Understanding the CO_2 Impacts of Zero-Emission Trucks

A Comparative Life-Cycle Analysis of Battery Electric, Hydrogen Fuel Cell and Traditional Diesel Trucks

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Prepared by the American Transportation Research Institute

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Jeffrey Short
Vice President
American Transportation Research Institute
Atlanta, GA

Danielle Crownover
Research Analyst
American Transportation Research Institute
Atlanta, GA

950 N. Glebe Road, Suite 210
Arlington, Virginia 22203
TruckingResearch.org

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TABLE OF CONTENTS

INTRODUCTION **7**
Research Objective 8

BACKGROUND **9**
Greenhouse Gas Emissions in the U.S. 9
Energy Consumption in the Transportation Sector 10
Toward Zero-Emission Vehicles 11
Realities of Zero-Emission Trucks: What Trucking Companies Need to Know 13

REASEARCH APPROACH **16**

BASELINE ANALYSIS OF CO_2 EMISSIONS IN VEHICLE LIFE-CYCLE **17**
CO_2 Emissions: Vehicle Production 17
CO_2 Emissions: Energy Production and Consumption 20
CO_2 Emissions: Vehicle Disposal and Recycling 24
Final Full Life-Cycle CO_2 Emissions 25

SCENARIO ANALYSIS **26**
Internal Combustion Engine (ICE) Scenarios 26
Battery Electric Vehicle (BEV) Scenarios 29
Fuel Cell Electric Vehicle (FCEV) Scenarios 35

CONCLUSIONS **37**

APPENDIX A: METHODOOGY FOR ICE MPG AND AVERAGE WEIGHT FIGURES **40**

LIST OF FIGURES

Figure 1: 2019 GHG Emissions by Source **9**
Figure 2: CO_2 Emissions by Economic Sector **10**
Figure 3: 2019 U.S. Transportation Sector GHG Emissions by Source **11**
Figure 4: Vehicle Production CO_2 Comparison Chart **20**
Figure 5: Energy Production and Consumption CO_2 Comparison Chart **23**
Figure 6: ICE Lifetime CO_2 vs BEV & FCEV **25**
Figure 7: Per Gallon CO_2 Reduction through Diesel Alternatives **28**
Figure 8: Average Operating Weight Responses **32**
Figure 9: EIA Projected Fuel Source for U.S. Electricity – 2021-2050 Transportation Mix **34**
Figure 10: Projected Decrease in Energy Production CO_2 for a BEV Truck by 2030 and 2050 .... **35**
Figure 11: Key Findings from the Scenario Analysis **39**
Figure A1: Ops Costs Average Carrier Weights **41**

LIST OF TABLES

Table 1: List of Source Countries for Key Materials 14
Table 2: Vehicle Energy Capacity and Range 17
Table 3: GREET Vehicle Weight Distribution Assumptions (in lbs.) for Class 8 Sleeper Cab 18
Table 4: Key Materials for Truck Chassis (All Vehicles) 19
Table 5: CO_2 Emissions Total (lbs.): Vehicle Production 19
Table 6: Fuel Economy and Lifetime Fuel Consumption (for One Million Miles) 21
Table 7: Lbs. of CO_2 per Unit of Energy 22
Table 8: Energy Source for U.S. Electricity Production - Transportation Mix (2019) 22
Table 9: Operations: CO_2 Emissions from Energy to Drive One Million Miles by Vehicle Type 23
Table 10: CO_2 Emissions Associated with Four Methods for Lithium Ion Battery Recycling 24
Table 11: Total Lbs. of CO_2 for Vehicle End-of-Life Disposal/Recycling 24
Table 12: Total Life-Cycle CO_2 Emissions (in lbs.) 25
Table 13: Comparison of ICE Fuel Alternatives to Conventional Diesel 27
Table 14: Vehicle, Trailer and Cargo Weight 31
Table 15: BEV CO_2 Reductions due to Electricity Source Changes 34
Table 16: Carbon Footprint of SMR and Solar-Based Electrolysis Approaches 36
Table 17: Key Findings 38
Table A1: Ops Costs Truckload Carriers with Average Operating Weights at or below 80,000 lbs. by Year 40
Table A2: Ops Costs Trip Types for Truckload Carriers with Average Operating Weights at or below 80,000 lbs., 2016-2020 41

ACRONYMS

AAA	American Automobile Association
ACT	Advanced Clean Trucks
AEO	Annual Energy Outlook
ATRI	American Transportation Research Institute
B2	Biodiesel 2%, Petroleum Diesel 98%
B5	Biodiesel 5%, Petroleum Diesel 95%
B20	Biodiesel 20%, Petroleum Diesel 80%
B100	Biodiesel 100%, Petroleum Diesel 0%, Pure Biodiesel
BEV	Battery Electric Vehicle
BTU	British Thermal Unit
CARB	California Air Resources Board
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DOE	Department of Energy
EIA	Energy Information Agency
EPA	Environmental Protection Agency
FCEV	Fuel Cell Electric Vehicle
GEM	Greenhouse Gas Emissions Model
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Technologies
HTSE	High-Temperate Steam Electrolysis
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICE	Internal Combustion Engine
LNG	Liquefied Natural Gas
KG	Kilogram
KWH	Kilowatt Hour
MMBTU	Metric Million British Thermal Unit
MOU	Memorandum of Understanding
NEMS	National Energy Modeling System
NOx	Nitrogen Oxides
OEM	Original Equipment Manufacturer
SMR	Steam Methane Reforming
SOH	State-of-Health
USDA	United States Department of Agriculture
ZET	Zero-Emission Truck

INTRODUCTION

With the introduction of zero-emission trucks (ZETs) to the Class 8 market, the trucking industry may have viable alternatives to internal combustion engines (ICEs).[1] Unlike ICE trucks, ZETs are not powered with diesel – they instead use electricity that is either stored in batteries or produced onboard with hydrogen to power an electric motor. The ZET approach to vehicle propulsion produces no direct tailpipe emissions during operations.

From a life-cycle perspective, however, ZETs are still responsible for generating greenhouse gases (GHG) such as carbon dioxide (CO_2), which is tied to climate change. While CO_2 emissions are not directly released by a ZET during operations, such emissions are released during the production of ZET fuels (electricity and hydrogen) and the production and disposal of ZET vehicles and their electricity storage equipment (lithium-ion batteries).

That said, the core motivations for a shift to ZETs remain environmental, and it may be possible to decrease the trucking industry's emissions through their deployment – although the scale of environmental benefit is unclear.[2]

While the environmental motivation to adopt ZETs is growing, there are several cost considerations. For the foreseeable future, these include:

- the replacement of existing Class 8 trucks with significantly higher-priced trucks;
- an entirely new approach to refueling; and
- changes to the operational structure of the trucking industry due to decreased range capabilities.

While these ZET-related costs may ultimately be passed on to consumers, the trucking industry must consider the short-term cost implications for investing in ZETs. Additionally, both industry and government must understand the calculus associated with life-cycle environmental impacts of ZETs, as they do not eliminate CO_2 emissions. To understand the full environmental and financial cost-benefit calculation, it is critical to first document life-cycle emissions for both ICE and ZET trucks. This report focuses on the life-cycle CO_2 emissions for the following truck types:

- Internal Combustion Engine Trucks. This is the traditional truck type used by the trucking industry. ICE trucks have a compression ignition engine that is powered by diesel. The combustion within the engine requires an exhaust system for the emissions.

- Battery Electric Vehicle (BEV) Trucks. BEV trucks are a type of ZET that have an electric motor powered by electricity stored in large onboard lithium-ion batteries. This vehicle type does not have tailpipe emissions. While there are millions of heavy-duty ICE trucks currently registered in the U.S., the number of BEV heavy-duty trucks in operation today is likely more than 50 and growing.

- Fuel Cell Electric Vehicle (FCEV) Trucks. FCEV trucks are a type of ZET that have an electric motor powered by electricity produced within a hydrogen fuel cell. The hydrogen

[1] Congressional Research Service. "Class 8 Truck Zero-Emission Routes." February 9, 2021. Available online: https://crsreports.congress.gov/product/pdf/IN/IN11598

[2] There are several other likely benefits to electric trucks that are not the focus of this paper, which include diversification in energy sources, smoother ride, better acceleration and less complicated repair and maintenance, to name a few.

fuel is stored onboard in large tanks. This vehicle type does not have tailpipe emissions. It is anticipated that FCEV heavy-duty trucks will be commercially available in two to three years.

For each of these truck types the life-cycle CO_2 emissions will be calculated. The life-cycle stages are:

- Vehicle Production. This includes the CO_2 emissions released during all vehicle production processes, including the extraction of raw materials and final vehicle assembly. For the BEV in particular, this includes both the production of the truck and the large lithium-ion battery.

- Energy Production and Consumption. This includes the CO_2 emissions released during the production of energy (e.g. the production of electricity at a power plant, or the refining of diesel fuel from crude oil). Additionally, this includes the CO_2 emissions from final fuel consumption (which only applies to ICE vehicles in this research).

- Vehicle Disposal and Recycling. This includes emissions related to the disposal or recycling of the truck and also the disposal and recycling of lithium-ion batteries for the BEV.

Research Objective

The purpose of this report is to better understand the life-cycle CO_2 emissions of three Class 8 sleeper cab trucks. These trucks will be referred to throughout the report as follows:

- Internal Combustion Engine (ICE) Truck
- Battery Electric Vehicle (BEV) Truck
- Fuel Cell Electric Vehicle (FCEV) Truck

The life-cycle stages, described earlier, will be referred to as:

- Vehicle Production
- Energy Production and Consumption
- Vehicle Disposal and Recycling

The research first sets a baseline life-cycle CO_2 calculation for each stage of the ICE truck, and then compares that ICE baseline to the two other truck types. The research then explores approaches to improving emissions for all three vehicle types through improvements in technology.

This research provides industry, government and other stakeholders with a technical environmental impact assessment of switching to ZETs, as well as a glimpse at the advancements that may be needed to further decrease industry emissions.

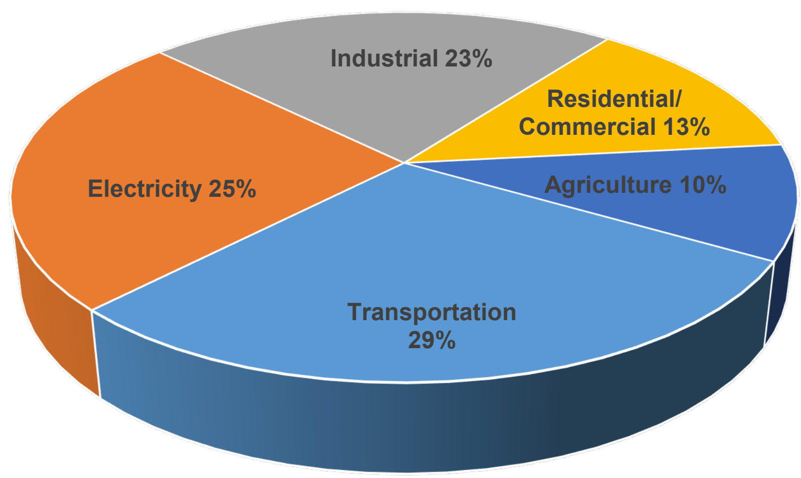
BACKGROUND

Greenhouse Gas Emissions in the U.S.

Greenhouse gases such as CO_2, which trap heat in the atmosphere, are naturally occurring and are essential to maintaining the global climate; without them the earth would be too cold to sustain human life. That said, when atmospheric GHG concentrations increase beyond a natural equilibrium, global temperatures slowly rise (referred to as climate change). Climate change has been shown to generate an atypical increase in surface, ocean and atmospheric temperatures along with changes in weather patterns. Long-term concerns related to climate change include ice shelf melting, sea level rise, and significant changes in local environments.

