Feasibility study of EPA NPRM Phase 3 GHG standards for Medium Heavy-Duty Vehicles

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Prepared For:

Truck and Engine Manufacturers Associations

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Executive Summary

With the proposed "Phase 3" GHG standards, EPA is seeking to put rules in place that will require the deployment of zero emission trucks. The readiness of the charging/hydrogen refueling infrastructure for ZEV trucks and the related cost impacts warrant a deeper analysis.

Ricardo investigated the three core readiness issues below to provide EMA with a comprehensive understanding of the magnitude of the infrastructure challenge:

State ZEV Adoption

MHD ZEV sales through 2032 are expected to reach ~1.5 million BEVs and ~128 thousand FCEV and H2-ICE vehicles. California is expected to continue to lead in the rates of ZEV adoption. Texas is estimated to be the second highest adopter of FCEV and H2-ICE vehicles. Medium-duty (MD) (Class 2b-5) short-haul single-unit trucks (no trailer) are expected to represent over ~60% of BEVs by 2032. ~50% of FCEV and H2-ICE are expected to be used for the multi-purpose long haul (200 miles daily mileage) and regional haul (420 miles daily mileage) applications.

Charging and electrical supply infrastructure readiness assessment to support the BEV adoption

Under our assessment, more than ~98% of the BEV trucks on the road will be using depot based L2 or DCFC 50 to 350 kW overnight charging. All of the above charging methods have been commercialized and available for use on LDVs for over 10+ yrs.

Unlike LDVs, however there are no national EV charging standards for MD/HD trucks. The FHWA has not provided any guidance for MHDV charging. With the proposed ZEV adoption rates under EPAs Phase 3 GHG standards for MHD vehicles ramping up as early as 2027, it is important to develop a cohesive strategy to ensure that the targeted BEV adoption can be met year-over-year.

The results of this study have led to several conclusions and recommendations, which are intended to inform and support policymakers, utilities, and site operators in planning for ZEV truck charging deployment:

Conclusions:

1. With a low population of ~3000 of BEV MHDVs currently on the road, the charging infrastructure at fleet depots is limited to meeting ongoing pilot programs
2. Current BEV adoption in national truck fleets is extremely low at 0.001% of total 2022 fleet size
    a. Several large fleet operators have not published any guidance on future fleet electrification plans or pilot programs

3. The target ZEV truck adoption rates set by EPA's proposed Phase 3 GHG standards will accelerate BEV MHDVs adoption, resulting in ~1.5 million BEV MHDVs on the road by 2032
   a. ~98% of on road BEV MDHVs in 2032 will require depot-based charging
   b. 82% (~1.2 million) of the chargers required will need to be Level 2 type chargers
4. The peak electrical demand from simultaneously charging all BEV MHDVs on the road in 2032 is 20,568 MW, which represents ~1.8% of the national installed capacity[1]
5. After assessing the worst-case scenario of peak electrical demand from simultaneously charging the total population of MHDVs on the road (~1.5 million) in addition to the peak hourly load event for the summer or winter of each year California along with the Northwestern and Northeastern coastal areas are the only regions with lower than target reference electrical margin
6. Unlike the national electric vehicle infrastructure program (NEVI), there are no State and Federal funding programs specifically dedicated to accelerating MDHV charging infrastructure
7. An estimated investment of $19.7 B is required through 2032 to develop a charging infrastructure that can support the projected on-road BEV MDHV population
   a. It must be emphasized that the estimated investment is sensitive to charger types used for MHDV charging; if more DCFCs are required, costs will increase substantially
   b. Current investment is estimated based on charger type used for each truck class and use-type in EPAs HD TRUCS model

Recommendations:

