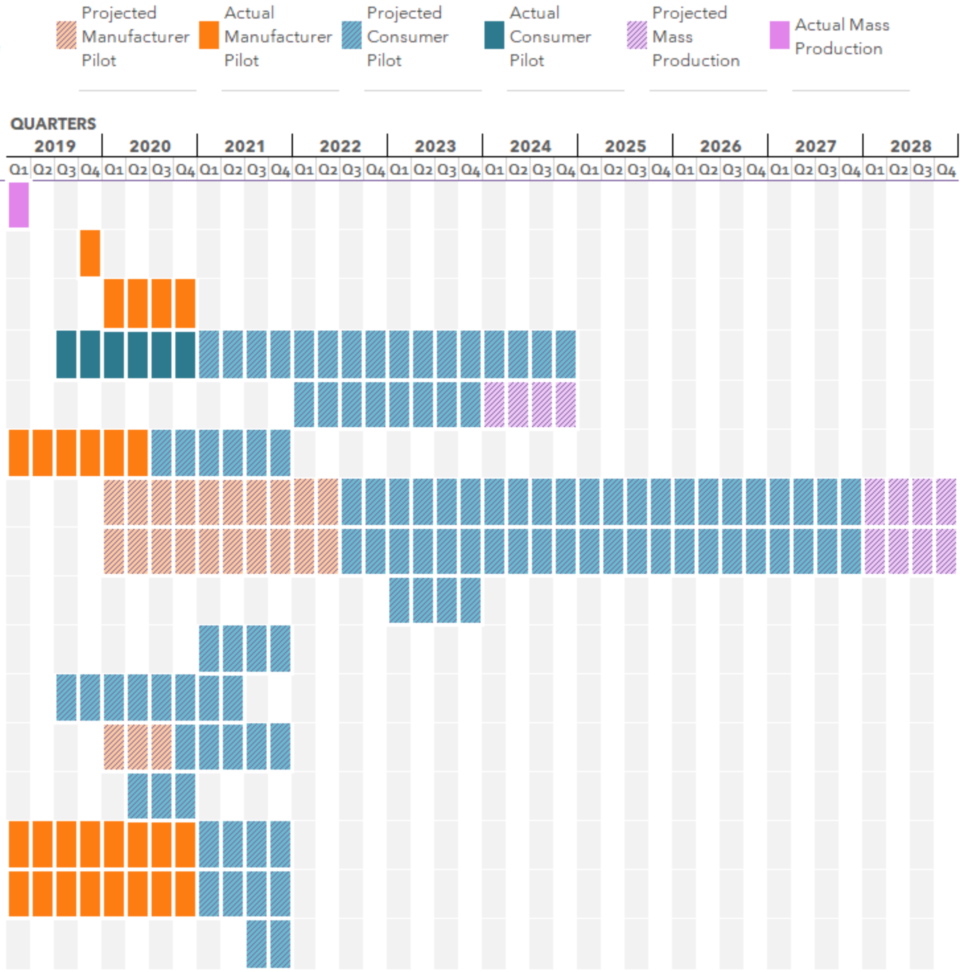

Figure 8. Anticipated Vehicle Availability. Based on automaker press releases – see each powertrain's vehicle availability sections for further detail.

Note: Cummins Westport is an OEM that manufactures natural gas engines for many of the vehicle manufacturers listed in the above timeline. Their ISX12N model is a low-NO_x engine used in heavy-duty trucks (Cummins Westport, 2020). For brevity, manufacturers' various NGV linehaul models were not listed because they are already available for mass production.

Renewable Natural Gas

Today's compressed natural gas vehicles are operationally comparable to conventional diesel trucks and can use RNG as easily as other forms of natural gas. Their engines are quieter than diesel and need less-frequent maintenance (Freightliner Trucks, 2018). The Cummins Westport ISX12N engine is the Class 8 NGV industry standard and it can operate in most vehicle models. NGVs are the only diesel linehaul alternative evaluated in this report that have achieved mass production.

Battery Electric

Light-duty BEVs have already penetrated the passenger vehicle and van markets – the last- and middle-mile EVs are more mature than linehaul electric vehicles. BEV tractors for linehaul are in pilot and prototype stages, with the earliest ready for the market at the end of 2020. Many players are in the BEV linehaul space: BYD, Volvo, Tesla, Lion Electric, Daimler and others. Because BEV powertrains are more advanced than FCEVs, they will be ready for adoption and be cost competitive on shorter timescales.

Hydrogen Fuel Cell Electric

Light-duty FCEVs that are on the market and road are more mature than existing fuel cell vehicles for middle-mile. FCEV tractors for linehaul are only in design/prototype stages, with unproven ranges. Three main players are in the NA FCEV linehaul space: Hyundai, Kenworth (with Toyota's fuel cell) and Nikola. Consumer pilots of some of the vehicles have begun, but over short distances. Before fuel cell electric vehicles can be considered ready for linehaul adoption – especially for the long-haul sector where they are most valuable – their ranges and general operability need more testing.

4.3 Vehicle Functionality

Renewable Natural Gas

CNG vehicles generally present slightly lower range potential than diesel vehicles but can be configured to have roughly the same range potential as diesel vehicles (~1000 miles) if fleet operators are willing to reduce available cargo weight/ volume in place of more gas storage.

NG can be odorized to guide safe use and its use in transport is well-regulated to protect against safety hazards.

Many CNG stations are distributed across the United States, and CNG-for-transport is growing in popularity across the globe (both fossil and renewable). This popularity and the fact that heavy-duty CNGVs are more mature than zero-emissions linehaul suggests greater ease of fueling station access for linehaul RCNGVs than for electric trucks. Battery electric and hydrogen-powered ZEV linehaul will, by contrast, navigate the concurrent emergence of trucks and linehaul-compatible fueling stations because their powertrains are mostly represented in the LDV space currently. Fast-fill retail stations will afford flexibility to some CNGV drivers, while slower fueling options may be compatible with fleet operators interested in overnight refueling.

Battery Electric

The 300-mile (or less) ranges of existing BEV models are compatible with short-haul, though some makers like Tesla promise better. Time will tell if they can deliver on these claims. Pending battery technology breakthroughs, BEVs are range-limited, and will have little utility to long-haul operations without widespread, accessible charging points. In the foreseeable future, BEV linehaul will be best suited to short-haul travel.

Purely battery electric vehicles utilize an electricity source to power an onboard battery. Any associated safety concerns can be effectively managed with built-in safety mechanisms and proper battery handling. Recharging entails one of two options: plug-in or wireless. While battery swapping plug-in charging systems could be advantageous to fleets, the infrastructure is still far-off and the need for spare batteries could offset some environmental benefits. Future highway wireless charging lane networks could alleviate the burdens of range anxiety that plug-in EVs face, but they would require significant capital investment, and realistically would require governmental coordination rather than private ownership. Discussions of wireless technology remain theoretical for the time-being; linehaul BEV prototypes on the market are plug-in vehicles. Plug-in linehaul is best served with Level 3 DC fast chargers, which shorten charging times to better compete with diesel, natural gas, and hydrogen fuel cell refueling times. Even with the best-available DC charging technology, BEVs will likely take longer to recharge than other powertrains. There are many fast charging stations across America and other countries. Still, charging station development has so far been coordinated with LDV needs, though fast charging development is of interest to all EV sectors. Coordinating fast charging, HDV-compatible stations in freight corridors would be strategic to maintain high station utility.

Hydrogen Fuel Cell Electric

On the road, fuel cells in the vehicle convert gaseous hydrogen to electricity, and then FCEVs operate like BEVs. FCEVs would have leverage over BEVs for long-haul if automakers deliver vehicle ranges above the cost-effective range of a BEV (approximately the dividing line between short- and long-haul, 250 miles). Nikola is targeting upwards of a 750-mile range, while Kenworth eyes 300 miles and Hyundai anticipates 250.

Like CNGVs, FCEVs have fast refueling times that afford them a logistical advantage over battery electric trucks. Like battery electric, initial hydrogen fueling setups have catered to non-linehaul demand. Widespread hydrogen fueling infrastructure for HDVs is not yet available but could be strategically developed along heavily trafficked linehaul corridors. H_2 presents the greatest safety concerns of the three linehaul alternatives. Safety guidelines are being established as research and regulatory bodies explore hydrogen's use in transport. With safety protocols in place, hydrogen's flammability risks can be managed.

4.4 Cost

The total cost of ownership for each powertrain was calculated in Appendix D. A full explanation of TCO inputs is also in the Appendix. The vehicle-focused TCOs consist of capital and operating costs, including fuel. Infrastructure costs were excluded. In this section, dollar per mile costs mentioned divided the TCO by the total miles traveled by each vehicle over the ownership period, such as 75,000 miles/year for ten years for the combination short-haul truck (see Table 9). Each vehicle was presumed to operate in Los Angeles, California. Costs for each fuel/energy source vary by region and production process. For example, different electricity rates, transport distances, and fuel production scales and distribution technologies can all impact total fuel production cost. Different production pathways also add variability to the financial value of carbon-reduction credits each powertrain receives. Fuel costs with and without incentives were shown to dramatically impact the overall competitiveness of each alternative powertrain. Heavy long-distance vehicles use more energy per mile. Fuel costs were reduced significantly by federal incentives through the Renewable Fuel Standard's credits for RNG, and even more by the state-level incentives for all three powertrains. California has the most advanced state fuel credit system – the Low Carbon Fuel Standard. The vehicle incentive modeled also significantly reduced capital costs. Incentives are discussed in further detail in the Policy Considerations section of this report.

Annual mileage and new vehicle purchase price increased as vocation type shifted from single unit long-haul delivery trucks to regional short- and then long-haul combination vehicles. Combination vehicles were shown to be more expensive on a TCO-basis than single-unit trucks and long-haul combination trucks had higher TCOs than short-haul. The stage of development of vehicle technology also indicates relative vehicle prices within each vocation type: diesel vehicles were least expensive, then CNG vehicles, followed by battery electric and finally fuel cell electric vehicles were found to be most expensive.[17] Whether a powertrain has reached economies-of-scale influences the TCO, and each TCO is subject to change as each transportation technology system develops. These TCO calculations should be considered estimates and not used to guide investment decisions.

Renewable Natural Gas

The TCO over ten years of planned ownership for a renewable combination short-haul CNGV in California with incentives was approximately $0.62/mile, attractive compared to $1.02/mile for diesel. The cost to operate CNG vehicles is highly regionally dependent, based on renewable fuel credits offered by each state. As seen in Appendix D, RNG is not at all near diesel price parity without incentives. In fact, CNGVs were consistently the most expensive powertrain system before incentives. Without incentives, the short-haul TCO equated to $3.47/mile for a landfill gas-fueled NGV in California, more than three times the TCO per mile of a comparable diesel truck. More-valuable (lower-CI) RNG could exceed diesel fuel prices by a larger margin. Estimating general RNG production costs pre-incentives is complicated because prices vary so much by biogas source. Producing landfill gas from some landfills may cost just one quarter of the price per DGE as some RNG sources like small farms, according to insight shared via correspondence with Marianne Mintz and other researchers in the Energy Systems division of ANL. This estimate is in line with the relationship between RNG supply curves for different RNG feedstocks modeled by UC Davis researchers for CARB and the California EPA (Myers Jaffe et al., 2016). While price estimates are subject to error, they ultimately suggest that the large order of magnitude of RNG fuel costs will render the RNG transportation market dependent on incentives, especially until the scale of available RNG is realized on the market. Though RNG is eligible for federal credits in the U.S., its demand is likely to be concentrated in regions like California and Oregon, where there are significant additive state-level incentives for alternative powertrains. In these areas with high incentives, RNG, in contrast to fossil natural gas, appears to be a cost-effective option to quickly and significantly reduce the carbon footprint of a linehaul vehicle. Elsewhere, a more cost-effective application may be to use biogas sources to decrease the carbon footprint of existing natural gas power plant feedstocks or to offset energy consumption at landfills and wastewater treatment plants (potentially avoiding some of the upgrading and distribution costs), ideally so that increased production of low-CI electricity could offset coal and fossil NG electricity generation.

Furthermore, credit market stability will impact the TCO of RNG vehicles – perhaps more so than for FCEVs and BEVs that do not also receive federal incentives in the U.S. Depending on a customer's appetite for risk in the credit markets, most vendors offer credit value sharing, which is factored into their unit fuel costs. This applies to all credit-eligible vehicle energy sources. Vendors may offer set incentive dollar per DGE discounts to fuel costs such that the final price of RNG is attractively lower than diesel retail rates. Discount values depend on the vendor and project. Vendors will likely be willing to share more of the value of the credit with higher fuel demand commitments, and of course vendors will price in their perception of taking on any or all risk of the long-term future value of incentives. Variations in contracts mean that this report's estimates of fuel cost will not be representative of every possible transaction.

Battery Electric

The TCO for a battery electric short-haul vehicle over ten years, without incentives, was approximately $1.17/mile in California. BEV TCOs consistently came closest to diesel parity (diesel short-haul was $1.02/mile) pre-incentives. Single unit battery electric long-haul even appeared to be roughly equivalent – if not cheaper – than diesel. Electricity is not covered by the federal Renewable Fuels Standard, but

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[17] Findings about vehicle purchase price came from a literature review and from data built into AFLEET, not AFLEET modeling results.

electricity made in California is incentivized for transportation use by California's LCFS. Multiple electricity pathways are already registered, with varying carbon intensities, and offered at different prices based on utility rate structure and other related factors. While this TCO modeled WECC grid electricity, different electricity prices could significantly shift the total BEV cost. Grid electricity costs vary regionally and temporally (due to peak prices, time-of-use rates, etc.), so the TCO of EVs ranges accordingly. The U.S. average grid electricity retail cost, according to the EIA, is 10.53 cents/kWh (CA grid electricity costs are higher), whereas, as of 2017, it costs six cents per kilowatt-hour for utility-scale photovoltaic solar power and two cents per kilowatt-hour of wind in the U.S., including incentives (Solar Energy Technologies Office, 2018; U.S. Energy Information Administration, 2019c; Wiser & Bolinger, 2017). Renewable electricity can be acquired through renewable energy credits (RECs) or other green tariffs, or by directly investing in distributed generation projects. The unsubsidized levelized cost to generate utility-scale solar photovoltaic electricity is between $32-44/MWh and $28-54/MWh for wind (Lazard, 2019). Costs for renewables have been decreasing over time and benefit from governmental incentives, like investment and production tax credits for low-carbon energy. With these federal tax subsidies utility-scale solar PV has a levelized cost as low as $31/MWh and wind may have an LCOE as low as $11/MWh in the U.S., meaning that investing in new wind supplies is the cheapest form of new electricity in the U.S. (Foehringer Merchant, 2018; Lazard, 2019). As more BEVs are deployed, higher station utilization rates will bring down charging station costs.