As shown in Figure 1, the largest source of U.S. GHG emissions is found in the transportation sector, followed closely by electricity.[3]

Figure 1: 2019 GHG Emissions by Source



Several decades ago, however, electricity was the largest emitter of the primary GHG, CO_2 (Figure 2).[4] This changed when electric utilities first began to move from coal to natural gas during the Great Recession. This shift in energy use was the result of low natural gas prices and underutilized natural gas power plant capacity, and resulted in lower CO_2 emissions.[5]

The shift away from coal after the Great Recession was further motivated by federal policy. The Obama-era Clean Power Plan (2015), which was administrated by the U.S. Environmental

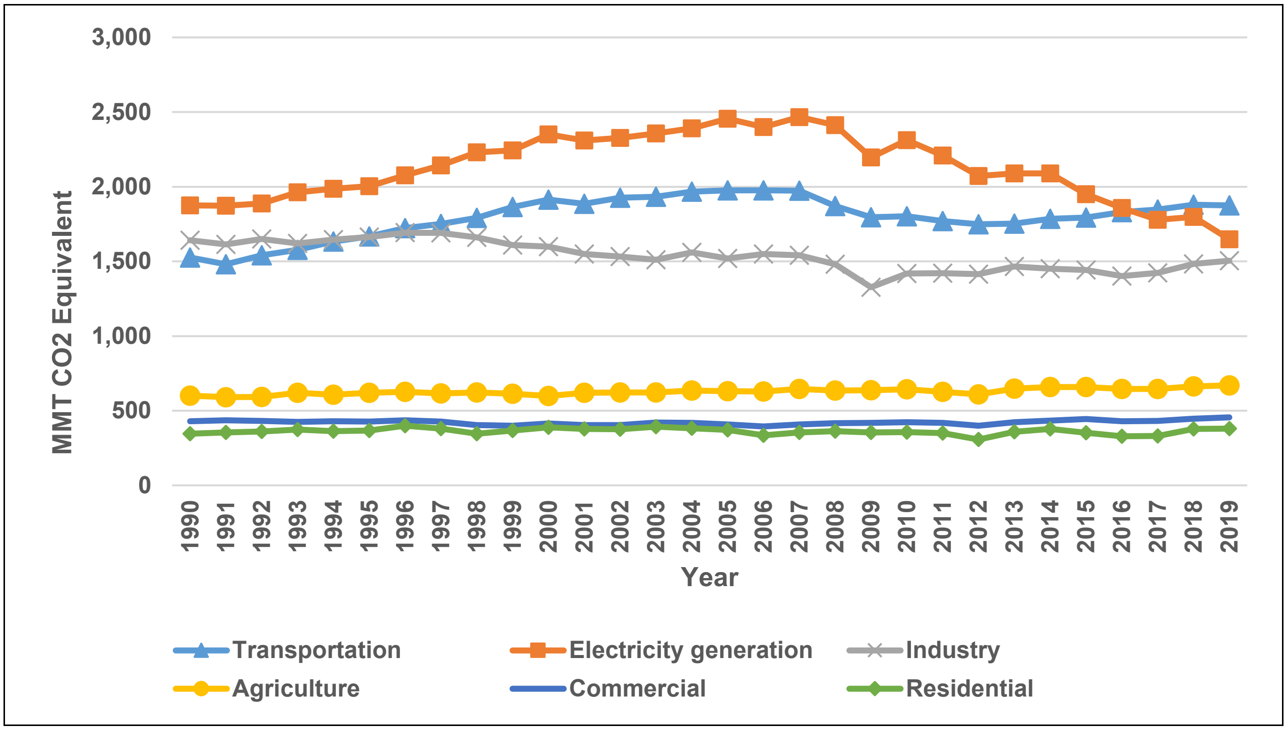
[3] United States Environmental Protection Agency. (2021). "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019." EPA. Available online: https://www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf?VersionId=yu89kg1O2qP754CdR8Qmyn4RRWc5iodZ

[4] United States Environmental Protection Agency. "Greenhouse Gas Inventory Data Explorer [Interactive Tool]." EPA. Available online: https://cfpub.epa.gov/ghgdata/inventoryexplorer/index.html#allsectors/allsectors/allgas/econsect/current

[5] Salovaara, Jackson. (2011). "Coal to Natural Gas Coal Switching and CO2 Emissions Reduction." Harvard Kennedy School. Available online: https://www.hks.harvard.edu/centers/mrcbg/publications/awp/awp6

Protection Agency (EPA), required states to decrease CO_2 emissions which ultimately led to decreased coal consumption in the electricity sector.[6]

Figure 2: CO_2 Emissions by Economic Sector



Energy Consumption in the Transportation Sector

The electricity sector's success with CO_2 reduction could be mirrored in the transportation sector through a change in energy sources. The movement of people and goods requires energy consumption. In the U.S., the majority of transportation-related energy is consumed by light-duty vehicles, which are typically personal vehicles.[7] Freight is also a large consumer of transportation energy. Maritime, rail, air cargo and trucking – all critical in moving the country's raw materials and finished goods – generate GHG emissions.

Today, the energy used in U.S. transportation is almost exclusively sourced from oil and natural gas, which are commonly referred to as fossil fuels. The breakout of the U.S. transportation sector GHG is shown by mode in Figure 3.[8]

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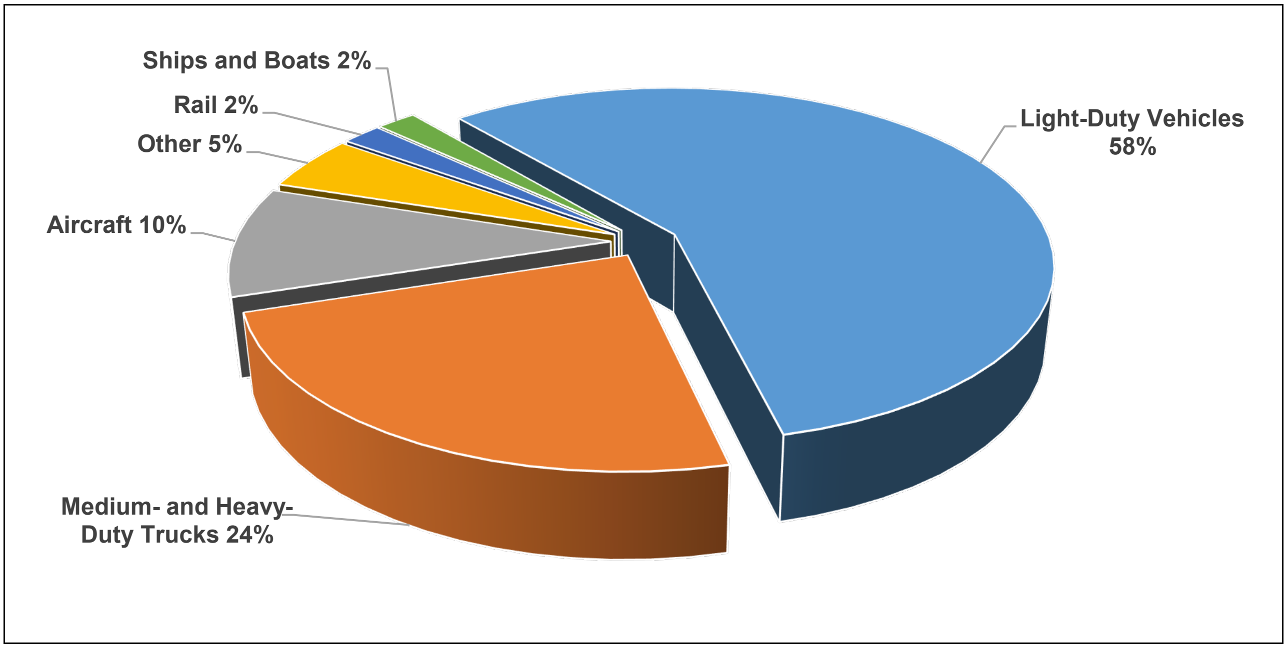
[6] United States Environmental Protection Agency. "FACT SHEET: Overview of the Clean Power Plan." EPA. Available online: https://archive.epa.gov/epa/cleanpowerplan/fact-sheet-overview-clean-power-plan.html
[7]United States Department of Transportation. "Energy Consumption by Mode of Transportation." Bureau of Transportation Statistics. Available online: https://www.bts.gov/content/energy-consumption-mode-transportation
[8] United States Environmental Protection Agency. "Fast Facts on Transportation Greenhouse Gas Emissions." EPA. Available online: https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

Figure 3: 2019 U.S. Transportation Sector GHG Emissions by Source



Light-duty vehicles are responsible for 58 percent of all transportation GHG, and nearly 17 percent of all U.S. GHG emissions. Trucking has a much lower figure, with medium- and heavy-duty trucks emitting 24 percent of transportation GHG and 7 percent of U.S. GHG.

Toward Zero-Emission Vehicles

To address air pollution and CO_2 emissions within the transportation sector, there has been a movement toward zero-emission vehicles that has strengthened in recent years, particularly through state-level environmental goals and regulations.

Incentive programs designed to move the trucking industry toward ZETs currently exist for both truck manufacturers (referred to as OEMs) and motor carriers. For example, the U.S. Department of Energy (DOE) awarded $127 million to its SuperTruck 3 program in 2021 – these funds will assist commercial motor vehicle manufacturers in the advancement of battery electric and fuel cell electric vehicles.[9]

Requiring ZET sales through regulations is another approach. The California Air Resources Board (CARB) Advanced Clean Trucks (ACT) rule requires medium- and heavy-duty vehicle manufacturers to sell ZETs as a portion of total sales within California. The ACT rule contains the following new truck sales requirements by 2035:

[9] U.S. Department of Energy. “DOE Announces $162 Million to Decarbonize Cars and Trucks.” Energy.gov. April 15, 2021. Available online: https://www.energy.gov/articles/doe-announces-162-million-decarbonize-cars-and-trucks; and Babcock, Stephane. (November 3, 2021). “U.S. DOE Announces More than $127 Million for SuperTruck 3.” ACT News. Available online: https://www.act-news.com/news/u-s-doe-announces-more-than-127-million-for-supertruck-3/

- 55 percent of trucks Class 2b-3 must be ZETs;
- 75 percent of Class 4-8 straight truck sales must be ZETs; and
- 40 percent of tractor-trailers must be ZETs.[10]

Additionally, a proposed amendment to the ACT rule would require all trucks sold in California to be ZETs by 2040. Other states have moved in this direction: there is a new 17-state memorandum of understanding (MOU) that has a goal of phasing out traditional ICE trucks in favor of ZETs.[11] The MOU aims to reach 30 percent ZET sales for all new medium- and heavy-duty trucks by 2030, with 100 percent of sales being zero-emission by 2050.[12]

The trucking industry's response to these initiatives is to adopt, or prepare to adopt, new truck technologies offered by vehicle manufacturers. Adoption of these vehicles does offer challenges, including significant changes to freight business models and considerably higher overhead costs in the near-term. Some trucking companies will simply not be able to use today's ZET technologies as part of their operations.

Independent of the industry's ability to use ZETs, there is a movement to mandate that motor carriers based in California purchase and utilize ZETs. CARB has developed a draft medium- and heavy-duty zero-emission fleet rule known as Advanced Clean Fleets to accelerate the number of medium- and heavy-duty ZET in use.[13] If adopted, it will require motor carriers to include an increasing percentage of ZETs in their fleet beginning in 2025.

According to one source, by the end of 2021 there were 1,215 ZETs deployed in the U.S., the majority of which were BEVs.[14] Of these, the report states that 47 were classified as heavy-duty trucks, though this figure has grown during 2022. This stands in stark contrast to the 23 million ICE Class 2b through Class 8 trucks on U.S. roads today.[15] Thus, real-world ZET operational and performance data is very limited.

Newer diesel engines have played a role in decreasing CO_2 emissions compared to earlier diesel engines. For example, the Diesel Technology Forum stated in comments submitted to the U.S. Senate that the more efficient diesel trucks that have been sold since 2010 have saved 12 billion gallons of fuel, which resulted in a reduction of "126 million tons of greenhouse gas emissions between 2011 and 2018."[16]

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[10] California Air Resources Board. "Advanced Clean Trucks Fact Sheet." 2021. Available online: https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-fact-sheet

[11] Lewis, Michelle. (April 1, 2022). "Nevada pledges to electrify all new trucks and buses by 2050." Electrek. Available online: https://electrek.co/2022/04/01/nevada-pledges-to-electrify-all-new-trucks-and-buses-by-2050/

[12] California Air Resources Board. "15 states and the District of Columbia join forces to accelerate bus and truck electrification." 2021. Available online: https://ww2.arb.ca.gov/news/15-states-and-district-columbia-join-forces-accelerate-bus-and-truck-electrification

[13] California Air Resources Board. "Advanced Clean Fleets." Available online: https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets/about

[14] Al-Alawi, et al. (January 2022). "Zeroing In On Zero-Emission Trucks". CALSTART. Available online: https://calstart.org/wp-content/uploads/2022/02/ZIO-ZETs-Report_Updated-Final-II.pdf

[15] MJB & A. (2021). "Medium- & Heavy-Duty Vehicles: Market structure, Environmental Impact, and EV Readiness." Available online: https://www.edf.org/sites/default/files/documents/EDFMHDVEVFeasibilityReport22jul21.pdf

[16] Diesel Technology Forum. (March 16, 2021). "Continued Investment, Innovation in Advanced Technology Diesel Engines Sustains Clean Air and Climate Progress." Bloomberg. Available online: https://www.bloomberg.com/press-releases/2021-03-16/continued-investment-innovation-in-advanced-technology-diesel-engines-sustains-clean-air-and-climate-progress

The Forum's comments list the progress that is being made with diesel technology: "new technology diesel engines have eliminated more than 26 million tons of nitrogen oxides (NOx) already since 2010," and "it would take more than 60 new-generation diesel trucks to equal the emissions from one truck sold in 1988."[17]

Realities of Zero-Emission Trucks: What Trucking Companies Need to Know

While there is a strong public policy push toward ZET adoption, there are several critical realities that the trucking industry faces:

Vehicle Cost. ZET vehicle costs (especially for early adopters) will be a strong barrier to entry. While a new Class 8 diesel truck tractor may cost roughly $135,000 - $150,000, the purchase price of a new Class 8 BEV can be as much as $450,000.[18] ACT Research estimates that the battery pack for a Class 8 BEV accounts for roughly 55 percent of the cost of the BEV truck.[19] This cost, in theory, may fall as battery production and the extraction of raw materials expands.