1. Dedicated federal funding for a comprehensive MHDV charging infrastructure
   a. Similar to the NEVI program, the federal government should set up funding to develop dedicated MHDV charging infrastructure at public and private depots nationwide
2. FHWA guidance on MHDV charging standard development
   a. To ensure a steady adoption of BEV MHDVs to meet EPAs Phase 3 GHG emission targets, the FHWA should use a two-phased approach to develop BEV MDHV charging standards for depot-based charging standards in Phase 1, followed by highway-based charging standards in Phase 2
3. Charging site design recommendations
   a. FHWA should set EV charging site designs requirements as part of developing the MHDV charging standards
4. Government needs to take necessary steps to drive utilities and fleet operator collaboration
   a. Although the aggregate impact of electrical demand from charging MHDVs is not overly significant, it will be important for utilities to work closely with fleet operators to leverage smart charging to manage electrical load and ultimately reduce TCO for fleet operators

[1] https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php#:~:text=At%20the%20end%20of%202021,solar%20photovoltaic%20electricity%20generating%20capacity

Hydrogen supply infrastructure readiness and cost impact analysis to support forecasted FCEV+H2ICE adoption

We compare the hydrogen demand based on targeted FCEVs and H2-ICEs adoption rates with the current and planned capacity of HD hydrogen refueling infrastructure. To meet the 2032 hydrogen target, an estimated investment of ~$5.3B (for ~700 stations) is required for HD refueling stations. With estimated available funding of ~$0.8B, an investment of $4.5B from various sources needs to be allocated to hydrogen refueling stations evenly over the next 9 years. Although FCEV and H2-ICEs are in the early pre-commercial stage, it is critical to build out hydrogen refueling infrastructure ahead of the ramp-up of FCEV and H2-ICE sales to facilitate adoption.

Conclusions:

1. The hydrogen demand is expected to be 0.9M tons/year by 2032
2. Regional-haul applications comprise over ~50% of total hydrogen demand by 2032
3. California and Texas are the dominant states that will drive hydrogen demand
4. 695 HD hydrogen refueling stations need to be developed by 2032 to meet the 2032 FCEV and H2-ICE targets. 219 stations are expected to be deployed in Texas and California by 2032
5. The estimated capital cost is ~$1.3M for a hydrogen refueling station with a dispensed capacity of 5000kg/day
6. With a total estimated available funding of ~$0.8B, the required additional investment beyond current commitments is $4.5B

Recommendations:

1. As over ~70% of FCEVs and H2-ICEs are expected to be deployed for longer mileage (>200 daily miles) applications, the majority of hydrogen fueled applications may not return to base daily. Thus, it is important to accelerate the deployment of hydrogen refueling corridors and hydrogen public refueling stations in truck clusters, such as ports, airports, railroads, warehouses, and freight hubs
2. Increase dedicated funding for HD hydrogen refueling stations. Insufficient incentives or funding programs currently exist for the hydrogen refueling infrastructure
3. Increase incentives for HD refueling stations. As the capital cost of an HD hydrogen refueling station is much higher than that of charging station or LD refueling station, the incentives should be designed to reflect the increased financial investment burden
4. HD FCEV and H2-ICE demonstration and pilot projects in California and Texas are important advanced indicators for broader national deployment. It is beneficial for refueling infrastructure providers to deploy their products in fleet applications and monitor performance, issues, and successes. These pilot and demonstration projects will lead to an improved generation of FCEV, H2-ICE, and hydrogen refueling stations that are well-accepted by the fleets

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1 Introduction

With the proposed “Phase 3” GHG standards, US EPA is putting rules in place that will indirectly mandate the large-scale introduction of medium-duty and heavy-duty (MHDV) zero-emission vehicles (ZEV) (electric, hydrogen ICE, and FCEVs) across all segments of transport.

As MHD ZEV sales rise, the potential consequences of widespread adoption are less understood, and the readiness of the necessary charging/refueling infrastructure and the cost impact warrants a deeper analysis and understanding.