With the high EER rating of electric vehicles under LCFS regulations (see Table 1), it is likely that low-carbon electricity sources may realize large dollar per kilowatt hour credits that further reduce the cost of operating a BEV. The current LCFS credit structure for heavy-duty BEVs modeled in this report lowered Californian grid-electricity fuel costs enough that the short-haul ten-year TCO was under seven cents per mile. As explained in Appendix D, the current state of EERs used by the LCFS may over-reward (by thousands of dollars) battery electric truck users by assuming their electricity use is more efficient than it is in practice. BEV TCOs were the most attractive alternative to diesel costs before incentives, and with potentially high low-carbon fuel credit eligibility and low electricity costs from renewables, BEVs are the most cost-competitive ZEV option.

One challenge is that battery electric vehicles are relatively expensive. BEV linehaul trucks cost nearly three times their diesel counterparts (see Appendix D). Lithium-ion batteries, while favorable from a technological standpoint, are 40% more expensive than other types of batteries (Clean Energy Institute, 2020). Though lithium-ion battery prices have dropped substantially in the last decade, the weight limitations that heavy battery systems impose upon cargo capacity reduce the economic efficiency of linehaul freight payloads (McKinnon, 2018). From a cost standpoint, it is more valuable to improve battery specific energy and efficiency than to increase the size of existing batteries to add range to BEVs. Ongoing research into battery technology will hopefully continue driving down the price of batteries/BEVs.

On a related note, novel research on the economic and environmental potential of a wireless power transfer fleet across the U.S. showed that that the capital investments and operations and maintenance costs for wireless power transfer vehicles "decrease by 63.2% for Class 8 trucks, compared to conventional ICE vehicles" but that retrofitting roadways could cost "2.5 million per lane per mile ± $1 million per lane per mile" with multi-decade payback periods (Limb et al., 2019). The 2019 study concluded that while it appears that a systemic change towards electrified roadways and wireless EVs could have long-term economic and environmental benefits, the large upfront infrastructure costs may be a barrier to adoption.

Hydrogen Fuel Cell Electric

The public retail price of hydrogen at stations in California ranges from $13/kg to $15/kg (Krishna Reddi et al., 2017). Most transportation demands for hydrogen today come from light-duty transport. The

International Energy Agency anticipates that initial costs of hydrogen fuel for linehaul can be expected to "range from 12% (at USD 9/kg) to 22% (at USD 18/kg) of the total cost of ownership," (International Energy Agency, 2019). Because industrial demands drive the hydrogen market, current fuel costs at refueling stations are too high to reach diesel price parity for transport. Costs can be reduced through increased incentives, technological development, and high fueling station utilization rates as more middle-mile FCEVs are deployed.

Production costs for electrolyzed hydrogen are in the same range as other H_2 production pathways ($0.90-$3.20/kg), but higher ($3.00-$7.50/kg) when the electrolysis is powered by renewables (International Energy Agency, 2019; Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013). Thankfully, research indicates that hydrogen produced from electrolysis could be less expensive than SMR hydrogen in the future, with low (and decreasing)-cost wind and solar energy potentially driving down the production price. According to the International Energy Agency's 2019 report "The Future of Hydrogen," constructing electrolyzers at "locations with excellent renewable resource conditions could become a low-cost supply option for hydrogen, even after taking into account the transmission and distribution costs of transporting hydrogen from (often remote) renewables locations to the end-users," (International Energy Agency, 2019). Europe has higher fuel costs and lower electricity costs for hydrogen production, making electrolyzed H_2 price parity easier to reach there. A study of renewable power-to-hydrogen in Italy projected "a cost of 5.0 €/kg for the hydrogen produced by alkaline electrolysis [using renewable electricity in 2013], which is already nearly competitive on the market if vehicle refueling is performed on-site (i.e., where hydrogen is generated)," in order to eliminate distribution costs (Ferrero, Gamba, Lanzini, & Santarelli, 2016). If fleet managers across the linehaul industry demonstrated greater interest in sustainable FCEVs, their demand could spur greater production of H_2 from electrolysis. Economies of scale greatly impact the cost of hydrogen networks, meaning that different operations could differ in TCO from the estimates provided in this report, and that over time, if the FCEV market grows, costs will likely decrease.

The ten-year TCO for combination short-haul FCEVs running on Californian grid-electrolyzed hydrogen was projected to be $2.54/mile before incentives. Hydrogen fuel pricing is site-specific, not network-based, making cost projections challenging, especially because few vendors have deployed heavy-duty refueling stations and few have refined their zero-carbon production processes. For example, NREL researchers found that grid-electrolyzed hydrogen production is cheaper when utility electricity rates include demand charges (Guerra, Eichman, Kurtz, & Hodge, 2019). Even with incentives, fuel cell electric short-haul was modeled at $2.09/mile – over a dollar higher per mile than diesel. Hydrogen is not covered by the federal Renewable Fuels Standard, but most fuel pathways for hydrogen made in California are covered by California's LCFS. A few vendor pathways are already registered and as transportation demand grows, more vendors will seek LCFS authorization of low-carbon intensity hydrogen. LCFS credits are obviously more valuable for lower-CI feedstocks of the fuel. In the presence of an LCFS price of $200/tonne of carbon, LCFS credits relative to CARB's 2020 diesel standard would reach over $4/kg for compressed electrolyzed hydrogen from wind or solar in California (over 14 times the assumed credit value for H_2 from California's grid – see Appendix D). Like BEVs, the post-incentive fuel costs for the Californian fuel cell electric truck modeled may be too artificially low if the associated 1.9 EER overestimates the fuel efficiency of linehaul FCEVs. The difference between CARB and ANL FCEV fuel economy ratios is smaller than that of BEVs, and at present does not appear to dramatically alter conclusions about the TCO of FCEVs.

By combining these subsidies with lower-LCOE renewable electricity sources of hydrogen, FCEVs could become economically attractive ZEVs. In the U.S., hydrogen fuel could be cost-competitive with fossil alternatives under about $4/kg, which is the DOE's 2020 target for the total electrolyzed hydrogen levelized cost ($2.30/kg production plus $1.70 for compression, storage, and dispensing) (Guerra et al., 2019; Office of Energy Efficiency & Renewable Energy - Fuel Cell Technologies Office, 2020). Though the TCO is not yet competitive with diesel linehaul, the FCEV market is developing, and renewable electrolysis is promising. Per IEA findings about cars, fuel cell electric trucks may be more competitive on a TCO basis with BEVs over longer driving ranges than this report estimated. Discrepancies may be attributed to uncertainties in pricing due to the nature of the emerging hydrogen fuel and long-haul electric truck industries, and the fact that capital costs dominate car TCOs while "fuel costs generally make up a greater share of total costs for heavier vehicles, and for vehicles with high [utilization] (such as long-haul trucks)" (International Energy Agency, 2019). As shown in Appendix D, hydrogen fuel costs are higher than the electricity costs for BEV counterparts.

At present, FCEVs are expensive – their purchase price was modeled to be between three to four times as expensive as equivalent diesel vehicle types (see Appendix D). Running costs are so far 30-40% cheaper than diesel vehicles, and maintenance costs are also lower (McKinnon, 2018). Improving hydrogen production and vehicle efficiency will reduce costs and life cycle GHG impacts. The price of fuel cells, refueling equipment – compressors in particular – and electrolyzers would all decrease with economies of scale.

4.5 Scalability

Renewable Natural Gas

A team of sustainable transportation researchers at UC Davis found in 2016 that California has the resource potential to produce roughly 660 million diesel gallon equivalents (MDGE) per year of RNG sourced from a collection of feedstocks (Myers Jaffe et al., 2016). Individual fleets' annual MDGE demands are far below this Californian potential, and below the U.S. RNG availability and resource potential described in Table 2. Renewable natural gas supplies appear to be insufficient to completely unseat diesel linehaul, however. Furthermore, current low-carbon WWTP and dairy waste biogas supplies are limited and in high demand across sectors. According to NREL, "there are over 1,700 dairy farms in California, of which about half are considered good candidates for biogas projects, but only 11 [captured biogas as of 2016]," (Milbrandt et al., 2016). Thus, scalability concerns about RNG (and negative-CI RNG in particular) should be centered on fuel production cost, resource competition, and practicality, rather than physical ability. Economic analysts Bates White wrote in 2019 that "RNG projects require substantial capital investment [the average project requires $17 million]. Total capital costs for smaller landfill projects are in the range of $5 million to $25 million, and upwards of $100 million for larger projects, including agricultural and wastewater projects" (Bates White Economic Consulting, 2019). While production volumes are still marginal compared to the broader NG market, they noted that RNG production "more than doubled" from 2015-2018, "with an average annual growth rate of 30 percent," (Bates White Economic Consulting, 2019). They concluded that increased RNG developments create a positive feedback loop that drives demand growth and in turn provides "assurance that the transportation market has the capacity to accommodate further growth in RNG volumes" so long as fuel incentives are present (Bates White Economic Consulting, 2019). TCO analysis in Appendix D demonstrates that RCNGVs are heavily dependent on incentives to be economical. Despite skepticism from energy agencies and researchers about total supply volumes, RNG can meet the demand from individual fleets under the right conditions. Accordingly, fuel vendors are likely to expect interested fleets to make substantial fuel purchase commitments in order to bring production online.

Battery Electric

Pending battery design breakthroughs, BEV systems are more scalable for short-haul than long-haul transport. Range anxiety is perhaps the largest barrier to increased BEV adoption. Range extension is a function of increased battery capacity and improved charging infrastructure access. Civil engineers at Michigan State and Northwestern Universities found that "building long-range [BEVs] may not be cost effective… until the unit battery cost is reduced significantly" because the total battery electric vehicle/charging infrastructure system, in its current form, has prices that are dominated by battery cost, which increases with larger battery sizes (Ghamami, Zockaie, & Nie, 2016). Consequently, a research priority is to develop lower-cost, high-range batteries. Research and development on reducing unit battery costs has been estimated to boost BEV adoption and increase driving range more effectively than by expanding charging infrastructure access (Nie & Ghamami, 2013). Infrastructure costs decrease as battery capacity grows, because charging points can be distributed more sparsely (Nie & Ghamami, 2013). Given current battery technology and prices, charging station development is the most effective way to increase EV adoption in the meantime (Ghamami et al., 2016). While researchers focus on lowering battery prices, which will be more effective in the long run, developers should invest in HDV-compatible DC fast charging BEV stations to expedite an electrified linehaul future. As BEV (passenger and heavy-duty) and renewable electricity demands grow, more charging points for low-carbon sources of electricity will come online. Similarly, international and U.S. grids will probably decrease in carbon intensity over time.

Researchers also found that high penetration of wireless charging technology would alleviate range anxiety and yield higher light-duty EV adoption rates compared to business-as-usual EV charging technologies, but they recognized many developmental challenges and conditional economic and environmental unknowns associated with the emerging technology (Bi, 2018; Lin, Li, & Dong, 2014). It is too soon to grasp the true impact wireless BEVs will have on the linehaul sector, especially given the coordinated governance that may be required to develop wireless charging networks at scale. Mass-scale battery swapping systems could be attractive for individual fleets, but the market for linehaul battery swapping is nonexistent right now. The future of battery electric linehaul largely rides on the progression of battery technology.

Hydrogen Fuel Cell Electric

Today's hydrogen production (about ten million metric tons annually in the U.S. alone) is orders of magnitude larger than the current transportation demand for the fuel (Fuel Cell Technologies Office, 2018). However, the market is mostly contracted to industrial demand and is carbon-heavy, because vehicle innovation is a bottleneck to H_2 penetration in the transportation sector and other industries do not have comparable low-carbon incentives. The demand for H_2 in transport, like that of electricity for BEVs, began when light-duty versions of the powertrain hit the road. Further developments in hydrogen-powered freight will likely await proof-of-concept from vehicle manufacturers; if FCEVs are best-suited to long-distance transport, can vehicle prototypes reach range aspirations? Once long-haul FCEVs demonstrate potential, hydrogen fuel producers will likely shift some supply to the linehaul market and invest in lower-carbon fuel pathways. Gaseous (compressed), not liquid, hydrogen is attractive because it has a lower CI and requires fewer capital investments.

Most hydrogen station development has focused on California but public retail fueling stations are usually fit to LDVs and cannot accommodate HDV-scale demands of gas, so HDV-friendly stations are needed. There are not many H_2 fueling stations compared to the number of RNG, diesel or charging stations. Developing fueling setups that can service many vehicles at a time will help prevent station underutilization, which is expensive. A 2019 study published in the International Journal of Hydrogen Energy noted that distribution costs for H_2 decrease with increased hydrogen demand (Lahnaoui et al., 2018). Economies of scale will lower costs across the supply chain for FCEVs.

There is a need for initial capital investments in electrolyzers to displace the overwhelming supply of hydrogen from non-electrolysis sources. In July 2020, NextEra Energy announced plans for a $65 million pilot of solar-powered electrolysis made by a 20 MW electrolyzer in Florida – targeted for 2023 (Stromsta, 2020). At one point, renewable electricity would have been considered too valuable to waste on inefficient hydrogen electrolysis production. Still, as the LCOE of wind and solar drop, renewable electrolysis' cost curve will follow; if renewable electricity costs decline in tandem with scaling up of hydrogen, the IEA's 2019 Future of Hydrogen analysis estimated that the price of renewable hydrogen could drop 30% by 2030 (International Energy Agency, 2019). Also, coordinating hydrogen production in areas with a lot of renewable energy curtailment would provide an energy storage option that could facilitate renewable electricity integration and reduce hydrogen production costs by leveraging low-cost surplus electricity. Though decoupling hydrogen production times from vehicle fueling shift times could be a hindrance, flexible electrolysis schedules allow producers to capture lower-cost, lower-CI sources of electricity.