The same issue will likely impact the FCEV. Estimates for fuel cell truck costs range from $200,000 to $600,000 with 60 percent of the overall cost solely credited to the fuel cell propulsion system.[20] The fuel cell propulsion unit and hydrogen storage system together are estimated to comprise roughly 80 percent of the total vehicle cost. Additionally, the hydrogen required to power an FCEV is costly; 70 percent of retail hydrogen stations in California sell hydrogen above $16 per kilogram.[21]

Sourcing of Materials and Supply Chain Issues. There are several key raw materials needed for lithium-ion batteries; depending on the battery chemistry, these might include lithium, graphite, cobalt, manganese and nickel.[22] While the aforementioned list of materials are critical for batteries and for the production of a large BEV national fleet, the U.S. is almost entirely dependent on other countries for these materials. Over the past decade, the U.S. has imported nearly 100 percent of the critical minerals needed for battery production from countries including China, Australia and Chile.[23] The main source countries for these materials are listed in Table 1.[24]

[17] Ibid.
[18] Hirsch, Jerry. (January 4, 2022). "The Electrification Journey". Transport Topics. Available online: https://www.ttnews.com/articles/electrification-journey
[19] Stinson, Jim. (September 14, 2021). "Money and range: Experts note roadblocks to EV adoption". Transport Dive. Available online: https://www.transportdive.com/news/act-expo-electric-trucks-battery-infrastructure/606386/
[20] Sharpe, Ben and Hussein, Basma. (February 2022). "A meta-study of purchase costs for zero-emission trucks." International Council on Clean Transportation. Available online: https://theicct.org/wp-content/uploads/2022/02/purchase-cost-ze-trucks-feb22-1.pdf
[21] California Energy Commission and California Air Resources Board. (December 2021). "Joint Agency Staff Report on Assembly Bill 8: 2021 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California." California Energy Commission. Available online: https://www.energy.ca.gov/sites/default/files/2021-12/CEC-600-2021-040.pdf
[22] United States Geological Survey. (January 2022). "Mineral Commodity Summaries: Lithium." Department of Interior. Available online: https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-lithium.pdf
[23] The White House. (February 22, 2022). "Remarks by President Biden at a Virtual Event on Securing Critical Minerals for a Future Made in America." Briefing Room Speeches and Remarks. Available online: https://www.whitehouse.gov/briefing-room/speeches-remarks/2022/02/22/remarks-by-president-biden-at-a-virtual-event-on-securing-critical-minerals-for-a-future-made-in-america/
[24] U.S. Geological Survey. (2022). "Mineral Commodity Summaries 2022." U.S. Department of Interior. Available online: https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf

Table 1: List of Source Countries for Key Materials

Mineral	Key Source Countries	Global Production (metric tons)	U.S. Production (% of global)
Lithium	Australia (55%), Chile (26%), China (14%), Argentina (6.2%)	100,000	<5.00%
Graphite	China (82%), Brazil (6.8%), Mozambique (3%), Russia (2.7%)	1,000,000	0.00%
Cobalt	Democratic Republic of Congo (70.5%), Russia (4.4%), Australia (3.2%)	170,000	0.40%
Manganese	South Africa (37%), Gabon (18%), Australia (16.5%), China (6.5%)	20,000	0.00%
Nickel	Indonesia (37%), Philippines (13.7%), Russia (9.2%)	2,700,000	0.60%

Lithium. The U.S. Geological Survey reports current reserves of 750,000 metric tons of lithium in the U.S., and approximately 22 million metric tons globally. Although the U.S. has significant lithium reserves, the country today has only one large-scale lithium mine that produces several thousand tons per year.[25] Most of the raw lithium used domestically comes from Latin America or Australia, and most of it is processed and turned into battery cells in China and other Asian countries.

Graphite. China is the largest producer of graphite. No graphite is produced in the U.S., though there are two mining projects under development that may produce graphite in the future. The U.S. consumes large amounts of graphite both in the manufacture of automotive parts and, more recently, in the manufacture of lithium-ion batteries for cars.

Cobalt and Nickel. These two metals are more scarce than lithium, and the mining of these materials is linked to environmental and human rights issues.[26] Two-thirds of the world's cobalt mining occurs in the Democratic Republic of the Congo where there are allegations of environmental and human rights neglect.[27] Additionally, several of the largest cobalt mining companies are owned by the Chinese government.[28] Indonesia is the world's largest nickel producer followed by the Philippines and Russia, the latter of which now faces international

[25] Penn, Ivan and Lipton, Eric. (May 6, 2021). "The Lithium Gold Rush: Inside the Race to Power Electric Vehicles." The New York Times. Available online: https://www.nytimes.com/2021/05/06/business/lithium-mining-race.html
[26] Amnesty International. (March 21, 2019). "Amnesty challenges industry leaders to clean up their batteries." Available online: https://www.amnesty.org/en/latest/news/2019/03/amnesty-challenges-industry-leaders-to-clean-up-their-batteries/
[27] Ibid.
[28] Lipton, Eric and Searcey, Dionne. (February 28, 2022). "Chinese Company Removed as Operator of Cobalt Mine in Congo." The New York Times. Available online: https://www.nytimes.com/2022/02/28/world/congo-cobalt-mining-china.html#:~:text=As%20of%202020%2C%20Chinese%2Dbacked,fail%20to%20benefit%20the%20Congolese.

sanctions.[29] [30] Like cobalt, there are environmental implications linked to the mining of nickel, and the Philippines closed 17 nickel mines in 2017 over environmental concerns.[31]

Manganese. South Africa is the leading producer of manganese with China purchasing 93 percent of battery-grade, high-purity manganese.[32] Currently, China is the world leader in electric vehicle battery production, with more than 90 lithium-ion battery cell manufacturing facilities; this can be compared to four that are operating within the U.S.[33]

Refueling Infrastructure. Beyond global sourcing of raw materials, there is also a lack of refueling infrastructure in the U.S., particularly for BEVs. There currently is no U.S. network where over-the-road trucks can stop for rest breaks and recharging at the same time. In a forthcoming report, ATRI documents the infrastructure requirements of a nationwide truck charging network and the electricity sector's ability to power the U.S. truck fleet.

CO2 and other Emissions. Beyond production and refueling issues, there are still ZET-related emissions to consider. In particular, it is not yet fully understood if the CO_2 emission benefits of switching from ICE trucks to ZET justify the costs and level of uncertainty that the industry faces to make that switch. The following CO_2 life-cycle analysis for ICE, BEV and FCEV trucks provides important comparative insights that can be used by both industry and government.

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[29] Pistilli, Melissa. (March 3, 2022). "Top 9 Nickel-producing Countries (Updated 2022)." Investing News. Available online: https://investingnews.com.au/daily/resource-investing/base-metals-investing/nickel-investing/top-nickel-producing-countries/

[30] The Editorial Board. (March 8, 2022). "A Nickel for Your Ukraine Thoughts." Wall Street Journal. Available online: https://www.wsj.com/articles/a-nickel-for-your-ukraine-thoughts-russia-metals-market-climate-11646781149

[31] Opray, Max. (August 24, 2017). "Nickel mining: the hidden environmental cost of electric cars." The Guardian. Available online: https://www.theguardian.com/sustainable-business/2017/aug/24/nickel-mining-hidden-environmental-cost-electric-cars-batteries

[32] Jackson, Dave. (November 10, 2020). "The Little-Known Critical Metal that's Powering the New Green Revolution." Stockhouse. Available online: https://stockhouse.com/news/newswire/2020/11/10/the-little-known-critical-metal-that-s-powering-new-green-revolution

[33] Whalen, Jeanne. (February 11, 2021). "Biden wants to create millions of clean-energy jobs. China and Europe are way ahead of him." The Washington Post. Available online: https://www.washingtonpost.com/technology/2021/02/11/us-battery-production-china-europe/

REASEARCH APPROACH

As noted earlier, the purpose of this report is to better document and compare the CO_2 life-cycle emissions of ICE trucks and two ZET truck types. The energy, environmental and operational data used in this report are derived from multiple sources, including public sector data and ATRI's *Operational Cost of Trucking*.[34] The estimates produced in this analysis are at the national level.

The intent of this report is to provide objective, disinterested assessments of both current and emerging technologies. Documenting empirical ZET environmental outcomes will not only help inform adoption decisions for ZETs, but could also highlight areas where both ZETs and ICE trucks can decrease their environmental impacts.

To better understand the complete life-cycle CO_2 emissions for all three vehicle types (ICE, BEV and FCEV), the research team primarily reviewed data from the GREET life-cycle analysis tool (referred to as the GREET Model), which was developed by the U.S. Department of Energy (DOE) Argonne National Laboratory.[35] The GREET Model generates metrics for all emissions related to the production, operation and eventual disposal of cars and trucks.

It should also be noted that the numbers in the GREET Model and other data sources used by ATRI often have many decimal places. While ATRI uses the complete decimal figures in its research calculations, the ATRI report tables often show outputs rounded to the nearest meaningful decimal place for formatting and presentation purposes. As a result, the numbers in the tables periodically do not add up due to rounding. Tables where numeric rounding occurs are marked in the report with an asterisk (*).

[34] Alex Leslie and Dan Murray, *An Analysis of the Operational Costs of Trucking: 2021 Update*, American Transportation Research Institute, Nov. 2021.

[35] The GREET Model's full title is "The Greenhouse gases, Regulated Emissions, and Energy use in Technologies" Model. It is described by the DOE as "a one-of-a-kind analytical tool that simulates the energy use and emissions output of various vehicle and fuel combinations." The model is housed within DOE's Office of Energy Efficiency and Renewable Energy and is provided to the public through the Argonne National Laboratory. Source: https://greet.es.anl.gov/index.php

BASELINE ANALYSIS OF CO_2 EMISSIONS IN VEHICLE LIFE-CYCLE

A traditional Class 8 ICE truck produces tailpipe emissions when operating, while the two ZETs studied in this report – BEV and FCEV – do not. The production, energy use and eventual disposal of ZETs, however, generate emissions.

There are a variety of vehicles covered within the GREET Model and the research team selected the most relevant vehicle to U.S. long-haul trucking – a Class 8 sleeper cab. As previously described, life-cycle emissions for the following three Class 8 propulsion types were analyzed:

- Internal Combustion Engine (ICE) fueled by diesel
- Battery Electric Vehicle (BEV) fueled by electricity
- Fuel Cell Electric Vehicle (FCEV) fueled by hydrogen

It was assumed that each vehicle has a usable life of one million miles.

CO_2 Emissions: Vehicle Production

First the emissions associated with the production of each truck type was estimated using the GREET model's vehicle life-cycle data. This dataset accounts for the emissions related to all materials and processes that are required to manufacture a heavy-duty truck (from raw material extraction to final assembly).

The goal of this research is to assess emissions for a typical Class 8 sleeper cab, a vehicle that would typically be used in long-haul trucking operations. Thus the modeled vehicles require a minimum range between refueling of approximately 500 miles.[36] The fuel capacity assumptions from the GREET model for the BEV and FCEV trucks (Table 2) when matched with available fuel economy data were found to meet a long haul vehicle's range requirements.[37]

Table 2: Vehicle Energy Capacity and Range

	ICE	BEV	FCEV
Fuel Capacity	300 gallons	1,622 kilowatt hours (kWh)	77 kilograms (kg)
Approximate Maximum Range (miles)	1,860 – 2,157	568 – 710	653 – 817

[36] Zhang, Chen, et al. "Development of heavy-duty vehicle representative driving cycles via decision tree regression." *Transportation Research Part D: Transport and Environment* 95 (2021): 102843.

[37] Since BEV batteries degrade, a range corresponding to 80%-100% battery capacity was used. The range was determined by these capacity constraints by using the miles per kWh identified for BEV later in the report. For FCEV, efficiency of the fuel cell does degrade according to industry experts, but it is not known to what degree. For a new FCEV, the efficiency used was 10.61 kg per mile for the upper limit of the range, and 80% degradation of the fuel cell efficiency was used for the lower limit. Finally for the ICE, a low end mpg of 6.2 was identified in the Federal Highway Administration's Highway Statistics 2020. On the high end, 7.19 mpg was used from ATRI's *Operational Cost of Trucking* and is described later in the report and in Appendix A.

For a truck to meet the above fuel capacity requirements, certain quantities of truck components, batteries and fluids are needed. Using the fuel capacity assumptions above, the GREET model estimates both the weight (Table 3) and the materials required for each category.

Table 3: GREET Vehicle Weight Distribution Assumptions (in lbs.) for Class 8 Sleeper Cab*

	ICE	BEV	FCEV
Truck Components	**17,493**	**14,621**	**20,777**
Chassis (w/o battery)	*10,182*	*10,182*	*10,182*
Body	*3,346*	*3,346*	*3,346*
Powertrain	*3,022*	-	*1,525*
Transmission System	*944*	*403*	*410*
Traction Motor	-	*624*	*638*
Electronic Controller	-	*66*	*68*
Hydrogen Tank Onboard Storage	-	-	*4,609*
Battery	**276**	**17,108**	**272**
Lead Acid	*276*	*69*	*69*
Li-Ion	-	*17,039*	*203*
Fluids	**447**	**287**	**287**
Total Weight (lbs.)	**18,216**	**32,016**	**21,337**

Within the truck components category, the chassis and body of all three vehicle types have identical weights. There are relatively small differences found in the weight of powertrain, transmission, and traction motor categories. The hydrogen storage tanks do add significant weight to the FCEV.

The major difference in weight among these vehicles, however, is found in the BEV's lithium-ion (Li-Ion) batteries. To store 1,622 kWh, the battery must weigh 17,039 lbs. based on today's technology. As previously noted, the GREET model assumption of 1,622 kWh for a Class 8 sleeper cab is higher than exists in the market today. This is clearly because a sleeper cab is employed in long-haul operations, and must travel hundreds of miles daily – without interruption for recharging – to be viable in this segment of the trucking market. This battery size theoretically would enable the vehicle and its cargo to travel 568-710 miles between charges, depending on temperature, payload, battery age and other operating conditions. It is noteworthy that no known Class 8 BEV trucks today are designed to achieve more than 300 miles per charge.

