Smart Freight Centre China

US Zero-Emission Road Freight in Focus: Policy, Technology, Infrastructure, and Market Outlook

—SFC China Global ZEFV Market Analyst Series

January 2025

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About Smart Freight Centre China

Smart Freight Centre China's vision is an efficient and zero emission global logistics sector. Smart Freight Centre China's mission is to collaborate with the organization's global partners to quantify impacts, identify solutions, and propagate logistics decarbonization strategies. Smart Freight Centre China's goal is to guide the China logistics industry in tracking and reducing the industry's greenhouse gas emissions to reach zero emissions by 2050 or earlier, consistent with a 1.5°C future.

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Executive Summary

Since California issued the Clean Truck Rule in 2020, zero-emission freight has become a focus of attention across U.S. states, prompting action at various levels. However, existing information is often fragmented and focused on different aspects, making it difficult to present a comprehensive picture of the U.S. zero-emission freight landscape. This report aims to provide readers with a clear and multi-dimensional understanding through a multi-faceted examination. The report outlines the progress of U.S. zero-emission freight from four key dimensions: policy, vehicle technology, infrastructure, and market. Through this multi-dimensional analysis, we strive to present a holistic view of this complex issue.

In the policy section, we introduce the U.S. zero-emission freight policy system, using various documents as clues to outline the specific time targets and action guidelines proposed by each document. Special focus is given to California's leading actions.

The market section provides a panoramic view of the U.S. zero-emission freight market. We analyze sales trends of zero-emission trucks, market shares of major manufacturers, and market penetration rates of different types of vehicles (such as urban delivery vehicles, long-haul trucks, etc.). We also discuss key factors affecting market development, such as total cost of ownership and policy incentives.

The technology section delves into the latest developments in the two main technological routes: battery electric and hydrogen fuel cell. We provide a detailed analysis of improvements in key indicators such as battery capacity, charging speed, and fuel cell efficiency, and how these technological advancements affect vehicle performance and operating costs.

The infrastructure section comprehensively reviews the current status and planning of charging and hydrogen refueling infrastructure in the United States. We not only present the quantity and distribution of infrastructure but also analyze the challenges faced in its construction, such as geographical imbalances and power grid capacity issues.

Through the comprehensive analysis of these four dimensions, this report aims to construct a comprehensive cognitive framework for readers, helping them better understand the current status, challenges, and future development directions of zero-emission freight in the United States. We believe that this multi-faceted examination will provide valuable reference for policy makers, industry participants, and researchers, promoting the further development of global zero-emission road freight initiatives.

Acronym List

Advanced Clean Truck (ACT) Regulation

Battery Electric Vehicle (BEV)

California Air Resources Board (CARB)

California Environmental Protection Agency (CalEPA)

California Hydrogen Business Council (CHBC)

California Public Utilities Commission (CPUC)

Clean Hydrogen Production Standard (CHPS)

Clean Truck Program (CTP)

Department of Energy (DOE)

Electric Vehicle Supply Equipment (EVSE)

Fuel Cell Electric Truck (FCET)

Fuel Cell Electric Vehicle (FCEV)

Global Commercial Vehicle Drive to Zero (GCV Drive to Zero)

Global Memorandum of Understanding (Global MOU)

Heavy-Duty Vehicle (HDV)

Hydrogen Production Tax Credit (PTC)

Medium- and Heavy-Duty Zero-Emission Vehicle (MHDZEV)

Medium-Duty Vehicle (MDV)

Memorandum of Understanding (MOU)

National Electric Vehicle Infrastructure (NEVI)

National Renewable Energy Laboratory (NREL)

National Zero-Emission Freight Corridor Strategy (NZEFCS)

National Zero-Emission Truck Coalition (NZETC)

Transportation Electrification Partnership (TEP)

United States Environmental Protection Agency (EPA)

Zero-Emission Vehicle (ZEV)

1 Zero-Emission Freight in the United States: Policy Overview

1. Introduction

Greenhouse gas emissions significantly impact public health and well-being. In the United States, the transportation sector stands out as the largest single source of these emissions, accounting for 33% of the total. Within this sector, heavy-duty vehicles are the second-largest contributor, responsible for 21% of all transportation-related emissions.[1]

The U.S. classifies commercial vehicles based on their gross vehicle weight rating (GVWR). This analysis encompasses vehicles ranging from Class 2b (8,501–10,000 lbs) to Class 8 (33,000 lbs and above). Throughout this report, vehicles within this range are collectively referred to as medium- and heavy-duty vehicles.

The zero-emission freight policy framework in the United States is a complex yet structured system, characterized by multiple levels and programs. With California often leading the way, this framework evolves incrementally, expanding from specific initiatives to broader applications. The framework can be conceptualized in four main tiers:

1. Federal laws
2. High-level plans, strategies, and programs
3. Specific regulations developed under strategic planning guidance
4. Various incentive measures directly guided by laws and bills

This multi-tiered approach allows for a comprehensive and adaptable strategy to address the challenges of transitioning to zero-emission freight transportation across the nation.

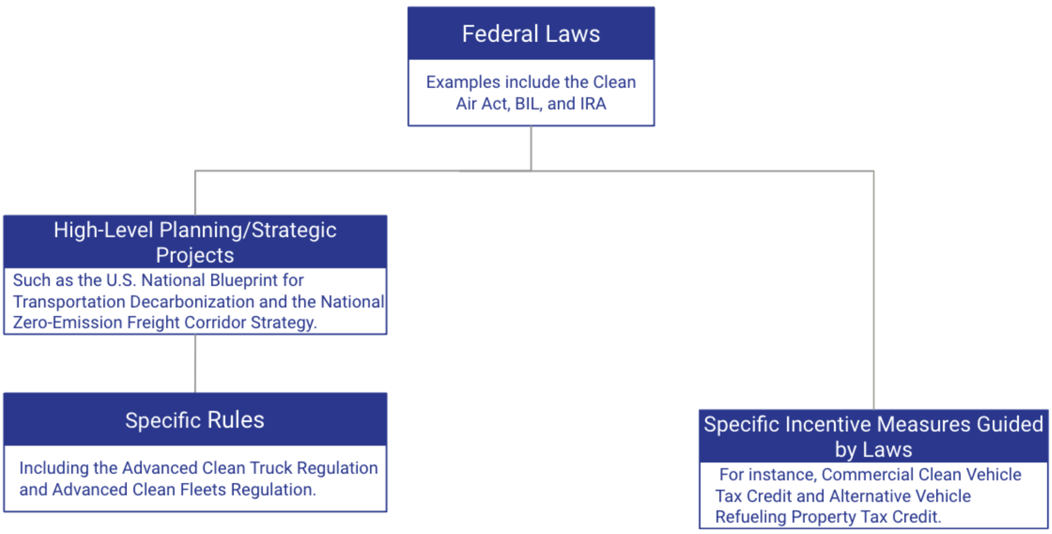

Figure: Schematic Diagram of the U.S. Zero-Emission Freight Policy Framework

[1] United States Department of Transportation. (2024). Decarbonizing US Transportation: Report to Congress. Retrieved from https://www.transportation.gov/sites/dot.gov/files/2024-07/DOT%20Report%20to%20Congress%20Decarbonizing%20US%20Transportation%20072924%20final.pdf

Federal laws establish the overarching framework and fundamental provisions, providing legal and financial support for zero-emission freight initiatives. Key legislation includes the Clean Air Act, the Bipartisan Infrastructure Law (BIL), and the Inflation Reduction Act (IRA). These laws set stringent emission standards and allocate substantial federal funding for infrastructure development and technological innovation. Notably, the Clean Air Act empowers the Environmental Protection Agency (EPA) to establish standards minimizing air pollutant emissions from mobile sources.

High-level plans and strategies outline detailed objectives and implementation pathways, guiding regulations at various government levels and private sector actions. Documents such as the U.S. National Blueprint for Transportation Decarbonization and the National Zero-Emission Freight Corridor Strategy define specific goals and strategies for each phase, driving nationwide progress in zero-emission freight. California, with its unique authority to set stricter emission standards, has implemented pioneering regulations like the Advanced Clean Truck Regulation (ACT), which mandates increasing sales of zero-emission heavy-duty trucks.

Incentive measures, directly guided by laws and bills, aim to encourage businesses and individuals to adopt zero-emission freight technologies through economic means. These include tax credits, subsidies, and reward programs, such as the Commercial Clean Vehicle Tax Credit (45W) and the Alternative Vehicle Refueling Property Tax Credit (30C), which directly boost market acceptance and adoption of zero-emission medium- and heavy-duty vehicles.

To provide a clear overview of this complex policy landscape, the following sections will examine three key areas: federal laws and their associated incentives, California's goals and supporting policies, and the overarching U.S. objectives and their policy support mechanisms.

2. Federal Laws and Supporting Incentive Measures

Since 1970, the Clean Air Act has been the cornerstone of U.S. environmental policy, providing the fundamental regulatory framework for controlling air pollution and vehicle emissions. Building on this foundation, the Biden administration has taken a groundbreaking approach to addressing climate change and advancing low-carbon development in the transportation sector. Through the Bipartisan Infrastructure Law (BIL, 2021) and the Inflation Reduction Act (IRA, 2022), the government has established a comprehensive set of strategies. These two new laws jointly invest over $100 billion[2] in clean transportation initiatives, setting the course for the government's ambitious 2050 climate goals. A key focus is the electrification of medium- and heavy-duty vehicles, a critical area for both emissions reduction and economic transformation.

While the BIL focuses on infrastructure development, the IRA represents the largest climate action in U.S. history. Together, they accelerate the transition to zero-emission vehicles across various sectors. By combining fiscal measures such as tax credits, grants, and loans, these acts provide support throughout the entire value chain, reinforcing and expanding the regulatory foundation established by the Clean Air Act.

These two acts share two common characteristics: broad, comprehensive support and targeted breakthroughs in key scenarios. Both maintain a technology-neutral stance, offering support for a range of zero-emission freight trucks and related processes. This flexibility encourages market-driven innovation while ensuring progress towards emission reduction goals.

Firstly, in terms of financial support, a notable feature of these acts is their coverage of the entire medium- and heavy-duty vehicle electrification value chain:

- **Manufacturing:** The IRA's Advanced Technology Vehicle Manufacturing program provides $3 billion in loans to support the production of clean vehicles and components.
- **Vehicle Purchase:** The IRA introduces commercial clean vehicle credits of up to $40,000 per vehicle, significantly lowering upfront cost barriers for fleet operators.

[2] Atlas Public Policy. (n.d.). $3 Billion in Federal Funding for EVs to Date. Atlas EV Hub. https://www.atlasevhub.com/data_story/3-billion-in-federal-funding-for-evs-to-date/

- **Charging Infrastructure:** Section 11401 of the BIL allocates $2.5 billion for charging and alternative fuel infrastructure, while the IRA's Alternative Fuel Refueling Property Credit further incentivizes charging station construction.
- **Grid Support:** Section 40107 of the BIL provides $3 billion to enhance grid flexibility, including vehicle-to-grid (V2G) technology, ensuring the power system can meet the growing demand from electric vehicles.

This multi-pronged approach ensures comprehensive support for the transition to zero-emission medium- and heavy-duty trucks, from production to operation.

Secondly, by identifying key work scenarios, both acts strategically advance zero-emission goals in the transportation sector. Ports, often major emission sources in urban areas and suitable for electrification due to their high-frequency, short-distance operations, receive specific support programs to fund their electrification progress. Additionally, federal fleets are expected to demonstrate transportation electrification, with the U.S. Postal Service (USPS) fleet allocated $1.71 billion for electrification upgrades.

The legislation also addresses domestic protectionism and social impacts. For instance, the IRA's incentives for domestic production of batteries and critical minerals aim to build resilient supply chains and create jobs. The BIL prioritizes community equity, targeting infrastructure development in rural and underserved communities.

To provide a deeper understanding of the specific measures in the BIL and IRA for promoting the transition of medium- and heavy-duty vehicles to zero emissions, the following table outlines the main key provisions and funding arrangements related to medium- and heavy-duty vehicles:

Title	Description	Lead Agency	Funds (Million USD)	Funding Type	Relevance to MHDV
Grants for charging and fueling infrastructure	A grant program for publicly accessible EV charging infrastructure, hydrogen fueling infrastructure, propane fueling infrastructure (limited to medium- and heavy-duty vehicles), and natural gas fueling infrastructure. Priority is given to rural areas, low- and middle-income communities, and communities with limited private parking.	Department of Transportation	2,500	Grants	Indirect (Infrastructure)
Reduction of Truck Emissions at Port Facilities	Projects aimed at reducing idling by trucks at port facilities, including research on port electrification, emerging technologies, and funding projects to reduce port-related emissions.	Department of Transportation	250	Grants	Direct
Deployment of Technologies to Enhance Grid Flexibility	Provides funding for various methods to enhance grid flexibility, including vehicle-to-grid technology.	Department of Energy	3,000	Grants	Indirect (Infrastructure)
Advanced Energy Manufacturing	Provides funding for a range of "advanced energy" manufacturing facilities,	Department of Energy	750	Grants	Direct

and Recycling Grant Program	including facilities manufacturing EVs and EV charging components.				
Port Infrastructure Development Program	Provides funding for projects to enhance port resilience, including port electrification and infrastructure for EV charging or hydrogen fueling for drayage trucks and related grid upgrades.	Department of Transportation	2,250	Grants	Indirect (Infrastructure)

Table: Provisions Related to MHDVs in the BIL

Title	Description	Lead Agency	Funds (USD)	Funding Type	Relevance to MHDV
Qualified Commercial Clean Vehicles	Provides a 30% credit for electric and other non-gasoline/diesel trucks and a 15% credit for combustion vehicles equipped with at least 15 kWh batteries. The credit is capped at 15% of the purchase price for PHEVs and 30% of the purchase price or incremental cost (whichever is lower) for EV and FCEV vehicles. For vehicles under 14,000 lbs, the credit is capped at $7,500. Valid through 2032.	Treasury Department	3.5 Billion	Tax Credit	Direct
Clean Heavy-Duty Vehicle Grant Program	A competitive grant program with a total allocation of $930 million, of which 30% will be dedicated to vocational zero-emission trucks. It includes funding for vehicle replacement, charging infrastructure, workforce development, and planning and technical activities to support the adoption of zero-emission vehicles.	Environmental Protection Agency	1 Billion	Grants, Subsidies	Direct
Advanced Technology Vehicles Manufacturing Program	The IRA includes $20 billion in loans for new clean vehicle manufacturing facilities nationwide, with $3 billion allocated to the Advanced Technology Vehicles Manufacturing Program to produce or integrate advanced technology vehicles in the U.S., provided such vehicles emit low or zero greenhouse gases in any operational mode or	Department of Energy	3 Billion	Direct Loan	Direct

[3] Vocational zero-emission trucks are specialized vehicles designed for specific industries (such as construction, waste management, and logistics) that produce no tailpipe emissions

	condition (including BEV and FCEV).				
Domestic Manufacturing Conversion Grants	The program will provide $1.7 billion (approx. 12.3 billion RMB) to support upgrades to 11 auto plants in 8 states—Michigan, Ohio, Pennsylvania, Georgia, Illinois, Indiana, Maryland, and Virginia—to help businesses produce products related to the EV supply chain, including electric motorcycles and school bus components, electric commercial vehicle batteries, hybrid trains, and electric vehicles.	Department of Energy	1.7 Billion	Grants, Subsidies	Indirect (All BEV)
U.S. Postal Service Clean Fleet	Provides $1.71 billion in funding for purchasing, designing, and installing infrastructure to support zero-emission delivery vehicles at Postal Service-owned or leased facilities. The program runs through September 30, 2031.	General Services Administration	1.71 Billion	Grants	Direct (Specific Fleet)
Alternative Fueling Property Credit	Provides a tax credit for heavy-duty truck charging infrastructure, increasing incentives from $30,000 per asset to $100,000 per asset.	Treasury Department	1.738 Billion	Tax Credit	Indirect (Infrastructure)
Clean Hydrogen Production Tax Credit	Clean hydrogen producers are eligible for a tax credit of up to $3 per kilogram of clean hydrogen produced. Eligible clean hydrogen must produce no more than 4 kg of CO2-equivalent per kg of hydrogen.	Treasury Department	N/A	Tax Credit	Indirect (Energy)

Table: Provisions Related to MHDVs in the IRA

3. California's Goals and Supporting Policies

The U.S. has ambitious goals for zero-emission freight, with California leading the way by setting a series of medium- and long-term targets. These targets and the corresponding policies are outlined through strategic planning documents to guide the transition of medium- and heavy-duty trucks to zero emissions.

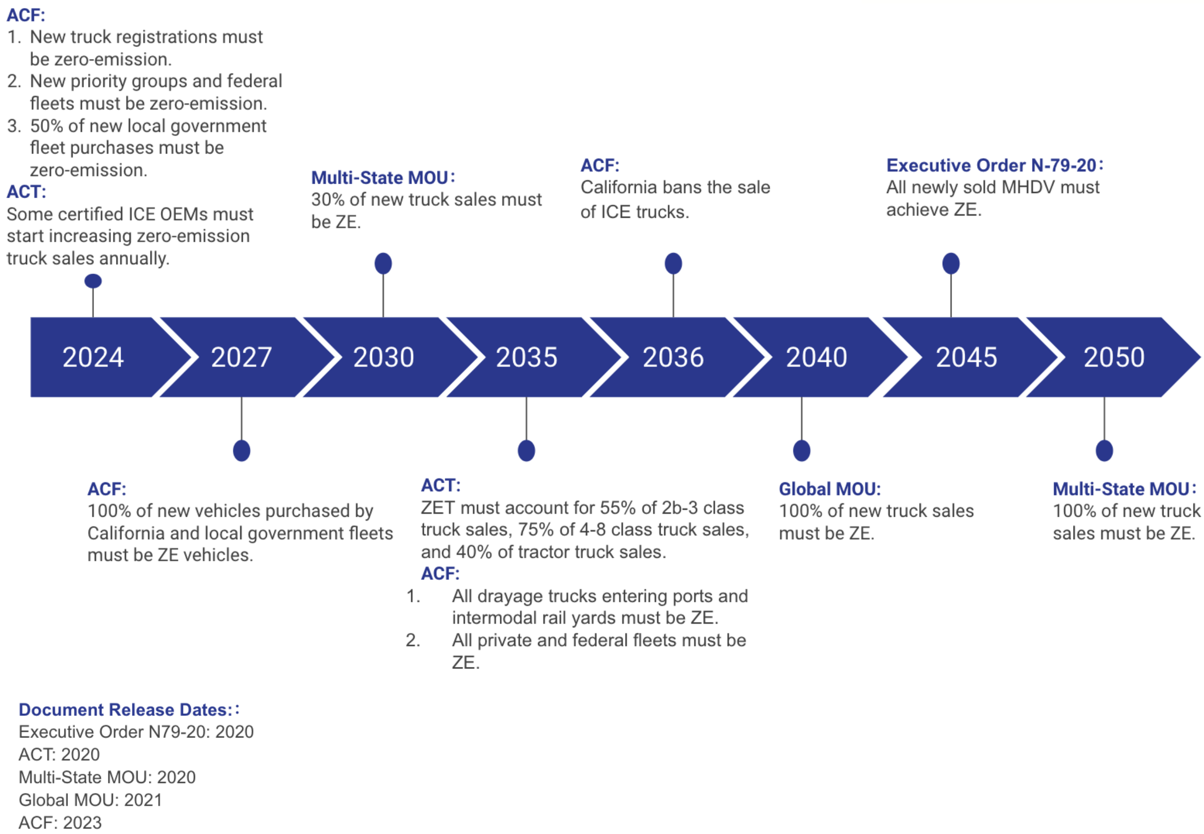

Figure: California's Goals and Supporting Policies

California's Executive Order N-79-20, signed by Governor Gavin Newsom in 2020, is a key top-level policy that signifies the state's significant commitment to zero-emission freight. The core goal of this executive order is to achieve 100% zero-emission sales of new passenger cars and trucks sold within the state. If feasible, all medium- and heavy-duty vehicles on California roads will be 100% zero-emission by 2045. To achieve this ambitious goal, California has introduced a series of complementary regulations and measures to ensure the effective support and advancement of these policy objectives.

3.1 Advanced Clean Truck Regulation (ACT)

In June 2020, California introduced the **Advanced Clean Truck Regulation (ACT)**, one of the most robust regulatory approaches globally. This regulation consists of two components: manufacturer sales requirements and reporting requirements.

	Details
Sales Requirements	**2024**: Starting from 2024, all manufacturers of certified 2b-8 class internal combustion engine vehicles will be required to sell zero-emission trucks.
	2035: Zero-emission trucks need to account for 55% of 2b-3 class truck sales, 75% of 4-8 class straight truck sales, and 40% of tractor truck sales. By 2045, all new trucks sold in California will transition to zero-emission vehicles.
Reporting Requirements	**Company and Fleet Reporting**: Large employers, including retailers, manufacturers, brokers, and others, must report information related to freight and shuttle services. Fleet owners with 50 or more trucks must report on their existing fleet operations.