V. Policy Considerations

5.1 U.S. Renewable Fuel Standard and its RINs

The Renewable Fuel Standard (RFS) is a federal program run by the EPA established by the Energy Policy Act of 2005, an amendment of the Clean Air Act (U.S. Environmental Protection Agency, 2020c). It sets renewable fuel volume requirements annually to increase biofuel presence in the market. The program is meant to encourage domestic biofuel production – thereby supporting rural economies and enhancing energy security – and to promote fuels that are less emissive of greenhouse gases on a life cycle basis (Stock, 2018). The RFS was expanded by the Energy Independence and Security Act (EISA) of 2007 with levels of financial incentives for certain transportation/jet fuel and heating oil types that demonstrate greenhouse gas reductions. Various production pathways qualify for each fuel type: RNG produced via biogas from landfills, municipal wastewater treatment plants, or agricultural digesters falls under the D3 Renewable Identification Number (RIN), which is under the D5 umbrella RIN (see Figure 9). RINs cover RNG but do not currently incentivize hydrogen nor electricity.

RIN D Code	Fuel Type	GHG Reduction Required	Fuels
D3/D7	Cellulosic Biofuels	60%	Renewable CNG and LNG, Cellulosic Ethanol, Cellulosic Diesel (D7), etc.
D4	Biomass-Based Diesel	50%	Biodiesel, Renewable Diesel, etc.
D5	Advanced Biofuels	50%	Sugarcane ethanol, biogas, etc.
D6	Renewable Fuel	20% or less	Corn ethanol, etc.

Table 3. RINs Available Through the U.S. federal Renewable Fuel Standard, Reproduced from EcoEngineers (EcoEngineers, 2015) .

Linehaul consumers of RFS-approved fuel could report use of registered D3 RNG in their vehicles but would not be owners of actual RINs. Fuel producers are generally the RIN generators who can "generate" a RIN for each gallon of renewable fuel sold for transport use: "the physical fuel and the RIN are separated when the fuel is designated, blended and sold/utilized as transportation fuel," (EcoEngineers, 2015). The credits may then be monetized, with a part of the projected RIN value often worked in advance into established fuel pricing between the fuel producer/vendor and consumer (EcoEngineers, 2015). The RIN market is supported by non-renewable fuel refiners and importers ("Obligated Parties," OPs) that must generate or purchase RINs to meet Renewable Volume Obligations (RVOs) as established by the RFS. Each

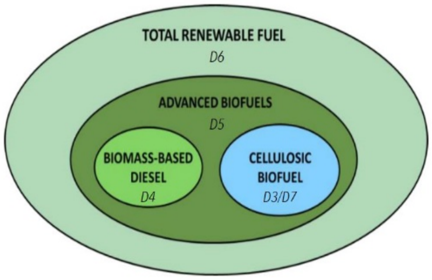

Figure 9. Nested RFS Fuel Categories, Modified from 115th U.S. Congress Committee on Energy and Commerce Memorandum Re: Hearing on Advanced Biofuels Under the Renewable Fuel Standard (Committee on Energy and Commerce Democratic Staff, 2018).

year, OPs must retire the RINs they acquire to the EPA to demonstrate compliance. The EPA does not certify RINs. Instead, fuel producers can register their renewable fuel pathways with the RFS through Quality Assurance Plans provided by EPA-approved third-party auditors to be able to generate valid credits (known as Q-RINs) (U.S. Environmental Protection Agency, 2020a). Because OPs are liable for Clean Air Act violations if the EPA finds that their purchased RINs do not meet RFS standards, OPs drive the demand for RFS-compliant valid Q-RINs on the renewable fuel market.

Future of the Renewable Fuel Standard

The EISA has RFS biofuel volume requirements ramping up through 2022 but the EPA Administrator is allowed to annually review or waive these volumes if "the program is causing severe economic or environmental harm or based on inadequate domestic supply" (U.S. Environmental Protection Agency, 2020c). The total statutory target has not been met since 2014 (Congressional Research Service, 2020). There are not statutory volume requirements planned for after 2022, but the RFS program does not end after 2022 – it will be up to the EPA to set new volume obligations. It is hard to account for competing demand pressure; if RFS fuel credits remain uncertain but credits for RNG in electricity sector appear more valuable, the electricity sector may have the advantage going into purchase agreements. Given that the RFS credit structure has been successful at encouraging alternative fuels, it is likely the program volumes will be extended.

5.2 Other Standards and Fuel Credit Markets

Canada has proposed a national Clean Fuel Standard regulation/tradeable credit system to be implemented in 2022 that will replace its current Renewable Fuels Regulation and require carbon intensity reductions for gaseous, liquid, and solid fuels (Government of Canada, 2020; The Jacobsen, 2020). As of April 2019, the European Parliament has binding CO_2 reductions and zero-emission fleet targets but no EU-wide incentives for zero-carbon HDVs (European Parliament, 2018). However, multiple countries offer tax benefits, special route/parking access, or other forms of indirect incentives. France, for example, created a staggered vehicle registration tax that functions as an environmental penalty based on grams of CO_2 emissions per kilometer (European Union, 2020). On the whole, the European Union has rules requiring that each of its Member States develop targets for public refueling/charging points to ensure minimum coverage for electricity, compressed and liquefied fossil and renewable natural gas, and (optionally) hydrogen resources (European Commission, 2014). Similarly, China has set targets for a national BEV charging network, given electric vehicle drivers special driving/parking access incentives, and created subsidies for electric vehicles with ranges over 150 kilometers in addition to its New Energy Vehicle policy (Hove & Sandalow, 2019; Ji & Huang, 2018).

There are also production incentives for renewable energy, biogas, and hydrogen, beyond those targeted at transportation. For example, by the International Energy Agency's count there are approximately 50 "targets, mandates and policy incentives in place globally [as of 2019] to directly support hydrogen," mostly for transport (International Energy Agency, 2019). Similar supportive policies exist for biogas and renewable electricity. Renewable energy credit markets are a prime example. Policies that incentivize production will help sustainable energy resources reach economies of scale and may indirectly reduce costs for alternative transportation. Tractor-truck emissions standards and carbon reduction targets exist in the U.S., Canada, China, Japan, India and the EU (Rodriguez, 2019). Finally, there are fuel economy standards, air quality standards, and a slew of policies directly targeted at LDVs that will drive the broader alternative fuel vehicle market forward – too many to discuss in depth in this report.

Low-Carbon Fuel Standards

California

At a state level, California created its own version of the RFS in 2011 called the Low Carbon Fuel Standard. Aimed at fuel decarbonization and land-use reduction, the LCFS sets annual reductions in allowable average fuel carbon content, wherein fuel producers whose average CIs are below the target generate credits and can sell them to producers who need to offset portfolio carbon intensities that are above compliance. For instance, the LCFS diesel CI standard for 2020 is 92.92 gCO_2e/MJ (California Air Resources Board, 2019b). LCFS credits exist for a wider range of alternative fuels than RINs – biogas and hydrogen are included. LCFS low- and zero-CI credits for electricity used as a transportation fuel in California are also available for California average grid electricity, green tariff "book-and-claim accounting" (indirect use of renewables) and direct consumption of renewable electricity, so long as the fuel pathway is certified through CARB's Alternative Fuels Portal (California Air Resources Board, 2019). Importantly, "low-CI electricity used [to power transportation] must be in addition to California Renewables Portfolio Standard (RPS) requirements" in order to qualify for LCFS credits (California Air Resources Board, 2019). Fuel producers must register their product and verify its feedstock and production pathway with the California Air Resources Board to be eligible for LCFS credit generation. Ranges of EER-adjusted LCFS Pathway Certified Carbon Intensities (as of April 27, 2020) are shown in Appendix C.

Other Low-Carbon Fuel Programs

British Columbia has a low-carbon fuels standard that mirrors California's, entitled the Greenhouse Gas Reduction Act (The Jacobsen, 2020). Oregon also has a similar but less developed program, the Oregon Clean Fuels Program. The Clean Fuels Program covers RNG and electricity but not hydrogen (Department of Environmental Quality, 2020). Washington explored a fuel standard program meant to begin in 2021. A bill passed in the state House in 2019 but failed to come to fruition (The Jacobsen, 2020). It will likely resurface in discussion. Alternative fuels will become cost-competitive on larger scales as other states develop their own fuel standards. Adoption of state incentives for low-carbon fuel may follow the trajectory of states' renewable energy policy rollouts.

State	**Credits**
California	Yes – Low Carbon Fuel Standard (LCFS)
Oregon	Yes – Clean Fuels Program
New York	No, but legislation like LCFS has been proposed.
Washington	No, but legislation like LCFS has been proposed. Puget Sound Clean Fuel Standard also proposed.
Colorado, South Dakota, Minnesota, Iowa	No, but conducted LCFS feasibility study/considering some form of low-carbon fuel standard.
Other States	No

Table 4. Status of Clean/Low-carbon Fuel Standards in the United States (The Jacobsen, 2020).

5.3 Fuel Credit Pricing

Volatility of the Fuel Credit Market

Fuel credit prices bridge the gap between renewable fuel supply and demand volumes created by fuel standards, reflecting the marginal cost of the renewable fuel. RFS demand volumes are specified in the EISA via RIN quantities that Obligated Parties (non-renewable fuel providers) must retire to the EPA and via percentage standards. The volumes are subject to annual review. Low-carbon fuel demand in California is reflected in the LCFS annual additive fuel carbon restrictions. Fuel credits reflect the currency of fuel policy, attracting renewable fuel producers/distributors while adding costs to fossil fuel providers, ultimately driving sustainability in the fuel market, much like renewable energy credits in the electricity sector. High credit prices reflect that the annual demand may be higher than alternative fuel supply – it signals that buyers on the credit market fear challenges in meeting renewable volume requirements (Cooper, 2018). If RIN/LCFS credit prices rise substantially, OPs may prefer to invest more in their own renewable fuel production and distribution. Accordingly, high credit values signal ease of alternative vehicle adoption and stimulated low-carbon fuel production. Alternatively, low credit prices indicate that the market is not furthering renewable fuel adoption such that there is less competition for the credits. The values of RFS and LCFS incentives fluctuate with supply and demand of low-carbon fuels, essentially – see Figures 10 and 11.

Much like the boom-bust development cycles created by the short-term renewals of federal Production Tax Credits in the wind power sector, the annual modifications to RFS fuel volume requirements, changes in political leadership, and fuel technology or capacity variability all affect market perception and the value of credits. Even fuel-related White House meetings and congressional letters have correlated with fluctuations in RIN prices (Covington & Burling LLP, 2019). Under the current conservative presidential administration, and because volume requirements have not yet been set past 2022, the RFS's RIN credit prices are at unprecedented low values (White House, 2018). Low volume requirements/RIN values mean that fewer investments will be made into new RNG supplies (Gorrie, 2014). Meanwhile, California's progressive environmental stance and the certainty they recently provided by extending the LCFS through 2030 means their credits are at record highs (Bledsoe & Farbota, 2019).

Figure 10. Weekly D3, D4, D5, and D6 RIN Prices ($/ethanol-gallon-equivalent) from 2015-2020 (U.S. Environmental Protection Agency, 2020h).

Figure 11. California LCFS Credit Prices ($/ton) for Last Three Years Based on Platts Data (Neste, 2020).

5.4 Future of Alternative Fuel Policy

LCFS provisions for zero-emissions electric and hydrogen credits are recent. The LCFS will likely further restrict carbon standards and continue to register new fuel pathways. Other states and countries are expected to develop similar programs (Kahn, 2018). While the RFS is focused on biofuels, it does prioritize greenhouse gas reduction and may extend incentives to hydrogen and or electric vehicles, though the current U.S. EPA Administrator, Andrew Wheeler, was recently reprimanded by bipartisan Representatives for failing to review dozens of pending additions to RFS pathways (Voegele, 2019). The RFS is likely to stay in place, but its future volume demands and RIN prices are hard to predict. Renewable Fuels Association Executive Vice President Geoff Cooper had this to say: "it seems like there's less risk that something could go wrong with the LCFS, whereas with the RFS, gosh—it seems like every day we've got a new headline coming out about some new clandestine, secret effort to undermine the RFS" (Kahn, 2018).

Note on the Broader U.S. Regulatory Climate Regarding Environmental Standards

In 2019, the Trump administration revoked California's ability to set its more stringent emissions standards and ZEV targets, though California and 22 other states and a few large cities have filed suit against the move (Shepardson, 2019). The dispute may not be settled before the 2020 presidential election, and could advance to the Supreme Court, but legal analysts believe that revoking California's Clean Air Act waiver is unlawful, giving the suit a strong case in court (Higgins, 2019). California's supporters believe in the urgency its emissions standards impose upon the entire vehicle industry and value that the waiver affords other states to follow California's lead. In contrast, fossil-fuel organizations and automakers desiring uniformity across the American market support the move to remove state-specific emissions standards. Attempting to roll-back California's waiver is part of the Trump administration's efforts to reverse many environmental rules nationwide: as of July, 2020, 68 have been formally dismantled and another 32 attempts are ongoing; 27 of the total 100 rules are air pollution/emissions-related (Popovich, Albeck-Ripka, & Pierre-Louis, 2020). Unfortunately, relaxing regulations will likely enable many industries to engage in harmful environmental practices and may hurt the economics of climate-friendly alternatives. While the technology options for emissions reductions remain the same with or without the Clean Air Act waiver, vehicle manufacturer and fuel vendor certainty in the market for alternative powertrains depends on reassurances from regulatory bodies, and this may influence vehicle availability and transportation systems scalability if ZEV investments are put on hold. In the interest of a zero-emissions future, some players in the transportation space will still move forward with their plans, even while policy specifics are in question. Politics and changes in leadership can have a significant impact on the alternative fuels industry, so the 2020 elections might lead to reversals in some of the policy developments under the current administration.

5.5 Vehicle Incentives in the U.S. Market

California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) offers alternative vehicle funding without requiring vehicle scrappage. HVIP is out of funding for Fiscal Year 2019-2020, but anticipates accepting new voucher requests for Fiscal Year 2020-2021 beginning in November 2020; fleets can apply for "up to 200 vouchers per calendar year," (California HVIP, 2020). HVIP announced restrictions to its offerings in October 2019 due to budget limitations (CALSTART, 2019). HVIP offers $45,000 per CNG vehicle – Cummins Westport engines are the only CARB-approved Low NO_x natural gas engine, and as of October 2019, only those that run on RNG produced in California are eligible. Any CNG fleet that receives this grant must use 100% renewable natural gas for a minimum of three years. HVIP also offers $150,000 for heavy-duty battery electric trucks and $300,000 for hydrogen fuel cell trucks with a gross vehicle weight rating above 33,000 pounds (Class 8). In addition to vehicle incentives, for any adoption of at least five FCEVs, up to $100,000 per vehicle is available to cover hydrogen infrastructure costs through HVIP. California's San Joaquin Valley also offers a fleet expansion grant worth $20,000 for any zero-emission, hybrid, or low-NO_x Class 7-8 vehicles (or $10,00 for Class 4-6) that spend 90% of their operating time within California and at least 50% of time within the Valley's Air Pollution Control District, without any old vehicle scrapping requirements (San Joaquin Valley Air Pollution Control District, 2012). Interested parties would need to get the District's approval before purchasing vehicles (the grant does not apply retroactively). Both Californian incentives are on a first come, first served basis.