To map production of the vehicle to CO_2 emissions, the GREET model calculates the CO_2 emissions associated with each material type by weight. As an example, the weight of the largest truck component listed in Table 3, the chassis, is listed by material type in Table 4.

Table 4: Key Materials for Truck Chassis (All Vehicles)*

	Percentage	Weight (lbs.)
Steel	78.0%	7,938
Rubber	9.4%	958
Cast iron	7.5%	769
Cast aluminum	5.0%	508
Plastic	0.1%	6

For each pound of material, the GREET model estimates grams of emissions released.[38] For the three vehicles, the total emissions of CO_2 emitted during production, converted into lbs. of CO_2, is shown in Table 5.

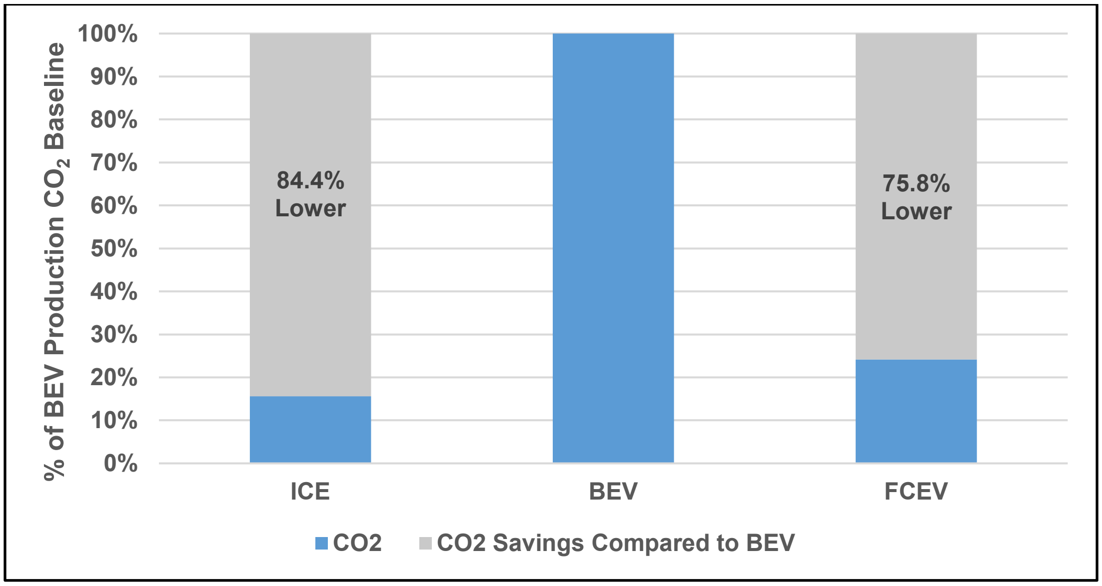
Table 5: CO_2 Emissions Total (lbs.): Vehicle Production*

	ICE	BEV	FCEV
Vehicle Components	56,103	49,916	97,348
Assembly	8,563	7,531	10,922
Battery	374	416,891	3,527
Fluid	9,687	3,717	3,717
Total	**74,728**	**478,055**	**115,514**

For BEVs, the process of extracting the materials used in the lithium-ion batteries creates a significant amount of emissions.[39] As a result of the *production* of these batteries, BEV total CO_2 for all production activities is far higher than FCEV total production CO_2 (which results in only 24.1 percent of a BEV's CO_2) or ICE total production CO_2 (which results in only 15.6 percent of a BEV's CO_2). This is illustrated in Figure 4 below.

[38] For more on the methodology used by the GREET model, please see the following website: https://greet.es.anl.gov/index.php
[39] Choudhury, Saheli. (July 26, 2021). "Are electric cars 'green'? The answer is yes, but it's complicated." CNBC. Available online: https://www.cnbc.com/2021/07/26/lifetime-emissions-of-evs-are-lower-than-gasoline-cars-experts-say.html

Figure 4: Vehicle Production CO_2 Comparison Chart



The battery production emissions for the BEV equal a little more than 130 lbs. of CO_2 emissions per kWh of battery capacity produced. Sources confirm this is a reasonable assumption, with one comprehensive report suggesting a range of 85 to 400 lbs. of CO_2 equivalent per kWh.[40]

It should be also noted that the CO_2 emissions calculated for BEV battery production include two 1,622 kWh batteries. One of these batteries comes with the original truck, and the second battery is a replacement that is installed at 500,000 miles. This follows the GREET model assumptions and was confirmed as a valid assumption through discussions with OEMs.

CO_2 Emissions: Energy Production and Consumption

Next, the CO_2 emissions for producing and consuming the energy required to operate each of the trucks for a lifetime mileage of one million miles was calculated using the GREET Model and industry sources. To do this, the total amount of fuel used (in the form of diesel, electricity or hydrogen) was identified, which first requires a fuel economy number for each truck.

The ICE fuel economy value of 7.19 miles per gallon (mpg) of diesel is based on operational data collected through ATRI's annual *Operational Costs of Trucking* research and calculated as a five-year average (representing 2016 through 2020).[41] The data behind ATRI's operational cost analysis is submitted directly and confidentially by motor carriers, providing accurate metrics of actual everyday use. More information on this mpg value can be found in Appendix A. Additionally, it should be noted that a similar value (7.17 mpg) is used in the GREET Model as a default fuel economy number for Class 8 sleeper cabs.

[40] Melin, H. E., & Storage, C. E. (2019). "Analysis of the climate impact of lithium-ion batteries and how to measure it." *Transport environment.* Available online: https://www.transportenvironment.org/wp-content/uploads/2021/07/2019_11_Analysis_CO2_footprint_lithium-ion_batteries.pdf

[41] Alex Leslie and Dan Murray, *An Analysis of the Operational Costs of Trucking: 2021 Update*, American Transportation Research Institute, Nov. 2021.

Because there is limited real-world data available for Class 8 BEV fuel economy, the fuel economy figure used in the analysis (0.438 miles per kWh) is based on OEM spec sheet figures for eight heavy-duty trucks. These eight trucks are part of a California Air Resources Board (CARB) initiative named the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project, or HVIP, which offers incentives for the purchase of ZET.[42] The maximum vehicle range (in miles) for each of the eight vehicles was divided by the maximum battery capacity (in kWh). The average of the eight vehicle miles per kWh was then calculated by ATRI as 0.438 miles per kWh.

Fuel economy data for an FCEV is also limited. Using the diesel fuel economy figure as a baseline, hydrogen use per-mile was estimated based on EPA's Greenhouse Gas Emissions Model (GEM) 55/65 cycle, and then normalized to a representative route.[43] The result was 10.61 miles per kg of hydrogen.

As shown in Table 6, lifetime fuel consumption is found by dividing one million miles by the lifetime fuel economy average.

Table 6: Fuel Economy and Lifetime Fuel Consumption (for One Million Miles)*

	ICE (diesel)	BEV (electricity)	FCEV (hydrogen)
Lifetime Average Fuel Economy	7.19 mpg	0.438 miles per kWh	10.61 miles per kg
Lifetime Fuel Consumption (one million miles)	139,082 gallons	2,280,897 kWh	94,251 kg

Next, based on the energy required to reach one million miles, the lifetime CO_2 emissions for fuel consumption were calculated. There are two stages of CO_2 emissions for energy – the first is energy production – which includes all emissions related to producing the final energy product (i.e. diesel, electricity or hydrogen). The second type of CO_2 emissions is from energy consumption (often referred to as tailpipe emission). Only the ICE has CO_2 emissions that result from consuming energy.

These two emissions numbers are summed to produce total lbs. of CO_2 per unit of energy. Table 7 shows the lbs. of CO_2 per unit of energy used in the lifetime CO_2 calculation.

[42] Started by CARB in 2009, the HVIP program is part of the California Climate Investments statewide initiative, which funds efforts to reduce GHG.
[43] United States Environmental Protection Agency. (2020). Phase 2 Greenhouse Gas Emissions Model (GEM) for Medium- and Heavy-Duty Vehicle Compliance (Version 3.5.1) [Computer Application]. Retrieved from: https://www.epa.gov/regulations-emissions-vehicles-and-engines/greenhouse-gas-emissions-model-gem-medium-and-heavy-duty#overview

Table 7: Lbs. of CO_2 per Unit of Energy*

	Energy Production: Lbs. of CO_2 per Energy Unit	Energy Consumption: Lbs. of CO_2 per Energy Unit	Total Lbs. of CO_2 per Energy Unit
Diesel (per gallon)	3.68	22.39	26.08
Electricity (per kWh)	0.91	-	0.91
Hydrogen (per kg)	20.50	-	20.50

The *diesel* CO_2 emissions per gallon is sourced from the GREET model. For the energy production diesel figure, the feedstock and fuel grams of CO_2 per mmBtu are added and converted to lbs. of CO_2 per gallon.[44] A similar calculation is made for diesel energy consumption. Total lbs. of CO_2 per gallon of diesel is 26.08.

The CO_2 emissions figures used for *electricity* were also from the GREET model. Feedstock and fuel grams of CO_2 per mmBtu were converted to lbs. of CO_2 per kWh for the "U.S. Electricity Mix" emissions figures.[45] These figures are shown in Table 8.

Table 8: Energy Source for U.S. Electricity Production – Transportation Mix (2019)*

Energy Source	Percent
Natural Gas	39.6%
Nuclear power	20.4%
Coal	20.0%
Renewables	19.4%
Residual oil	0.4%
Biomass	0.3%
Total	100.0%

The "Renewables" category includes hydroelectric, wind and solar. The estimated CO_2 per kWh for production of electricity was found to be 0.91 lbs. of CO_2 per kWh. There was no CO_2 associated with energy consumption.

Finally, the *hydrogen* figure in Table 7 is based on the steam methane reforming (SMR) method of production, which converts natural gas into hydrogen, which is the most commonly used

[44] mmBtu = Metric Million British Thermal Unit
[45] GREET's U.S. Electricity Mix uses data generated by the 2019 Annual Energy Outlook (AEO) developed by the U.S. Energy Information Administration (EIA). EIA's Annual Energy Outlook is generated using the National Energy Modeling System (NEMS) which identifies interactions between the economy, energy demand, supply and prices. Source: U.S. Energy Information Administration. (2019). "Annual Energy Outlook 2019". EIA. Available online: https://www.eia.gov/outlooks/archive/aeo19/pdf/aeo2019.pdf

process.[46] This process results in 20.5 lbs. of CO_2 per kg of hydrogen during production.[47] There are no CO_2 emissions associated with energy consumption for hydrogen.

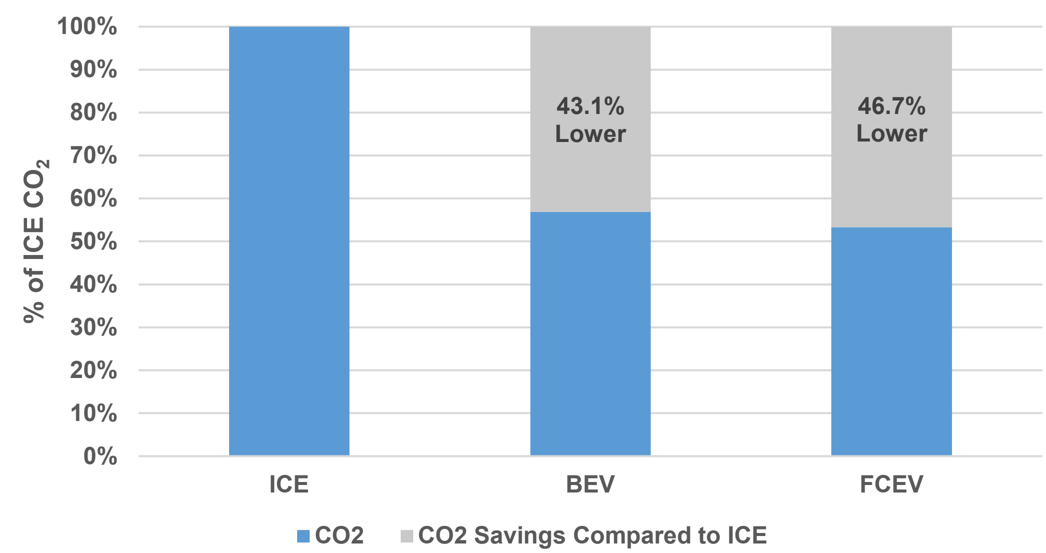
The lifetime energy emissions were next calculated, multiplying the lifetime fuel use by the lbs. of CO_2 per unit of fuel for production and consumption (Table 9).

Table 9: Operations: CO_2 Emissions from Energy to Drive One Million Miles by Vehicle Type*

	ICE	BEV	FCEV
Energy Production (Lifetime Lbs. of CO_2)	511,655	2,065,341	1,932,422
Energy Consumption (Lifetime Lbs. of CO_2)	3,115,244	-	-
Total	3,626,899	2,065,341	1,932,422

The ICE is associated with almost double the operations-related CO_2 emissions when compared to the BEV (which is 56.9 percent of an ICE's operations CO_2) or the FCEV (which is 53.3 percent of an ICE's operations CO_2). This is illustrated in Figure 5 below.

Figure 5: Energy Production and Consumption CO_2 Comparison Chart



[46] Rapier, Robert. (July 10, 2020). "Hydrogen Production with a Low Carbon Footprint." Forbes. Available online: https://www.forbes.com/sites/rrapier/2020/07/10/hydrogen-production-with-a-low-carbon-footprint/?sh=147d7a9e7c2c
[47] Ibid.