Table: ACT Regulation Details

The design of the Advanced Clean Truck Regulation follows a similar path to California's 1990 Zero-Emission Vehicle (ZEV) credit mechanism for light-duty vehicles. It operates on a "set credit compliance limit - sell or buy zero-emission vehicle credits - achieve compliance through market mechanisms" pathway. According to this regulation, starting in 2024, all diesel trucks sold in California in the 2b-8 class categories, including pickup trucks, must meet a certain proportion of zero-emission vehicle sales.[4]

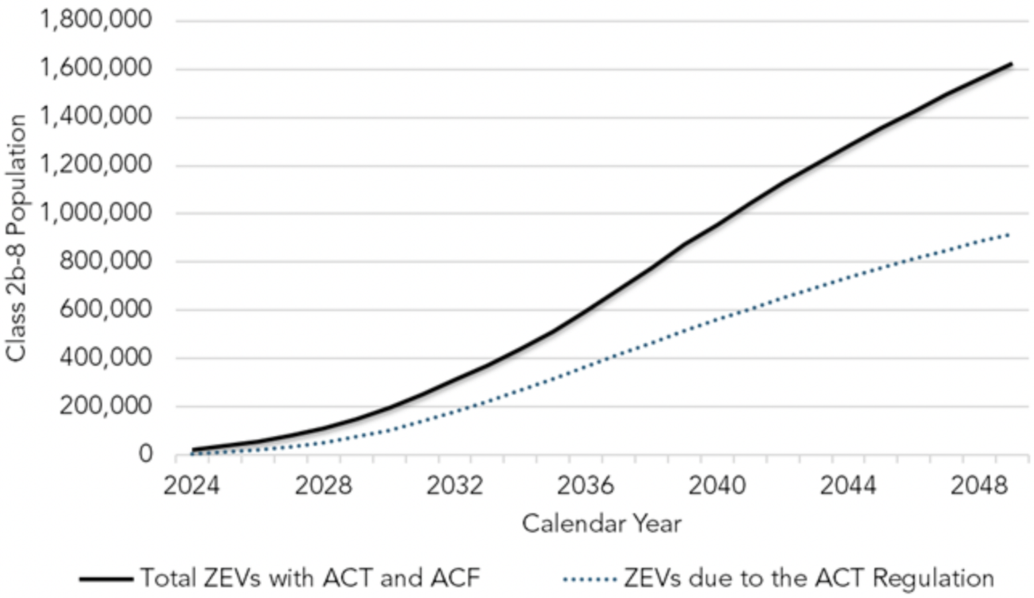

Figure: Class 2b-8 population

This regulatory policy provides a secured market foundation for zero-emission truck manufacturers, supporting their business development, supply chain construction, and innovation to meet new job requirements. The regulation not only ensures a smooth transition but also represents an efficient economic intervention.

According to the regulation, manufacturers must meet the specified zero-emission vehicle (ZEV) sales ratios annually using credits. Both zero-emission trucks and near-zero emission trucks can earn credits, but the credits awarded vary by vehicle class, with higher classes earning more credits per vehicle sold/purchased. For near-zero emission trucks, there is an NZEV adjustment factor, which is one percent of the pure electric range, capped at a maximum of 0.75. Credits generated by hybrid electric trucks are always less than those for a corresponding zero-emission truck, capped at 75% of the normal zero-emission credit amount.[5]

For manufacturers, starting in 2021, each sale of a ZEV (Zero Emission Vehicle) and NZEV (Near Zero Emission Vehicle) model earns credits that are stored in a credit bank. Manufacturers can later "withdraw" from this credit bank to fulfill compliance obligations, with the remainder of the credits continuing to be stored for future use.

For vehicle classes exceeding 8,500 pounds GVWR starting from Class 2b, mandatory compliance requirements begin in 2024 with increasingly stringent sales ratios required each year. Companies selling more than 500 units annually will be obligated to fulfill these credit compensation duties. If sales targets are not met, manufacturers face fines and must make up for the credit shortfall in the following year. The credit

[4] Qin, L., & An, F. (2020). Analysis and Insights on California's Advanced Clean Trucks Regulation. Innovation Center for Energy and Transportation (iCET). http://www.icet.org.cn/admin/upload/2020110944169937.pdf

[5] California Air Resources Board. (n.d.). Advanced Clean Trucks. https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks

system allows manufacturers to flexibly manage their compliance needs under certain rules through the purchase or trade of credits.

After the ACT regulation was introduced in California, it quickly expanded from domestic to international scope. Based on the ACT regulation, in 2020, 15 U.S. states signed the "Multi-State Medium and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding" (as of June 2024, 17 states and the District of Columbia have signed). From this memorandum, the "Global Memorandum of Understanding on Zero-Emission Medium and Heavy-Duty Vehicles" was first formed in 2021. As of June 2024, 36 countries are participating. According to the Global Memorandum, major countries have committed to jointly work towards achieving 100% zero-emission sales of all new trucks and buses by 2040, with an interim target of 30% zero-emission vehicle sales by 2030 to promote the goal of achieving net-zero carbon emissions by 2050.

3.2 Advanced Clean Fleets , ACF

As a supplement to the ACT and to better promote the introduction of zero-emission technologies into California's truck and bus fleets, the state of California passed the Advanced Clean Fleets (ACF) rule on April 28, 2023. This is the world's first regulation explicitly announcing the cessation of internal combustion engine truck sales.

The ACF requires fleets suitable for electrification to reduce emissions by gradually adopting zero-emission vehicles. Terminal delivery trucks and yard trucks must achieve zero emissions by 2035, and manufacturers are required to sell only zero-emission medium and heavy-duty vehicles in California starting from 2036, which is nine years ahead of the target date proposed by the Governor's executive order in 2020. The specific goals included in the regulation are as follows:

Category	Description	Start Time	Completion Time
Manufacturers	From 2036, manufacturers can only sell zero-emission medium and heavy-duty vehicles in California.	2036	Ongoing
Drayage Trucks	Starting from the end of 2023, newly registered drayage trucks must be zero-emission. By 2035, all drayage trucks entering seaports and intermodal rail stations must be zero-emission.	2023	2035
High-Priority and Federal Fleets	Starting from 2024, fleets must only purchase ZEVs, and from 2025, phase out internal combustion engine vehicles at the end of their service life.	2024	2035
State and Local Agencies	From 2024, at least 50% of new vehicles purchased by California and local government fleets must be zero-emission, increasing to 100% by 2027. Small government fleets begin purchasing ZEVs from 2027.	2024	2027

Table: Details of the Advanced Clean Fleets Rule

Sales requirements are one of the most effective methods to compel private sector participants, especially manufacturers, to increase supply and scale production. This policy not only provides manufacturers with a clear market direction but also offers certainty to other stakeholders in the zero-emission vehicle ecosystem, thus stimulating investments in zero-emission fleets and the expansion and upgrading of the electrical grid. Moreover, this requirement allows energy providers to confidently plan and develop infrastructure to meet anticipated demand, reducing the risk for businesses and financiers investing in zero-emission trucks, buses, and related infrastructure. According to predictions by the California Air Resources Board (CARB), due to the implementation of the ACF regulation, by 2035, approximately 510,000 zero-emission trucks will be on California roads, and this number is expected to increase to 1,350,000 by 2045. The ACF regulation specifically targets the most heavily polluting truck fleets, with Class 7 to 8 vehicles accounting for 67% of this fleet type.

3.3 Incentive Measures

3.3.1 Hybrid and Zero-Emission Truck and Bus Incentive Project - Clean Truck and Bus Vouchers (HVIP)

California's Hybrid and Zero-Emission Truck and Bus Incentive Project (HVIP) is a key initiative aimed at accelerating the adoption of cleaner commercial vehicles in the state. Launched in 2009 by the California Air Resources Board (CARB) and managed by CALSTART, a national non-profit organization dedicated to advancing clean transportation technologies, HVIP addresses the incremental cost issues of zero-emission vehicles and supports the deployment of hybrid technologies. By providing point-of-sale discounts in the form of vouchers, the program effectively reduces the purchase costs of a range of vehicles, including buses, school buses, shuttle buses, and Class 2b to 8 trucks deploying zero-emission technologies such as battery electric and hydrogen fuel cell systems.

HVIP is an integral part of California’s strategy to improve air quality and reduce greenhouse gas emissions, promoting economic vitality through clean technology innovation. Additionally, the program allocates extra funds for vehicles operating in disadvantaged communities, emphasizing the state's commitment to environmental justice and equitable clean transportation.

Category	Details
Objective	To assist fleets in purchasing ZECVs and accelerate their early market introduction.
Vouchers	Offers point-of-sale discounts ranging from $20,000 to $310,000, depending on the vehicle.
Eligibility	Applicable to eligible electric, hybrid, or natural gas trucks and buses (not to be combined with the Carl Moyer Program).

Table: HVIP Program Details

Since its inception in 2009, HVIP has achieved significant results. As of November 30, 2023, the program has allocated $986.4 million, with $328 million already implemented and $205.2 million benefiting priority populations. A total of 13,105 vehicles have been deployed, reducing 1,016,462 metric tons of CO2-equivalent greenhouse gases, 1,320 tons of nitrogen oxides, 13 tons of reactive organic gases/hydrocarbons, and 55 tons of particulate matter. Particularly in the medium and heavy-duty truck sector, from its establishment in 2010 until May 2023, HVIP has supported the purchase of over 7,762 zero-emission trucks and buses, 2,500 hybrid trucks, 2,400 natural gas engine trucks, and 290 trucks equipped with electric power take-off units in California fleets. The program also focuses on small fleets and disadvantaged communities, with over 20% of participating fleets operating 10 or fewer vehicles, and more than 70% of voucher applications being for vehicles deployed in disadvantaged communities. These figures demonstrate HVIP’s significant contribution to promoting the adoption of clean commercial vehicles, improving air quality, and reducing greenhouse gas emissions.[6]

3.3.2 Carl Moyer Memorial Air Quality Standards Achievement Program

The Carl Moyer Memorial Air Quality Standards Achievement Program, commonly referred to as the Carl Moyer Program, is a collaborative initiative between the California Air Resources Board (CARB) and 35 local air districts in California. Named after Dr. Carl Moyer in recognition of his contributions to improving air quality, the program offers competitive grants to help businesses, non-profit organizations, and government agencies replace polluting equipment and machinery with low-emission alternatives. The focus of the program is on cleaning the air by replacing old heavy-duty diesel with electric, alternative fuel, or clean diesel technologies.

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[6] California HVIP. HVIP Impact. Retrieved August 24, 2024, from https://californiahvip.org/impact/

Funding for the Carl Moyer Program comes from various sources, including state funds, vehicle registration fees, and occasionally special local funding measures. Since its inception, the program has funded thousands of clean air projects, disbursing hundreds of millions of dollars, significantly reducing air pollutants and thus aiding California in meeting its aggressive air quality and climate goals. This ongoing incentive scheme provides approximately $90 million annually in subsidies, with implementation overseen by the respective air pollution control districts within their jurisdictions.

4. U.S. Goals and Supporting Policies

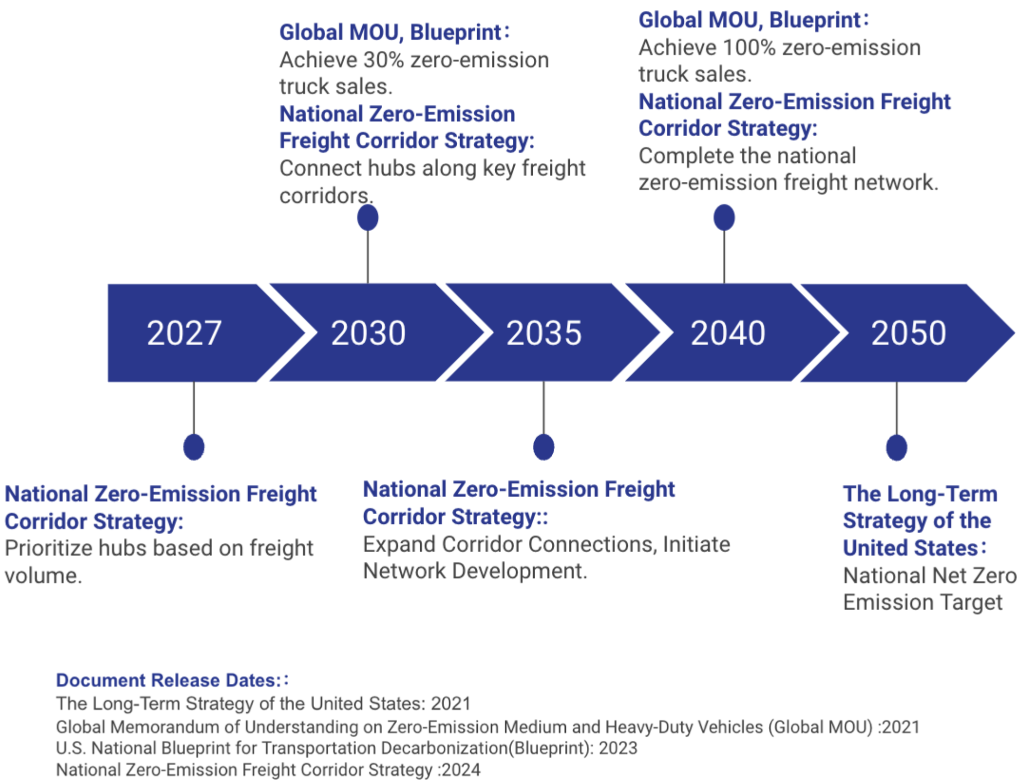

Figure: U.S. Goals and Supporting Policies

Beyond individual state actions, the United States has also been actively coordinating at the federal level, gradually releasing plans for zero-emission freight trucking on a national scale in recent years.

4.1 U.S. National Blueprint for Transportation Decarbonization

In November 2021, the Biden-Harris administration released The Long-Term Strategy of the United States which set the ambitious long-term goal of achieving net-zero emissions by 2050. As part of its specific planning in the transportation sector, four departments—the Department of Energy (DOE), Department of Transportation (DOT), Environmental Protection Agency (EPA), and Department of Housing and Urban Development (HUD)—officially launched the U.S. National Blueprint for Transportation Decarbonization in January 2023. This landmark interagency strategy and action framework aims to eliminate all emissions from the transportation sector by 2050. The blueprint marks the first time the U.S. government has applied a whole-of-government approach, addressing the climate crisis through federal leadership and interdepartmental collaboration. It meticulously plans the transition to a decarbonized transportation system to address the negative impacts of transportation system greenhouse gas emissions on vulnerable groups, and provides equitable, affordable, and convenient options for passenger and commercial vehicle transportation systems. By further developing and deploying clean energy technologies such as electric vehicles, hydrogen energy, and sustainable fuels, and by building the accompanying clean transportation infrastructure, the blueprint will create well-paying jobs across various sectors of the transportation industry and aims to strengthen U.S. energy independence.

Phase	Specific Content
First Phase (Before 2030)	Support deployment of research and investment: Maximize the impact of historic BIL/IRA investments and catalyze cooperation and private investment
Second Phase (2030-2040)	Accelerate transformation: Expand the deployment of clean solutions. Adjust strategies and implementation plans based on global events, consumer responses, and technological advancements
Third Phase (2040-2050)	Complete the transition: A sustainable and equitable future. Ensure no region is left behind and make all efforts to achieve a net-zero emissions economy

Table: Specific Content of the U.S. National Blueprint for Transportation Decarbonization

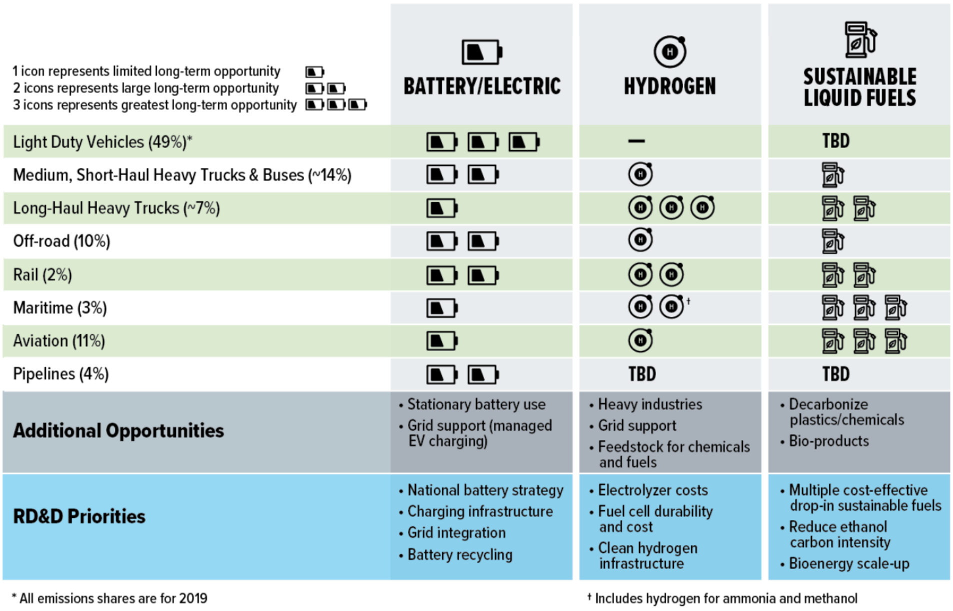

Table: Technological Solutions for Achieving a Net-Zero Economy by 2050 for Transportation Modes[7]

Achieving zero emissions requires comprehensive solutions across all modes of transport. The Blueprint sets specific targets for different types of transportation modes and assesses the application potential of various technological solutions. For medium and heavy-duty trucks, the Blueprint specifies targets as outlined in the "Global Memorandum of Understanding on Zero-Emission Medium and Heavy-Duty Vehicles," aiming for 30%

[7] U.S. Department of Energy. (2023). The U.S. national blueprint for transportation decarbonization. https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf

of new truck sales to be zero-emission by 2030 and 100% by 2040. Additionally, the plan aims to achieve 100% zero-emission vehicle procurement for government fleets by 2035.

4.2 National Zero-Emission Freight Corridor Strategy

As the commitment to decarbonizing the transportation sector deepens, the Joint Office of Energy and Transportation between the U.S. Department of Transportation (DOT) and the U.S. Department of Energy (DOE) released the "National Zero-Emission Freight Corridor Strategy" in March 2024. This strategy, based on the "U.S. National Blueprint for Transportation Decarbonization" and the "Global Memorandum of Understanding on Zero-Emission Medium and Heavy-Duty Vehicles," guides the deployment of commercial zero-emission medium and heavy-duty transportation vehicles from 2024 to 2040.

The strategy aims to stimulate the private sector through public investments, focusing on utilities and regulatory energy planning, adjusting industry activities, and sending signals to the electricity and hydrogen markets to plan and deploy necessary power generation, transmission, and distribution projects. Based on the targets for zero-emission truck sales outlined in the Blueprint, the strategy provides guidance for public and private stakeholders to invest in the construction of charging and hydrogen refueling infrastructure along the national highway freight network.

The strategy will accelerate the construction of infrastructure in four phases along major freight corridors and hubs.