New HVIP restrictions limit "credit stacking" – fleet operators may only be able to combine incentives on a case-by-case basis (CALSTART, 2019). Other grants like the South Coast AQMD Carl Moyer Program (which can no longer be used in addition to HVIP) and Volkswagen settlement Environmental Mitigation Trust funds are available and require vehicle scrapping. There are hundreds of regulations and incentives for alternative fuels, fueling infrastructure, and vehicles across many other states, offered both by state agencies and utilities – the DOE's Office of Energy Efficiency and Renewable Energy's Alternative Fuels Data Center maintains a "State Laws and Incentives" list on their website (Alternative Fuels Data Center, 2020h). Many are niche policies and not all are applicable for HDVs, but the interest in alternative powertrains in each state is reflected in the amount of political and financial support available.

Private companies, both in the U.S. and abroad, also offer incentives. For instance, natural gas vendor Clean Energy Fuels also has a financing program entitled "ZeroNow" that offers a $40,000 incentive towards the purchase price of a new Class 8 natural gas truck, and also includes a five-year/ 375,000-mile Cummins extended warranty, which could be added to grant funding like HVIP (Clean Energy Fuels, 2020). Included in the ZeroNow five-year plan is a guarantee of RNG provisions at a cost below diesel market prices. In a sense, this fuel agreement facilitates consumer hedging against fluctuations in the fuel credit market. Similar private programs may come about in the future.

VI. Driving Change

In a roadmap for linehaul fleet transition, proactive parties can reduce fleets' carbon footprints via renewable compressed natural gas today. RNG presents significant GHG reduction potential for short- and long-haul, but the most valuable carbon-negative biomethane may be costly to develop at large scales. Given that CNGVs do not meet zero-emissions vehicle targets, committing to this powertrain is best for fleet operators that prioritize GHG-accounting and want to tap into RNG's carbon-negative potential. CNGVs are particularly attractive for long-haul fleet operators interested in lowering their carbon footprints sooner than fuel cell electric vehicles will be able to accommodate them. Fleet operators could also capitalize upon NGV availability and transition a percentage of their fleet to RCNGVs while awaiting the development of ZEVs for linehaul. This approach would work well for operations that replace a fraction of their aging fleet every 5-10 years. Those ZEV-focused operators should explore leasing agreements for their vehicles and contracts to use public fueling stations in order to avoid long-term commitments to a powertrain that relies on incentives for scalability and cannot meet ZEV targets.

Hydrogen's exact role in the future of linehaul remains uncertain, as FCEV companies make bold promises but have yet to demonstrate significant results. The current H_2 market is dominated by unsustainable production methods and fuel costs are projected to be high, but renewably sourced hydrogen might also come at lower unit costs in the future. Both electric powertrains could spur renewable energy development. Electric powertrains can serve as energy storage with the potential to smooth electricity demand curves or capitalize upon surplus renewable energy. Flexible hydrogen production may make the gas a better candidate for storage than linehaul battery electric vehicles. Hydrogen's role as an energy carrier from distributed/grid electricity back to vehicle electricity means that a smaller fraction of the original energy from feedstocks is transferred to vehicle motion, compared to battery electric vehicles (McKinnon, 2018). For all energy sources modeled in this report besides zero-emissions renewable feedstocks, the efficiency difference yields higher carbon footprints for FCEVs over BEVs of the same vocation type. Note that long-haul FCEVs could not be modeled in the current iteration of GREET. Consequently, battery electric vehicles are the optimal ZEV powertrain for short-haul systems. Battery electric linehaul will also benefit from the newfound consumer acceptance of light-duty models. BEVs are ideal for short-haul because their systems are more energy efficient WTW than hydrogen, but – pending design validation – FCEVs become more attractive than BEVs for zero-emissions long-haul. These findings on electric powertrains are consistent with available literature. U.S. Department of Energy researchers noted the relationship between BEVs and FCEVs:

> For BEVs, as the capacity of the battery pack increases, an ever-greater fraction of that capacity is used to move the mass of the batteries rather than the mass of vehicle, passengers, and cargo. This results in a nonlinear relationship between vehicle purchase cost and vehicle range. For FCEVs, after adding the basic components of the powertrain—i.e., the compressed gaseous storage tank, fuel cell, balance of plant components, and small battery—an increase in vehicle range requires only slightly larger components, which has a relatively small impact on vehicle mass and cost. (Morrison, Stevens, & Joseck, 2018)

As the trucking industry transitions from long-distance routes to a hub-and-spoke model of localized fleets, true long-haul – where hydrogen FCEVs are projected to have an advantage – may become less prevalent in fleet operations (David Cullen, 2017). Battery electric vehicles may dominate linehaul, wherein hydrogen linehaul can serve as a niche zero-emissions solution for long-distance transport, and CNGVs as a convenient waste-to-fuel decarbonization tool. For alternative vehicle rollouts to be successful, fueling infrastructure availability must be included in consumers' route planning and optimization decisions. The future of vehicle autonomy may alleviate some range limitations tied to driver schedules, as routes could be optimized solely around fueling and delivery needs. Fuel providers interested in capturing the linehaul market ought to position themselves near ports and along heavily trafficked shipping corridors. Linehaul operators and the companies that hire their services have the power to insist on renewable feedstocks for their fuels and electricity.

All powertrains studied in this report will benefit from reaching economies of scale. All face the challenge of refueling station access being lower than conventional diesel fuel stations, which is both a logistical and perception problem. Each powertrain has different strengths and weaknesses in terms of range, cost, access, and environmental impacts. As outlined in ES Figure 3, they all have the potential to improve the state of the linehaul sector from a diesel baseline, under various circumstances. The environmental implications of large-scale battery consumption tied to vehicle electrification need further review. Considering both the fuel and vehicle life cycles, no new powertrain does as much good if its adoption is additive to the current highly emissive transportation system. Such is the motivation for alternative fuel vehicle incentives that require vehicle scrappage/replacement. The key is a low-carbon transition of the linehaul industry away from fossil fuels.

6.1 Chicken-or-Egg Challenges

A common concern throughout alternative fuel vehicle literature – both woven into analysis and the direct subject of studies – is how to facilitate market penetration of alternative powertrains in order to subvert the dominance of conventional fossil fuel vehicles. There are multiple barriers to success: cost, consumer acceptance, and fuel infrastructure availability (European Commission, 2014; Mohrdieck et al., 2014). In this study, the five adoption criteria used to evaluate the potential fit of alternative transportation systems highlight each powertrain's potential to push against these barriers. There are multiple ways to facilitate market penetration. Hydrogen vendors, for example, may argue that without vehicle demand for hydrogen fuel, they lack motivation to expand production to clean forms of hydrogen gas. In turn, fuel cell electric heavy-duty vehicle manufacturers may lament a need for more demand from early adopters to help their businesses get out of pilot stages and into economies of scale. But consumers will likely not demand freight FCEVs in many market applications (at scale) unless the trucks offer a financially viable way to improve operations and can be trusted to have widespread fueling access. Sometimes described as a chicken-or-egg problem, there is not a clear answer to whether efforts to spur fuel or vehicle development will be most effective. While a vehicle may have merit, oftentimes external factors involving regulatory measures or incentives are needed to boost the transportation alternative out of this chicken-or-egg feedback loop for it to be competitive with conventional systems.

Possible interventions include those from policymakers (tax incentives, carbon or vehicle-miles-traveled taxes, and standards), automakers (subsidies, increased marketing, and R&D), and fuel and infrastructure providers (pursuing renewable feedstocks and increasing distribution) (Keith, Naumov, & Sterman, 2017). Europe's approach has been to require carbon reductions, mandate alternative fuel infrastructure development, and standardize equipment across its countries (European Commission, 2014). Many countries have attempted tax incentives targeted at vehicles, but carbon taxes are not widespread. In the U.S., regulators have focused on improving and deploying vehicles – requiring higher fuel economies, creating vehicle volume targets for fleets, and some tax incentives (Keith et al., 2017). Despite these efforts, more initiatives are needed to ensure that alternative powertrain systems are developed at a scale that can oust carbon-intense transportation. Because of the feedback loops built into the transportation system, a multifaceted approach to regulatory incentives and market development would have compounding benefits. Coordinated regulation and incentives could spur alternative fuel production and initial vehicle adoption. Interest in alternative vehicles would grow investment into fueling/charging access, which, in turn, would reduce range anxiety and increase market confidence, which will push vehicle manufacturers to innovate to compete for demand; the cycle would feed on itself to help vehicles and fuel infrastructure reach economies of scale. Promoting renewable electricity is a clear example of an initiative that would drive the adoption of electric powertrains. Much like there is no definitive answer to the chicken-or-egg philosophical question, there is not a silver-bullet approach to transportation development. However, engagement from scientists and other experts can guide uncertain decisionmakers on "near-term investment, policy and research efforts to support the development of… low-carbon energy systems" (O. Schmidt et al., 2017). Beyond synthesizing the status of the alternative linehaul market, this review and comparative analysis aims to pinpoint opportunities in research, policy, and market development where further engagement from stakeholders can facilitate a swift transition to sustainable linehaul.

Appendices

A. Excluded Alternative Powertrains

There were multiple powertrains considered for this report that were ultimately excluded from consideration for a variety of reasons. Appendix A explains why each was excluded.

Natural Gas

Total fuel cycle, a.k.a. well-to-wheel, CO_2 emissions from a compressed natural gas linehaul vehicle and its North American fossil natural gas fueling infrastructure are approximately 18.5% lower per ton-mile than from diesel counterparts based on GREET modeling. However, methane has a more powerful greenhouse effect than an equal mass of carbon dioxide, such that natural gas leakage in an NGV network could overwhelm any tailpipe CO_2 emissions benefits. Existing research summarized by Alvarez et al. suggests high methane leakage rates (around 13 teragrams annually, or 2.3% of oil/natural gas production in the U.S.) from the U.S. natural gas supply chain are contributing as much to global warming on a 20-year time horizon as the CO_2 emissions from natural gas combustion (Alvarez et al., 2018). Further research on natural gas supply chain emissions is needed, such that NG leakage may be even greater (H. Cai, Burnham, Chen, & Wang, 2017; Clark, McKain, et al., 2017). Opportunities for technological improvement in the natural gas sector could reduce emissions wherein fossil NGVs may become more viable, but current emissions rates do not inspire confidence that fossil natural gas can reliably provide a sustainable linehaul future (Brandt et al., 2014; Clark, Johnson, et al., 2017). Multiple studies project climate damages or simply negligible environmental net benefits of transitioning from diesel to natural gas trucks, as CH_4 emissions outweigh CO_2 reductions (Camuzeaux et al., 2015). The International Energy Agency has cautioned against conventional natural gas as a bridge fuel to complete decarbonization, ruling it out of their future trucking decarbonization scenarios (International Energy Agency, 2017).

Emissions of greenhouse gases occur throughout the natural gas supply chain: in fuel extraction and processing, transmission/ storage, local distribution and then use. In the case of transport, use-phase emissions are classified as pump-to-wheel emissions associated with the vehicle: fueling/refueling and engine operation. Camuzeaux et al. found that converting from diesel to NG heavy-duty trucks reduced WTW CO_2 emissions but led to greater well-to-pump and in-use CH_4 emissions, and poorer vehicle efficiency. They predicted decades of climate damage due to switching to fossil natural gas unless WTW emissions could be significantly reduced and NGV efficiency improved (Camuzeaux et al., 2015). Their sensitivity analyses suggested that reducing WTP emissions may make more of a difference than improving vehicle efficiencies on net sustainability, which furthers the case for RNG vehicles (Camuzeaux et al., 2015). In another fuel cycle study, Cai et al. compared multiple Class 8 CNGVs to their diesel counterparts. They confirmed that NGV WTW greenhouse gas emissions – slightly higher than those of diesel vehicles – are largely due to vehicle efficiency and leaks from the natural gas supply chain (H. Cai et al., 2017). Concerningly, atmospheric CH_4 measurements significantly exceed process/ component bottom-up emissions estimates, suggestive of scattered high-emitters across the supply chain whose origins are hard to trace (Brandt et al., 2014; Zavala-Araiza et al., 2017). Identifying the few super-emitters that are responsible for an estimated "half of total methane emissions" is crucial to tightening up the natural gas supply chain (H. Cai et al., 2017).

Biofuels

Familiar fuels like natural gas and diesel made from organic materials (biofuels) can facilitate a transition to low-carbon transport. Though not officially defined, there are three classes of biofuels (BFLs). First generation (conventional) biofuels are produced from sugar, starches, or vegetable oil feedstocks that are also food sources like corn. Conventional biodiesel is a first generation BFL. Because their production demands high resource inputs, first generation biofuels don't present an impressive GHG reduction from fossil fuels; accounting for upstream impacts, most conventional biodiesel is more carbon-emissive than fossil diesel (Royal Academy of Engineering, 2017). Production of first generation BFLs like biodiesel also raises "food or fuel" concerns – potentially spiking food/agriculture prices, increasing water and land-use competition and/or harming biodiversity. Various resource-limited regions may struggle with the food or fuel dichotomy less than others: the European Biogas Association and European Commission recognized that the EU has sufficient land to preclude some "food or fuel" concerns, such that energy crops could potentially engage in biofuel production in Europe (Kovacs & European Biogas Association, 2013). Second generation "advanced" BFLs are produced from wastes, residues or non-food biomass like switchgrass. Renewable natural gas is considered an advanced biofuel, and biodiesel made from waste cooking oil or animal fat is labeled second generation as well (Alternative Fuels Data Center, 2020g; Dahman, Dignan, Fiayaz, & Chaudhry, 2019). Because second generation biodiesel production could still have indirect impacts on agriculture, it is estimated that biodiesel from waste oil may have a CI "only 25% lower than that of diesel," though some studies estimate "carbon footprints 60% to 90% lower than conventional diesel," (Royal Academy of Engineering, 2017). Third generation BFL is from algae, which can be used to make biodiesel. Algal biodiesel is a nascent fuel and life cycle analyses widely disagree about its environmental impacts, but the "average [estimated] carbon footprint of microalgae diesel is around 3.5 times higher than that of diesel," disqualifying it from further consideration (Royal Academy of Engineering, 2017). Because a lot of second and third generation BFL production is still in the research and development phase, these fuels have a limited availability of supply and may not be scalable. Biodiesel is usually blended at a 5% ratio with petroleum diesel, which further limits its decarbonization potential. There is an alternative chemical process for alternative diesel production makes hydrogenated "renewable diesel" which does not need to be blended with fossil diesel, but it is still subject to the same feedstock environmental concerns, so the label "renewable" is misleading (Knothe, 2009). In 2019, Sen et al. modeled the optimal sustainable heavy-duty truck fleet composition and excluded fossil CNGVs and biodiesel trucks because the two powertrains did not significantly improve upon the life cycle environmental or cost impacts of conventional HDVs (Sen et al., 2019). Ultimately, biodiesel and renewable diesel BFLs were not considered for this report because they present scalability concerns and a less of a carbon reduction potential than renewable natural gas.