CO_2 Emissions: Vehicle Disposal and Recycling

Vehicle disposal and recycling is associated with the least amount of CO_2 emissions in the life-cycle of all three vehicles. The GREET Model addresses emissions separately for the vehicle itself and the lithium-ion battery.

Using GREET data, it was found that the disposal of each vehicle type (excluding the lithium-ion battery) resulted in 2,268 lbs. of CO_2 emissions.

In addition to vehicle disposal and recycling, the BEV and FCEV also have lithium-ion batteries which must be recycled, resulting in an additional CO_2 figure. There are several approaches to recycling lithium-ion batteries, including smelting (the most carbon-intense method), leaching and physical processing.[48] It is unclear which approach will be used in the future for truck battery recycling, but GREET does provide a CO_2 emissions figure for each of the approaches (Table 10).

Table 10: CO_2 Emissions Associated with Four Methods for Lithium-Ion Battery Recycling

	Pyro (Smelting)	Hydro: Inorganic Acid Leaching	Hydro: Organic Acid Leaching	Direct: Physical Processes	Average of the Four Approaches
Lbs. of CO_2 per Ton	4,552	4,095	1,500	1,181	2,832
BEV Li-Ion lbs. of CO_2 (2 batteries)	77,565	69,775	25,552	20,127	48,255
FCEV Li-Ion lbs. of CO_2 (2 batteries)	924	831	304	240	575

The averages for the BEV and FCEV battery recycling were next added to the disposal figures to reach the total end-of-life CO_2 figures (Table 11).

Table 11: Total Lbs. of CO_2 for Vehicle End-of-Life Disposal/Recycling

	ICE	BEV	FCEV
Disposal	2,268	2,268	2,268
Li-Ion Battery Recycling	-	48,255	575
Total	**2,268**	**50,523**	**2,843**

[48] Gaines, Linda. (July 7, 2018). "Lithium-ion battery recycling processes: Research towards a sustainable course." OSTI. Available online: https://www.osti.gov/servlets/purl/1558994#:~:text=There%20are%20three%20basic%20process,direct%20recycling%20(physical%20processes).

Final Full Life-Cycle CO_2 Emissions

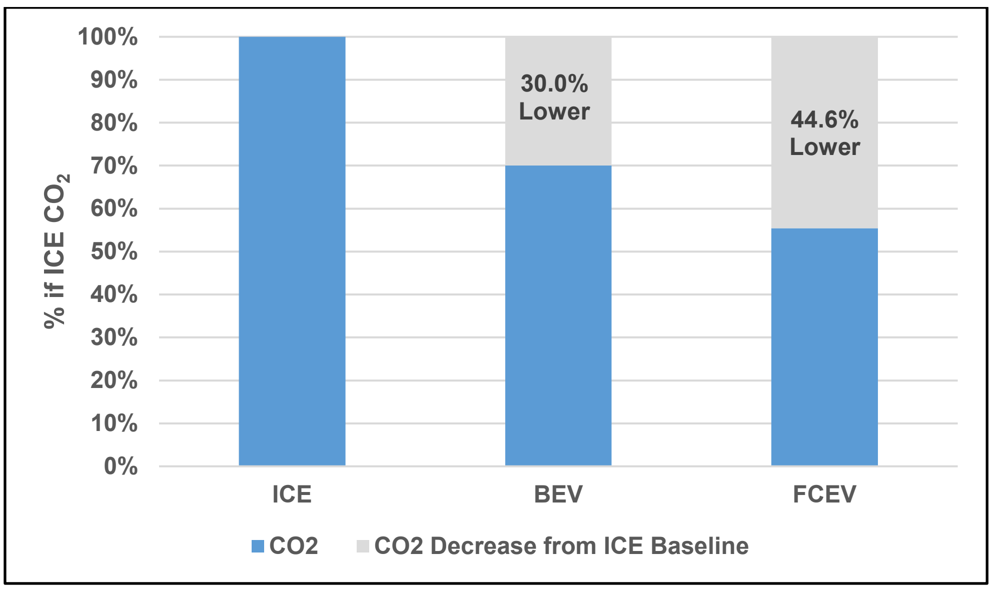
The final CO_2 figures for each vehicle life-cycle are shown in Table 12.

Table 12: Total Life-Cycle CO_2 Emissions (in lbs.)

	ICE	BEV	FCEV
Vehicle Production CO_2	74,728	478,055	115,514
Energy Production and Consumption CO_2	3,626,899	2,065,341	1,932,422
Disposal/Recycling CO_2	2,268	50,523	2,843
Total Life-Cycle CO_2	3,703,895	2,593,919	2,050,779

As can be seen in Figure 6, a switch to a conceptual BEV or FCEV still results in significant lifetime CO_2 emissions. To put these findings into perspective, Figure 6 shows the decrease that might be realized per vehicle through the use of the BEV and FCEV modeled in this analysis.

Figure 6: ICE Lifetime CO_2 vs BEV & FCEV



These figures are, however, based on the best available information of two very new and emerging technologies. The estimates offer insight into the current CO_2 emissions-related prospects for Class 8 trucks, but these scenarios can have many future modifications that could change these results.

The following section assesses several alternative scenarios that could decrease CO_2 emissions for each vehicle type beyond what is shown in Figure 6.

SCENARIO ANALYSIS

Potential scenarios to reduce the CO_2 emissions due to advances in technology were assessed for each of the vehicle types (ICE, BEV and FCEV).

Internal Combustion Engine (ICE) Scenarios

Internal combustion engines have powered vehicles for well over 100 years. As a result, there are few unknowns related to the engine itself, though there are continuous efforts to improve engine performance.[49] The most realistic approach to decreasing ICE CO_2 is through alternative fuels such as biodiesel, renewable diesel and natural gas.[50]

Biodiesel. This fuel is an alternative to petroleum-based diesel which can be used in conventional diesel engines. Biodiesel is manufactured from feedstock such as vegetable oils and animal fats, and is available in a pure form (B100) or as a blend with petroleum-based diesel to produce B2, B5 or B20 (which are 2, 5 and 20 percent biodiesel, respectively). One downside to biodiesel is that in higher concentrations it does not perform well in cold conditions.

In 2019, approximately 1.8 billion gallons of biodiesel were consumed in the U.S., mostly through blending with traditional diesel fuel.[51] The trucking industry consumed 36.5 billion gallons of diesel fuel (including blended biodiesel) in 2019.[52] Regarding emissions, a life-cycle analysis found that B100 has 74 percent lower emissions compared to petroleum diesel.[53] CO_2 emissions from biodiesel in particular are more favorable than those of petroleum diesel because they are offset by the carbon dioxide absorbed during the growth period of the feedstock used to produce the fuel.[54]

Renewable Diesel. Renewable diesel is a recent addition to the list of available diesel-alternatives. Renewable diesel contains many of the same vegetable oil and animal fat sources, but is chemically different from biodiesel and has the same fuel quality standards as petroleum diesel.[55] The U.S. consumes nearly 1 billion gallons in U.S. renewable diesel annually.[56]

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[49] Whittaker, John. (August 21, 2021). "Cummins Continues Advancing Diesel Technology." The Post-Journal. Available Online: https://www.post-journal.com/news/business/2021/08/cummins-continues-advancing-diesel-technology/

[50] Diesel Technology Forum. (May 18, 2021). "Bulk of Greenhouse Gas Reductions from Transport Sector in California Delivered By Renewable Diesel, Biodiesel." Available online: https://www.dieselforum.org/news/bulk-of-greenhouse-gas-reductions-from-transport-sector-in-california-delivered-by-renewable-diesel-biodiesel

[51] U.S. Energy Information Administration. "Biofuels explained." EIA. Available online: https://www.eia.gov/energyexplained/biofuels/biodiesel.php

[52] American Trucking Associations. "ATA American Trucking Trends 2021." ATA. Available online: https://www.trucking.org/news-insights/ata-american-trucking-trends-2021

[53] Huo, Wang, et al. (March 12, 2008). "Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels." Argonne National Laboratory. Available online: https://greet.es.anl.gov/files/e5b5zeb7

[54] U.S. Department of Energy. "Biodiesel Benefits and Considerations." Alternative Fuels Data Center. Available online: https://afdc.energy.gov/fuels/biodiesel_benefits.html

[55] U.S. Energy Information Administration. (November 13, 2018). "Renewable diesel is increasingly used to meet California's Low Carbon Fuel Standard." EIA. Available online: https://www.eia.gov/todayinenergy/detail.php?id=37472

[56] U.S. Energy Information Administration. "Biofuels explained." EIA. Available online: https://www.eia.gov/energyexplained/biofuels/use-of-biodiesel.php

Natural Gas. Natural gas accounts for 30 percent of energy used in the U.S. and 0.2 percent is used for transportation.[57] Natural gas trucks use either a spark-ignited engine or a diesel-like compression injection.[58] Class 8 heavy-duty trucks tend to use liquefied natural gas (LNG) for traveling long-haul distances, as LNG is denser than compressed natural gas (CNG), allowing for more energy stored by volume. Additionally, some natural gas spark-ignited engines emit between 70 and 85 percent fewer pollutant emissions than diesel or gasoline powered vehicles.[59] There are about 175,000 natural gas vehicles in U.S. operations, and the majority are commercial motor vehicles in the transit, refuse, and medium- and heavy-duty truck sectors.[60]

Table 13 compares fuel economy and CO_2 statistics for each ICE-related fuel type.[61]

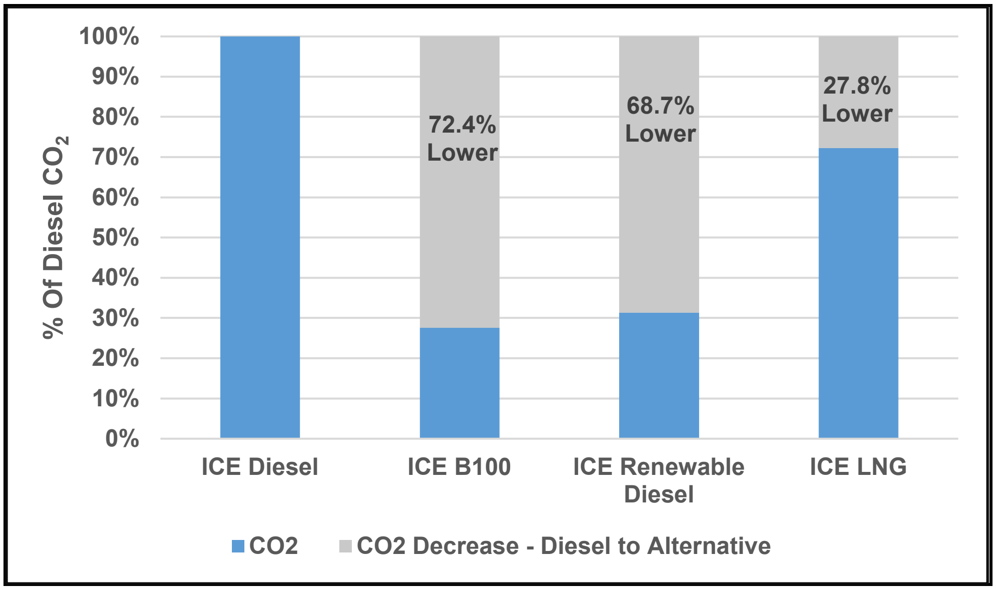
Table 13: Comparison of ICE Fuel Alternatives to Conventional Diesel*

	ICE Diesel	ICE B100	ICE Renewable Diesel	ICE LNG
Fuel Economy [62]	7.19	6.47	6.47	4.46
Lifetime Fuel Consumption (gallons per one million miles)	139,082	154,536	154,536	224,215
Energy Production CO_2 Emissions (lbs.) per gallon	3.68	-14.45	-13.42	1.87
Energy Consumption CO_2 Emissions (lbs.) per gallon	22.399	20.92	20.76	9.82
Total CO_2 Emissions (lbs.) per Gallon [63]	26.08	6.48	7.34	11.69
Lifetime Operations CO_2 Emissions (lbs.)	3,626,899	1,000,694	1,134,291	2,620,117

Figure 7 illustrates the decrease in CO_2 that could be realized through the use of diesel alternatives, using the data from the previous table.

[57] U.S. Department of Energy. "Natural Gas Fuel Basics." Alternative Fuels Data Center. Available online: https://afdc.energy.gov/fuels/natural_gas_basics.html
[58] U.S. Department of Energy. "How Do Compressed Natural Gas Class 8 Trucks Work?" Alternative Fuels Data Center. Available online: https://afdc.energy.gov/vehicles/how-do-natural-gas-class-8-trucks-work
[59] Castillo, Juan C. et al. (January 28, 2022). "Natural Gas, a Mean to Reduce Emissions and Energy Consumption HDV? A Case Study of Colombia Based on Vehicle Technology Criteria." *Energies*. Available online: https://www.mdpi.com/1996-1073/15/3/998/pdf
[60] Baker, Linda. (May 13, 2020). "Electric, natural gas trucking sectors duel over who deserves funding – now." Freight Waves. Available online: https://www.freightwaves.com/news/the-future-is-electric-not-so-fast
[61] Fuel economy figures generated from ATRI's *Operational Costs of Trucking* data and the GREET Model.
[62] ICE B100, Renewable Diesel and LNG were sourced from industry experts. B100 and Renewable were assumed to have 90% of diesel's fuel economy.
[63] GREET Model

Figure 7: Per Gallon CO_2 Reduction through Diesel Alternatives



Biodiesel and Renewable Diesel. As shown in Figure 7, the alternative diesel fuels significantly decrease CO_2 emissions throughout the life of the truck. This is primarily due to the CO_2 decreases realized during the production of the fuel. Of the two diesel alternatives, the ICE B100 is at a disadvantage for long-haul trucking due to its performance in colder climates as well as the impact on truck warranties.[64] To some degree, both of these diesel alternatives could be incorporated into current fuel distribution systems with one large exception – biodiesel specifically is known to cause issues in pipelines that also carry jet fuel.[65] Thus, biodiesel is typically transported in trucks, trains or barges.[66] Also, higher levels of biodiesel or pure biodiesel may require engine modifications such as alternative hoses and gaskets. These changes are, however, less extensive than what is needed for electricity or hydrogen as a transportation fuel.