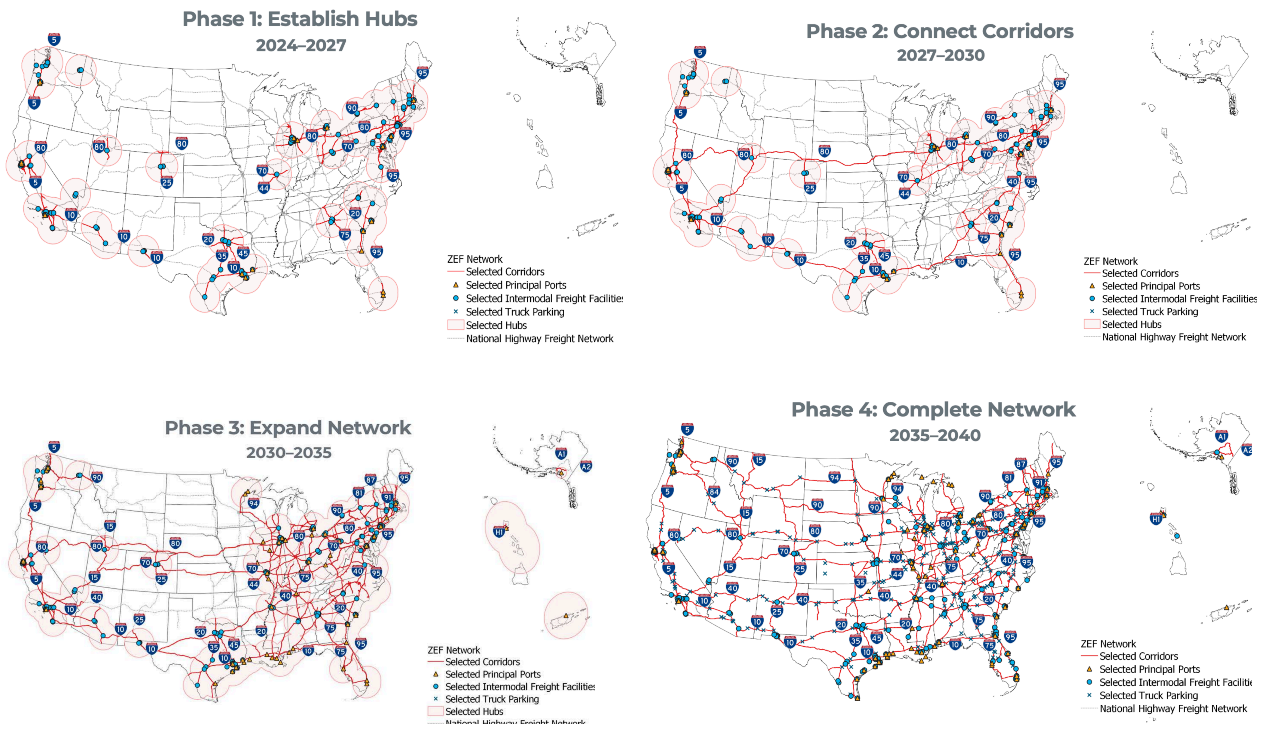

Figure: Four Phases of the National Zero-Emission Freight Corridor Strategy[8]

[8] U.S. Department of Energy. (2022). Zero-emission vehicle corridor strategy. https://driveelectric.gov/files/zef-corridor-strategy.pdf

Infrastructure Phase	Phase 1	Phase 2	Phase 3	Phase 4
Timeline	2024-2027	2027-2030	2030-2035	2035-2040
Outcomes	Establish hubs	Connect hubs	Expand corridors	Complete network
Corridor Length	12,000 miles	19,000 miles	37,000 miles	49,000 miles
Completion Percentage	23%	36%	72%	94%
ZEF Hub Area	898,000 sq mi	1,280,000 sq mi	3,120,000 sq mi	-
Primary Beneficiary Vehicle Types and Usage Scenarios	Classes 3-7	Classes 3-7	Classes 3-8	Classes 3-8
	Local and regional backhaul operations, first and last mile delivery, short-haul	Local and increased regional freight transport	Local, regional, and point-to-point operations, supporting long-haul	Local, regional, and long-haul freight transport

Table: Infrastructure Phases and Timeline

Key freight hubs are identified in areas best suited for early deployment of battery electric medium and heavy-duty vehicles, where fleets primarily perform return-to-base operations. This layout strategy leverages operations with fixed routes and ensures vehicles can regularly return to base for charging, maximizing the efficiency and practicality of electric vehicles.

The first phase of the U.S. Zero-Emission Freight Corridor Strategy primarily focuses on medium-sized vehicles, especially trucks used for first and last mile delivery. This phase centers on building and perfecting infrastructure within key freight hubs to support regional freight needs, including port drayage, and laying the groundwork for the promotion of long-haul zero-emission transportation modes. During this period, the selection of key hubs will be based on their adaptability and openness to early deployment of zero-emission medium and heavy-duty vehicles, ensuring that these areas can maximize the return on initial investments.

Entering the second phase, the construction of the zero-emission freight corridor will prioritize expanding to connect established key hubs, particularly infrastructure along the I-5 corridor, serving all major ports on the West Coast. This phase will see a broader geographical expansion, including states that have not yet implemented California's Advanced Clean Trucks Regulation or do not have plans for zero-emission medium and heavy-duty trucks. Additionally, this phase will begin focusing on building and accelerating the Department of Energy’s regional clean hydrogen hubs to support port transportation and preliminary long-haul zero-emission solutions.

The goal of the third phase is to extend the zero-emission freight corridor across the entire United States, covering major national arteries like I-80, I-95, I-10, and I-70, and providing charging and fueling facilities for all coastal ports and their surrounding areas. This phase will emphasize enhancing the prevalence of battery electric and hydrogen fuel cell truck technologies and increasing the accessibility of hydrogen fueling stations along the ZEF corridors, covering about 37,000 miles, which is 72% of the national highway network, and providing decarbonization options for over two billion tons of annual goods transportation.

The final phase of the strategy is expected to achieve comprehensive electrification of medium and heavy-duty vehicles along the ZEF corridors, providing ubiquitous access to charging and hydrogen fueling from East to West and North to South corridors. By 2035, with the full operational deployment of the Department of Energy’s regional clean hydrogen hubs, further support will be provided for the clean hydrogen transportation fuel supply in key areas. This phase of the zero-emission freight corridor will extend to about 49,000 miles, covering 94% of the national highway network and about 3.12 million square miles, providing broad decarbonization opportunities for over 2.3 billion tons of annual goods transportation volume.

This strategy employs an innovative "deployment factors" approach to identify priority development areas, integrating data across multiple dimensions to comprehensively assess and plan the deployment of zero-emission freight infrastructure. Specifically, the strategy utilizes national highway freight network data to identify high-traffic freight segments, ensuring resources are directed where they are most needed; analyzes the distribution of ports, inland ports, and multimodal freight facilities to optimize infrastructure layout; uses

EPA's non-attainment area data for air quality, especially focusing on regions in urgent need of air quality improvement, incorporating environmental benefits into the decision-making process; considers state policies supporting the deployment of zero-emission vehicles, ensuring investments align with local policy directions; and evaluates total cost of ownership forecasts for zero-emission vehicles to ensure the economic feasibility of investments. This multi-dimensional analysis approach not only focuses on freight needs but also comprehensively considers environmental, social, and economic factors. Meanwhile, the strategy is designed as a "living document" that can be regularly updated based on market developments, technological advancements, and new data, thus maintaining its relevance and efficacy. For example, as new battery technologies emerge or hydrogen fuel costs decrease, the strategy can adjust priority development areas or infrastructure types accordingly. This flexible approach provides a consistent planning tool for federal, state, and local governments as well as the private sector (such as utilities, zero-emission fuel suppliers, and fleet operators), facilitating the coordination of efforts to accelerate the development and application of zero-emission freight infrastructure.

4.3 National Zero-Emission Freight Corridor Strategy

On August 5, 2021, the EPA announced the Clean Truck Plan, which is the most protective set of regulations ever implemented for the road industry. The first and third rules are directly related to reducing emissions from medium and heavy-duty trucks.

The first rule of the Clean Truck Plan was signed on December 20, 2022, focusing on reducing emissions that contribute to smog and soot, applicable to heavy-duty engines and vehicles starting with the 2027 model year. This rule requires engine manufacturers to reduce nitrogen oxide emissions from medium and heavy-duty vehicle engines from the current standard of 0.2 grams per horsepower-hour (g/hp-hr) to 0.035 g/hp-hr by 2027. In addition to the ultra-low emission standards, these new rules also introduce new requirements for emission testing, certification procedures, and extended service and warranty requirements.

The third rule, announced on March 29, 2024, is titled "Heavy-Duty Vehicle Greenhouse Gas Emissions Standards - Phase Three." This rule establishes stricter standards to reduce greenhouse gas emissions from heavy-duty vehicles starting with the 2027 model year (MY).

This release of Phase Three standards updates the EPA's Phase Two greenhouse gas emission standards issued in 2016, setting new limits on exhaust carbon dioxide emissions for vehicles from the 2027 model year onwards. The release of this rule also signifies the completion of the EPA's Clean Truck Plan.

Compared to Phase Two, the newly introduced Phase Three standards differ significantly in terms of strictness, applicability, timeline, technological paths, and implementation costs, summarized as follows:

Category	Phase 2	Phase 3
Strictness	By 2021, emissions were reduced by 17% compared to 2010 levels.	By 2032, greenhouse gas emissions from heavy-duty vehicles will be reduced by 29% compared to 2021 levels, varying by vehicle type.
Applicability	Narrower scope.	Applies to a broader range of vehicles, including school buses, delivery trucks, waste transport vehicles, utility trucks, transport and shuttle buses, and day and sleeper cabs on tractor-trailers.
Timeline	Effective immediately.	Phased implementation, designed to allow more time for the development of vehicle technology and the deployment of charging and refueling infrastructure.
Technological Path	Primarily relies on advanced diesel and internal combustion engine vehicles.	Includes a wider range of technologies such as hybrid vehicles, plug-in hybrid electric vehicles, all-electric vehicles, and hydrogen fuel cell vehicles. Manufacturers can choose suitable emission control technology as long as they meet mandatory standards.

Implementation Cost	Lower.	High costs, with EPA estimating an annual compliance cost of $1.1 billion for the industry, although it is expected to bring long-term savings in fuel costs and maintenance expenses.

Table: Comparison of Phase Two and Phase Three of the Clean Truck Plan

The table below summarizes the reduction in CO2 emission limits for Phase 3 compared to the 2027 model year limits under Phase 2 standards. Compared to Phase 2, the 2032 emission standards for light, medium, and heavy-duty vocational trucks will be tightened by 60%, 40%, and 30%, respectively. For tractor-trailers, the 2032 emission limits for day cab tractor-trailers will be tightened by 40%, while those with sleeper cabs will be tightened by 25%. The implementation of Phase 3 greenhouse gas emission standards will be delayed for certain specific vehicle categories: for day cab tractors, implementation will be delayed until the 2028 model year; for heavy-duty vocational trucks, until the 2029 model year; and for sleeper cab tractors, until the 2030 model year.

Vehicle Type	2027MY	2028MY	2029MY	2030MY	2031MY	2032MY
Light-Duty Vocational Trucks	17%	22%	27%	32%	46%	60%
Medium-Duty Vocational Trucks	13%	16%	19%	22%	31%	40%
Heavy-Duty Vocational Trucks	--	--	13%	15%	23%	30%
Day Cab Tractor-Trailers	--	8%	12%	16%	28%	40%
Sleeper Cab Tractor-Trailers	--	--	6%	12%	25%	25%

Notes:

Light-Duty Vocational Trucks: 2b-5 class trucks with a vehicle weight between 8,500-19,500 lbs.

Medium-Duty Vocational Trucks: 6-7 class trucks with a vehicle weight between 19,500-33,000 lbs.

Heavy-Duty Vocational Trucks: 8 class trucks with a vehicle weight over 33,000 lbs.

Day Cab Tractor-Trailers: All cabin structure 6-7 class heavy-duty tractors and 8 class day cab tractors.

Sleeper Cab Tractor-Trailers: 8 class tractors with a sleeper cabin.

Table: Comparison of Phase 3 Emission Reductions vs. Phase 2

This update to the emission standards follows a technology-neutral principle. Although internal combustion engine technology has not been entirely excluded, the stringent reduction targets provide a strong incentive for fleets to adopt zero-emission technologies. The standards leverage what the EPA calls "anticipated available and cost-effective vehicle technology," focusing on current and developing clean vehicle technologies to further reduce emissions in the transportation sector.

According to EPA's analysis and forecasts, different types of heavy-duty trucks are expected to gradually transition to zero-emission vehicles in the coming years, though the speed and extent of this transition will vary by vehicle type. Starting in 2027, it is expected that 17% of light-duty vocational trucks will be zero-emission vehicles, while 83% will still be internal combustion engine vehicles. The transition for day cab tractor-trailers will occur slightly later, with 8% expected to be zero-emission vehicles by 2028, while 92% will still be ICE vehicles. Sleeper cab tractor-trailers will transition at the slowest pace, with significant changes expected by 2030, at which time 6% of these vehicles are expected to be zero-emission vehicles, while 94% will still be ICE vehicles.

Regulatory Subcategory Grouping	MY 2027		MY 2028		MY 2029		MY 2030		MY 2031		MY 2032	
	ZEV	ICEV	ZEV	ICEV	ZEV	ICEV	ZEV	ICEV	ZEV	ICEV	ZEV	ICEV
Light Heavy-Duty Vocational	17%	83%	22%	78%	27%	73%	32%	68%	46%	54%	60%	40%
Medium Heavy-Duty Vocational	13%	87%	16%	84%	19%	81%	22%	78%	31%	69%	40%	60%
Heavy Heavy-Duty Vocational	N/A, begins in MY 2029				13%	87%	15%	85%	23%	77%	30%	70%
Short-Haul (Day Cab) Tractors	N/A, begins in MY 2028		8%	92%	12%	88%	16%	84%	28%	72%	40%	60%
Long-Haul (Sleeper Cab) Tractors	N/A, begins in MY 2030						6%	94%	12%	88%	25%	75%

Figure: Forecasted Progress of Zero-Emission Transition by Vehicle Type. Resource: U.S. EPA

4.4 Hydrogen Energy Planning Related to the Freight Industry

In the field of zero-emission freight, the U.S. government has adopted a technology-neutral approach in most of its policies. However, the U.S. also has a well-established hydrogen energy policy framework that provides strong support for the development of hydrogen fuel cell trucks.

The United States was one of the earliest countries to integrate hydrogen energy and fuel cells into its energy strategy. As early as 1970, the U.S. introduced the concept of a "Hydrogen Economy." It is one of the most mature countries in terms of hydrogen energy application and has the world's largest fleet of hydrogen fuel cell forklifts. The U.S. was once the biggest promoter of the hydrogen energy industry. Since 1990, the U.S. government has introduced numerous policies and action plans to promote hydrogen energy development. In 2014, the U.S. released the "Comprehensive Energy Strategy," which positioned the development of low-carbon technologies as a strategic cornerstone for clean energy. The strategy explicitly stated that hydrogen, as an alternative energy source, would play a leading role in the transformation of the transportation industry. Today, the U.S. has developed full technical capabilities across the entire hydrogen value chain, including hydrogen production, transportation, storage, and utilization.

In 2023, the U.S. released its first national hydrogen energy development strategy, the "U.S. National Clean Hydrogen Strategy and Roadmap," which aims to establish a clean energy economy, accelerate domestic manufacturing growth, and create more jobs. The strategy outlines three key objectives and sets targets for clean hydrogen production: 10 million metric tons of clean hydrogen per year by 2030, 20 million metric tons by 2040, and 50 million metric tons by 2050. The first key strategy aims to ensure the strategic use of clean hydrogen, particularly in industrial sectors, heavy-duty transportation, long-term energy storage, and other alternative fields, to maximize the benefits of clean hydrogen. The second strategy focuses on promoting innovation and scaling up, stimulating private sector investment, and developing the clean hydrogen supply chain to reduce the cost of clean hydrogen. The third strategy is centered on developing regional networks for large-scale clean hydrogen production and end-use, maximizing infrastructure investment benefits, and promoting the scale-up of applications to enhance the market value of clean hydrogen. Notably, the "U.S. National Clean Hydrogen Strategy and Roadmap" also sets out phased key performance indicators from 2022 to 2036, covering hydrogen production, infrastructure, supply chain, end-use applications, and supporting technologies. Experts estimate that by 2025, the total demand for hydrogen in the U.S. will reach 13 million metric tons, with the total number of fuel cell vehicles (including light, medium, and heavy-duty FCEVs) growing to 150,000, alongside 125,000 fuel cell forklifts.[9]

[9] Wang, L. (2023, June 26). U.S. hydrogen economy vision overly optimistic. China Energy News, p. 11.

Time	Policy/Document Name	Goals	Specific Details
2020/11	Hydrogen Program Plan	Research hydrogen technologies, set key technology targets, and promote hydrogen in multiple sectors	• Hydrogen Production: Develop electrolyzers with an operational life of 80,000 hours, a cost of $300/kW, and a conversion efficiency of 65%. • Hydrogen Transportation: Reduce the cost of hydrogen transport to $2/kg H2. • Hydrogen Storage: Reduce the cost of on-board hydrogen storage systems to $8/kWh for 2.2 kWh/kg and 1.7 kWh/L systems, and $0.5/kWh for 1.0 kWh/kg and 1.3 kWh/L portable fuel cell power systems. The cost of high-strength carbon fiber for hydrogen storage should be reduced to $13/kg. • Hydrogen Utilization: Reduce the cost of hydrogen in the transportation sector to $2/kg H2, in the industrial and power sectors to $1/kg H2, and reduce the cost of fuel cells for long-haul heavy-duty trucks (PEMFC) to $80/kWh with a 25,000-hour operational life, and for stationary power generation fuel cells (SOFC) to $900/kWh with a 40,000-hour operational life.
2021/6	Hydrogen Shot	• Reduce the cost of clean hydrogen from $5/kg to $1/kg by 2030; interim target of $2/kg by 2025. • Achieve targets through increased use of renewable energy, nuclear power, and thermal conversion by 2030.	• In July 2021, the U.S. Department of Energy announced $52.5 million in funding for 31 projects to advance next-generation clean hydrogen technologies and support its Hydrogen Earthshot initiative. These projects will focus on technology innovation in integrated hydrogen production, storage, distribution, and utilization, including fuel cells.
2021/11	Infrastructure Investment and Jobs Act	Invest in national infrastructure and establish at least four regional clean hydrogen hubs	• From 2022 to 2026, allocate $5 billion to build the clean hydrogen supply chain and support clean hydrogen production and storage. • Allocate $8 billion to establish at least 4 regional clean hydrogen hubs (H2Hub) to promote clean hydrogen production, storage, transportation, and end-use. • Allocate $1 billion for electrolyzer research and development to reduce the cost of clean hydrogen production. • Establish hydrogen carbon intensity standards and designate a national strategic roadmap.
2022/8	Inflation Reduction Act	Allocate $369 billion over the next 10 years to address energy security and climate change, accelerating the deployment of clean energy technologies like green hydrogen.	• Provide tax credits of up to $3/kg for green hydrogen to further promote the development and application of clean hydrogen.

2022/9	National Clean Hydrogen Strategy and Roadmap	Set long-term goals for hydrogen production, delivery, storage, end-use, and employment	• The U.S. aims to produce 10 million metric tons of clean hydrogen per year by 2030, 20 million metric tons by 2040, and 50 million metric tons by 2050. • Achieving full clean hydrogen production could reduce the U.S.'s total greenhouse gas emissions by about 10% from 2005 levels. • Highlight the demand for hydrogen in the industrial, transportation, and energy storage sectors and forecast future growth. • Propose models and scales for expanding the hydrogen network to prepare for hydrogen export.
2023/6	U.S. National Clean Hydrogen Strategy and Roadmap	Provide a snapshot of current U.S. hydrogen production, transportation, storage, and usage, and outline a strategic framework for achieving large-scale clean hydrogen production and use, exploring scenarios for 2030, 2040, and 2050.	• Hydrogen Production: Gradually reduce hydrogen production costs from $2/kg in 2026 to $1/kg by 2030. Increase production capacity to 10 million metric tons of green hydrogen per year by 2030, while continuously optimizing electrolyzer technology. • Infrastructure and Supply Chain: Focus on improving hydrogen refueling efficiency, storage and transportation technologies, and material recycling rates. The long-term goal is to achieve a large-scale hydrogen supply cost of $4/kg, covering the entire process from production to distribution and refueling. • End-Use Applications and Supporting Technologies: Focus on reducing fuel cell costs, particularly for heavy-duty truck fuel cells, from $170/kW to $80/kW. Also, expand the application of hydrogen in the transportation, industrial, and energy sectors.

Source: Zeng, B., & Zhu, B. (2023, March 17). Hydrogen Energy Series Report (III) – The Current Situation and Prospects of Hydrogen Energy Development in the United States. Zhongtai Securities Research Institute. Retrieved from https://pdf.dfcfw.com/pdf/H3_AP202303201584397701_1.pdf

Table: Review of Key U.S. Hydrogen Policies in Recent Years

Smart Freight Centre China

2 Overview of the Zero-Emission Freight Market and Technology Pathways in the United States

1. General Overview of the Zero-Emission Truck Market

In the United States, the development of zero-emission truck technologies has primarily followed two different technological routes: Battery Electric Trucks (BET) and Fuel Cell Electric Vehicles (FCEV). Both technologies use electricity to power the vehicles, but they differ fundamentally in energy storage and conversion. Battery Electric Trucks store electrical energy directly in battery packs and rely on the power released from the batteries to drive the electric motor. In contrast, Fuel Cell Electric Vehicles use hydrogen as fuel, storing hydrogen in high-pressure tanks, and generating electricity in the fuel cell stack through a chemical reaction between hydrogen and oxygen from the air.