Hybrids

Some EVs, called plug-in hybrid electric vehicles (PHEV for short), combine battery power with another fuel source, like a small gasoline tank, and then optimize power use between energy sources. The liquid fuel yields a range extension to the battery, while the battery ideally makes the PHEV better for the environment than a conventional ICE vehicle. Similarly, the umbrella term "hybrid electric vehicles" often is used to refer to vehicles (HEVs) that use a small battery powered by regenerative braking and a larger fuel tank: they do not require an external electricity supply. Hybrid electric vehicles are not that common in the freight industry, and while some hybrid diesel-electric, etc. prototypes have been made, their carbon-savings would only about 30% for long-haul, and still entail fossil-fuel consumption (McKinnon, 2018). For a sustainable linehaul future, this paper focuses on technologies that can be independent of fossil fuels, though it recognizes that hybrids are sometimes portrayed as a technological stepping-stone to zero-emissions vehicles.

Power to Methane Gas

In a "power-to-gas" (P2G) process, electrical energy is used to make gas. The gas produced can be used as fuel. Hydrogen production via electrolysis is classified as a power-to-gas process. Another power-to-gas process being studied in current literature produces methane. This synthetic natural gas (CH_4) is created using hydrogen and a carbon-oxygen (CO_x) source. Through either a biological or chemical methanation process, the compounds are combined and yield methane and water as products. Some proponents of power-to-synthetic natural gas argue that it can be a green way to create fuel while simultaneously sequestering carbon (if the CH_4 is made with hydrogen from renewable water electrolysis combined with the carbon dioxide emissions of other processes) (Mohrdieck et al., 2014). Others highlight that converting hydrogen to natural gas via P2G can ease the transition to a future fully hydrogen-based system, where renewable hydrogen is injected directly into the existing natural gas distribution grid (Nižetić et al., 2019). However, research to investigate the environmental merit of P2G methanation highlights flaws in the power-to-natural gas argument. Even when using sequestered carbon and renewable hydrogen, the production to end-use process "has extremely low energy efficiency and despite the overall CO_2 neutrality [(use of the natural gas produces as much CO_2 as was consumed during methanation)] leads to local CO_2 emissions," (Mohrdieck et al., 2014). A less wasteful, more environmentally responsible approach is to use hydrogen directly. Consequently, the only P2G technology considered for future linehaul adoption in this report is hydrogen electrolysis, not power-to-natural gas.

B. Greenhouse Gas Footprint Models

Various greenhouse gas emissions are converted into the standard unit of CO_2e carbon dioxide equivalents via global warming potentials (GWPs) based on gases' potential to trap heat in the atmosphere relative to an equal mass of CO_2. GWP values are reviewed periodically by the Intergovernmental Panel on Climate Change (IPCC) – most recently in their Fifth Assessment Report (AR5) in 2014. Gas lifetimes in the atmosphere vary, so GWPs are specific to time horizons of impact – 100 years is often the reference point (GWP_{100}) but because urgent action is needed to mitigate climate change, the 20-year GWP_{20} is meaningful too (IPCC, 2014; U.S. Environmental Protection Agency, 2020d). For example, methane traps more heat in the atmosphere when released as compared to carbon dioxide, but is also shorter-lived (U.S. Environmental Protection Agency, 2020d). Thus, a unit of methane's effects are more pronounced on shorter time scales: according to the AR5, CH_4 has a GWP_{20} of 84-87 and a GWP_{100} of 28–36 (IPCC, 2014). The range of GWP values – due to lingering research uncertainty – yields variety in emissions reporting, but 28 is commonly used for GWP_{100}. For example, assuming one kilogram of methane has a GWP_{100} of 28 signals a CO_2e value equivalent to that of 28 kg of CO_2 because it traps heat 28 times more effectively than carbon dioxide. Some researchers might opt for other values to demonstrate greater potential environmental impact, like Alvarez et al. who used a CH_4 GWP_{100} of 32 in their assessment of methane emissions in 2018 (Alvarez et al., 2018). GREET defaults to AR5 data but allows users to select older IPCC reports' GWP values in its "Global Warming Potentials of Greenhouse Gases: relative to CO_2" section. The AR5 value GREET uses for methane GWP_{100} is 30, and this report's modeling used default GREET GWP_{100} values.

Global Warming Potentials of Greenhouse Gases: Relative to CO_2		
AR Edition/Type	AR5/GWP	
Time Horizon (Years)	*100*	*20*
CO_2	1	1
CH_4	30	85
N_2O	265	264

Table 5. Fuel Specs – Metrics for Carbon Dioxide, Methane, Nitrous Oxide: Global Warming Potentials, Reproduced from GREET1_2019 (Argonne National Laboratory, 2019b).

GREET also accounts for the greenhouse effects of VOCs, CO, NO_x, BC and OC emitted during the fuel cycle (Argonne National Laboratory, 2019b).

The GREET model has relied on the U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI) data that is highly compatible with its process-based approach to emissions modeling (Burnham, 2018). In 2012, the Environmental Defense Fund (EDF) commissioned 16 studies to better understand these emissions (Environmental Defense Fund, 2017). In 2018, ANL recognized that EDF research was potentially more comprehensive and updated GREET to offer two options for modeling natural gas heavy-duty vehicles. They have since been updated with 2019 values. The first, "EPA 2019," is the conventional GREET approach that reflects updated GHGI values. The alternative "EDF 2019" version develops metrics in line with the 2018 Alvarez et al. report specific to NG production, using updated emissions data from the EDF-commissioned studies. Consequently, emissions of natural gas HDVs modeled by GREET are dependent on the model selected. Still, all current methane research may underestimate total natural gas vehicle WTW emissions, as many of the EDF studies recognized a need for even more data in their reporting. The EPA GHGI is widely referenced in policymaking and business, so its underestimate of emissions may slow regulatory action (Heath, Warner, Steinberg, & Brandt, 2015). The EDF 2019 model captures emissions broadly but loses the granularity of the EPA model. For an environmental-risk-averse approach to emissions modeling, EDF's emissions metrics paint a picture closer to worst-case scenario; the GREET EDF 2019 model demonstrates approximately 50% greater NGV-associated greenhouse gas emissions than GREET EPA 2019, even as both models are updated with developing research (Burnham, 2018). Consequently, the EDF 2019 methane leakage metrics were used in this report's emissions accounting.

GREET's built-in assumptions for combination linehaul fuel economy are shown in Table 6. They mirror the fuel economy values and relationships to diesel fuel economy that are in AFLEET (see Appendix D).

Fuel Economy Relative to Diesel *(MPDGE)*	**CIDI Diesel Vehicle**	**Electric Vehicle**	**Hydrogen Fuel Cell Vehicle**	**SI CNG Vehicle**
Combination Long-Haul Truck	6.2	172.3%	-	90.0%
Combination Short-Haul Truck	5.8	192.7%	145.4%	90.0%

Table 6. Fuel Economy and Emissions Relative to Baseline Diesel Combination Trucks, Reproduced from GREET1_2019 (Argonne National Laboratory, 2019b).

All hydrogen linehaul data in GREET came from placeholder pathways. Even though simulations of these pathways are completed in ANL's model, no thorough research was conducted to examine key input assumptions for the pathways and the results require further review, pending data availability. A few other surprising results require further evaluation. WWTP-powered CNG short-haul reduced emissions compared to long-haul, whereas g/mile emissions increased from long- to short-haul (marginally) for the other CNG feedstock models. In addition, centralized production of nuclear power-electrolyzed hydrogen returned results that were not intuitive, suggesting that the pathway in GREET may need more research to measure its WTW impacts. Thus, the pathway was excluded from this report.

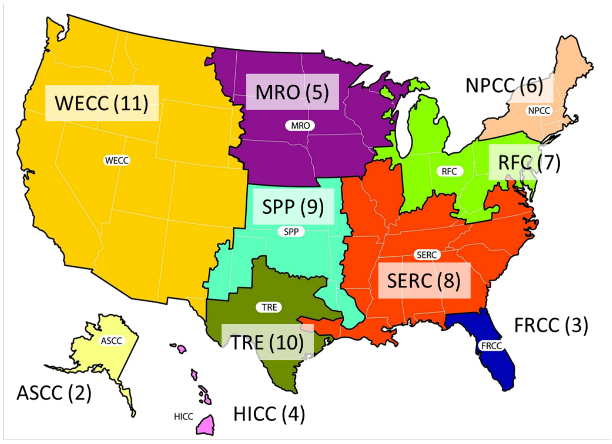

Figure 12. Regional Electricity Grids Built into the GREET1_2019 Model (Argonne National Laboratory, 2019b).

	U.S. Mix		CA Mix		WECC Mix		SERC Mix	
	Transportation	Stationary	Transportation	Stationary	Transportation	Stationary	Transportation	Stationary
Residual Oil	0.4%	0.4%	0.0%	0.0%	0.2%	0.2%	0.2%	0.2%
Natural Gas	33.4%	33.4%	40.9%	40.9%	24.5%	24.5%	35.4%	35.4%
Coal	29.0%	29.0%	2.1%	2.1%	19.0%	19.0%	30.7%	30.7%
Nuclear Power	20.3%	20.3%	9.6%	9.6%	5.1%	5.1%	28.5%	28.5%
Biomass	0.3%	0.3%	1.1%	1.1%	0.5%	0.5%	0.4%	0.4%
Others	16.5%	16.5%	46.3%	46.3%	50.7%	50.7%	4.8%	4.8%

Other Power Plants Mix used for User Defined Mix of Renewables	**Mix for Transportation Use**	**Mix for Stationary Use**
Hydroelectric	43.02%	43.02%
Geothermal	2.48%	2.48%
Wind	41.41%	41.41%
Solar PV	10.12%	10.12%
Others	2.97%	2.97%

Table 7a&b. Reproduced from GREET1_2019: Tables 10.2.b) Electric Generation Mixes (from Annual Energy Outlook 2019) and 10.2.e) Shares of Technologies for Other Power Plants for GREET Simulations (Argonne National Laboratory, 2019b).

Though the use of biogas to create electricity for use in battery electric vehicles is another approach discussed in this report, GREET does not have a pathway to model electricity production from renewable natural gas. Based on the three negative CI dairy-manure electricity pathways registered through CARB to-date, it is possible that this pathway would yield carbon-negative, zero-tailpipe-emissions BEVs (California Air Resources Board, 2020b). However, electricity production efficiency losses reduce the carbon-negative benefits of negative-CI gas. Furthermore, the electrolysis feedstocks of interest could not be modeled for centralized production of hydrogen due to limitations in the GREET model. Only distributed refueling station electrolysis was modeled in this report.

HDV Fuel-Cycle Model - GREET

			Considering Total Greenhouse Gases as CO_2e/100 yr. Impact			
	GREET Model Classification - Fuel and Truck		**WTW GHG Emissions, Haul Basis (g/ton-mile):**	**WTW GHG Emissions (g/mile):**	**GHG (g/mile) Change from Diesel Trucks:**	**Fuel Average GHG Change from Diesel:**
	Fuel:	**Vocation Type:**				
Fossil Fuel ICE	Conventional and LS Diesel	CIDI Combination Long Haul	106	2017	-	-
		CIDI Combination Short Haul	113	2153	-	
	CNG, on Fossil NA NG	CIDI Combination Long Haul	106	2013	-0.20%	0.92%
		CIDI Combination Short Haul	115	2197	2.04%	
Renewable Compressed Natural Gas ICE	CNG, on LFG RNG	SI Combination Long Haul	25	471	-76.65%	-75.69%
		CIDI Combination Short Haul	29	544	-74.73%	
	CNG, on Animal Waste (AD Gas) RNG	SI Combination Long Haul	-26	-489	-124.24%	-123.39%
		CIDI Combination Short Haul	-25	-485	-122.53%	
	CNG, on WWTP (AD Gas) RNG	SI Combination Long Haul	-39	-738	-136.59%	-135.74%
		CIDI Combination Short Haul	-39	-751	-134.88%	

				Considering Total Greenhouse Gases as CO_2e/100 yr. Impact			
	GREET Model Classification - Fuel and Truck						
	Fuel:		**Vocation Type:**	**WTW GHG Emissions, Haul Basis (g/ton-mile):**	**WTW GHG Emissions (g/mile):**	**GHG (g/mile) Change from Diesel Trucks:**	**Fuel Average GHG Change from Diesel:**
Hydrogen Fuel Cell Electric	Steam Methane Reformation	G.H2, Central Plants, Fossil NA NG	Fuel Cell Combination - Short Haul	83	1585	-26.38%	-13.53%
		G.H2, Refueling Station, Fossil NA NG		95	1807	-16.07%	
		L.H2, Central Plants, Fossil NA NG		115	2193	1.86%	
		G.H2, Central Plants, LFG RNG		24	457	-78.77%	-69.87%
		G.H2, Refueling Station, LFG RNG		23	438	-79.66%	
		L.H2, Central Plants, LFG RNG		55	1051	-51.18%	
		G.H2, Central Plants, Animal Waste (AD Gas) RNG		-17	-315	-114.63%	-107.26%
		G.H2, Refueling Station, Animal Waste (AD Gas) RNG		-22	-426	-119.79%	
		L.H2, Central Plants, Animal Waste (AD Gas) RNG		14	272	-87.37%	
		G.H2, Central Plants, WWTP (AD Gas) RNG		-27	-512	-123.78%	-116.80%
		G.H2, Refueling Station, WWTP (AD Gas) RNG		-34	-646	-130.00%	
		L.H2, Central Plants, WWTP (AD Gas) RNG		4	73	-96.61%	
	Electrolysis	G.H2, Refueling Station, U.S. Grid Mix		170	3235	50.26%	50.26%
		G.H2, Refueling Station, W.E.C.C. Grid Mix		123	2297	6.69%	-
		G.H2, Refueling Station, SERC Grid Mix		191	3643	69.21%	-