There are efforts in the U.S. to increase biodiesel and renewable diesel production and consumption. The U.S. Department of Agriculture (USDA), for instance, is working to expand the availability of higher-blend renewable diesel in 23 states, hoping to increase annual consumption by more than 800 million gallons.[67] The U.S. Energy Information Administration (EIA) predicts renewable diesel production capacity greatly increasing through 2024. If all projects are fully operational as intended, U.S. renewable diesel production could total 5.1 billion gallons annually by the end of 2024, which would be a five-fold increase.[68]

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[64] Biodiesel. (January 2020). "OEM Support Summary." Available online: https://www.biodiesel.org/docs/default-source/fact-sheets/oem-support-summary.pdf?sfvrsn=4e0b4862_12
[65] ATMOS International. "Any FAME in your pipeline?" Available online: https://www.atmosi.com/en/news-events/blogs/any-fame-in-your-pipeline/
[66] U.S. Department of Energy. "Biodiesel Production and Distribution." Alternative Fuels Data Center. Available online: https://afdc.energy.gov/fuels/biodiesel_production.html
[67] USDA Press. (August 19, 2021). "USDA Invests $26 Million in Biofuel Infrastructure to Expand Availability of Higher-Blend Renewable Fuels in 23 States." USDA. Available online: https://www.usda.gov/media/press-releases/2021/08/19/usda-invests-26-million-biofuel-infrastructure-expand-availability
[68] Ibid.

ICE LNG. It is estimated that an LNG vehicle would produce 1 million fewer lbs. of CO_2 during lifetime operations when compared to conventional diesel. A switch to LNG would require additional fueling infrastructure and higher-priced new vehicle equipment.

Battery Electric Vehicle (BEV) Scenarios

While diesel engine technologies are well established, BEVs that haul freight are a relatively new phenomenon. Due to the small number of heavy-duty BEV trucks in operation, there is a dearth of data on BEV truck performance. Thus this new technology comes with several unknowns. For trucking companies, these operational unknowns (i.e. challenges) include issues related to battery life, battery performance and freight-hauling capabilities.

Battery Life. Battery life depends on numerous vehicle-based factors, including number of charges and charging rate (examples include 120v, 240v, Direct Current Fast Charge).

It is well understood that lithium-ion batteries begin to slowly degrade once the charging and discharging process commences. Battery degradation is greatly influenced by the number of charge cycles and charging rates. This degradation can be measured through a battery's state-of-health (SOH) status, which is a battery's current state of maximum charge versus its rated state of charge. A vehicle's battery may have a SOH of 80 percent, for instance, after several hundred or even several thousand charging cycles. For long-haul trucking the SOH remains an unknown. To illustrate this, the 1,622 kWh battery would have a maximum capacity of 1,297 kWh when the SOH is 80 percent. This of course means that the vehicle can travel fewer miles per charge.

Lithium-ion battery life is strongly influenced by the number of charging cycles the battery is subjected to. A charging cycle for a BEV occurs when a battery is charged, and then the energy is discharged as the vehicle operates. For trucking, it is expected that annual vehicle charging cycles will be far more intensive than a typical automobile. The ATRI *Operational Cost of Trucking* dataset indicates that the average truckload-only carrier mileage per year per truck is 101,529 miles.[69] For the BEV modeled in the earlier section, that would be approximately 143 full charges annually if the battery were to charge to its rated level, and it would be 178 when its SOH is at 80 percent.

Separate from the number of charging cycles, there is evidence that the *rate* at which a BEV is charged could impact battery life. Because of operational constraints (such as driver hours-of-service) and the large energy capacity of a truck battery, faster charging may be necessary. While there is still research needed in this area, there is evidence from automotive research that faster charging will lead to a slightly faster decrease in battery SOH.[70]

Battery Performance. Ambient temperatures can affect the battery performance of electric vehicles. Cold weather slows the chemical and physical reactions that make batteries work,

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[69] This is in contrast to automobile drivers, which on average drive less than 14,000 miles per year per data from the Federal Highway Administration available online at: https://www.fhwa.dot.gov/ohim/onh00/bar8.htm

[70] GREENCARS. (March 5, 2022). "Why DC Fast Charging Reduces EV Battery Life." Available online: https://www.greencars.com/post/why-dc-fast-charging-reduces-ev-battery-life

specifically conductivity and diffusivity, leading to longer charging times and a temporary reduction in range.

Conversely, higher temperatures generally lead to faster chemical and physical reactions. This often means that the “unwanted” chemical reactions that make batteries degrade happen faster at higher temperatures. In addition, low or elevated temperatures can initiate the use of electric air conditioning or heating systems, which can draw significant amounts of battery power – with an accompanying reduction in driving range.

Testing conducted by the American Automobile Association (AAA) on five electric passenger vehicles, using the Society of Automotive Engineers’ J1634 test procedure, documented an average 12 percent decrease in combined driving range when the cars were operated at 20°F as opposed to 75°F.[71] A four percent decrease in combined driving range was found at 95°F when compared to 75°F.

More significantly, use of heating and air conditioning was found to decrease combined driving range by an average of 41 percent at 20°F and by 17 percent at 95°F when compared to the 75°F baseline. The study notes that owners of electric vehicles should be aware of environmental conditions, and plan for reduced driving ranges during periods of hot or cold temperatures. Other analyses of electric car performance offer similar findings.[72]

Based on anonymized data from 5.2 million trips taken by 4,200 electric cars representing 102 different make/model/year combinations, 70°F was found to be the most efficient temperature for operations.[73]

Topography also has a strong influence on energy consumption and battery operation as well. On an uphill grade, all vehicles expend more energy than when traveling on level ground. Energy consumption for electric vehicles tends to steadily increase as road grade increases.[74] Although little data has been generated for trucks, consumption steadily increases for automobiles as the grade changes from downhill to flat, and then drastically increases on uphill grades.

Although battery-powered vehicles tend to be heavier than ICE vehicles, they can regenerate energy from braking when driving downhill which adds energy back into the vehicle’s battery. The amount of energy is dependent upon several factors, including the size of the vehicle, the amount of braking applied, and the slope and length of the grade. Studies have found regeneration provides marginal increases in battery charge.[75]

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[71] American Automobile Association, *AAA Electric Vehicle Range Testing* (February 2019).
[72] Al-Wreikat, Y., Serrano, C., Ricardo Sodre, J. Effects of Ambient Temperature and Trip Characteristics on the Energy Consumption of an Electric Vehicle, *Journal of Energy* (January 2022).
[73] Argue, Charlotte. (June 3, 2020). “How Extreme Cold and Heat Affect EV Range.” Fleet Forward. Available online: https://www.fleetforward.com/359666/how-extreme-cold-and-heat-affect-ev-range
[74] National Renewable Energy Laboratory. *Contribution of Road Grade to the Energy Use of Modern Automobiles Across Large Datasets of Real-World Drive Cycles*. Released January 2014. (nrel.gov/docs/fy14osti/61108.pdf)
[75] Perry, Tristan, *Can Tesla & Other EVs Charge Themselves When Going Downhill?* Green Car Future (November 15, 2021).

Battery Weight and Cargo Capacity. Battery weight may substantially limit the long-haul capabilities of a BEV. As discussed earlier in the baseline analysis, the long-haul ICE truck tractor weight is 18,216 lbs., while the BEV's weight (including the battery) is 32,016 lbs.

To understand the cargo implications of this weight difference, the ICE, BEV and FCEV weight examples were paired with an empty 11,264 lb. trailer (per GREET). Next, cargo weight was added to the calculation. Using ATRI's *Operational Cost of Trucking* dataset, average operating weight for truckload carriers was calculated for a five-year period (2016 – 2020). The average operating weight was found to be 62,291 lbs. An in-depth discussion of the methodology used to identify this can be found in Appendix A.

Cargo weight was identified by subtracting the ICE truck tractor weight (18,216 lbs.) and trailer weight (11,264 lbs.) from the 62,291 lb. vehicle weight. The average cargo weight assuming the above truck and trailer weights was 32,811 lbs.

This same cargo weight was next combined with the BEV and FCEV vehicle and trailer weights to show what total weights with identical average cargo weight would be, as well as the remaining weight capacity. The BEV had much lower remaining weight capacity due to the battery weight (Table 14).

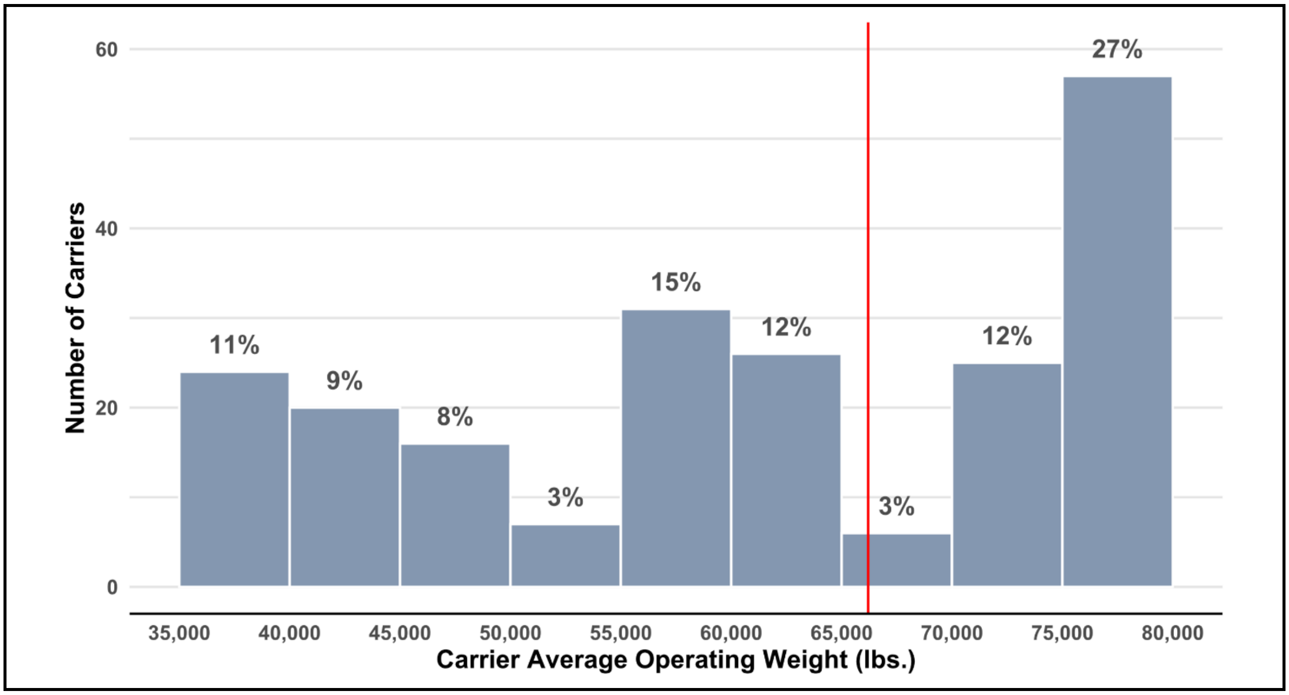
Table 14: Vehicle, Trailer and Cargo Weight

Weight Type (lbs.)	ICE	BEV	FCEV
Tractor Weight	18,216	32,016	21,337
Trailer Weight	11,264	11,264	11,264
Average Cargo Weight	32,811	32,811	32,811
Total Weight	62,291	76,091	65,412
Remaining Capacity[76]	17,709	3,909	14,588

Next the individual carrier operational cost data for each year were analyzed. In Figure 8, the annual responses are binned into 5,000-pound weight segments to illustrate the distribution of carrier operating weights. All operating weights to the right of the red line would be over-weight if ICE tractors were replaced with BEV due to the battery weight. This segment includes 42 percent of carrier responses and represents 34 percent of trucks in the data.

[76] In the U.S. the maximum weight of cargo is dependent upon the total weight of the vehicle, trailer and cargo - this is generally limited to 80,000 lbs.

Figure 8: Average Operating Weight Responses



To be clear, this dataset does not offer a specific estimate of how many additional truck trips might be needed to address battery weight. It does, however, identify a challenge. Those carriers operating closer to the maximum allowable weight will likely have to modify their operations if they wish to use long-haul battery electric vehicles. The easiest way to do this is to move the same cargo using more trucks and drivers. This would decrease efficiency, increase traffic congestion, and lead to higher costs and higher CO_2 emissions. Separately, the increased traffic congestion, with vehicles moving more slowly and braking more often, would generate pollution emissions beyond those identified in this report.[77]

Approaches to Improving BEV CO_2. Though these challenges are significant, there are approaches to improving BEV CO_2 through battery advancements and potential changes to the U.S. electricity sources.

Batteries. One approach to decreasing BEV CO_2 levels is through improvements to batteries. If battery materials can be procured with fewer emissions, extend battery lifespans, weigh less and store more energy – their carbon footprint will decrease substantially.