Although battery swapping technology has received strong policy support in China, it has not gained widespread adoption in the United States during its early trials. The U.S. attempted the battery swapping model twice, in 2007 and 2013, but faced numerous challenges during actual operation. Firstly, the initial investment required to establish battery swapping stations was substantial, involving costs for land acquisition, vehicle technology modifications, battery reserves, and the construction of swapping facilities—costs that far exceeded those of regular charging stations. Secondly, the technological standards were not yet mature at that time, with significant differences in battery placement and specifications across different vehicle models, making standardization and interchangeability of batteries difficult. Additionally, the battery swapping model involved complex multi-party interest negotiations, particularly concerning the specialized management of power batteries. Many vehicle manufacturers were concerned about losing control over core technologies, leading to opposition to the battery swapping model. These factors combined have made it difficult for battery swapping technology to gain widespread promotion in the United States.

According to the latest "Zeroing in on Zero-Emission Trucks: Market Update" [10] published by CALSTART, the U.S. electric truck industry made significant progress in 2023. By the end of December 2023, the cumulative number of Zero-Emission Trucks (ZET) deployed in the U.S. had grown to over 30,000 vehicles, with approximately 25,378 new ZETs deployed in 2023 alone, including 1,200 heavy-duty trucks, reflecting a rapid development trend in the industry.

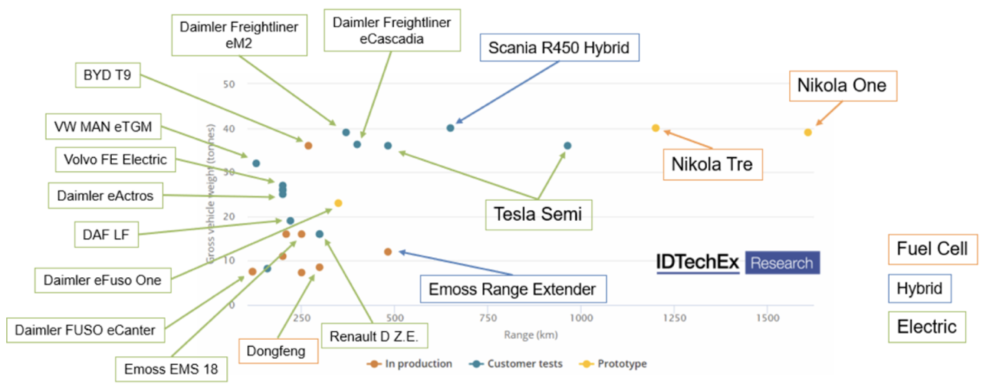

Figure: Overview of Zero-Emission Freight Market Technologies (From: IDTechEx)

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10 Al-Alawi, B. M., & Richard, J. (2024, May). Zeroing in on Zero-Emission Trucks: Market Update. CALSTART. https://calstart.org/wp-content/uploads/2024/05/ZIO-ZET-May-2024-Market-Update_Final.pdf

In terms of vehicle types, box trucks remain the mainstay of zero-emission truck deployments in the United States, with approximately 25,931 units deployed between 2017 and 2023. Other vehicle types deployed during the same period include 1,276 tractor-trailers, 1,162 heavy-duty trucks, 1,070 medium-duty step vans, 534 medium-duty trucks, and 57 garbage trucks, with a total of around 4,000 medium- and heavy-duty trucks.

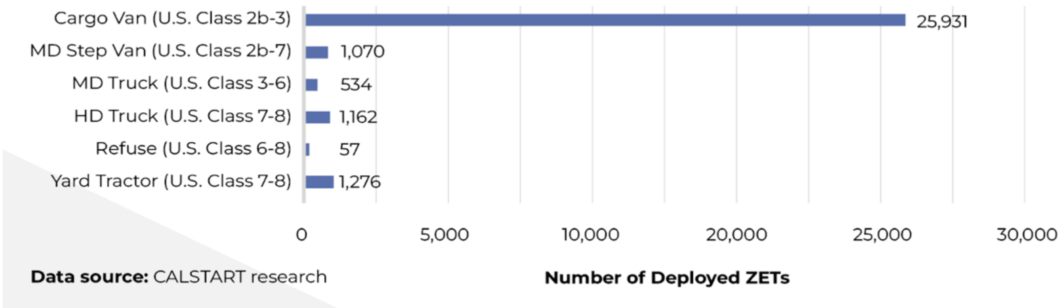

Figure: Cumulative Adoption of Zero-Emission Truck Types in the U.S. (2017–2023)[11]

The rapid development of the U.S. zero-emission truck industry has been driven by multiple factors, including international initiatives, national-level incentives, and state regulatory activities. These factors have collectively contributed to the continuous advancement of zero-emission truck technologies and an increasingly diverse range of vehicle options. For example, in the categories of tractor-trailers, heavy-duty trucks, medium-duty trucks, and medium-duty step vans, the number of available models increased from 91 models utilizing battery-electric and hydrogen fuel cell technologies in 2021 to 144 models available by July 2024, reflecting the industry's innovative vitality. In terms of technology paths, as of 2024, battery-electric remains the dominant choice for zero-emission freight, with a BET to FCEV ratio of 11:1 across all vehicle types, and all tractor-trailers are using BET technology.

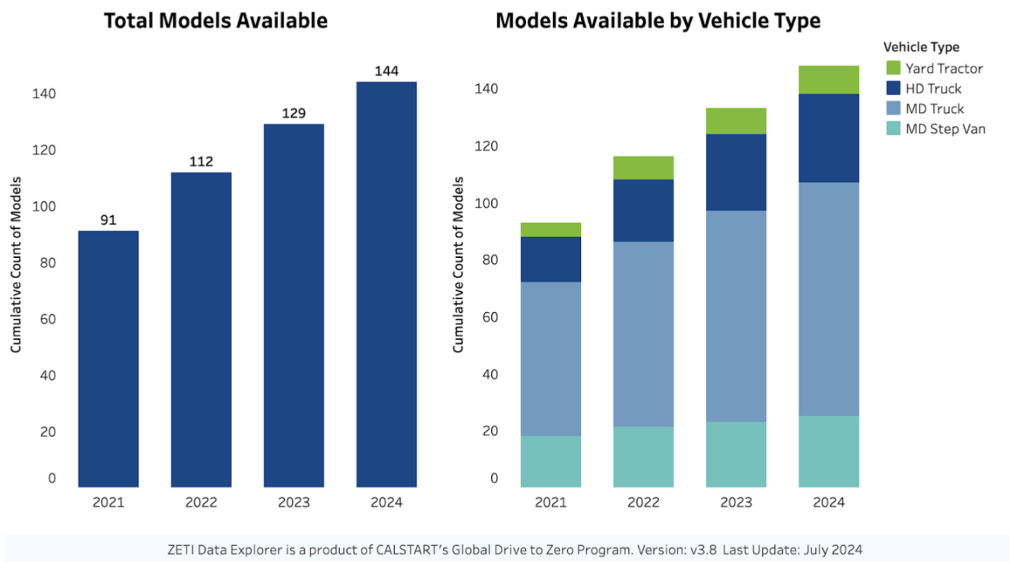

Figure: Available Models of Zero-Emission Medium-Duty Electric Trucks by Category in the U.S.

[11] CALSTART (2024): Drive to Zero's Zero-Emission Technology Inventory Data Explorer. Version 1.5. Available online at: https://globaldrivetozero.org/zeti-data-explorer/

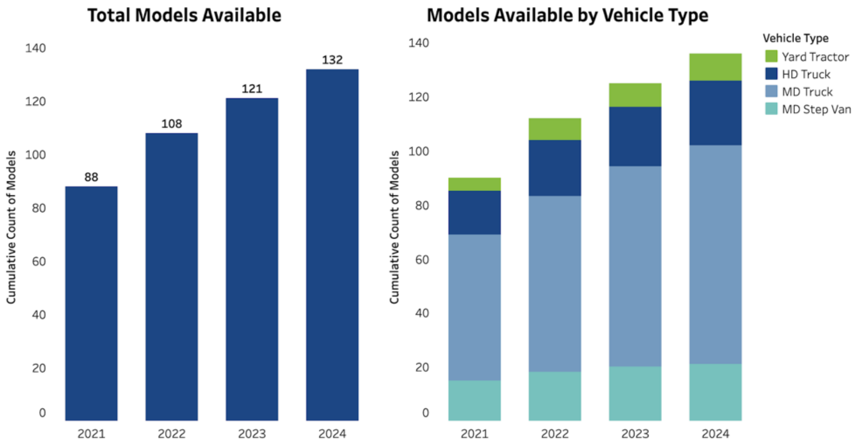

Figure: Available Models of Zero-Emission Heavy-Duty Electric Trucks by Category in the U.S.

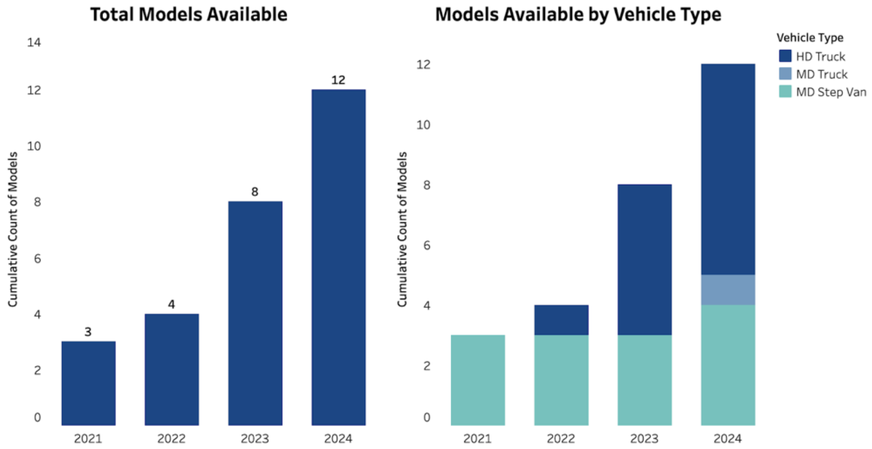

Figure: Available Models of Zero-Emission Hydrogen Fuel Cell Trucks by Category in the U.S.

In the market landscape, the production of zero-emission trucks in the United States has evolved from being dominated by converters in the early stages to now having more than 40 Original Equipment Manufacturers (OEMs) offering at least one zero-emission truck product. Traditional mainstream truck manufacturers such as Freightliner, International, Kenworth, Mack, and Volvo are actively investing in the zero-emission truck market. At the same time, a number of emerging companies such as Battle Motors, Bollinger, Harbinger, Lion, Nikola, Quantron, and Volta are also making their mark in this field, injecting new vitality into the industry.

From the user's perspective, the energy costs of electric trucks and hydrogen fuel cell trucks in the United States have not yet reached parity with diesel trucks. When comparing the energy costs of three different power systems for an 8-class truck traveling 800 kilometers with a full load, diesel trucks still have the lowest refueling costs:

- The energy consumption efficiency of electric trucks is 1.06 kWh/km, with a total energy consumption of 850 kWh for an 800-kilometer journey. At an average electricity price of $0.32/kWh, the refueling cost is $272.
- The efficiency of hydrogen fuel cell trucks is 11.83 kilometers per kilogram of hydrogen, requiring 68 kg of hydrogen for an 800-kilometer journey. At the 2019 average hydrogen price in California of $15/kg, the refueling cost is $1,020.

- Traditional diesel trucks have an efficiency of 2.97 kilometers per liter, requiring 269.36 liters of diesel for an 800-kilometer journey. At a price of $0.92 per liter, the refueling cost is $246.[12]

2. Zero-Emission Truck Technology

The U.S. SuperTruck program is a significant commercial vehicle technology research initiative launched by the U.S. Department of Energy in 2009. The main objectives of the program are to significantly reduce fuel consumption in heavy-duty trucks, improve overall vehicle transportation efficiency, and ultimately achieve zero-emission goals. This ambitious plan is divided into three phases, with each phase setting higher technological goals, driving continuous innovation in the commercial vehicle sector.

The first phase (SuperTruck I) began in 2010 and was completed by 2015, focusing primarily on reducing fuel consumption and improving transportation efficiency for heavy-duty trucks. The second phase (SuperTruck II) was launched in 2016, setting more challenging goals, including increasing engine thermal efficiency to 55%, improving fuel economy by 30%, and more than doubling freight efficiency.

Currently, the program is in its third phase (SuperTruck III), spanning from 2021 to 2025. The U.S. government has invested over $100 million in this phase, focusing on zero-emission heavy-duty trucks, electrification technologies, and the development of charging and hydrogen refueling infrastructure. The primary goal of this phase is to develop an electric or hydrogen-powered heavy-duty truck with a range exceeding 644 kilometers, with load capacity comparable to traditional diesel trucks. Additionally, plans include the development of megawatt-level fast charging facilities or efficient hydrogen refueling stations.

Major U.S. heavy-duty truck manufacturers are actively participating in this project, forming joint development teams with suppliers to advance technology research and development. This collaborative approach accelerates the innovation process and ensures that the research results can be gradually transformed and applied to mass-produced heavy-duty truck products.

In May 2024, the North American Advanced Clean Transportation (ACT) Expo, the largest advanced clean transportation event in North America, was held in Las Vegas, USA. Many commercial vehicle and component companies showcased their latest technological achievements at the event. Kenworth's SuperTruck 2 prototype, as the final model of the SuperTruck II project, demonstrated several breakthrough technologies. Although the SuperTruck II prototype is still a diesel vehicle, its fuel efficiency for heavy-duty trucks is comparable to that of medium-duty trucks in China. At the same time, this model demonstrates forward-thinking consideration for future diversified energy technologies in its design. By increasing the width of the rear chassis from 850mm to 1000mm, it has reserved compatible space for various power systems including diesel, natural gas, pure electric, and hydrogen fuel. This also allows the technologies deployed to be applied to alternative fuel trucks.The SuperTruck program includes projects to demonstrate medium- and heavy-duty hydrogen fuel cell trucks under real-world conditions over the next five years.

Feature	SuperTruck 2	Traditional Heavy-Duty Truck
Aerodynamics	Bullet-shaped design, 48% reduction in drag coefficient, estimated <0.35	Conventional boxy design, higher drag coefficient

[12] The calculation is based on recent average energy prices in the United States or specific regional data and is intended to provide a rough cost comparison. It should be noted that actual operating costs may vary due to market fluctuations, technological advancements, and specific usage scenarios.
Data Sources:
Electric truck energy efficiency: Tesla Semi official data
Electricity price: U.S. Energy Information Administration (EIA), 2023 data
Hydrogen fuel cell efficiency: Hassan, Q., et al. (2023).
Hydrogen Fuel Cell Vehicles: Opportunities and Challenges. Sustainability, 15(3), 2434.
Hydrogen price: Argonne National Laboratory, 2019 California average data Diesel truck efficiency: CSX Corporation, 2023 report
Diesel price: U.S. Energy Information Administration (EIA), 2023 average data

Fuel Efficiency	37 tons total weight, fuel consumption of 18.1L/100km at 100 km/h	Chinese medium-duty truck: 18 tons total weight, highway fuel consumption of 18L/100km
Engine Technology	MX-11 engine, 440 horsepower, 48V mild hybrid system, thermal efficiency of 55.7%	11-liter engine with 400+ horsepower or 13-liter engine with 500+ horsepower, no mild hybrid system
Tire Technology	New concept low rolling resistance tires, CRR of 4.2, vehicle weight reduction of 162 kg	Conventional tires, CRR of about 5.0
Vehicle Weight	Total weight of 11.9 tons for the semi-trailer, 3.2 tons lighter than mainstream	Traditional semi-trailer weighs about 15.1 tons
Cab Design	Mid-mounted cab, 330-degree view, multifunctional sleeper berth	Traditional front-mounted cab, limited view, smaller rest space
Chassis Design	Adjustable stiffness suspension, adaptable to various road conditions	Fixed stiffness suspension, less adaptability
Multi-Fuel Compatibility	Frame width at the rear is 1000mm, compatible with multiple power systems	Usually only compatible with a single fuel system

Source: Commercial Vehicle Zone https://www.cvzone.com.cn/article/detail/id/15316

Table: Comparison Between SuperTruck 2 and Traditional Heavy-Duty Truck Technologies

3. Medium- and Heavy-Duty Electric Trucks

3.1 Vehicle Performance and Levels

When evaluating technical capabilities, battery capacity measured in kilowatt-hours (kWh) is a key indicator of the performance level of battery electric freight trucks. The energy stored in the battery pack directly affects the truck's range, particularly in long-haul operations where charging opportunities are scarce, making range even more critical. Larger batteries can extend the vehicle's range, but if the gross vehicle weight rating (GVWR) remains unchanged, a larger battery might increase the vehicle's curb weight and limit payload capacity. Therefore, improving battery technology to gradually increase energy density is necessary to reduce its impact on payload capacity.

In the United States, the median range for existing medium- and heavy-duty electric trucks is 274 kilometers, with heavy-duty trucks at 256 kilometers, medium-duty trucks at 272 kilometers, and medium-duty step vans at 240 kilometers. [13]The battery capacities for these vehicles typically range between 400 kWh and 700 kWh. Currently, the median range for China's heavy-duty electric trucks is slightly higher at 278 kilometers. When looking at extreme values, the maximum ranges for heavy-duty electric trucks in the United States and China are 805 kilometers for the Tesla Semi and 800 kilometers for the SANY Mota 1165, respectively. According

[13] CALSTART (2024): Drive to Zero's Zero-Emission Technology Inventory Data Explorer. Version 1.5. Available online at: https://globaldrivetozero.org/zeti-data-explorer/

to CALSTART's research, the U.S. electric truck market offers more options for models with ranges exceeding 500 kilometers compared to China.

Overall, in the U.S. market, automotive manufacturers are introducing a range of electric trucks with high-capacity batteries to meet diverse transportation needs. In the heavy-duty truck segment, some manufacturers have launched trucks with ultra-high-capacity batteries. Tesla leads the market with a 1,000 kWh battery, followed by Nikola with a 753 kWh battery and Futuricum with a 680 kWh battery. The emergence of these high-capacity batteries represents a significant technological breakthrough in heavy-duty electric trucks, potentially greatly enhancing the feasibility of long-haul transport. In the medium-duty truck segment, the U.S. and European markets offer more diversified specifications and generally higher battery capacities. Leading manufacturers such as Freightliner, International, Peterbilt, and Kenworth offer battery specifications ranging from 282 kWh to 325 kWh. For box trucks, battery capacities in the U.S. market are generally higher than those in the Chinese market.[14]

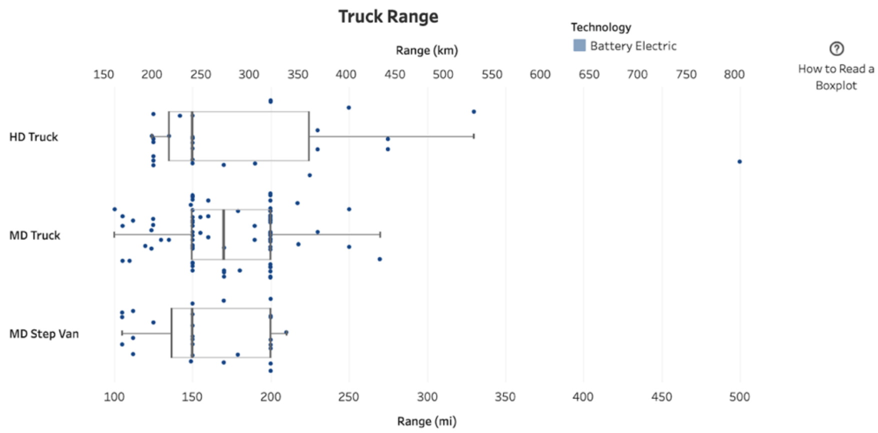

Figure: Distribution of Medium- and Heavy-Duty Truck Ranges in the U.S.