		G.H2, Refueling Station, C.A. Grid Mix		84	1606	-25.41%	-25.41%
		G.H2, Refueling Station, User Defined Mix of Renewables		1	16	-99.26%	-100.60%
		G.H2, Refueling Station, Hydro Power Plants		-3	-55	-102.55%	
		G.H2, Refueling Station, 100% Wind or Solar Power Plants		0	0	-100.00%	

			Considering Total Greenhouse Gases as CO_2e/100 yr. Impact			
	GREET Model Classification - Fuel and Truck					
	Fuel:	**Vocation Type:**	**WTW GHG Emissions, Haul Basis (g/ton-mile):**	**WTW GHG Emissions (g/mile):**	**GHG (g/mile) Change from Diesel Trucks:**	**Fuel Average GHG Change from Diesel:**
Battery Electric	Electricity, U.S. Grid Mix	Combination Long Haul	107	2044	1.34%	-3.84%
		Combination Short Haul	103	1959	-9.01%	
	Electricity, CA Grid Mix	Combination Long Haul	53	1015	-49.68%	-52.27%
		Combination Short Haul	51	972	-54.85%	
	Electricity, W.E.E.C. Grid Mix	Combination Long Haul	76	1452	-28.01%	-31.70%
		Combination Short Haul	73	1391	-35.39%	
	Electricity, S.E.R.C. Grid Mix	Combination Long Haul	121	2302	14.13%	8.30%
		Combination Short Haul	116	2206	2.46%	
	Electricity, 100% Wind, Solar, or Hydro	Combination Long Haul	0	0	-100.00%	-100.00%
		Combination Short Haul	0	0	-100.00%	

Emissions Data compiled using GREET1_2019 (Argonne National Laboratory, 2019b).

C. Certified Carbon Intensities

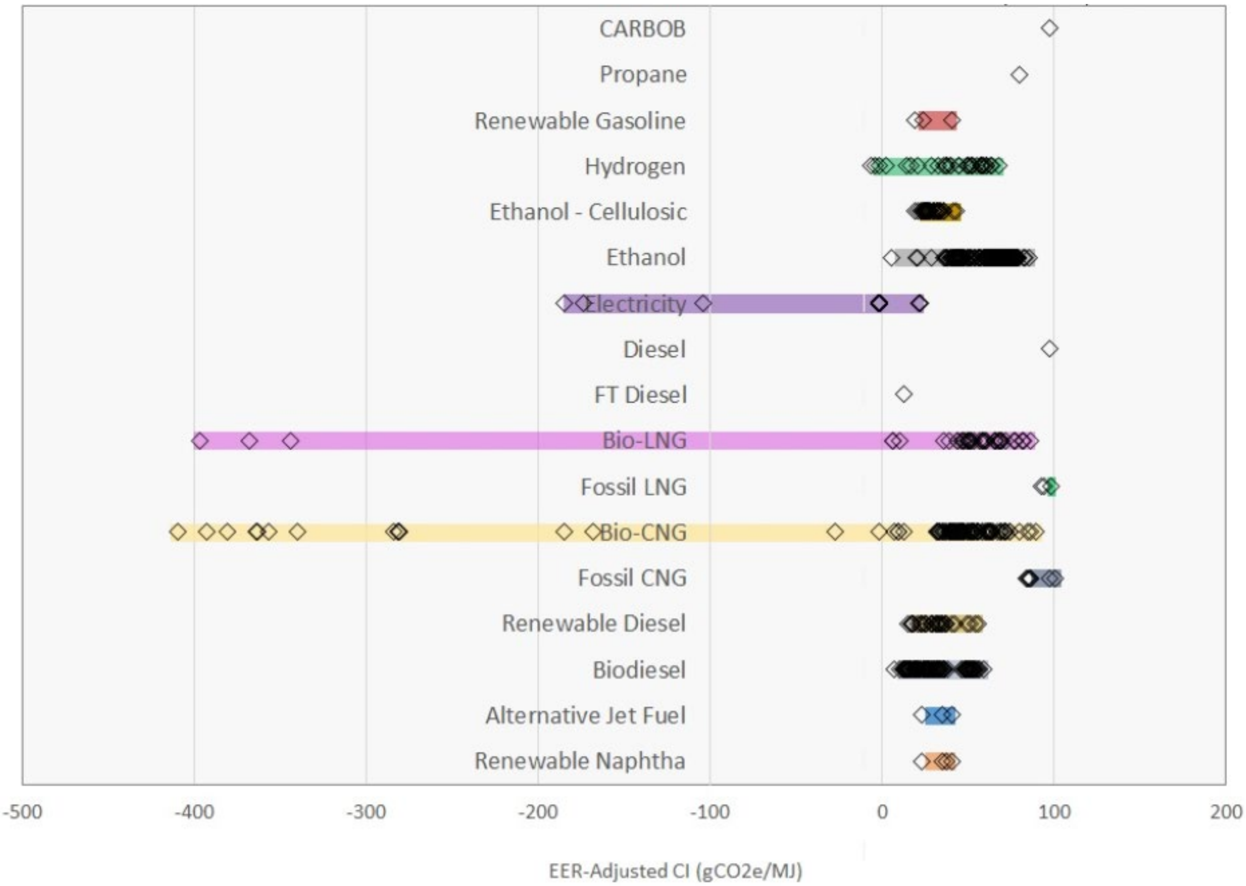

Figure 13. LCFS Pathway Certified EER-Adjusted Carbon Intensities (as of April 27, 2020) (California Air Resources Board, 2020b).

Note: "The length of each bar indicates the range of carbon intensity that may be achieved by a fuel pathway. The wide range of carbon intensities is due to the life cycle emissions methodology of the LCFS, variations in feedstock types, origin, raw material production processing efficiencies, and transportation, all of which contribute to an individual producer's fuel pathway CI," (California Air Resources Board, 2020b).

As of September 2018, the carbon intensities of all California LCFS-registered fuel pathways are generated with the CA-GREET3.0 model available on the California Air Resources Board's website. The model is based on GREET1 2016, an older version of the "Greenhouse gases, Regulated Emissions, and Energy use in Transportation" life cycle transportation emissions model made and updated annually by Argonne National Laboratory. The old model includes outdated emissions metrics. For example, in 2018, Argonne updated GREET to offer two approaches (EDF or EPA GHGI) to quantifying NG methane supply chain emissions, as discussed in Appendix B. Further, the CA-GREET3.0 model uses older, smaller (IPCC-AR4) GWP values as its default (though the AR5 values are available within). This means that total emissions aggregated in CI scores (gCO_2e/MJ fuel energy) through CARB's tool may be scaled by smaller factors than current science recommends: a UC Davis life cycle analysis of RNG found that "increasing GWP from 25 to 30 [for methane in a 100 year timeline] increases the carbon intensity of landfill CNG… by 11%," (Myers Jaffe et al., 2016). Since various inputs and assumptions are available in the LCFS CA-GREET3.0 model, and a similar evaluation of fuel environmental impacts for federal Renewable Fuel

Standards is delegated to third-party analysts, insight into CI-score evaluation methodology for pathway registry would be valuable to evaluate the true scale of accounting discrepancies. It appears that these regulatory tools will often underestimate total emissions for CI scores, as emissions research moves faster than regulatory offices update their approvals processes.

Fuel	**Old LCFS Baseline, Pre CA-GREET3.0**	**2019 LCFS new CI baseline using CA-GREET3.0**	**CI Change**	**Reduction from Diesel**
	(gCO₂e/MJ, not EER-adjusted)		*(%)*	*(%, EER-adjusted)*
ULS Diesel	102.1	100.45	-2%	0%
LFG - Reported	46.42	70	51%	-23%
Dairy Digester	-276.24	-150	46%	-266%
MSW Digester	-22.93	45	296%	-50%
WWTP Digester	19.34	45	133%	-50%

Table 8. Old and New CI Values Classified by CARB (California Air Resources Board, 2020b).

Individual fuel production processes must be monitored and approved for their official CI score to be calculated, and that registration only lasts for two years; if CARB updates its accounting system, all registered CIs are grandfathered in for the remainder of their two years before a vendor must have their facility's CI re-approved. In Q1 of 2021 all old pathway codes based on CA-GREET2.0 will be deactivated and required to reevaluate their CIs with CA-GREET3.0 (California Air Resources Board, 2019b). Any vendors that claim their fuel has a certain carbon intensity but have not had their fuel pathway registered should be evaluated with skepticism.

By combining underestimates of GHG emissions with a potentially overly optimistic set of CARB electric linehaul EERs, it is probable that some electric production pathway/HDV combinations will be viewed more positively by the LCFS than they deserve.

D. Total Cost of Operations Models

Assumed ten-year ownership of vehicles (with resale thereafter[18]), driving and fueling at public stations that are five miles "off route" in Los Angeles, California with no incentives, tax shielding, nor loans. Fuel price sensitivity was excluded, and fuel prices were based on California price data. The CNG vehicle had a low-NO_x engine that used landfill gas. BEV (abbreviated in AFLEET as EV) used grid electricity and FCEV (abbreviated in AFLEET as FCV) used onsite refueling station grid electrolysis – both powered by the W.E.C.C. regional grid mix. Annual vehicle miles traveled and fuel economies were determined by AFLEET – see Tables 9 and 10.

Heavy-Duty Vehicle Information			
Vehicle Type	Combination Long-Haul Truck	Combination Short-Haul Truck	Single Unit Long-Haul Truck
Vocation Type	Long Haul Freight Truck	Regional Haul Freight Truck	Delivery Straight Truck
Annual Mileage	170,000	75,000	23,000

Table 9. HDV Classifications, Reproduced from AFLEET_2019 (Argonne National Laboratory, 2019a).

Fuel Economy *(MPDGE)*	**Diesel**	**All-Electric Vehicle (EV)**	**Gaseous Hydrogen (G.H2) Fuel Cell Vehicle (FCV)**	**Compressed Natural Gas (CNG)**
Combination Long-Haul Truck	7.3	10.7	7.4	6.6
Combination Short-Haul Truck	7.4	12.1	7.7	6.7
Single Unit Long-Haul Truck	6.6	23.0	14.4	5.9

Table 10. Vehicle Fuel Economies, Reproduced from AFLEET_2019[19] (Argonne National Laboratory, 2019a).

AFLEET had no built-in linehaul FCEV pricing data, nor for a battery electric combination long-haul truck, likely because these vehicles have not yet been fully developed for the market. Purchase price estimates used a 1.2 scalar relationship with FCEVs and BEVs, based on trucking insight shared by Chris Cannon, Chief Sustainability Officer for the Port of Los Angeles in a recent article: "[fuel cell electric truck] equipment is… 20 to 25 percent more expensive than battery electric right now" (Carpenter, 2019). Combination short-haul and single unit long-haul FCEVs' prices were scaled up from AFLEET BEV prices, while the combination long-haul BEV price was scaled down from a projected Nikola Class 8 long-haul fuel cell truck purchase price of $375,000 (Carpenter, 2019). Though 1.2 summarizes the price increase from existing low-range BEVs up to FCEV competitors, it is possible that the scalar would not translate as well in the reverse. Considering nonlinear battery mass-cost relationships involved in adding range (battery capacity) to BEVs, 1.2 may not translate as well from long-haul FCEVs on the market to a future long-haul BEV prices. Purchase prices for vehicles not yet on the market are inherently hypothetical.

Only the short-haul truck TCO was modeled with incentives, as HVIP-eligible vehicles to-date are mostly short-haul oriented. The HVIP incentive covers $45,000 for a low-NOx CNGV, $150,000 for heavy-duty BEV, and $300,000 for fuel-cell electric linehaul (California Air Resources Board & CALSTART, 2020).

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[18] AFLEET assumes heavy trucks have a 28-year median lifetime (Argonne National Laboratory, 2019a).

[19] These yield the fuel economy ratios built into ANL's AFLEET model as discussed in Methods. AFLEET's fuel economy numbers supplemented GREET values with other data, which is why the MPDGE values are slightly different from Table 6.

New Vehicle Purchase Price *($)*	**Diesel**	**All-Electric Vehicle (EV)**	**Gaseous Hydrogen (G.H2) Fuel Cell Vehicle (FCV)**	**Compressed Natural Gas (CNG)**
Combination Long-Haul Truck	$100,000	$312,500	$375,000	$165,000
Combination Short-Haul Truck	$90,000	$290,000	$348,000	$130,000
Single Unit Long-Haul Truck	$75,000	$190,000	$228,000	$115,000

Table 11. Vehicle Prices Before Incentives (Argonne National Laboratory, 2019a).

Varying Californian fuel prices between private and public stations are shown in the table below. The fuel units are consistent with AFLEET. This report's key TCOs are based around public fueling stations. AFLEET's cost metrics for fuels are averages from the Oct 2018-July 2019 Alternative Fuels Data Center's (AFDC) fuel price reports and price data from the EIA's 2015 Annual Energy Outlook for electricity prices. AFLEET does not have built-in cost adjustments for unconventional sources of CNG and hydrogen, and thus adjustments were made to its model. RNG prices without incentives were assumed to be five times the price of diesel, scaled to $/CNG GGE, based on values between four and six-times that of diesel cited by different industry sources. According to AFLEET/AFDC price reports, the average retail hydrogen price in 2018-2019 was between $15.85-16.54, but their metrics were based on market-available H_2 that is largely SMR-sourced and this report's focus was on electrolysis potential. Retail prices are a function of production, delivery, and station dispensing/distribution costs. For this model of distributed hydrogen production, transportation/delivery costs were null because the gas was produced onsite. In 2013, NREL researchers evaluated the costs of different hydrogen production scenarios projected to commercial scale and found that the levelized per kilogram cost of H_2 from distributed U.S. grid mix electrolysis was $6.75 (in 2007 dollars): $4.32/kg ($5.35 in 2020 dollars according to the Bureau of Labor Statistics consumer price index) for production plus $2.43/kg ($3.01 in 2020 dollars) for compression, storage, and dispensing (Ramsden et al., 2013; U.S. Bureau of Labor Statistics, 2020). A more recent (2019) NREL study on the "Cost Competitiveness of Electrolytic Hydrogen" estimated U.S. grid-electrolyzed hydrogen production costs to be between $2.6-12.3/kg, depending on regional retail tariff structure, assuming flexible generation at a 90% capacity factor (Guerra et al., 2019). The U.S. Department of Energy just projected a baseline high-volume distributed H_2 production (1,500 kg/day) cost of $4.98/kg H_2 (Peterson, Vickers, & DeSantis, 2020). Using a conservative average of those three distributed H_2 production cost estimates, this report assumed that it costs approximately $5.93/kg to produce grid-electrolyzed hydrogen. It could cost more to produce electrolyzed hydrogen at lower scales.