U.S. vehicle manufacturers are researching next generation batteries that have attributes such as faster charging, lower cost and higher energy capacity.[78] One concept that has emerged is

[77] Tunnell, Michael, Fixing the 12% Case Study: Atlanta, Georgia Fuel Consumption and Emissions Impacts, American Transportation Research Institute (February 2019).
[78] Ewing, Jack and Lipton, Eric. (March 7, 2022). "Carmakers Race to Control Next-Generation Battery Technology." The New York Times. Available online: https://www.nytimes.com/2022/03/07/business/energy-environment/next-generation-auto-battery.html

solid-state batteries, which in theory could meet these requirements. Barriers to this technology do exist however.

Reuters indicates that solid-state lithium-ion batteries have been created "one at a time in a lab, but researchers have been unable so far to scale that up to a mass production."[79] This is because "it is hard to design a solid electrolyte that is stable, chemically inert and still a good conductor of ions between the electrodes. They are expensive to fabricate and are prone to cracking because of the brittleness of the electrolytes when they expand and contract during use."[80] Several major auto manufacturers have invested in solid-state technologies, although it is not clear just how soon that technology will be available for mass-market production. There is optimism that some form of the technology will be available by 2026 to 2030.[81]

Change in Energy Sources for Electricity. If U.S. electricity production continues to decrease in CO_2 emissions per kWh, ultimately BEV trucks will also have lower CO_2 emissions.[82] Looking into the next decade, EIA expects that renewables will surpass natural gas as a source of electric power by 2030. Additionally, EIA predicts solar energy to surpass wind by 2040 as the largest source of renewable generation.[83] Finally, by 2050, EIA predicts the share of renewable electricity generation will increase to 42 percent.[84] These projections are illustrated below in Figure 9.[85]

[79]Kelly, Tim and Ghosh, Sayantani. (September 7, 2021). "Explainer: How will solid-state batteries make electric vehicles better?" Reuters. Available online: https://www.reuters.com/technology/how-will-solid-state-batteries-make-electric-vehicles-better-2021-09-07/

[80]Ibid.

[81] Ewing, Jack and Lipton, Eric. (March 7, 2022). "Carmakers Race to Control Next-Generation Battery Technology." The New York Times. Available online: https://www.nytimes.com/2022/03/07/business/energy-environment/next-generation-auto-battery.html

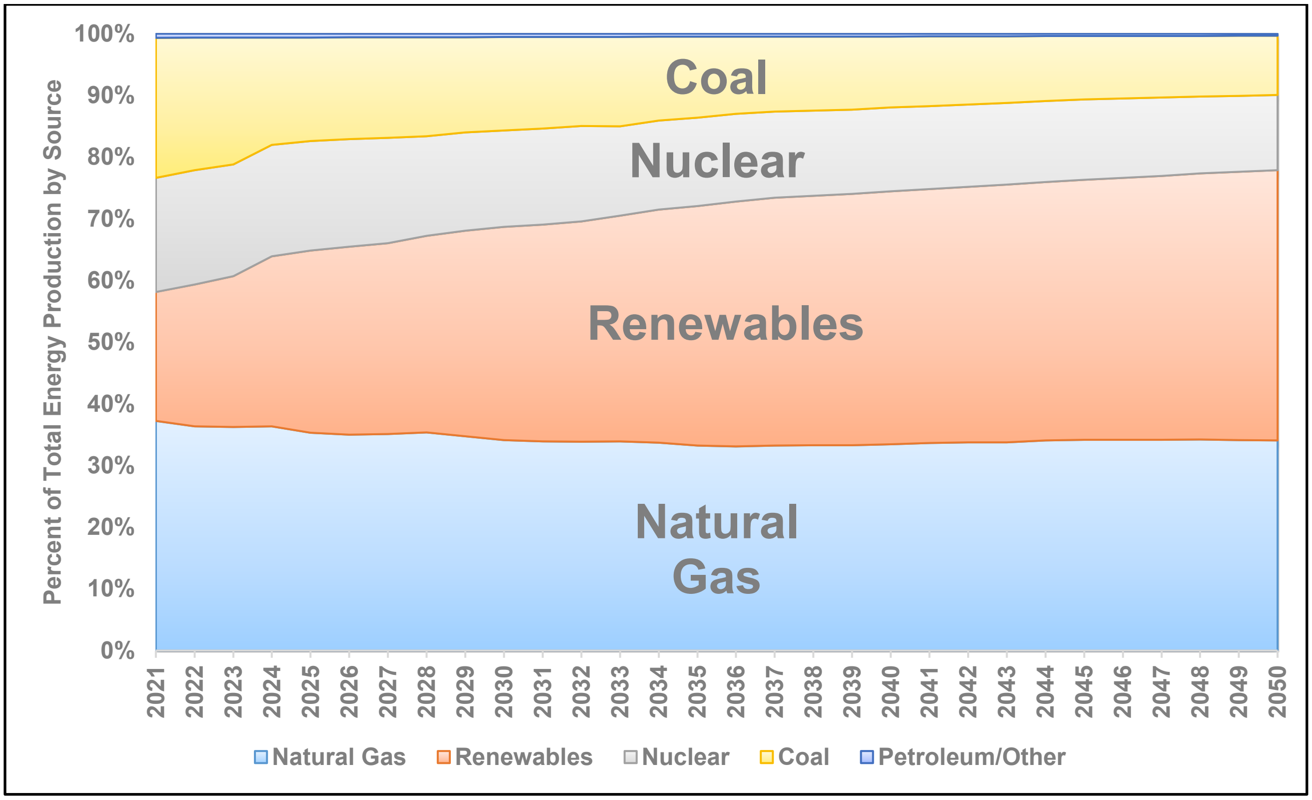
[82] Zummo, Paul. (March 2022). "America's Electricity Generation Capacity 2022 Update." American Public Power Association. Available online: https://www.publicpower.org/system/files/documents/Americas_Electricity_Generation_Capacity_2022_Update.pdf

[83] U.S. Energy Information Administration. (February 8, 2021). "EIA projects renewable share of U.S. electricity generation mix will double by 2050." EIA. Available online: https://www.eia.gov/todayinenergy/detail.php?id=46676

[84] Ibid.

[85] U.S. Energy Information Administration. (March 3, 2022). "Annual Energy Outlook 2022 [Tables 54 and 56]." EIA. Available online: https://www.eia.gov/outlooks/aeo/tables_ref.php

Figure 9: EIA Projected Fuel Source for U.S. Electricity – 2021-2050 Transportation Mix



The projections indicate that over the next several decades there will be a large drop in coal-sourced electricity, a steady drop and plateauing of natural gas to 34 percent of total energy production by 2050, and an increase in renewables to 44 percent by 2050.

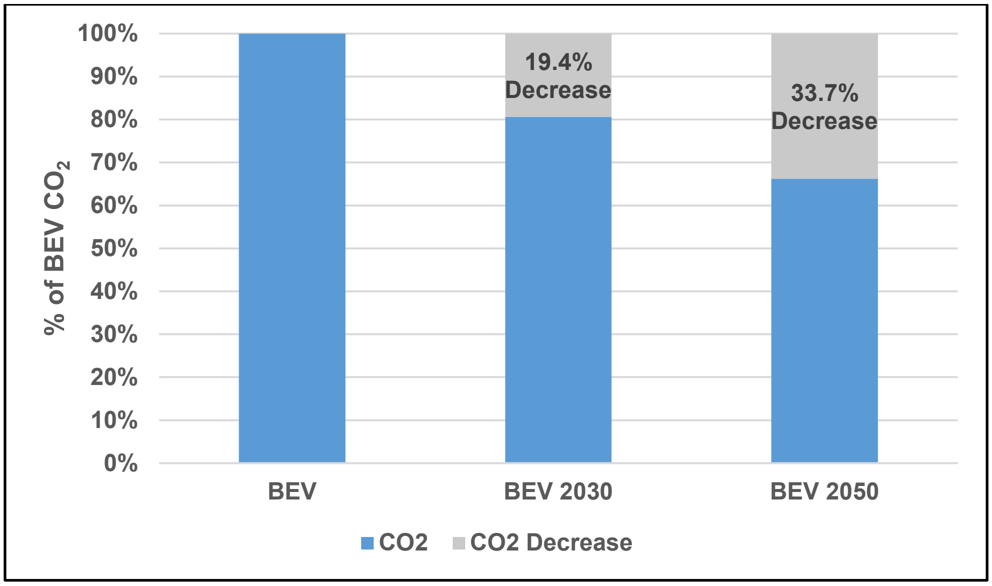
Using the EIA projections and the GREET model, Table 15 shows the decrease in lbs. of CO_2 per kWh produced for electricity with the current U.S. electricity mix, as well as the projected mix in 2030 and 2050.

Table 15: BEV CO_2 Reductions due to Electricity Source Changes*

	BEV	BEV 2030	BEV 2050
Electricity lbs. of CO_2 (per kWh)	0.91	0.73	0.60
Lifetime kWh Consumption (one million miles)	2,280,897	2,280,897	2,280,897
Lbs. of CO_2, lifetime	2,065,341	1,665,055	1,368,538

This is further illustrated in Figure 10.

Figure 10: Projected Decrease in Energy Production CO_2 for a BEV Truck by 2030 and 2050



Fuel Cell Electric Vehicle (FCEV) Scenarios

Nearly all domestic hydrogen (95 percent) is produced through a process called steam methane reforming (SMR).[86] This approach to hydrogen production uses heat to convert a low-cost fuel such as natural gas into hydrogen and CO_2. The hydrogen can be used as a transportation fuel with zero tailpipe emissions while the CO_2 is emitted into the atmosphere during production.[87] As shown earlier, the estimated CO_2 released in the production of one kg of hydrogen is 20.5 lbs., and 94,251 kg of hydrogen are needed to travel one million miles.

There are alternatives to SMR that might produce less CO_2 and could be financially feasible in the future. Electrolysis, which uses electricity to split water into hydrogen and oxygen using an electrolyzer could be a viable approach.

One method of electrolysis uses alkaline electrolyzers – which move hydroxide ions through the electrolyte from the cathode to the anode, resulting in hydrogen.[88] When using solar powered electricity for this process, the CO_2 released is approximately 4.4 to 5.1 lbs. of CO_2 to produce one kg of hydrogen.[89]

A second electrolysis method that is being researched is known as high-temperature steam electrolysis (HTSE), in which electricity and heat is used in an electrolysis system. This process

[86] U.S. Department of Energy. "Hydrogen Production: Natural Gas Reforming." Hydrogen and Fuel Cell Technologies Office. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming
[87] Ibid.
[88] Ibid.
[89] Rapier, Robert. (July 10, 2020). "Hydrogen Production With A Low Carbon Footprint." Forbes. Available online: https://www.forbes.com/sites/rrapier/2020/07/10/hydrogen-production-with-a-low-carbon-footprint/?sh=2a570a1a7c2c

could be applied through nuclear, solar or geothermal heat. Using a solar-based HTSE could result in a carbon footprint as low as 2.2 lbs. of CO_2 per kg of hydrogen produced.[90]

A comparison of the CO_2 released during SMR versus the two electrolysis approaches is found below in Table 16.

Table 16: Carbon Footprint of SMR and Solar-Based Electrolysis Approaches*

	Production Lbs. of CO_2 per kg of Hydrogen	Lifetime CO_2 (94,251 kg Hydrogen)	Decrease in CO_2 from SMR Baseline
Steam Methane Reforming (SMR)	20.50	1,932,407	0%
Solar-Based Alkaline Electrolysis	4.74	446,739	-77%
Solar-Based HTSE	2.20	207,786	-89%

The decrease in CO_2 using electrolysis is quite significant, but it should be noted that these approaches do not currently exist on a commercial scale needed to supply the trucking industry.

Hydrogen could be made in proximity to renewable electricity and then distributed, thus guaranteeing that it is from a source of renewable electricity. Conversely, with long-haul BEV trucks, there is no guarantee that the electricity used for a given recharge is renewable or from a source such as coal.

One potential system where excess solar in a region is intermittently used by hydrogen production facilities to power the electrolysis process has been explored.[91]

> "Renewable power has grown rapidly in the past decade. In some places, it has created intermittent periods of excess power. For example, California has created so much solar power that at times it was cheaper to pay Arizona to take the excess power than to significantly curtail power… Negatively-priced power would be an ideal source of electricity for hydrogen production, depending on the level of intermittency."

It is suggested in the article that excess solar power in certain regions and time periods is negatively priced, thus making this lower CO_2 option one that may be financially viable.

[90] Ibid.
[91] Rapier, Robert. (July 10, 2020). "Hydrogen Production With A Low Carbon Footprint." Forbes. Available online: https://www.forbes.com/sites/rrapier/2020/07/10/hydrogen-production-with-a-low-carbon-footprint/?sh=2a570a1a7c2c

CONCLUSIONS

This research documents – from a data-driven perspective – that the trucking industry can decrease CO_2 emissions through a variety of vehicle types. The report looks first at baseline CO_2 emissions for ICE, and then compares those emissions to operationally-comparable BEV and FCEV trucks. Next, approaches for further reducing those emissions were researched. Additionally the report has highlighted some challenges and potential caveats that may lay ahead for deploying emissions-reduction technologies such as BEV and FCEV trucks.