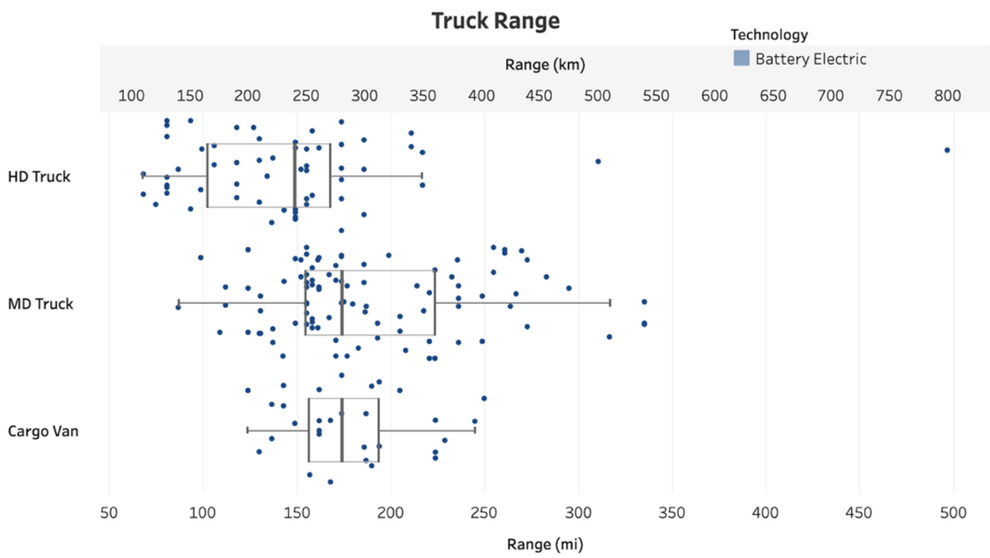

Figure: Distribution of Medium- and Heavy-Duty Truck Ranges in China

[14] Qiu, Y., Song, S., & McLane, R. (2022). Zero-emission truck performance in the US and Europe and its implications for China. CALSTART. https://globaldrivetozero.org/site/wp-content/uploads/2022/05/EFC-Task-2_CH.pdf

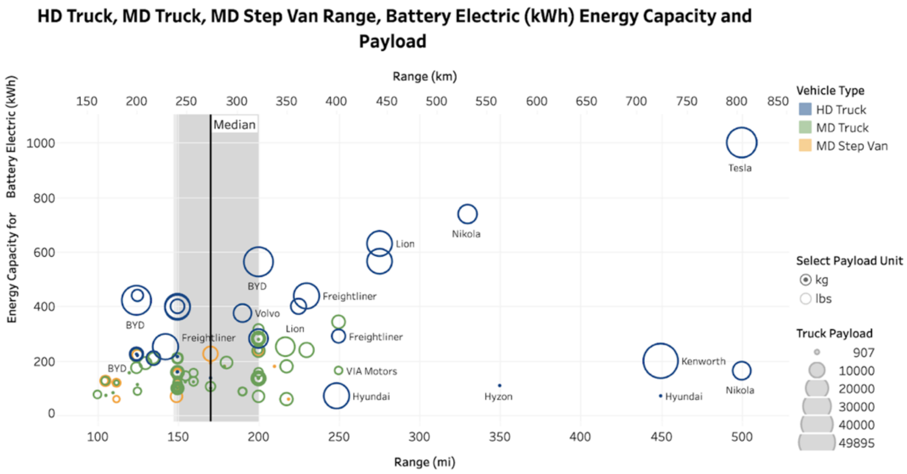

Figure: Distribution of Medium- and Heavy-Duty Truck Range, Battery Capacity, and Payload in the U.S.

The table below comprehensively presents the technical specifications of the top five electric heavy-duty truck models available in the U.S. market in terms of single-charge range, covering models from major manufacturers such as Tesla, Nikola, Volvo, Lion, and Freightliner. From the technical parameters, the Tesla Semi stands out in several key metrics, particularly in range, charging speed, battery capacity, and charging power. The Semi uses standard lithium-ion batteries and is equipped with megawatt charging technology. Its maximum range of 805 kilometers and ability to charge to 70% in 30 minutes enhance the economic efficiency of freight operations. Additionally, the Tesla Semi's energy efficiency reaches 2.0 kWh/mile, surpassing other competitors, highlighting its advantages in energy management systems and overall vehicle system optimization.

Currently, the Tesla Semi is in small-scale production, primarily used for internal Tesla transportation; it is expected to produce 500-1,000 units in 2024, with a long-term goal of reaching an annual production capacity of 50,000 units.[15]

OEM	Model	Maximum Range (km)	Charging Speed	Horsepower	Battery Capacity	Charging Power	Energy Efficiency (kWh/mile)	Battery Weight (kg)	Charging Connector Type
Tesla	Semi	805	30 minutes to 70% charge	> 1,000 hp	1,000 kWh	840 kW-1,400 kW	2	9,072-10,433	Proprietary Connector
Nikola	Tre BEV	531	90 minutes to 80% charge	645 hp	733 kWh	175 kW-350 kW	NA	Not disclosed	CCS1
Volvo	VNR Electric	443	90 minutes to 80% charge	455 hp	565 kWh	250 kW	2.2	3,629-5,443	CCS1

[15] Cooban, A. (2023, July 19). Musk said Tesla will build 50,000 Cybertrucks a year. Analysts say it's likely to be far fewer. Yahoo Finance. https://finance.yahoo.com/news/musk-said-tesla-build-50-203017245.html

Lion	Lion8	418	90 minutes to 80% charge	670 hp	630 kWh	500 kW	2.51	Not disclosed	CCS1
Freightliner	eCascadia	402	90 minutes to 80% charge	470 hp	438 kWh	270 kW	2.2		

Table: Top 5 Electric Heavy-Duty Truck Models by Range in the U.S. Market

3.2 Battery Technology

3.2.1 Battery Systems for Heavy-Duty Electric Trucks: Technical Features and Application Analysis

The battery systems of heavy-duty electric trucks differ significantly from those of passenger vehicles, mainly due to the specific usage scenarios and working conditions of commercial vehicles. Heavy-duty commercial vehicles typically operate 350 days a year, working 16 to 22 hours daily, facing extreme temperature fluctuations from -30°C to +50°C and intense road vibrations. Additionally, towing heavy loads requires the motor to generate high torque, which imposes high current loads on the battery system. These harsh operating conditions present severe challenges to battery design.[16]

Electric truck energy efficiency typically ranges between 1-2 kWh per mile (0.62-1.24 kWh per kilometer), which is 2-3 times that of passenger vehicles. This directly determines the battery capacity needed to achieve specific driving distances. For example, the Tesla Semi is equipped with a battery pack of up to 875 kWh, providing a range of 500 miles (800 kilometers). The Volvo VNR Electric series has a slightly smaller battery capacity of 565 kWh, with a range of approximately 275 miles (450 kilometers). Actual driving distance can be affected by factors such as road conditions and payload.

The battery systems of heavy-duty electric trucks usually consist of 4 to 6 large battery packs connected in parallel, with each pack providing about 100 kWh of energy, for a total capacity of 400-600 kWh. This large capacity design enables trucks to travel hundreds of kilometers on a single charge, meeting the demands of long-haul transport. Each battery pack operates at 400 volts, with newer designs reaching up to 800 volts. High-voltage systems improve efficiency and support fast charging. During peak power output, such as rapid acceleration or climbing hills, the motor may draw more than 1,000 amps from the battery system to meet the instantaneous high power demands of heavy-duty trucks.

Two common battery cell specifications are used: 2170 (21 mm in diameter, 70 mm in height) and 4680 (46 mm in diameter, 80 mm in height). The typical charging capacity of a 2170 cell is about 5 ampere-hours, while a 4680 cell is around 9 ampere-hours. A 100 kWh battery pack requires approximately 5,200 2170 cells or 2,900 4680 cells. The battery pack uses a hybrid series-parallel connection internally. 96 cells connected in series can reach nearly 400 volts, while newer architectures with 192 cells in series can reach 800 volts. Each series unit consists of 15 to 30 parallel battery cells. This design ensures both high voltage output and the ability to supply large currents.

Given the harsh working environment of trucks, these battery cells are installed in heavy-duty steel enclosures equipped with cooling plates, providing additional mechanical and vibration protection while managing battery temperature to extend their lifespan. Each battery pack weighs between 500 and 600 kilograms, and a truck with six battery packs weighs nearly 3,600 kilograms. Although this additional weight reduces some cargo capacity, its overall impact on long-haul transport economics is relatively limited. As battery pack complexity increases, the role of the Battery Management System (BMS) becomes crucial. Each battery pack has a dedicated BMS responsible for monitoring and diagnostic functions. In heavy-duty trucks, an additional master

[16] Maluf, N. (2023, May 24). Rethinking electric truck design. EE Power. https://eepower.com/industry-articles/rethinking-electric-truck-design/

BMS unit is required to manage the coordinated operation of multiple parallel battery packs, ensuring the safety and efficiency of the entire system.[17]

3.2.2 Technical Routes for Heavy-Duty Electric Truck Battery Systems

In terms of technical routes, lithium-ion batteries continue to dominate the U.S. electric truck market due to their high energy density and relatively stable lifecycle. Two main lithium-ion battery chemistries dominate the market for medium- and heavy-duty zero-emission vehicles as well as light vehicles: Nickel-based (including Nickel Manganese Cobalt (NMC) and Nickel Cobalt Aluminum (NCA)) and Lithium Iron Phosphate (LFP).

- Nickel-based Chemistries (NMC, NCA): These chemistries are known for their high energy storage capacity. NMC and NCA batteries are particularly suitable for long-haul trucks because of their higher energy density, which enables longer charging distances. However, these chemistries also raise concerns about cobalt scarcity and safety issues related to thermal stability.
- Lithium Iron Phosphate (LFP): LFP chemistry is favored for its cost-effectiveness, durability, and safety. Although it offers lower energy density, making it less suitable for long-distance applications, its robustness and lower cost make it a preferred choice for vehicles prioritizing safety and longevity.

Given the complexity of batteries, the development and adoption of next-generation battery technologies are expected to be gradual, requiring long-term research and development and complex manufacturing processes. Over the next five years, battery manufacturers are likely to make incremental modifications to existing chemistries to enhance performance and safety while reducing costs. These improvements may include adjustments to electrode and electrolyte compositions and structures to improve efficiency and lifecycle. Within a decade, ongoing innovative technologies are expected to be validated and promoted, including:

- Silicon Anodes: Expected to increase the capacity of traditional lithium-ion batteries by using silicon, which can accommodate more lithium than graphite.
- Solid-State Batteries: Offering the potential for higher energy density and increased safety by replacing liquid electrolytes with solid ones.
- Sodium-Ion Batteries: As a cost-effective alternative to lithium-ion systems, especially favorable for stationary storage applications due to abundant materials.

The technical parameters of various batteries in the U.S. market are summarized as follows:

Characteristic	LFP	NCM	NCA
Cathode Material	Lithium Iron Phosphate	Lithium Nickel Manganese Cobalt Oxide	Lithium Nickel Cobalt Aluminum Oxide
Energy Density (Wh/kg)	130-160	180-250	250-325
Cycle Life (cycles)	10,000-20,000	5,000-10,000	5,000-10,000
Safety	Safe	Safe	Less Safe

Table: Characteristics of Common Lithium-Ion Battery Chemistries[18]

[17] Maluf, N. (2023, May 24). Rethinking electric truck design. EE Power. https://eepower.com/industry-articles/rethinking-electric-truck-design/

[18] Clemens, K. (2023, April 26). Tesla Kicks Off Future of LFP Batteries in EVs. EEPower. https://eepower.com/tech-insights/tesla-kicks-off-future-of-lfp-batteries-in-evs/#

Overall, LFP batteries are a good choice for applications where cost and safety are the primary considerations. When energy density and performance are the top priorities, NMC and NCA batteries are better options. For example, electric vehicles increasingly use LFP batteries as a more cost-effective and sustainable alternative to traditional lithium-ion batteries. Tesla uses LFP batteries in the 300-mile (480 km) version of the Semi Light, while nickel-based lithium batteries are used in the 500-mile (800 km) version.

Current battery technology limits its application in long-haul freight trucks. This limitation primarily arises from the gap between the high energy demands of long-haul trucks and the performance of existing battery technology. A typical 8-class truck consumes 1.7 kWh of energy per kilometer at a speed of 112 km/h. To enable an electric truck to travel 800 kilometers on a single charge, a battery pack with a capacity of 1.7 MWh (assuming 80% usable) would be required.

However, even with more advanced battery technologies, such as lithium titanate, with a gravimetric energy density of 200 Wh/kg and a volumetric energy density of 400 Wh/L, the battery pack would weigh 8.4 tons and occupy 4,218 liters of space to achieve the required 1.7 MWh capacity. This weight and volume would significantly impact the truck's payload capacity and space utilization.

3.3 Technology Maturity Assessment - Run-on-Less Electric

In January 2022, the Run-on-Less Electric (RoL-E) project released significant research findings. This project conducted comprehensive tests on 13 commercial battery-electric trucks in real-world conditions across eight U.S. states. These electric vehicles covered multiple categories, including Class 8 yard tractors, Class 8 regional haul tractors, Class 6 medium-duty box trucks, and Class 3-5 medium-duty step vans and walk-in vans. The study utilized a comparative analysis method, comparing these electric vehicles with diesel trucks of the same categories to assess whether electric vehicles could meet the daily operational requirements. The report indicated that the technology of these electric trucks is sufficiently mature to handle the duty cycles and task requirements traditionally fulfilled by diesel trucks across all vehicle categories.

However, the study also identified some challenges. Specifically, for the application of heavy-duty trucks in long-haul or specific regional transport, battery-electric trucks still face some difficulties. For instance, in scenarios involving unpredictable dynamic routes, longer driving distances, extended waiting times, and situations where drivers cannot return to base daily, battery-electric trucks still face challenges in fully replacing diesel trucks (NACFE, 2022a).[19]

Vehicle Type	Daily Distance or Operating Time	Speed	Duty Cycle and Use Case
Yard Tractor	10-22 hours per day	Mostly below 20 mph	Single to multiple shifts, fixed routes
Heavy-Duty Regional Tractor	Less than 300 miles per day	Mostly below 40 mph	Single shift, return to base, regional haul, fixed routes
Medium-Duty Box Truck	Less than 120 miles per day	Mostly below 40 mph	Return to base, local pickup and delivery, variable routes
Medium-Duty Step Van	Less than 50 miles per day	Mostly below 40 mph	Return to base, urban delivery or last-mile delivery, fixed routes
Cargo Van	Less than 100 miles per day	Mostly below 40 mph	Return to base, urban delivery or last-mile delivery, fixed routes

Table: Duty Cycles of Heavy-Duty Battery-Electric Freight Trucks in the Run-on-Less Electric Project[20]

[19] North American Council for Freight Efficiency. (2024). Electric Truck Depots Are Evolving: How 10 Fleets Grew Their BEV Populations. https://nacfe.org/research/run-on-less/run-on-less-electric-depot/

[20] Qiu, Y., Song, S., & McLane, R. (2022). Zero-emission trucks in the United States and Europe: Performance and implications for China. CALSTART. https://globaldrivetozero.org/site/wp-content/uploads/2022/05/EFC-Task-2_CH.pdf

4. Medium- and Heavy-Duty Hydrogen Fuel Cell Trucks

4.1 Vehicle Performance and Levels

Although most zero-emission trucks currently rely on battery-electric technology, the availability of hydrogen fuel cell trucks is gradually increasing. As of July 2024, the U.S. medium- and heavy-duty truck market offers 12 hydrogen fuel cell models, 58% of which are heavy-duty trucks. Compared to battery-electric trucks, fuel cell heavy-duty trucks have faster refueling times, which is crucial for fleets to reduce daily operational downtime. Additionally, fuel cell heavy-duty trucks have a longer range compared to similarly equipped battery-electric trucks. Fuel cell technology is becoming more mature and optimized for heavy-duty applications, ultimately achieving ranges and refueling times similar to conventional vehicles while meeting zero-emission goals. This makes fuel cell heavy-duty vehicles likely candidates to replace diesel and battery-electric heavy-duty trucks in the future. According to the latest "Hydrogen Economy Roadmap," the total number of fuel cell vehicles is expected to grow to 150,000 (including light, medium, and heavy-duty FCEVs) by 2025, along with 125,000 fuel cell forklifts.

Overall, hydrogen fuel cell heavy-duty trucks are increasingly becoming the focus of the transportation industry due to their advantages in fast refueling and long-range capabilities. Currently, a typical long-range heavy-duty hydrogen fuel cell truck is equipped with two hydrogen tanks, each capable of storing 40-60 kilograms of hydrogen at 350 bar pressure. With one refueling, these heavy-duty vehicles can travel 500-1,000 miles, demonstrating excellent range capabilities.[21] According to compiled driving cycle data, the hydrogen fuel efficiency of Class 8 vehicles ranges from 5.5 to 9.2 miles (8.85 to 14.81km) per kilogram of hydrogen. In terms of refueling, the refueling rate for heavy-duty trucks is approximately 120 grams per second, meaning that a complete refueling process takes about 16 minutes.[22]

Overall, the current technology comparison between different powertrain systems for heavy-duty vehicles is as follows:

	Diesel Engine	Battery	Hydrogen Fuel Cell
Tailpipe Emissions	Yes	No	No
Total Vehicle Cost	$119,000–$134,000	$164,641–$585,000	$135,503–$249,900
Well-to-Tank Efficiency	~86%	~55.3%	~76%
Tank-to-Wheel Efficiency	~23%	~68%	~45%
Fuel Consumption	2.76 km/L	0.31 km/kWh	5.5–9.2 miles/kg of hydrogen
Range	1569–3138 km	100–805 km	1062–1777 km
Refueling Time	6–12 minutes	2.85–20 hours	16.67 minutes
Specific Energy	42.9 MJ/kg	0.432–0.792 MJ/kg	118 MJ/kg

1. Total vehicle cost is based on a specific case study conducted in California. Data sourced from the University of California, Davis: National Center for Sustainable Transportation.
2. For comparison purposes, fuel well-to-tank efficiency is based on the same pathway (natural gas as the source).

Table: Comparison of Three Powertrain Systems for Heavy-Duty Vehicles[23]

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[21] Fakhreddine, O., Gharbia, Y., Derakhshandeh, J. F., & Amer, A. M. (2023). Challenges and Solutions of Hydrogen Fuel Cells in Transportation Systems: A Review and Prospects. World Electric Vehicle Journal, 14(6), 156. https://doi.org/10.3390/wevj14060156

[22] H2 MOBILITY Deutschland GmbH & Co. KG. (2021). Overview Hydrogen Refuelling For Heavy Duty Vehicles. https://h2.live/wp-content/uploads/2022/03/H2M_Overview_HDV_Refuelling_2022.pdf

[23] Hassan Q, Azzawi IDJ, Sameen AZ, Salman HM. Hydrogen Fuel Cell Vehicles: Opportunities and Challenges. Sustainability. 2023; 15(15):11501. https://doi.org/10.3390/su151511501

The following table lists the top four hydrogen fuel cell heavy-duty truck models in the U.S. market in terms of range, which are either in pilot testing or early production phases.

OEM	Model	Maximum Range (km)	Refueling Time	Maximum Speed	Continuous Power	Hydrogen Storage Capacity
Nikola	Tre FCEV	1,448	Less than 20 minutes	70 mph	536 hp	70 kg
Kenworth	T680	724	20–30 minutes	70 mph	415 hp	58.8 kg
Hyundai	XCIENT Chassis	724	8-20 minutes	57 mph	469 hp	31 kg
Hyzon	HYZON CLASS 8	563	15 minutes	55-65 mph	612 hp	50 kg

Table: Top 4 Hydrogen Fuel Cell Medium- and Heavy-Duty Trucks by Range in the U.S. Market

Several hydrogen fuel cell heavy-duty trucks have already reached mass production and commercial application. For instance, Nikola's Tre FCEV and Hyzon's Class 8 trucks have entered mass production and have been delivered to customers. Their ranges reach 1,448 kilometers and 563 kilometers, respectively, showcasing the efficiency and reliability of hydrogen fuel cell technology in actual operations.

Meanwhile, the collaboration project between Kenworth and Toyota is also progressing steadily, with their T680 and Peterbilt 579 models currently in the pilot phase and expected to be commercialized by 2024. These models have undergone real-world operational testing at locations like the Port of Los Angeles, showing strong performance and market adaptability. Hyundai's XCIENT Fuel Cell truck, with a range of 724 kilometers and a refueling time of 8 to 20 minutes, is already on sale in multiple markets.

In addition to mass-produced models, several new models are under development, such as Honda's Class 8 hydrogen fuel cell truck and Ineos's Grenadier Hydrogen FCEV. These models are expected to be launched in the coming years, offering more options to the market.

4.2 Current Status of Fuel Cell Technology

Currently, in the commercial vehicle sector, Proton Exchange Membrane Fuel Cells (PEMFC) are the primary short-term technological focus, while solid oxide fuel cells have potential in storage and other fields for medium to long-term development. The automotive industry is a key application area for proton exchange membranes.

In 2024, the U.S. Hydrogen and Fuel Cell Technologies Office updated its "Multi-Year Plan," outlining a series of detailed plans to achieve the goal of "realizing affordable clean hydrogen and fuel cell technologies to achieve a sustainable, resilient, and equitable net-zero emissions economy":

- By 2026, the cost of producing clean hydrogen is expected to be $2 per kilogram, and by 2031, it is expected to be $1 per kilogram.
- By 2026, the cost of electrolyzer systems is expected to be $250 per kilowatt (for low-temperature electrolyzers) and $500 per kilowatt (for high-temperature electrolyzers).
- By 2028, dispensed hydrogen cost for heavy-duty vehicles of $7 per kilogram
- By 2030, the cost of fuel cell systems for heavy-duty trucks is expected to be $80 per kilowatt.