Hydrogen price estimates in this report also accounted for compression, storage, and dispensing costs, which vary based on outlet pressure at the refueling station, delivery and storage methods, and other factors. Based on a brief literature assessment, estimates of distribution costs range from $2/kg total (in 2007 USD) to a 2016 DOE estimate of "$3.00/GGE–$5.00/GGE for 700 bar dispensing, and $2.70/GGE–$3.70/GGE for 350 bar dispensing" (National Renewable Energy Laboratory, 2011; Rustagi, Elgowainy, & Gupta, 2016). The 2019 NREL cost competitiveness study referenced a 2016 DOE estimate that compression, storage, and dispensing costs total to $2.69/kg H_2 (Guerra et al., 2019). Hydrogen price estimates in this report recognized that low utilization of refueling stations may lead to higher prices. ANL and DOE researchers cited $6–$8/kg H_2 as the levelized costs for a 200 kg/day capacity gaseous hydrogen refueling station in 2017. Levelized costs reflect the station construction and operation costs over its lifetime and were high in their estimate due to low utilization of expensive equipment and a lack of economies of scale at the small station modeled – reflective of the current conditions at hydrogen fueling stations (Krishna Reddi et al., 2017). Regardless of fuel type, station costs are distributed across all customers at public retail stations but would fall upon fleet operators interested in having private fueling setups. Though this report was interested in a public fueling station, it was assumed that low utilization meant that the burden of station facility costs could be passed to customers. So, while the production costs used in this report optimistically assessed high-scale operations, this report used a conservative, higher estimate of station compression, storage, and distribution costs ($6/kg) to reflect the small state of the growing hydrogen fuel market. Centralized production of hydrogen would benefit from economies of scale but could incur potentially high delivery costs.

The price for landfill gas with incentives came from RNG price estimates in a 2016 UC Davis report prepared for the California Air Resources Board and California EPA entitled "The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute" (Myers Jaffe et al., 2016). Version 1.3 of CARB's LCFS Credit Price Calculator was used to estimate the value of LCFS incentives for BEVs and FCEVs. The calculator used EER values and certified carbon intensities to estimate the carbon reduction benefits of alternative fuels relative to gasoline or diesel, and then quantify the economic value of the carbon reductions based on the LCFS price per tonne of carbon (California Air Resources Board, 2019a). California's average grid electricity has an LCFS CA-GREET3.0 carbon intensity of 93.75 gCO_2e/MJ and compressed H_2 produced in California from electrolysis using California average grid electricity is in CA-GREET3.0 as 164.46 gCO_2e/MJ (California Air Resources Board, 2018c). This assessment reflected the LCFS diesel CI standard for 2020 as 92.92 gCO_2e/MJ and assumed an LCFS credit price of $200/metric ton of CO_2 based on recent trends (California Air Resources Board, 2019b; Neste, 2020).

Two versions of a heavy-duty BEV EER (as seen in Table 1) were also reflected in the model; the LCFS-certified EER of 5.0 and a more conservative 3.5 was used based on CARB's "Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles" report (see Footnote 3) (California Air Resources Board, 2018b). Both BEV EER values are higher than the ratios built in for combination linehaul (all-electric combination short-haul has a default AFLEET miles per DGE relative ratio of 1.64) (Argonne National Laboratory, 2019a). 5.0 is the EER that CARB, as the LCFS administrator, will use to generate heavy-duty BEV credits for the foreseeable future, but five will likely overvalue the true energy efficiency benefits of BEVs, consequently overvaluing their low-carbon fuel incentive. It is possible that CARB would refer to its Battery Electric Truck report and add a linehaul battery electric EER closer to 3.5 in the future, which is why this report modeled both EERs' resultant incentive values. Using California's grid under the current battery electric truck EER of 5.0 could save BEV users $0.27/kWh of electricity (more than the average price of Californian grid electricity), whereas a 3.5 EER incentive of $0.167/kWh would essentially cancel out electricity costs.[20] In other words, AFLEET reads the 5.0 EER's $0.27/kWh incentive as a negative $0.11/kWh (i.e. a negative $4.17/DGE) electricity price. Note that the certified EER of 1.9 for fuel cell electric trucks is also larger than the fuel economy ratio of 1.04 for short-haul FCEVs relative to diesel built into AFLEET. The difference in ratios and subsequent impact on price is less pronounced for this powertrain and thus only the official CARB heavy-duty FCEV EER was factored into incentive calculations. Yet, it is possible that hydrogen LCFS credits are also overvaluing the carbon benefits that fuel cell trucks offer transportation systems. The LCFS incentive for grid-electrolyzed H_2 in California is $0.29/kg of H_2.[21]

Though carbon-negative energy supplies hold even higher value in the incentives market and there are LCFS-registered negative-CI pathways for electricity and hydrogen produced from biomethane, they were not the focus of this TCO. The projected limited availability of biomethane, combined with the conversion efficiency losses that result in higher gCO_2e/MJ and subsequent lower $/MJ value for BEV and FCEV uses for RNG, suggest that biomethane-for-electric-transport applications will be quite niche.

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[20] Importantly, if AFLEET's 1.64 short-haul BEV:diesel MPDGE ratio were used in place of the high EER numbers CARB considers, California's grid electricity would only earn back $0.04/kWh through a $200 LCFS credit in 2020. Thus, energy used in battery electric linehaul may receive an overgenerous stimulus through the current iteration of the LCFS and even if CARB added a 3.5 BEV EER.

[21] Also, H_2 would not receive an incentive if ANL's ratios were used in place of CARB's EER, because the CA-grid electricity would no longer model as improving emissions per MJ from the 2020 diesel standard.

Fuel and DEF Prices at Public Stations		**No Incentives**	**With Incentives**
	Fuel Unit	*($/Fuel Unit)*	
Diesel	*diesel gallon*	$3.86	$3.86
Grid Electricity	*kWh*	$0.16	-$0.11, -$0.006
G.H2 from grid electrolysis	*hydrogen kg*	**$11.93**	**$11.64**
CNG from LFG	*CNG GGE*	$16.78	$1.12
Diesel Exhaust Fluid (DEF)	*DEF gallon*	$2.80	$2.80

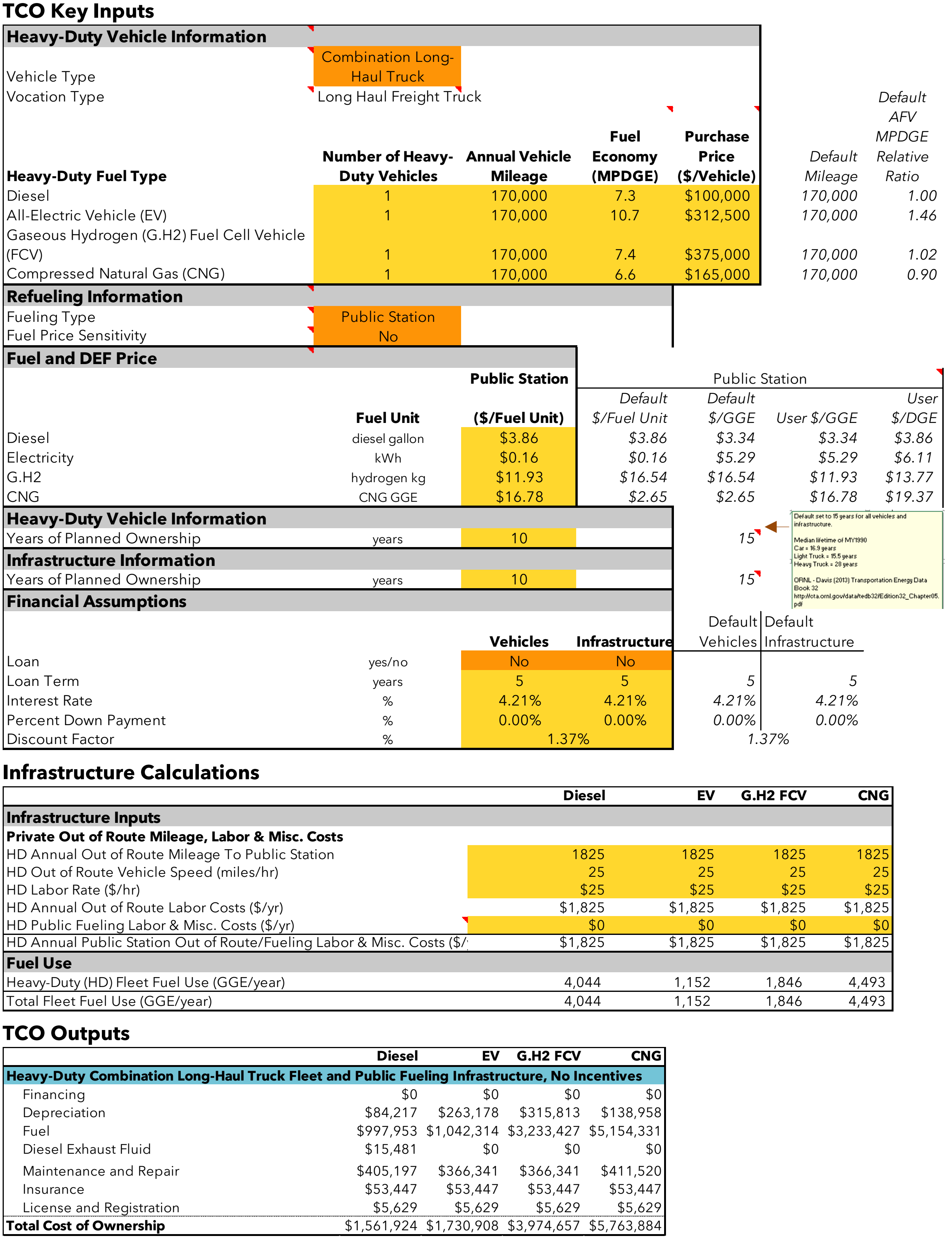
Table 12. Fuel Prices Before and After Incentives (Argonne National Laboratory, 2019a).

Broader station infrastructure costs (as they vary by private or public access, station scale, fuel type, etc.) were determined to be outside the scope of this report, but can also be modeled using Argonne's AFLEET tool, which aggregates many different information sources to estimate infrastructure costs. AFLEET indicates that fuel prices at private stations are generally marginally cheaper than their public counterparts. If fleet operators were to deploy linehaul vehicles with a new private fueling station of each type (EV DC fast charging station, etc.), infrastructure costs would, of course, increase. Infrastructure costs would prove to be a significant driver of the total cost of operations if a new station was underutilized.

One last word of caution: fuel prices are scale- and site-dependent. Incentives are calculated based on specific supplier pathways, estimates of EERs that change over time, and a credit price that fluctuates on the market. The vehicle market is evolving quickly, and truck costs may change. The costs summarized in Appendix D are considered reasonable estimates at the time of publication but are not guarantees.

Lifetime Cost of Ownership Calculator - AFLEET

AFLEET TCO Calculator Example - Combination Long-Haul, No Incentives



TCO Key Inputs

Heavy-Duty Vehicle Information	
Vehicle Type	Combination Long-Haul Truck
Vocation Type	Long Haul Freight Truck

Heavy-Duty Fuel Type	**Number of Heavy-Duty Vehicles**	**Annual Vehicle Mileage**	**Fuel Economy (MPDGE)**	**Purchase Price ($/Vehicle)**	*Default Mileage*	*Default AFV MPDGE Relative Ratio*
Diesel	1	170,000	7.3	$100,000	*170,000*	*1.00*
All-Electric Vehicle (EV)	1	170,000	10.7	$312,500	*170,000*	*1.46*
Gaseous Hydrogen (G.H2) Fuel Cell Vehicle (FCV)	1	170,000	7.4	$375,000	*170,000*	*1.02*
Compressed Natural Gas (CNG)	1	170,000	6.6	$165,000	*170,000*	*0.90*

Refueling Information	
Fueling Type	Public Station
Fuel Price Sensitivity	No

Fuel and DEF Price	**Fuel Unit**	**Public Station ($/Fuel Unit)**	Public Station *Default $/Fuel Unit*	*Default $/GGE*	*User $/GGE*	*User $/DGE*
Diesel	diesel gallon	$3.86	*$3.86*	*$3.34*	*$3.34*	*$3.86*
Electricity	kWh	$0.16	*$0.16*	*$5.29*	*$5.29*	*$6.11*
G.H2	hydrogen kg	$11.93	*$16.54*	*$16.54*	*$11.93*	*$13.77*
CNG	CNG GGE	$16.78	*$2.65*	*$2.65*	*$16.78*	*$19.37*

Heavy-Duty Vehicle Information			
Years of Planned Ownership	years	10	*15*
Infrastructure Information			
Years of Planned Ownership	years	10	*15*

Default set to 15 years for all vehicles and infrastructure.