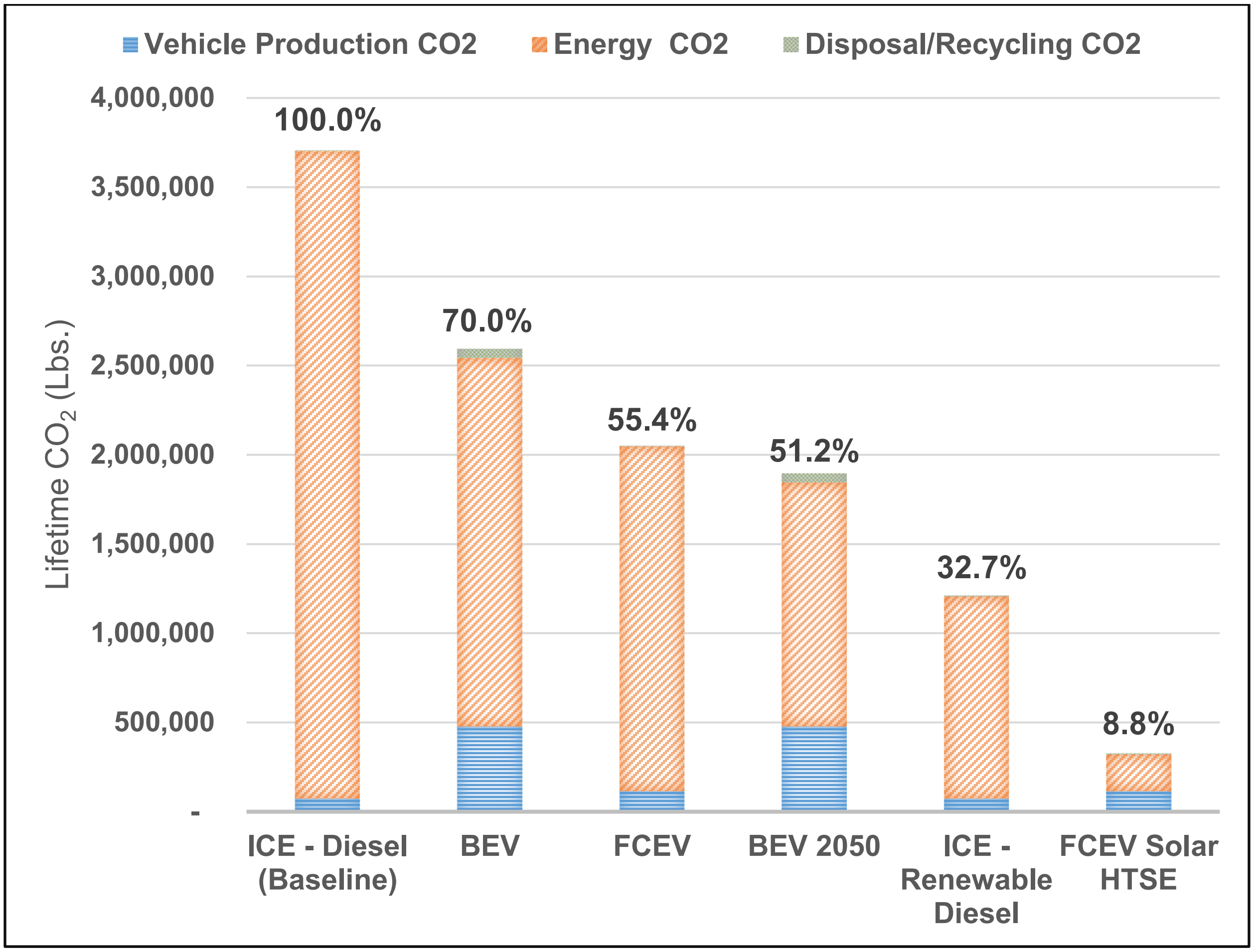
The key finding of this report is that zero-emission trucks still generate significant CO_2 emissions, and will continue to have CO_2 emissions in the coming decades. Other key findings are shown in Table 17.

Table 17: Key Findings

Key Findings	Summary	Description
Vehicle Production Findings	BEV truck production emits more than six times the CO_2 as an ICE truck due to the BEV's Lithium-Ion Battery.	There are two key factors that separate long-haul BEV trucks from other types of BEVs: 1. Long-haul trucks must operate continuously, often covering more than 100,000 miles per year, which results in a more frequent battery replacement cycle. 2. To cover daily long-haul mileage, the battery must be large and thus contain a significant amount of mined lithium-ion battery materials. The 17,039 lb. lithium-ion battery modeled in this report is a necessity for long-haul trucking. Yet this battery requires tons of materials that must be mined, producing a significant amount of CO_2 emissions. As a result of this, vehicle production for the BEV truck produced considerable CO_2 (478,055 lbs.), far outweighing the carbon footprint of both ICE (74,728 lbs.) and FCEV (115,514) trucks.
Energy Production and Consumption Findings	ZETs have lower energy emissions (with nearly half the CO_2 emissions of ICE trucks), but lack the infrastructure needed for deployment.	ICE trucks burning conventional diesel emit the largest amount of CO_2. The two alternatives reviewed have lower energy-related emissions: BEV trucks (using electricity) have 43.1 percent lower emissions than ICE emissions, and FCEV trucks (using hydrogen) have 46.7 percent lower emissions when using today's energy sources. While these are significant CO_2 decreases, they do not equate to "zero-emission" vehicles. Additionally, fuel must be delivered to long-haul trucks – and the infrastructure and energy capacity to do this on a large scale does not currently exist for either electricity or hydrogen. In summary, these requirements are plausible, but it would likely take decades for a meaningful impact to be felt.
Vehicle Disposal and Recycling Findings	BEV battery recycling could produce more than 77,000 lbs. of CO_2.	The least amount of CO_2 emissions is associated with disposal and recycling of the truck. The notable CO_2 emissions source in this category was BEV lithium-ion battery recycling. There are several approaches to recycling a large truck battery and it is unclear which one will be used in the future. The range of possible CO_2 results for BEV lifetime battery recycling is between 20,127 and 77,565 lbs. The average CO_2 emissions among four options was 48,255, which is a little more than 10 percent of the battery manufacturing CO_2.

Figure 11 shows the potential CO_2 emission reductions (in pounds of CO_2 and as a percentage of the diesel baseline) for each of the vehicle types when changes in energy sources are applied.

Figure 11: Key Findings from the Scenario Analysis



Overall, the three truck types studied in this report have a pathway for lowering CO_2 emissions in the coming decades. Research is needed to improve upon CO_2 reduction efforts, and specifically to lower energy source CO_2. While public policy is currently focused on moving the industry toward BEV, this research shows that even greater truck CO_2 emission reductions can be achieved through other approaches.

APPENDIX A: METHODOOGY FOR ICE MPG AND AVERAGE WEIGHT FIGURES

To better understand real-world ICE mpg and operating weight for over-the-road trucking, operational data from ATRI's annual *Operational Costs of Trucking* program were used.[92] ATRI's "Ops Costs" data is submitted directly and confidentially by motor carriers, providing accurate metrics of real-world use. All carriers from the truckload sector with an average operating weight at or below the standard 80,000 lbs. federal limit were included. The truckload metrics that were utilized were based on data averages for the last five years (representing 2016 through 2020). This truckload subset does not include over-weight operations or carriers in other sectors; it does, however, include both day cabs and sleeper cabs as well as fleet sizes ranging from owner-operators to more than 10,000 tractor-trailers. Table A1 presents the total number of carriers and tractor-trailers as well as mpg and operating weight averages used in the analysis.

Table A1: Ops Costs Truckload Carriers with Average Operating Weights at or below 80,000 lbs. by Year

Year	Truckload Carriers	Tractor-Trailers	MPG	Operating Weight
2016	43	17,684	7.1	70,538
2017	38	23,485	7.5	57,221
2018	48	45,600	7.3	57,870
2019	27	23,256	7.0	58,197
2020	44	41,224	7.1	69,871
5-Year Total	**198**	**151,249**	**7.19**	**62,291**

Fuel economy was weighted by fleet size as follows: each truckload carrier's average fuel economy was multiplied by the number of tractor-trailers in their fleet, the product was summed for carriers in the truckload subset, and the sum was divided by the total number of tractor-trailers in the subset. While the number of tractor-trailers per year varies considerably, the average fuel economy was highly consistent from year to year in this subset of the operational cost data.

Operating weight was weighted by the same method. Each truckload carrier's average operating weight was multiplied by the number of tractor-trailers in their fleet, the product was summed for carriers in the truckload subset, and the sum was divided by the total number of tractor-trailers in the subset. Operating weight includes the weight of the tractor, trailer, and cargo. While there was greater variation in operating weights, lower annual operating weight averages tend to coincide with better annual MPG averages.

A trip length breakdown for the truckload subset was calculated using the same method as weighting by fleet size, in order to capture the fuel efficiency of different driving conditions, resulting in the fuel economy figure of 7.19 miles per gallon. Regional pickups and deliveries between 100 and 500 miles constituted 45.6 percent – nearly half – of all trips made by

[92] Alex Leslie and Dan Murray, *An Analysis of the Operational Costs of Trucking: 2021 Update*, American Transportation Research Institute, Nov. 2021.

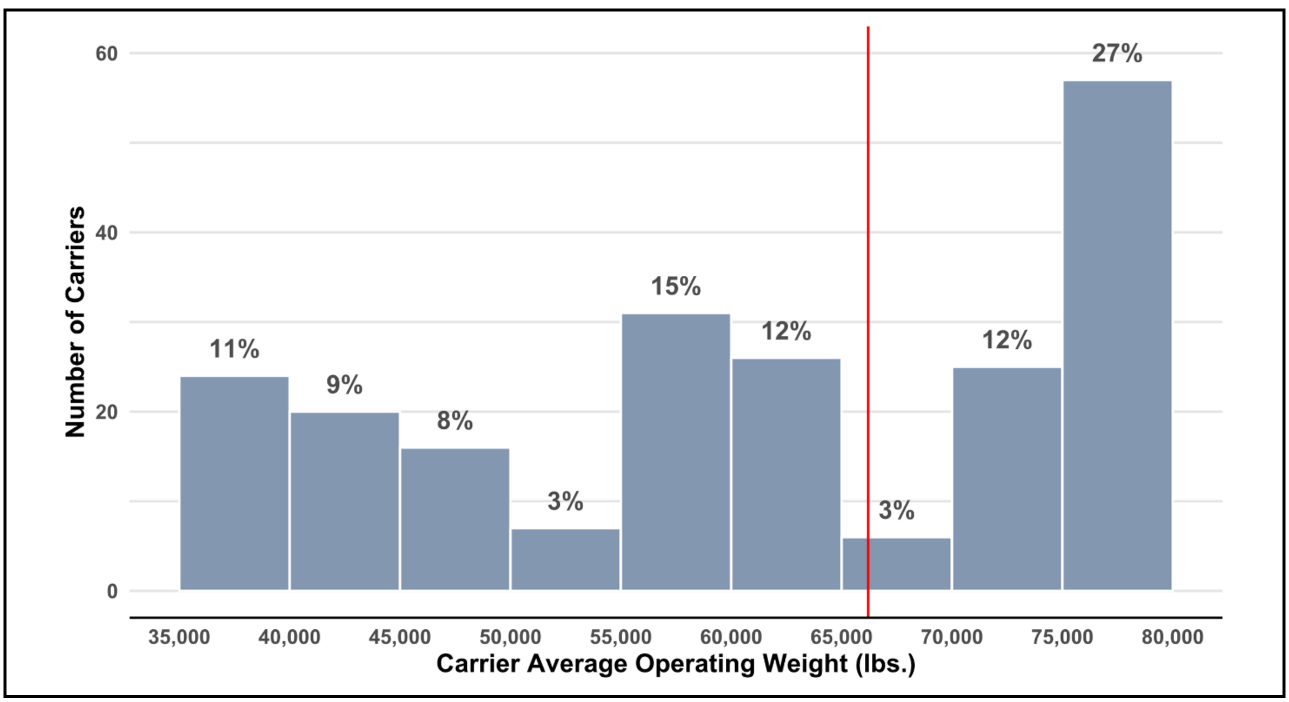
truckload carriers with average operating weights at or below 80,000 lbs. during this period (Table A2). Regional trips include more highway driving, resulting in better fuel efficiency than local pickups and deliveries, but they may include a greater proportion of congested urban miles than longer interregional or national trips. The next most common trip type was interregional pickups and deliveries, which accounted for 25.4 percent of all trips. Trip type percentages were highly consistent from year to year in this subset of the operational cost data.

Table A2: Ops Costs Trip Types for Truckload Carriers with Average Operating Weights at or below 80,000 lbs., 2016-2020

Trip Type	Percentage
Local (less than 100 miles)	13.5%
Regional (100 - 500 miles)	45.6%
Interregional (500 - 1,000 miles)	25.4%
National (over 1,000 miles)	13.5%

Though the average truckload operating weight in ATRI's *Operational Costs of Trucking* data over the past 5 years is 62,291 lbs., many carriers have average operating weights much closer to the standard 80,000 lbs. threshold. Figure A1 shows the distribution of carrier averages in 5,000-lbs. bins (not weighted by fleet size). All operating weights to the right of the red line in Figure A1 would be over-weight if ICE tractors were replaced with BEV tractors based on BEV scenario tractors being approximately 13,801 lbs. heavier than ICE tractors. This potentially "BEV-overweight" segment includes 42 percent of truckload carriers representing 34 percent of truckload trucks in the data.

Figure A1: Ops Costs Average Carrier Weights



American Transportation Research Institute
2110 Powers Ferry Road, Suite 470
Atlanta, GA 30339
(770) 432-0628
ATRI@Trucking.org
TruckingResearch.org