Within the hydrogen fuel cell sub-program, the near- to mid-term focus is on developing efficient, long-life, low-cost fuel cells for heavy-duty trucks. The long-term focus is on developing advanced materials and components for next-generation fuel cells for various applications. The next-generation fuel cell technologies under development include:

- Platinum-free proton exchange membrane fuel cells
- Anion exchange membrane fuel cells

- Bipolar membrane fuel cells
- Direct liquid fuel cells
- Intermediate-temperature fuel cells (operating temperatures between 150°C and 500°C)
- Reversible fuel cells
- Fuel cell cogeneration concepts.

Currently, significant progress has been made in the technology of fuel cell systems for heavy-duty trucks in the U.S., particularly in cost reduction. Research shows that as production scales up, the cost of fuel cell systems has significantly decreased. For example, when the annual production reaches 50,000 units, the cost of a 275 kW net power Proton Exchange Membrane Fuel Cell (PEMFC) system drops from $302 per kilowatt to $179 per kilowatt, and when the annual production reaches 100,000 units, the cost further drops to $170 per kilowatt. The system costs in 2021 and 2022 were $196 per kilowatt and $179 per kilowatt, respectively, and it is expected to drop to $140 per kilowatt by 2025 and further to $80 per kilowatt by 2030, with a long-term goal of $60 per kilowatt.[24]

Catalysts account for the largest proportion of fuel cell system costs. In catalyst development, the best catalyst in 2023 was identified as PtCo embedded in ZIF carbon. After 90,000 accelerated stress test (AST) cycles, this catalyst showed significant performance improvements. Further evaluations ensure that it meets the 25,000-hour operational requirement for heavy-duty vehicle drive cycles. These advances indicate that the performance of Membrane Electrode Assemblies (MEA) improved by 17% and 47% in 2021 and 2023, respectively, when using innovative embedded catalysts and support materials, significantly enhancing the feasibility and efficiency of hydrogen fuel cells in heavy-duty transportation.[25]

Moreover, significant progress has been made in electrode technology for high-power density fuel cells. Grooved electrode designs have been shown to improve power density by up to 50% compared to flat electrodes made from the same material, particularly under the dry conditions required by heavy-duty vehicles. This design significantly improves fuel cell performance by separating oxygen and proton transport into different channels.

To commercialize heavy-duty fuel cell trucks, the durability of fuel cell systems must approach the level of stationary systems. Currently, the lifespan of stationary systems is at least 10,000 hours. For a long-haul Class 8 truck traveling 104,000 miles (about 167,400 kilometers) per year, considering an average highway and off-road speed of 65 miles per hour (104 kilometers per hour), the annual operating time is about 1,600 hours. Therefore, to avoid replacement within five years, fuel cells need to have a durability threshold of at least 8,000 hours. Although there are some differences in durability requirements between trucks and passenger cars, recent test results suggest that PEMFC technology already meets the durability requirements for long-haul Class 8 trucks.[26]

Several methods for storing hydrogen on trucks have been developed, including high-pressure, cryogenic technology, metal hydrides, and absorptive carbon. Among them, compressed hydrogen in carbon fiber reinforced composite tanks (5,000-10,000 psi) and cryogenic liquid hydrogen at -20°C in insulated tanks are relatively mature technologies and have been the primary methods for onboard hydrogen storage. Current research focuses on reducing the cost of carbon fiber composites, which account for about 75% of the cost of compressed hydrogen storage tanks. For heavy-duty truck applications, cryogenic hydrogen storage may be the best option due to its relatively high volumetric energy density. However, this method still requires further development of insulation technology and engineering design to balance liquefaction energy and boil-off effects.

In 2020, the energy density and cost targets for onboard hydrogen storage systems were set at 1.8 kWh/kg system (5.5 wt%), 1.3 kWh/L system (0.04 kg H2/L), and $10/kWh ($333/kg stored hydrogen capacity). Long-

[24] U.S. Department of Energy. (2022). 2022 Cost Projections of PEM Fuel Cell Systems for Heavy-Duty Vehicles. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/23002-hd-fuel-cell-system-cost-2022.pdf?Status=Master

[25] U.S. Department of Energy. (2023). Fuel Cell Technologies – 2023: FY 2023 Merit Review and Peer Evaluation Report. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/2023-amr-07-fuel-cell-technologies.pdf

[26] U.S. Department of Energy. (2021, January 7). Durability-Adjusted Fuel Cell System Cost (Record #21001). DOE Hydrogen Program Record. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/21001-durability-adjusted-fcs-cost.pdf

haul fuel cell trucks need to carry at least 70 kilograms of hydrogen (95% usable) to achieve a maximum daily driving range of 500 miles. Based on data from 10,000 psi hydrogen storage tanks, the hydrogen storage unit is large (1,600 kilograms, 3,000 liters) and costs about $35,000. Therefore, the size and storage cost of hydrogen storage containers are major challenges for long-haul truck fuel cells. However, detailed information on the characteristics of hydrogen storage tanks specifically developed for truck applications is still limited.[27]

[27] U.S. Department of Energy. Hydrogen Storage https://www.energy.gov/eere/fuelcells/hydrogen-storage

3 Overview of the Zero-Emission Freight Infrastructure in the United States

1. Electric Truck Recharging Infrastructure

1.1 Overview

Infrastructure development is a key challenge in achieving zero emissions in the transportation sector. According to the latest statistics from the U.S. Department of Energy's Alternative Fuels Data Center (AFDC), as of July 2024, the United States had a total of 68,000 charging stations (including private and public), with nearly 193,000 individual chargers/connectors. However, in terms of electrification of medium- and heavy-duty trucks, the U.S. is still in its early stages.[28]

Specifically:

1. Medium-Duty Trucks (Class 3-5):
   - Available charging stations: 498 (426 public, 66 private)
   - Individual chargers/connectors: Approximately 1,600
   - DC fast charging stations: 86, with 368 fast chargers
2. Heavy-Duty Trucks (Class 6-8):
   - Available charging stations: Approximately 126 (90 public, 36 private)
   - Individual chargers/connectors: 475
   - DC fast charging stations: 37, with 184 fast chargers

In terms of geographical distribution, DC fast chargers are mainly concentrated in California. Given the expected continued growth in the market penetration of electric trucks and relevant government policy requirements, the United States urgently needs to accelerate the pace of DC fast charging station construction.

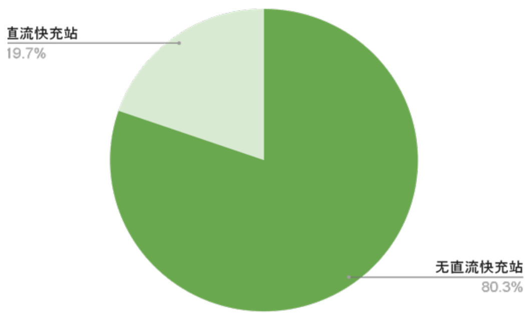


Figure: Proportion of Charging Station Types Suitable for Medium- and Heavy-Duty Trucks

[28] U.S. Department of Energy, Alternative Fuels Data Center, https://afdc.energy.gov/fuels/electricity-locations#/analyze?country=US&tab=station&fuel=ELEC&maximum_vehicle_class=MD&access=public&access=private， Access Date：7/2024

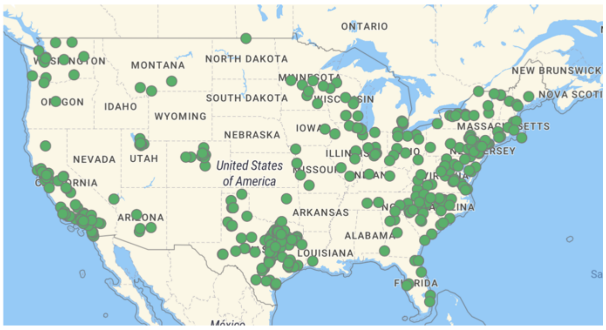


Figure: Distribution of Medium-Duty Truck Charging Stations

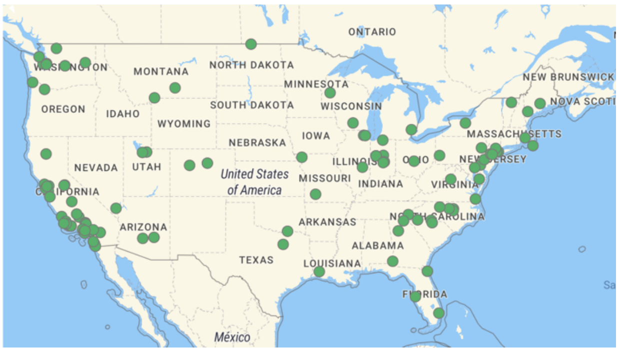


Figure: Distribution of Heavy-Duty Truck Charging Stations

Overall, the spatial distribution of charging stations in the U.S. is uneven: Most public charging stations are located in the highly urbanized areas of the Northeast (New England states) and Western states (California, Oregon, Washington), while parts of the Midwest and South severely lack charging infrastructure.

In terms of charging methods, medium- and heavy-duty trucks in the U.S. currently have several options. These vehicles can charge at lower power levels overnight or use fast or ultra-fast charging equipment during breaks in daily operations, the latter known as "opportunity charging." Opportunity charging equipment can be installed at private sites (such as warehouses and logistics centers) or public charging stations. For vehicles that return to the same location daily, such as sanitation trucks, buses, and last-mile delivery vehicles, overnight charging equipment can be installed at their docking locations. Additionally, dedicated overnight charging stations can be set up in public areas.

The U.S. is heavily investing in charging infrastructure for medium- and heavy-duty trucks. According to estimates by Atlas Public Policy, the total planned investment is approximately $30 billion. This large sum will support various medium- and heavy-duty truck projects at all levels, from federal to local.[29]

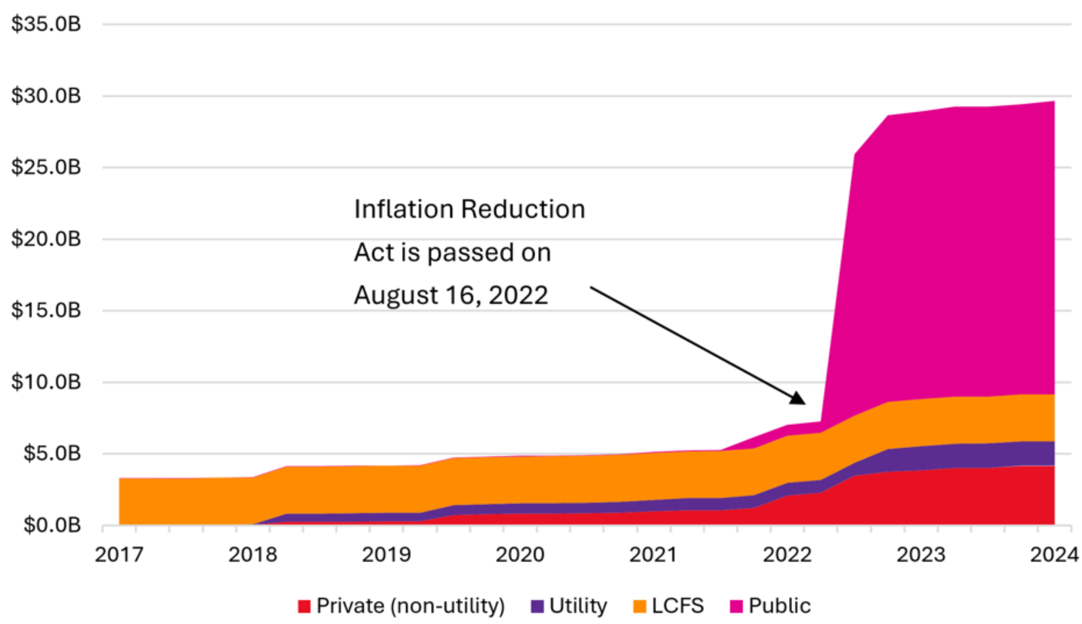
Regarding funding sources, about 70%, or $21 billion, comes from federal funds, mainly supported by the Inflation Reduction Act and the Bipartisan Infrastructure Law. The remaining 30%, or $9 billion, comes from other sources, including state and local governments, utilities, and private sector investments.

To advance development in this area, the U.S. government has taken several initiatives. The U.S. Department of Transportation has established a five-year "Charging and Fueling Infrastructure Grant Program." This program, based on the Bipartisan Infrastructure Law, provides $700 million in grants for fiscal years 2022 and 2023. These funds will be used to build charging stations and alternative energy refueling facilities (such as hydrogen) in areas with weak infrastructure in urban and rural regions. This is an important step toward achieving the Biden administration's goal of building 500,000 new electric vehicle charging stations and alternative energy refueling facilities nationwide.

[29] Atlas EV Hub. (n.d.). NEW: Estimated $30 Billion for Medium-and Heavy-Duty Charging Infrastructure. Atlas Public Policy. From https://www.atlasevhub.com/weekly-digest/new-estimated-30-billion-for-medium-and-heavy-duty-charging-infrastructure/

Meanwhile, the Department of Energy announced a $72 million investment in the "SuperTruck: Charging" program. This program aims to demonstrate how to integrate vehicles with the grid, enabling parking lots and truck stops to provide affordable and reliable charging services while improving grid resilience. The program focuses on accelerating the broad construction of the charging infrastructure needed for medium- and heavy-duty electric trucks. These initiatives are collectively advancing the electrification of medium- and heavy-duty trucks and the transition to clean energy in the United States.

In addition to government support, private sector investment in medium- and heavy-duty truck infrastructure is also seeing significant growth. By the end of 2023, private investment is expected to reach $4.2 billion. While California remains the largest investment market, other states are quickly following suit, narrowing the gap. Currently, at least 278 fleets have committed to investing in electric medium- and heavy-duty trucks. These include well-known companies such as e-commerce giant Amazon, brewer Anheuser-Busch, and food distribution company Sysco.



Source: https://www.atlasevhub.com/weekly-digest/new-estimated-30-billion-for-medium-and-heavy-duty-charging-infrastructure/

Figure: Estimated cumulative investments in MDHD charging by announcement date as of December 2023

1.2 Electric Vehicle Charging Connectors/Chargers

Currently, the U.S. primarily uses three types of charging standards and corresponding chargers/adapters:

1. Level 1 AC Charging: Uses the J1772 standard connector. Mainly used for home charging, powered through a 120V AC outlet. It accounts for less than 1% of public charging facilities, with only 6 Level 1 charging stations dedicated to medium- and heavy-duty trucks.

J1772 connector

2. Level 2 AC Charging: Primarily uses the J1772 standard connector, and also supports the NACS (North American Charging Standard) connector. NACS was initially a proprietary standard for Tesla but is rapidly becoming the new industry standard. Tesla vehicles can use the NACS connector for Level 2 charging,

including Tesla's own destination chargers and home chargers. Additionally, all Tesla models come with a J1772 adapter, allowing them to use non-Tesla Level 2 charging equipment. Level 2 charging typically uses 240V (residential) or 208V (commercial) power, with output power ranging from 2.9 to 19.2 kW. As of 2022, nearly 80% of public charging ports in the U.S. were Level 2. All commercial electric vehicles are compatible with Level 1 and Level 2 charging.


J1772 connector


J3400 (NACS) connector

3. DC Fast Charging: Uses CHAdeMO, CCS (Combined Charging System), and NACS standard connectors. Tesla vehicles can directly use the NACS connector for fast charging. These are primarily installed in busy corridors for fast charging. As of 2022, over 20% of public charging ports in the U.S. were DC fast chargers. With the increasing adoption of medium- and heavy-duty electric trucks and the planning of zero-emission freight corridors, DC fast charging facilities are expected to increase.


CCS connector


CHAdeMO connector


J3400 (NACS) connector

Introduction to the three types of DC fast charging systems:

- SAE Combined Charging System (CCS): The CCS connector (also known as the SAE J1772 Combo) is currently the most common choice on the market. Its advantage is that it can accommodate AC Level 1, Level 2, and DC fast charging using the same charging port, with two additional lower pins added during DC fast charging. Most electric vehicle models support CCS connector charging.
- CHAdeMO: This is another common type of DC fast connector, promoted by Japanese automakers. While it remains common in certain regions, its usage is gradually declining.
- J3400 (NACS): SAE International is developing a standardized J3400 connector based on Tesla's NACS connector. This connector is suitable for all charging levels, including Tesla's Supercharger. It's worth noting that although Tesla vehicles do not have CCS or CHAdeMO charging ports, they are equipped with adapters that can provide up to 19.2 kW of power with CCS or CHAdeMO connectors. Additionally, Tesla sells full-power adapters to support the complete charging capabilities of these connector types.

As the J3400 (NACS) standard is being promoted, several automakers have announced plans to adopt this connector as early as 2025. This move will allow non-Tesla electric vehicles to use J3400 connectors at Tesla charging stations, further enhancing the universality and convenience of charging facilities.

This trend toward standardization reflects a collective effort in the electric vehicle industry to simplify the charging experience and improve compatibility, which is expected to significantly improve electric vehicle charging infrastructure in the coming years.

Charging Type	Maximum Charging Power
Level 1	1.9 kW
Level 2	2.9-19.2 kW
DC Fast Charging	500 kW

Table: Charging Power Comparison

Medium- and heavy-duty trucks primarily charge using CCS, and their charging methods are mainly divided into three categories based on the scenario, including overnight charging, fast opportunity charging, and ultra-fast opportunity charging. These charging methods differ significantly in terms of power output, charging standards, applicable scenarios, and charging efficiency.[30]

Charging Type	Rated Power Output	Charging Standard	Layout Location	Estimated Charging Mileage per Hour	Estimated Charging Time (hours/day)
Overnight Charging	100 kW	CCS	Garage, Public Truck Rest Area	30-80 miles	8
Fast Opportunity Charging	350 kW	CCS	Public Charging Stations, Garage, Destination	110-285 miles	0.5
Ultra-Fast Opportunity Charging	1 MW	Megawatt Charging System (MCS)	Public Charging Stations, Garage, Destination	315-805 miles	0.5

Source: https://theicct.org/wp-content/uploads/2024/01/ID-28-%E2%80%93-U.S.-infra-jobs-report-letter-70112-ALT-v6.pdf

Table: Comparison of Different Charging Types

As shown in the table above, most zero-emission trucks on the market face charging speed limitations, with the most commonly used maximum charging power being around 350 kW. This results in longer charging times or requires increased onboard battery capacity to meet operational needs, which reduces payload capacity and increases costs. To address these challenges, faster charging infrastructure is becoming increasingly important. Tesla has made progress in this area by installing fast chargers with up to 750 kW of power, allowing its Semi truck to regain 300 to 500 miles of driving range (70%) in 30 minutes. Currently, the first 1.2 MW charging station was completed in Bakersfield, California (May 2024).[31]

The Megawatt Charging Standard (MCS) being developed by charging standards organization CharIN is expected to charge a battery from 0 to 100% in less than 15 minutes, significantly reducing downtime and improving the efficiency of zero-emission trucks. Although the standard is about to be introduced, there are currently no trucks on the market that truly support MCS. Therefore, it may still be some time before we see trucks compatible with this standard being put into actual use. This fast-charging technology aligns with truck drivers' normal rest times, paving the way for the electrification of long-haul transport.[32]

In 2024, automakers will focus on increasing charging power on the truck side, charging equipment suppliers will introduce more high-power charging equipment, and state governments and related agencies will pilot advanced technologies from these two aspects, jointly promoting the development and application of electric truck technology.

1.3 Challenges in Electric Truck Infrastructure

1.3.1 Shortage of Charging Stations

[30] Bui, A., Pierce, L., Ragon, P. L., Sen, A., Slowik, P., & Waites, T. (2024). Charging up America: The growth of United States electric vehicle charging infrastructure jobs. International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2024/01/ID-28-%E2%80%93-U.S.-infra-jobs-report-letter-70112-ALT-v6.pdf

[31] WattEV opens US' first megawatt charge station with 1.2MW speeds and solar, https://electrek.co/2024/05/06/wattev-opens-us-first-megawatt-charge-station-with-1-2mw-speeds-and-solar/

[32] Lund, J. (2024). New Year, New Priorities: CALSTART's Top 5 Action Items for Accelerating U.S. Zero-Emission Truck Adoption in 2024. CALSTART. https://calstart.org/new-year-new-priorities-calstarts-top-5-action-items-for-accelerating-u-s-zero-emission-truck-adoption-in-2024/

In March 2021, the White House announced that the number of public charging stations in the U.S. had surpassed 100,000, calling it a "milestone," while the number of public charging stations in China had already exceeded 800,000.