Median lifetime of MY1990
Car = 16.9 years
Light Truck = 15.5 years
Heavy Truck = 28 years

ORNL - Davis (2013) Transportation Energy Data Book 32
http://cta.ornl.gov/data/tedb32/Edition32_Chapter05.pdf

Financial Assumptions		**Vehicles**	**Infrastructure**	Default Vehicles	Default Infrastructure
Loan	yes/no	No	No		
Loan Term	years	5	5	*5*	*5*
Interest Rate	%	4.21%	4.21%	*4.21%*	*4.21%*
Percent Down Payment	%	0.00%	0.00%	*0.00%*	*0.00%*
Discount Factor	%	1.37%		*1.37%*	

Infrastructure Calculations

	Diesel	**EV**	**G.H2 FCV**	**CNG**
Infrastructure Inputs				
Private Out of Route Mileage, Labor & Misc. Costs				
HD Annual Out of Route Mileage To Public Station	1825	1825	1825	1825
HD Out of Route Vehicle Speed (miles/hr)	25	25	25	25
HD Labor Rate ($/hr)	$25	$25	$25	$25
HD Annual Out of Route Labor Costs ($/yr)	$1,825	$1,825	$1,825	$1,825
HD Public Fueling Labor & Misc. Costs ($/yr)	$0	$0	$0	$0
HD Annual Public Station Out of Route/Fueling Labor & Misc. Costs ($/	$1,825	$1,825	$1,825	$1,825
Fuel Use				
Heavy-Duty (HD) Fleet Fuel Use (GGE/year)	4,044	1,152	1,846	4,493
Total Fleet Fuel Use (GGE/year)	4,044	1,152	1,846	4,493

TCO Outputs

	Diesel	**EV**	**G.H2 FCV**	**CNG**
Heavy-Duty Combination Long-Haul Truck Fleet and Public Fueling Infrastructure, No Incentives				
Financing	$0	$0	$0	$0
Depreciation	$84,217	$263,178	$315,813	$138,958
Fuel	$997,953	$1,042,314	$3,233,427	$5,154,331
Diesel Exhaust Fluid	$15,481	$0	$0	$0
Maintenance and Repair	$405,197	$366,341	$366,341	$411,520
Insurance	$53,447	$53,447	$53,447	$53,447
License and Registration	$5,629	$5,629	$5,629	$5,629
Total Cost of Ownership	$1,561,924	$1,730,908	$3,974,657	$5,763,884

Total Cost of Ownership Using Public Fueling Infrastructure

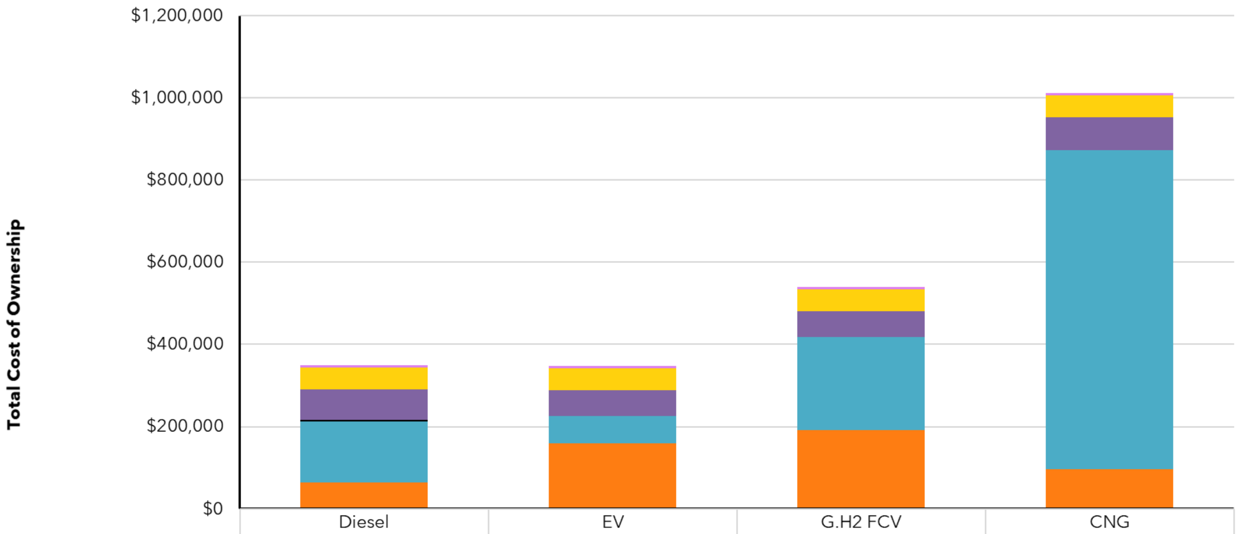
	Diesel	EV	G.H2 FCV	CNG
Heavy-Duty Single Unit Long-Haul Truck Fleet, No Incentives				
Financing	$0	$0	$0	$0
Depreciation	$63,163	$160,012	$192,015	$96,849
Fuel	$150,144	$65,309	$226,578	$775,481
Diesel Exhaust Fluid	$2,329	$0	$0	$0
Maintenance and Repair	$75,121	$63,027	$63,027	$80,621
Insurance	$53,447	$53,447	$53,447	$53,447
License and Registration	$5,629	$5,629	$5,629	$5,629
Total Cost of Ownership	$349,833	$347,424	$540,695	$1,012,028

	Diesel	EV	G.H2 FCV	CNG
Heavy-Duty Combination Long-Haul Truck Fleet, No Incentives				
Financing	$0	$0	$0	$0
Depreciation	$84,217	$263,178	$315,813	$138,958
Fuel	$997,953	$1,042,314	$3,233,427	$5,154,331
Diesel Exhaust Fluid	$15,481	$0	$0	$0
Maintenance and Repair	$405,197	$366,341	$366,341	$411,520
Insurance	$53,447	$53,447	$53,447	$53,447
License and Registration	$5,629	$5,629	$5,629	$5,629
Total Cost of Ownership	$1,561,924	$1,730,908	$3,974,657	$5,763,884

	Diesel	EV	G.H2 FCV	CNG
Heavy-Duty Combination Short-Haul Truck Fleet, No Incentives				
Financing	$0	$0	$0	$0
Depreciation	$75,795	$244,229	$293,075	$109,482
Fuel	$434,324	$404,272	$1,380,173	$2,243,240
Diesel Exhaust Fluid	$6,738	$0	$0	$0
Maintenance and Repair	$189,395	$172,252	$172,252	$192,185
Insurance	$53,447	$53,447	$53,447	$53,447
License and Registration	$5,629	$5,629	$5,629	$5,629
Total Cost of Ownership	$765,327	$879,829	$1,904,576	$2,603,982

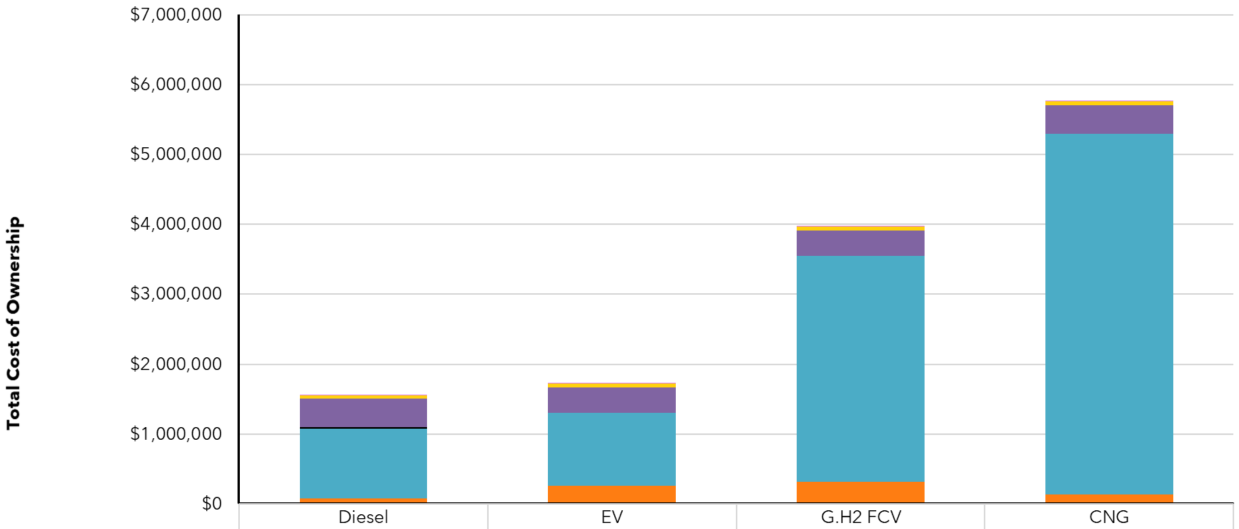
	Diesel	EV 5.0 EER	EV 3.5 EER	G.H2 FCV	CNG
Heavy-Duty Combination Short-Haul Truck Fleet, with HVIP Vehicle and State and Federal Fuel Incentives					
Financing	$0	$0	$0	$0	$0
Depreciation	$75,795	$94,229	$94,229	-$6,925	$64,482
Fuel	$434,324	-$276,176	-$15,064	$1,346,623	$149,728
Diesel Exhaust Fluid	$6,738	$0	$0	$0	$0
Maintenance and Repair	$189,395	$172,252	$172,252	$172,252	$192,185
Insurance	$53,447	$53,447	$53,447	$53,447	$53,447
License and Registration	$5,629	$5,629	$5,629	$5,629	$5,629
Total Cost of Ownership	$765,327	$49,381	$310,493	$1,571,026	$465,470

Heavy-Duty Single Unit Long-Haul Truck Fleet, Using Public Fueling Infrastructure, No Incentives



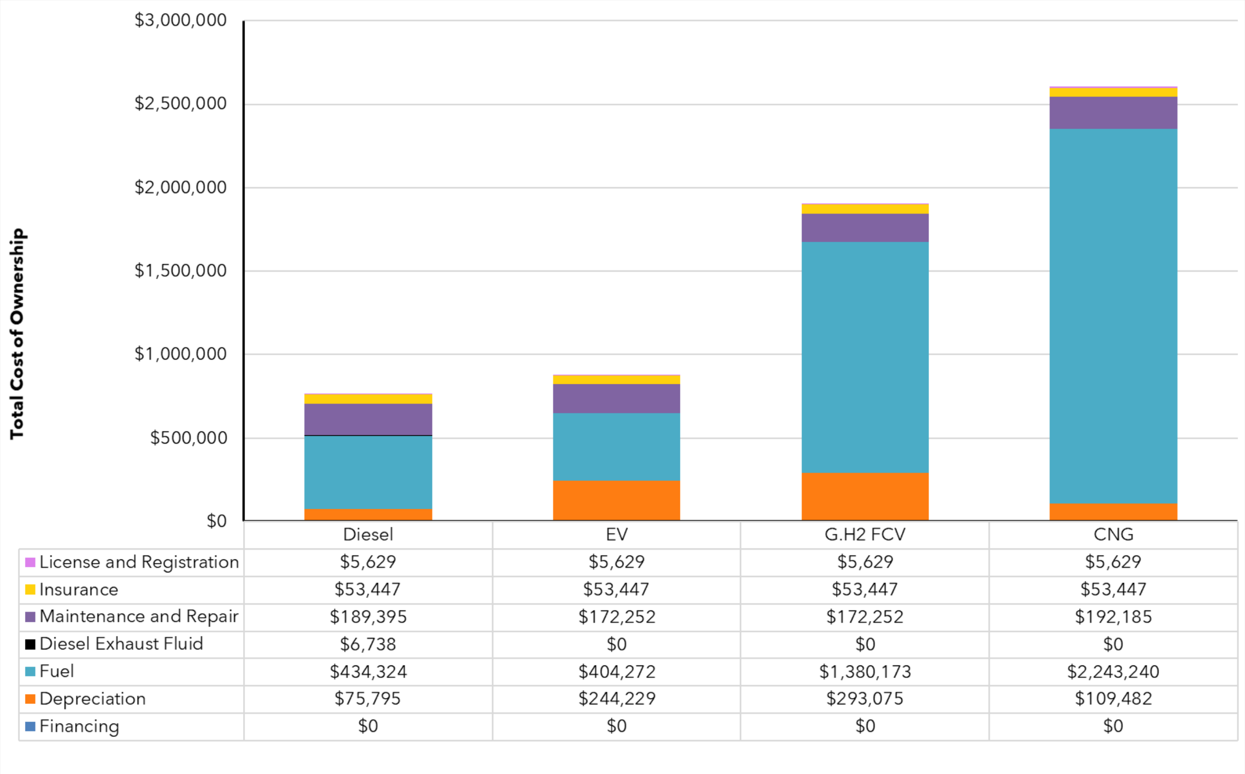
	Diesel	EV	G.H2 FCV	CNG
■ License and Registration	$5,629	$5,629	$5,629	$5,629
■ Insurance	$53,447	$53,447	$53,447	$53,447
■ Maintenance and Repair	$75,121	$63,027	$63,027	$80,621
■ Diesel Exhaust Fluid	$2,329	$0	$0	$0
■ Fuel	$150,144	$65,309	$226,578	$775,481
■ Depreciation	$63,163	$160,012	$192,015	$96,849
■ Financing	$0	$0	$0	$0

Heavy-Duty Combination Long-Haul Truck Fleet, Using Public Fueling Infrastructure, No Incentives



	Diesel	EV	G.H2 FCV	CNG
■ License and Registration	$5,629	$5,629	$5,629	$5,629
■ Insurance	$53,447	$53,447	$53,447	$53,447
■ Maintenance and Repair	$405,197	$366,341	$366,341	$411,520
■ Diesel Exhaust Fluid	$15,481	$0	$0	$0
■ Fuel	$997,953	$1,042,314	$3,233,427	$5,154,331
■ Depreciation	$84,217	$263,178	$315,813	$138,958
■ Financing	$0	$0	$0	$0

Heavy-Duty Combination Short-Haul Truck Fleet, Using Public Fueling Infrastructure, No Incentives



	Diesel	EV	G.H2 FCV	CNG
■ License and Registration	$5,629	$5,629	$5,629	$5,629
■ Insurance	$53,447	$53,447	$53,447	$53,447
■ Maintenance and Repair	$189,395	$172,252	$172,252	$192,185
■ Diesel Exhaust Fluid	$6,738	$0	$0	$0
■ Fuel	$434,324	$404,272	$1,380,173	$2,243,240
■ Depreciation	$75,795	$244,229	$293,075	$109,482
■ Financing	$0	$0	$0	$0

Heavy-Duty Combination Short-Haul Truck Fleet, Using Public Fueling Infrastructure with Incentives

	Diesel	EV (5.0 EER)	EV (3.5 EER)	G.H2 FCV	CNG
■ License and Registration	$5,629	$5,629	$5,629	$5,629	$5,629
■ Insurance	$53,447	$53,447	$53,447	$53,447	$53,447
■ Maintenance and Repair	$189,395	$172,252	$172,252	$172,252	$192,185
■ Diesel Exhaust Fluid	$6,738	$0	$0	$0	$0
■ Fuel	$434,324	-$276,176	-$15,064	$1,346,623	$149,728
■ Depreciation	$75,795	$94,229	$94,229	-$6,925	$64,482
■ Financing	$0	$0	$0	$0	$0

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