In terms of charging infrastructure for medium- and heavy-duty electric trucks, there are currently about 630 charging stations for these trucks, totaling 1,523 Level 1 and Level 2 chargers; among them, only 123 stations have DC fast chargers, with a total of 552 DC fast chargers. According to ICCT projections, by 2025, to meet the energy needs of 229,000 electric MHDVs (Medium- and Heavy-Duty Vehicles), the nation will need 124,000 overnight chargers and 11,900 fast chargers (assuming MCS chargers are only available in 2027). By 2030, 1.1 million electric MHDVs will require 522,000 overnight chargers, 28,500 fast chargers, and 9,540 ultra-fast chargers.[33] At the same time, small fleets and independent operators, who cannot afford to invest in private charging stations, will heavily rely on public charging stations. For example, California estimates that two-thirds of short-haul trucks will not charge in garages. However, the current number of public charging stations specifically for MHDVs is scarce and unable to meet the demand.[34]

As the goal of zero-emission vehicles progresses and mainstream automakers accelerate the launch of electric models, the U.S. auto industry is feeling the urgency of building a fully functional and easy-to-use charging network. However, building public charging infrastructure is a time-consuming and complex process that involves joint investments from multiple sectors, including automotive and energy, with diverse and changing operational entities. According to statistics from Wood Mackenzie Energy Consulting, the U.S. has over 60 different charging networks, operated by charging equipment companies, power companies, automakers, energy companies, retailers, and more. How to connect this "scattered puzzle" is a significant challenge.

1.3.2 High Cost of Charging Stations

A major obstacle to expanding the charging infrastructure in the U.S. is the high installation and maintenance costs. First, DC fast chargers are crucial for reducing range anxiety during long-distance travel, but they are extremely expensive. The cost of a single charger usually ranges between $30,000 and $40,000 and in some cases can even reach up to $80,000, which severely limits its large-scale deployment. In contrast, Level 1 chargers are less expensive, ranging from $300 to $1,500, suitable for home or residential use; Level 2 chargers cost between $2,000 and $7,000 on average and are commonly found in workplaces, shopping malls, and other public places.[35] To truly enhance transportation efficiency and alleviate range anxiety for medium- and heavy-duty trucks, the installed chargers will primarily be DC fast chargers, leading to higher overall costs compared to regular electric passenger vehicles.

In addition, determining the total cost of installing a charger involves several different variables, including permits/regulations, site preparation costs, grid interconnection availability, grid capacity, utility upgrades (e.g., transformers/switchgear), installing lighting, parking availability, and the level of construction required. These hidden costs can significantly increase the overall investment.[36]

Besides the initial installation costs, maintenance expenses are also a continuous challenge. Level 2 chargers may require certain components to be replaced every 3-5 years, and the annual maintenance cost for DC fast chargers typically ranges from $500 to $1,000, depending on usage frequency. These costs are usually borne

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[33] Pierce, L., & Slowik, P. (2024). Assessment of U.S. electric vehicle charging needs and announced deployments through 2032. International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2024/03/ID-89-%E2%80%93-Chargers-2032_final-v2.pdf

[34] U.S. Department of Energy, Alternative Fuels Data Center，https://afdc.energy.gov/fuels/electricity-locations#/analyze?country=US&tab=station&fuel=ELEC&maximum_vehicle_class=MD&access=public&access=private

[35] Fröde, P., Lee, M., & Sahdev, S. (2023, October 5). Can public EV fast-charging stations be profitable in the United States? McKinsey & Company. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/can-public-ev-fast-charging-stations-be-profitable-in-the-united-states

[36] Marklines. (2023, December). US Electric Vehicle Charging Infrastructure (2) Issues and charging costs. https://www.marklines.com/en/report/rep2577_202312

by businesses or local governments and may be passed on to users through charging fees, potentially increasing the cost of using electric vehicles.

To address these challenges, the U.S. government has taken some measures. For example, the Inflation Reduction Act offers a tax credit of up to 30% of the total installation cost to encourage the construction of charging infrastructure. However, even with such incentives, the overall investment remains substantial. There is still some disagreement within the industry regarding specific cost estimates, with no widespread consensus on specific price levels, but there is general agreement that high costs are a major barrier to expanding the charging network.

1.3.3 The U.S. Power Grid Urgently Needs Upgrading

The U.S. power infrastructure faces dual challenges of aging and growing demand, which are especially prominent against the backdrop of increased demand for electric trucks. The interconnected power grid in the 48 contiguous states is managed by more than 80 grid balancing authorities to ensure that power supply meets consumer demand across the country. Power is transmitted over long distances from power plants to local substations via transformers and transmission lines, and then distributed to end users via distribution lines.

According to estimates by the American Transportation Research Institute (ATRI), U.S. truck fleets consume 553.5 billion kilowatt-hours of electricity annually, accounting for 14.0% of the total U.S. electricity consumption in 2019. Long-haul combination trucks are the largest electricity consumers, using 417.4 billion kilowatt-hours, which accounts for 10.6% of the total consumption. This data may underestimate actual demand, as the annual mileage of long-haul trucks could be higher.[37]

The growing demand for electricity puts additional pressure on the already aging grid infrastructure. Most of the U.S. power infrastructure was built between the 1950s and 2000s and is still in use today. ATRI's research team analyzed over 24,600 power stations and found that hydropower, coal, and nuclear power stations have the highest average ages, at 68 years, 46 years, and 41 years, respectively. In contrast, renewable energy systems such as solar and wind power stations are newer, with average ages of 5 years and 11 years, respectively. Not only are power plants aging, but distribution systems are also facing similar issues. The U.S. Department of Energy estimates that 70% of power transformers and transmission lines are at least 25 years old. The design life of transformers is about 40 years, but the risk of fire increases over time. The lifespan of transmission lines varies by type, with overhead high-voltage lines lasting up to 100 years and underground lines lasting about 40 to 60 years.

Aging infrastructure not only prevents end-users from fully utilizing the latest technology but also decreases reliability. This problem affects the growing demand for charging electric trucks. According to the American Society of Civil Engineers, there is a significant investment gap between the current infrastructure investment rate and the rate needed to ensure a viable future grid. This gap is estimated to be $208.1 billion from 2020 to 2029.

1.3.4 Charging Stops

Additionally, the scarcity of legal charging stops is another challenge for transportation electrification infrastructure at this stage. Due to the high cost of establishing a new network of parking and charging stations in the U.S., charging must take place at existing truck stops along interstate highways. However, truck parking is itself a major issue facing the industry, leading to productivity losses and reduced income for drivers. Data from 2019 shows that there are about 313,000 truck parking spaces in the U.S., including 40,000 in public

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[37] American Transportation Research Institute. (2022, December 6). New ATRI Research Evaluates Charging Infrastructure Challenges for the U.S. Electric Vehicle Fleet. https://truckingresearch.org/2022/12/06/new-atri-research-evaluates-charging-infrastructure-challenges-for-the-u-s-electric-vehicle-fleet/

rest areas and 273,000 in private truck stops. To make long-haul truck electrification feasible, charging services must be provided at these parking spaces during mandatory driver rest periods. However, a federal regulation dating back to 1956 prohibits any commercial activities, including charging services, at public rest areas. This regulation poses many challenges for public rest area charging, such as the inability to charge fees or the inability for private companies to provide services.[38]

Even more challenging is the fact that a coalition of multiple associations is strongly opposed to amending this regulation due to concerns about impacting local retailers' interests. These factors together create a complex situation that requires a balance between technological innovation, regulatory adjustments, and commercial interests to advance the development of electric truck charging infrastructure.

1.3.5 Charging Costs

On average, the cost of charging an electric vehicle is lower than the cost of refueling a gasoline vehicle of the same class, but this depends on various factors, including the time of charging (whether electricity demand is at peak), the type of charger, the capacity of the electric vehicle's battery, and more.

When fuel prices are high, electric vehicles are significantly cheaper than gasoline vehicles. It can be inferred that compared to gasoline vehicles, electric vehicles can save more money for owners in areas where electricity costs are low. However, there are exceptions: On the West Coast of the U.S., electricity prices are often lower (below the national average), while gasoline prices are significantly higher; the situation on the East Coast is the opposite, with some owners complaining that charging an electric vehicle is more expensive than refueling a gasoline vehicle, especially in the northeastern states (New England).

2. Hydrogen Fuel Cell Truck Infrastructure

2.1 Overview

2.1.1 Current Infrastructure Status

Fuel Cell Electric Vehicles (FCEVs) represent an emerging clean energy transportation technology, showing significant potential in the medium- and heavy-duty truck sectors. FCEVs generate electricity to power electric motors through hydrogen fuel cells, with the fuel being pure hydrogen stored in the vehicle's tanks. This technology allows vehicles to complete refueling in about 20 minutes and can travel up to 750 miles（1,207 km）, greatly enhancing transportation efficiency.

However, the widespread adoption of FCEVs faces challenges related to insufficient infrastructure. As of July 2024, data from the U.S. Department of Energy indicated that there were only 73 open retail hydrogen refueling stations nationwide, with 62 located in California, 2 in Hawaii, and 9 distributed across Colorado and northeastern states. Among these hydrogen stations, 58 are public refueling stations, while 14 are private. Notably, only 5 hydrogen stations are suitable for 6-8 class heavy-duty trucks and buses, and all these stations are privately operated.[39]

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[38] Stinson, J. (2021, February 26). The debate over EV charging at interstate rest stops. Trucking Dive. https://www.truckingdive.com/news/ev-charging-interstate-rest-stops-debate

[39] U.S. Department of Energy, Alternative Fuels Data Center，https://afdc.energy.gov/fuels/electricity-locations#/analyze?country=US&tab=station&fuel=ELEC&maximum_vehicle_class=MD&access=public&access=private

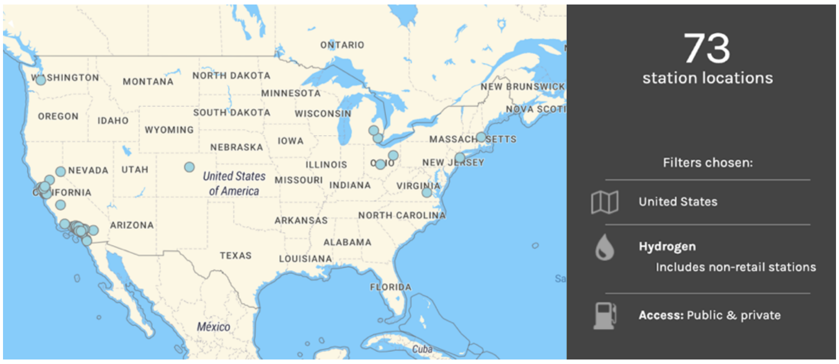


Figure: U.S. Existing Hydrogen Refueling Stations

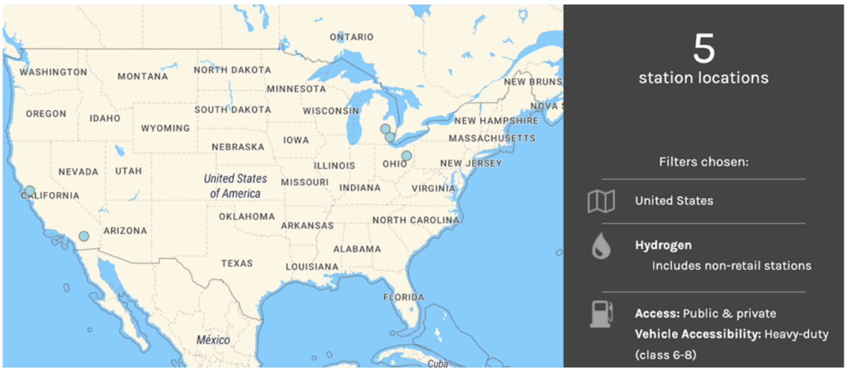


Figure: U.S. Heavy-Duty Hydrogen Fuel Cell Truck Refueling Stations

California, as the pioneer in hydrogen infrastructure development in the U.S., still faces severe infrastructure shortages. According to data from the Hydrogen Fuel Cell Partnership, California currently has only 3 hydrogen refueling stations that support heavy-duty trucks, all located around Los Angeles, offering 35/70 MPa hydrogen pressure. However, California is actively pushing for development, planning to build 68 new hydrogen stations, with 45 set to be located in the San Francisco and Los Angeles areas.[40] In terms of technology, the National Renewable Energy Laboratory (NREL) set a new record for fast hydrogen refueling for heavy trucks in October 2022: 82.3 kilograms of hydrogen were refueled in 6.6 minutes, with a peak rate of 23 kilograms per minute.[41] These advancements provide critical support for the future large-scale deployment of hydrogen-powered heavy trucks.

To address the challenges of inadequate infrastructure, various parties are actively taking action. The U.S. Department of Energy has launched the H2@Scale initiative, a public-private partnership aimed at advancing hydrogen infrastructure to provide American consumers with more transportation energy options. Additionally, the Federal Highway Administration (FHWA) is planning a national network of alternative fuel corridors, including hydrogen corridors (HVD). These corridors require that the distance between public hydrogen refueling stations does not exceed 100 miles (160 kilometers) to ensure that hydrogen-powered vehicles can travel conveniently across the country.

As of July 2024, the development of hydrogen infrastructure in the U.S. shows an uneven pattern. California leads the nation, particularly in the Bay Area of Northern California and around Los Angeles, where a complete hydrogen corridor network has already been established. These corridors are marked with blue solid lines,

[40] California Fuel Cell Partnership. (n.d.). Station Map. Retrieved August 16, 2024, from https://h2fcp.org/stationmap

[41] National Renewable Energy Laboratory. (2022, June 8). Fast fill: NREL's hydrogen infrastructure testing team achieves fueling milestone. Retrieved August 16, 2024, from https://www.nrel.gov/news/program/2022/fast-fill-nrels-hydrogen-infrastructure-testing-team-achieves-fueling-milestone.html

indicating that they have been completed and are in use. Although these corridors have been built, they currently primarily serve light-duty vehicles rather than medium- and heavy-duty trucks.[42]

Figure: Hydrogen Alternative Fuel Corridors

Compared to the demand for light-duty vehicles, the introduction of heavy-duty hydrogen trucks (such as line-haul trucks) will require larger-capacity hydrogen refueling stations. These large stations can not only increase equipment utilization but also reduce the cost per kilogram of hydrogen through economies of scale, ultimately benefiting both light- and heavy-duty vehicle users. From an investor's perspective, the cost of an 18-ton/day liquid hydrogen refueling station in California is currently around $11.9 million.[43]

From a user perspective, the cost of refueling medium- and heavy-duty hydrogen fuel cell trucks varies by location and is constrained by factors such as hydrogen production, transportation, storage, and related geographical advantages. In California, for example, the refueling cost for heavy-duty trucks is approximately $16-$25 per kilogram, meaning that it would cost at least $1,120 to fully refuel a heavy-duty truck with a maximum range of 500 miles. In comparison, during years when diesel prices are low, the cost to refuel a diesel truck of similar specifications for the same distance would be around $300.[44] Therefore, reaching cost parity between hydrogen trucks and diesel trucks remains a significant challenge, with reducing hydrogen prices being a crucial step. According to the U.S. National Clean Hydrogen Strategy and Roadmap, it is anticipated that the transportation sector's hydrogen distribution cost will drop to $5 per kilogram in the early market and to $2 per kilogram in an expanded high-value product market.

Despite these challenges, hydrogen refueling station construction is expected to accelerate as market demand grows. Future hydrogen refueling experiences may resemble traditional refueling, with some hydrogen stations potentially repurposed from existing gas stations. The growth in FCEV demand, the construction of large-capacity stations, and the scaling up of equipment production are expected to reduce the costs of hydrogen refueling stations.

The type and scale of hydrogen refueling stations will vary based on geographic location and demand characteristics. They can mainly be divided into two types: one relies on liquid hydrogen trucks, compressed hydrogen tube trailers, or pipelines to deliver hydrogen; the other produces hydrogen on-site using electrolysis or steam methane reformers. On-site hydrogen production stations are typically more suitable for remote areas with smaller consumer bases, while hydrogen transport-based stations are better suited for urban areas with higher demand. In the early market, smaller-scale hydrogen stations (daily hydrogen supply of 100-350 kilograms) may be prioritized to meet initial demand. As the FCEV market expands, large stations with a daily hydrogen supply exceeding 1,000 kilograms will become economically advantageous. To stimulate FCEV

[42] Environmental Systems Research Institute (ESRI). (n.d.). Alternative Fuel Stations. Retrieved August 16, 2024, from https://www.arcgis.com/home/webmap/viewer.html?webmap=76afef469aa64311b307840c4d3ce412&extent=-168.9157,18.987,-65.2926,57.5203

[43] Bracci, J. (2024). Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy24osti/88818.pdf

[44] CSX Corporation. (2024). Fuel efficiency. Retrieved August 16, 2024, from https://www.csx.com/index.cfm/about-us/the-csx-advantage/fuel-efficiency/

market growth, hydrogen station layout strategies include building clusters of hydrogen stations and setting up standalone hydrogen stations at strategic locations.

2.1.2 Ongoing Supportive Projects

To meet the specific requirements of hydrogen refueling stations for heavy-duty trucks, the U.S. Department of Energy has launched several demonstration projects to address the unique needs of heavy-duty fuel cell trucks, including hydrogen refueling pressure, volume, and rate. These projects mainly include:

- **Development of Reference Hydrogen Stations (HD Reference Station Development):** This project aims to provide a reference for the design and testing of hydrogen stations. By establishing a standardized model for heavy-duty hydrogen stations, the industry can better understand and optimize the design and operation of these stations. The reference station will consider various factors, such as fleet size, refueling strategy (continuous refueling vs. off-peak refueling), and hydrogen supply method (gaseous hydrogen vs. liquid hydrogen), to provide comprehensive technical and economic references for future heavy-duty hydrogen stations.
- **Fast Hydrogen Refueling Technology Development:** This project is focused on increasing the speed of hydrogen refueling for heavy-duty trucks to meet the efficiency requirements of commercial operations. Research indicates that the refueling rate significantly impacts the cost and efficiency of hydrogen stations. For example, increasing the refueling rate from 1.8 kilograms/minute to 7.2 kilograms/minute for a typical heavy-duty truck fleet may increase refueling costs but will also significantly reduce refueling time. The project's goal is to develop technology that can achieve a refueling rate of 3.6 kilograms/minute or higher while ensuring safety and cost-effectiveness.

Both projects are led by the National Renewable Energy Laboratory (NREL).

2.2 Overview of Hydrogen Production, Transportation, and Storage Technologies in the United States

2.2.1 Hydrogen Production

In the United States, hydrogen production technologies can be categorized into four major processes: thermal processes, biological and thermochemical processes, electrolysis, and photolytic processes. Currently, Steam Methane Reforming (SMR) is the most common method of hydrogen production, primarily using natural gas as a feedstock.

The U.S. produces approximately 10 million tons of hydrogen, with 99% of this hydrogen being produced from fossil fuels. Specifically, 95% is derived from natural gas via SMR, 4% comes from coal, and only 1% is produced through electrolysis.[45] However, since 2020, the development of water electrolysis for hydrogen production has accelerated. As of May 2022, the operating and under-construction Proton Exchange Membrane (PEM) electrolysis capacity in the U.S. exceeded 620 MW, more than tripling from 170 MW in 2021.[46]

[45] U.S. Department of Energy. (2020, July). Department of Energy hydrogen program plan. https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf

[46] U.S. Department of Energy. (2022, May 16). PEM Electrolyzer Capacity Installations in the United States (Record No. 22001). Hydrogen and Fuel Cell Technologies Office. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/22001-electrolyzers-installed-in-united-states.pdf

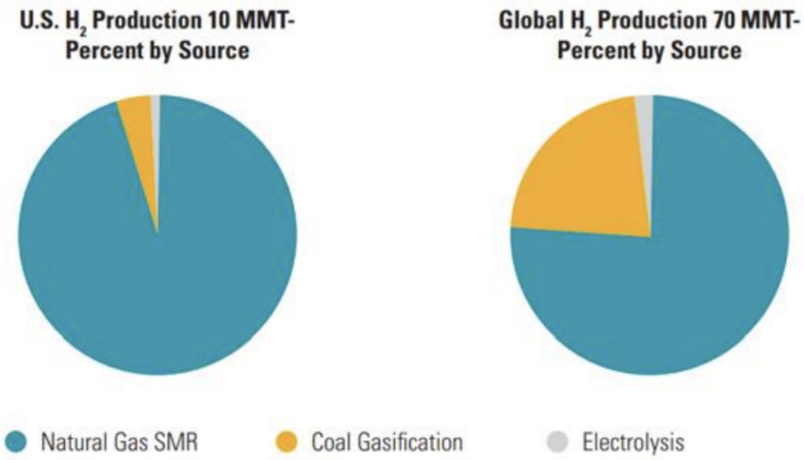


Figure: Comparison of Hydrogen Production Methods in the U.S. and Globally

In terms of consumption structure, in 2021, hydrogen in the U.S. was mainly used for petroleum refining, ammonia synthesis, and the chemical industry, accounting for 55% and 35% respectively. Additionally, hydrogen is widely used in other applications, including over 50,000 fuel cell forklifts, more than 80 fuel cell buses, over 13,000 fuel cell vehicles, and over 500 MW of fuel cell stationary power plants and backup power systems.[47]

According to the "National Clean Hydrogen Strategy and Roadmap," the U.S. aims to increase clean hydrogen production capacity to 10 million tons per year by 2030, corresponding to an electrolysis capacity of approximately 121 GW. The goal is to increase this to 20 million tons per year by 2040 and 50 million tons per year by 2050.

2.2.2 Hydrogen Transportation

The transportation of hydrogen in the U.S. primarily involves pipelines, cryogenic liquid tankers, and gaseous tube trailers.

Pipeline transportation is currently the most cost-effective and energy-efficient way to transport hydrogen to most markets. As of December 2020, the U.S. operated 1,608 miles (2,572 kilometers) of hydrogen pipelines, with over 90% located along the Gulf Coast in Texas, Louisiana, and Alabama. Shorter hydrogen pipelines are found in other parts of Texas, Louisiana, and nine other states. For example, California has 16 miles (25.6 kilometers) of hydrogen pipelines, Indiana has 14 miles (22.4 kilometers), and the remaining seven states each have less than 10 miles (16 kilometers). By comparison, the U.S. has over 300,000 miles (480,000 kilometers) of natural gas pipelines.

For longer-distance transportation and some large stations, liquid hydrogen becomes a viable option. Hydrogen is cooled to -253°C and stored in large insulated tanks for transport in liquid form. Although the liquefaction process consumes a significant amount of energy (over 30% of the hydrogen's energy), liquid hydrogen can be more economical than gaseous tube trailers for long-distance transportation.

To further expand hydrogen infrastructure, the U.S. is exploring the use of fiber-reinforced polymer pipelines (which are 20% cheaper than steel pipelines) and repurposing some natural gas transmission infrastructure to transport mixtures of natural gas and hydrogen (currently with a maximum blend of 30%).

[47] Fan, L., Tu, Z., & Chan, S. H. (2021). Recent development of hydrogen and fuel cell technologies: A review. Energy Reports, 7, 8421-8446. https://doi.org/10.1016/j.egyr.2021.08.003

However, these methods also face a series of challenges, such as hydrogen embrittlement, increased safety risks, and the complexity of separating hydrogen from natural gas mixtures. Compared to new hydrogen pipelines, repurposing existing pipelines can reduce costs by up to 60% but introduces additional technical challenges.

Until recently, hydrogen has only started to gain attention as a primary fuel source. As a result, the U.S. hydrogen-related regulatory framework is either limited in scope or only addresses hydrogen indirectly. A clear and centralized regulatory environment would enable the energy industry to make the necessary long-term, capital-intensive infrastructure investments needed to move away from localized hydrogen production plans. Currently, oversight of pipeline infrastructure depends on whether the pipeline is onshore or offshore, interstate or intrastate. Hydrogen is not explicitly included in existing pipeline regulations but is indirectly addressed as a flammable or hazardous gas. The only regulation directly governing hydrogen is the Pipeline and Hazardous Materials Safety Administration (PHMSA) Hazardous Materials Regulations. PHMSA oversees the management of hazardous materials, requirements for cryogenic and compressed gases, and details concerning containers (such as cylinders and tanks) used for road, rail, and water transport.

2.2.3 Hydrogen Storage

Hydrogen storage technologies in the U.S. are mainly divided into three forms: gaseous storage, liquid storage, and solid-state storage. Gaseous storage typically requires high-pressure tanks (350-700 bar), liquid storage requires cryogenic conditions (-252.8°C), and solid-state storage is achieved through adsorption or absorption.

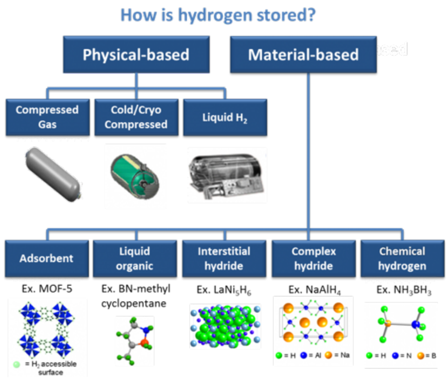
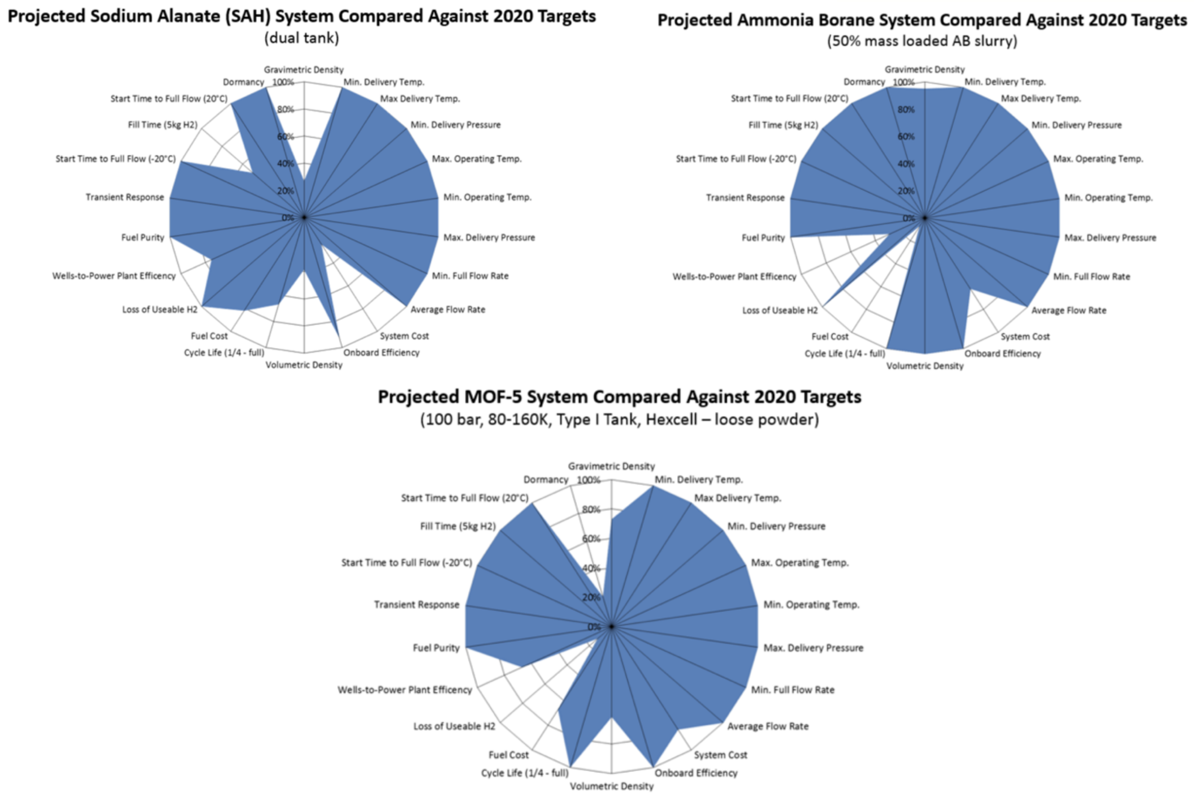


Figure: Overview of Hydrogen Storage Technologies[48]

The U.S. Department of Energy (DOE) has set specific system targets, including 1.5 kWh/kg system (4.5 weight% hydrogen), 1.0 kWh/L system (0.030 kg hydrogen/L), and $10/kWh ($333/kg hydrogen storage capacity). As of July 2024, significant breakthroughs have been made in mainstream hydrogen storage technologies for these indicators, but limitations remain in terms of cycle life.

[48] U.S. Department of Energy. (n.d.). Hydrogen storage. Office of Energy Efficiency & Renewable Energy. Retrieved August 16, 2024, from https://www.energy.gov/eere/fuelcells/hydrogen-storage



Source: https://www.energy.gov/eere/fuelcells/hydrogen-storage-engineering-center-excellence

Figure: Comparison of Current U.S. Hydrogen Fuel Cell System Status and 2020 Targets

To address the challenges faced by high-density hydrogen storage technologies, the DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) is simultaneously pursuing short-term and long-term strategic routes. The short-term strategy primarily focuses on compressed gas storage technology, using advanced pressure vessels made from fiber-reinforced composite materials. The long-term strategy is focused on two key areas:

- **Cold-compressed or cryo-compressed hydrogen storage:** By increasing hydrogen density and using insulated pressure vessels, this strategy aims to meet DOE's targets.
- **Materials-based hydrogen storage technologies:** These include adsorbents, chemical hydrogen storage materials, and metal hydrides, which have the potential to meet DOE's hydrogen storage goals.

In the medium- and heavy-duty truck sectors, hydrogen supply primarily occurs in three ways: delivery of compressed gas via pipelines or high-pressure tanks, delivery in cryogenic liquid form, and on-site production. The industry is actively developing processes and hardware components capable of meeting distribution requirements, including rapid hydrogen refueling. Recent and mid-term research and development efforts are focused on reducing the costs of these technologies, ensuring the safety of materials used in hydrogen operations, and minimizing hydrogen losses during transportation and distribution.

Metal hydride storage technology has attracted the attention of researchers, but its application in transportation is still limited. Apart from a practical application using titanium-zirconium alloys, no land-based transportation system utilizing metal hydrides as a storage medium has been successfully developed. This field still has significant research and development potential and may bring breakthrough advancements in the application of hydrogen energy in transportation in the future.[49]

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[49] Drawer, C., Lange, J., & Kaltschmitt, M. (2023). Metal hydrides for hydrogen storage – Identification and evaluation of stationary and transportation applications. Journal of Energy Storage, 67, 109988. https://doi.org/10.1016/j.est.2023.109988

2.3 Key Challenges Facing Hydrogen Infrastructure

2.3.1 Insufficient Number of Hydrogen Stations

The scarcity of hydrogen refueling stations is one of the most significant barriers to the adoption of hydrogen fuel cell electric vehicles (FCEVs), particularly for medium and heavy-duty trucks. Unlike the widespread network of traditional fueling stations, the limited availability of hydrogen infrastructure severely restricts the practicality and attractiveness of hydrogen-powered vehicles. Even in California, which leads in hydrogen technology, there are only five hydrogen stations specifically serving heavy-duty vehicles. This number is far from sufficient to support a comprehensive hydrogen transportation network.

This shortage of infrastructure not only impacts daily operations but also hinders the development of so-called "hydrogen corridors." These corridors are envisioned as low-carbon transportation routes connecting major cities and logistics hubs. Their successful implementation heavily relies on the availability of adequately spaced hydrogen refueling stations. However, the current network of hydrogen stations falls short in both quantity and distribution, making it challenging to realize this vision.

2.3.2 Cost and Equipment Challenges

One of the primary challenges in developing hydrogen infrastructure is the high cost associated with it. Currently, the estimated cost of constructing a hydrogen refueling station is approximately $11.9 million. This high cost is mainly due to the specialized equipment required for hydrogen production, storage, transportation, and refueling. Such equipment includes high-pressure hydrogen tanks, hydrogen compressors, and cryogenic liquefaction equipment, all of which are expensive and require substantial initial investment.

Additionally, similar to electric vehicle charging infrastructure, hydrogen infrastructure faces issues with equipment supply delays. Key components such as transformers and switchgear may experience bottlenecks, which can directly impact the construction timeline of hydrogen refueling stations and, consequently, the expansion rate of the entire hydrogen network.

2.3.3 Cost and Equipment Challenges

Transporting hydrogen to refueling stations presents another significant challenge. To ensure economic viability, the distance between hydrogen production sites and refueling stations must not be too great. This necessitates a comprehensive approach to planning the hydrogen network, considering the overall layout of hydrogen production, transportation, and usage to optimize supply chain efficiency.

For larger hydrogen stations, transporting liquid hydrogen is becoming more common, as it is more economical for large-scale transportation. However, this requires specialized cryogenic storage equipment and more space. If pipeline transportation is used, it is crucial to ensure that the hydrogen purity meets the requirements of fuel cell vehicles, which may differ from the purity standards for other industrial uses of hydrogen.

Moreover, hydrogen transportation itself requires specialized equipment and safety measures, further increasing the complexity of the logistics chain. Establishing an efficient and safe hydrogen supply chain is a key challenge in the development of hydrogen infrastructure.

2.3.4 Regulatory and Approval Challenges

The United States currently lacks a comprehensive regulatory framework specifically tailored to hydrogen and its related infrastructure. Several federal agencies, such as the Occupational Safety and Health Administration (OSHA), Environmental Protection Agency (EPA), and Pipeline and Hazardous Materials Safety Administration (PHMSA), are involved in hydrogen regulation to varying degrees.

Even in California, which is relatively supportive of hydrogen development, obtaining permits for constructing hydrogen refueling stations can take 10 to 12 months. [50]This lengthy approval process significantly extends the overall project timeline, potentially causing a refueling station project to take 2 to 3 years from planning to completion.

There is an urgent need to streamline the approval process, increase efficiency, and ensure safety standards are met. Addressing these regulatory uncertainties is crucial for establishing a nationwide hydrogen infrastructure.

2.3.5 Educational and Perception Challenges

Raising public awareness and acceptance of hydrogen technology is a long-term challenge. This involves educating small fleet operators, utility companies, and other stakeholders, as well as communicating with residents living near hydrogen facilities.

Many people may still have safety concerns about hydrogen, often associating it with historical incidents like the Hindenburg disaster. Overcoming these fears and building public confidence is essential for promoting hydrogen technology. This not only requires technical explanations but also demonstrating the safety and reliability of hydrogen technology in real-world applications.

2.3.6 Ownership and Usage Rights Issues

The development of hydrogen refueling stations involves not only technical and operational challenges but also complex issues related to ownership and usage rights. These legal and commercial considerations have a significant impact on the development, operation, and long-term sustainability of hydrogen refueling stations.

Firstly, the ownership structure of the site directly affects the development and permitting process for hydrogen stations. Operators face a choice between purchasing or leasing the site. Purchasing provides greater control and long-term stability but requires more initial capital investment. In contrast, leasing may reduce upfront costs but introduces additional complexities. In the case of leasing, the agreement must clearly define how the hydrogen station operator can use the property, including the types of modifications and installations permitted. The obligations and requirements of all parties must be clearly outlined in the agreement, including responsibilities for maintenance, safety measures, and environmental compliance. Given the long-term operational needs of hydrogen stations, the lease agreement should include appropriate terms for lease duration and renewal. If pipeline installation or other infrastructure construction is required, easement issues may arise, necessitating negotiations and coordination with relevant parties.

Secondly, usage rights for the hydrogen station must also be carefully considered. Operators need to decide whether the station will be open to the public or reserved for specific types or fleets of fuel cell vehicles. This decision will affect the station's design, capacity planning, and business model. Regardless of the usage model chosen, hydrogen station owners must ensure that the allocated equipment is compatible with the fuel cell vehicles of their target users. This may involve coordination with vehicle manufacturers and anticipation of future changes in technology standards.

If the station is exclusive, appropriate access control measures, such as membership card systems or dedicated applications, will need to be implemented. Depending on the different usage rights, the station may need to develop various pricing strategies, such as market-based pricing for public use or long-term contract pricing for dedicated fleets.

Additionally, ownership and usage rights issues may affect the financing and insurance of the hydrogen station. For example, leasing the site may impact the ability to obtain certain types of financing, while restrictions on usage rights may affect insurance terms and rates.

[50] Joint Office of Energy and Transportation (Joint Office), "Webinar: Discover the National Zero-Emission Freight Corridor Strategy", YouTube, https://www.youtube.com/watch?v=L_oHWNDgArc&t=528s

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Appendix:

Category	United States			China	
	Weight (lbs)	Class	Weight (tons)	Truck Weight (tons)	Tractor Weight (tons)
Light Heavy-Duty Vehicles (LHDV)	8,501 - 10,000	2b	3.86 - 4.54	3.5 - 4.5	-
Medium Heavy-Duty Vehicles (MHDV)	10,001 - 14,000	3	4.54 - 6.35	4.5 - 5.5	-
	14,001 - 16,000	4	6.35 - 7.26	5.5 - 7	-
	16,001 - 19,500	5	7.26 - 8.85	7 - 8.5	3.5 - 18
	19,501 - 26,000	6	8.85 - 11.79	8.5 - 10.5	-
Heavy Heavy-Duty Vehicles (HHDV)	26,001 - 33,000	7	11.79 - 14.97	10.5 - 12.5	-
	33,001 - 60,000	8a	14.97 - 27.22	12.5 - 16	-
				16 - 20	18 - 27
				20 - 25	27 - 35
				25 - 31	35 - 40
	Above 60,001 lbs	8b	> 27.7	> 31	40 - 43
					43 - 46
					46 - 49
					> 49

Source: Global Drive to Zero. (2022). Electric Freight Consortium: Global Overview of Zero-Emission Medium and Heavy-Duty Vehicles. Retrieved from https://globaldrivetozero.org/site/wp-content/uploads/2022/05/EFC-Task-2_CH.pdf

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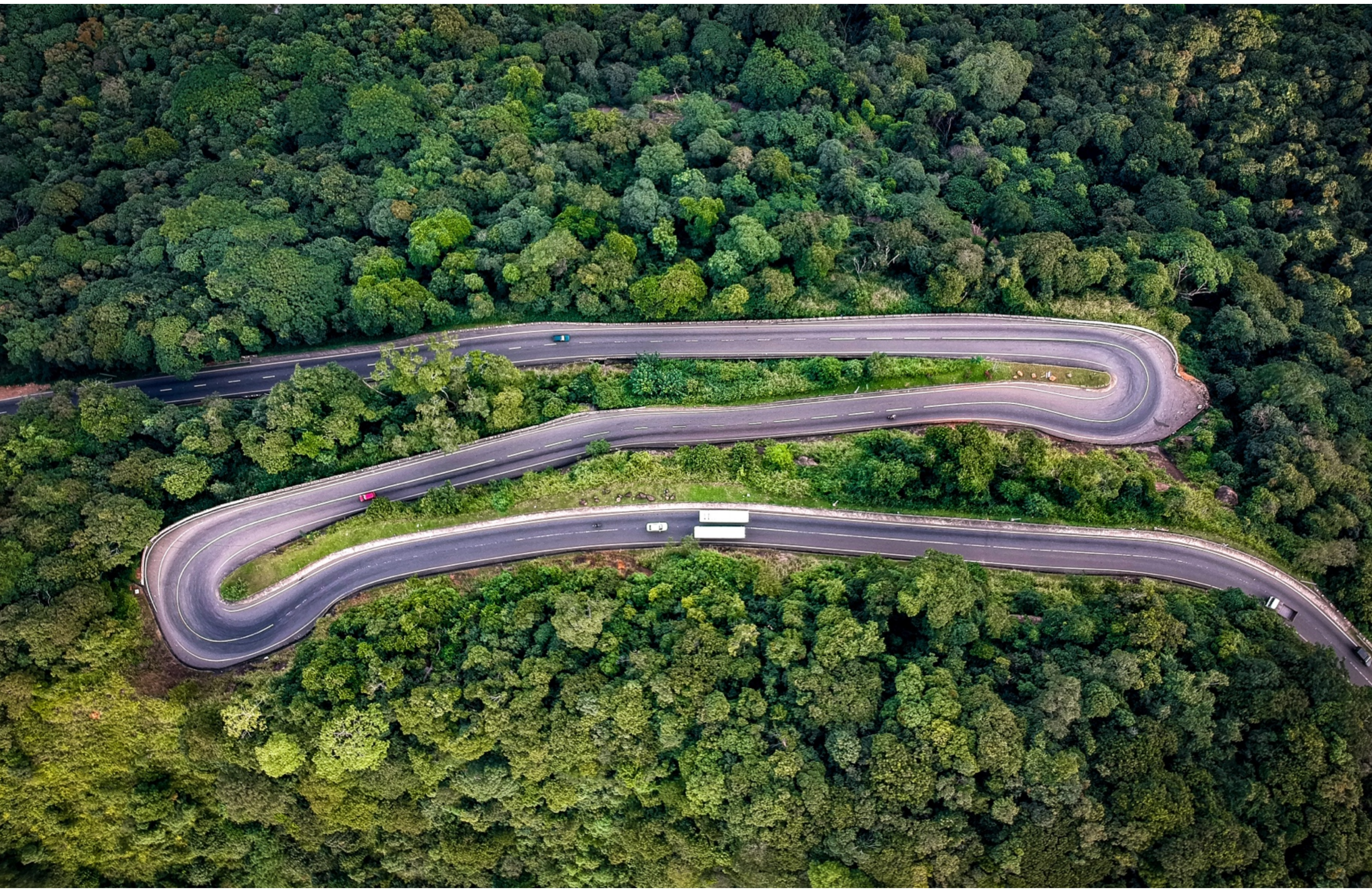

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