Table 1: EPA proposed Projected ZEV Adoption Rates for MY 2027-2032 Technology Packages[2]

Regulatory subcategory	MY 2027 (%)	MY 2028 (%)	MY 2029 (%)	MY 2030 (%)	MY 2031 (%)	MY 2032 (%)
LHD Vocational	22	28	34	39	45	57
MHD Vocational	19	21	24	27	30	35
HHD Vocational	16	18	19	30	33	40
MHD All Cab and HHD Day Cab Tractors	10	12	15	20	30	34
Sleeper Cab Tractors	0	0	0	10	20	25
Heavy Haul Tractors	0	0	0	11	12	15
Optional Custom Chassis: School Bus	30	33	35	38	40	45
Optional Custom Chassis: Other Bus	0	6	11	17	23	34
Optional Custom Chassis: Coach Bus	0	0	0	10	20	25
Optional Custom Chassis: Refuse Hauler	15	19	22	26	29	36
Optional Custom Chassis: Concrete Mixer	18	21	24	27	29	35
Optional Custom Chassis: Emergency Vehicles	0	0	0	0	0	0
Optional Custom Chassis: Recreational Vehicles	0	0	0	0	0	0
Optional Custom Chassis: Mixed Use	0	0	0	0	0	0

[2] Proposed Rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles - Phase 3 (published April 27, 2023)

2 Background

In this study, Ricardo investigated both potentially positive and negative consequences of meeting the ZEV adoption rates under EPAs proposed Phase 3 GHG emission standards, and provided EMA with a detailed analysis of the following key issues:

1. Segment and regional adoption of battery-electric vehicles (BEVs) and hydrogen-fueled heavy-duty trucks under EPAs Phase 3 GHG emission standards forecast
2. Charging and electrical supply infrastructure readiness to support the forecasted ZEV truck adoption rates
3. Hydrogen supply infrastructure readiness and cost impact analysis to support the forecasted ZEV truck adoption rates

The results of the study will be used to provide commentary on the proposed rulemaking, with specific focus on infrastructure readiness to support the regulations.

3 ZEV Sales Forecast

EPA provided projected Medium- and Heavy-Duty (MHD) ZEV sales from calendar years 2027 to 2032. To evaluate the gaps between the capacity and demand of charging infrastructure and hydrogen refueling stations on the state level, Ricardo has conducted the analysis and forecast of this study as follows:

1. MHD ZEV national sales between calendar years 2022 to 2026
2. Adoption rate and MHD ZEV sales by state from calendar years 2022 to 2032
3. Hydrogen ICE (H2-ICE) sales forecast

MHD ZEV sales forecasted as of 2032 have been segmented according to vehicle class (regulatory classes) and vocation classification (source use types). This section explains the approach that Ricardo used to estimate MHD ZEV sales (2027-2032) and adoption rates by state, and the results across MHD ZEV technology packages and vehicle segments.

The forecast is based on battery electric vehicles (BEVs), fuel cell electric vehicles (FCEV), and H2-ICE vehicles.

3.1 Methodology

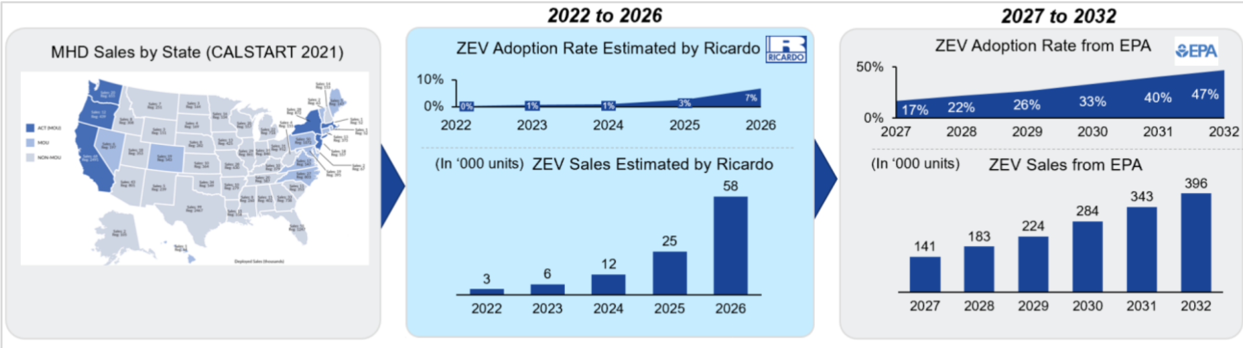
3.1.1 2022 – 2026 Sales Forecast

To estimate the MHD ZEV sales between 2022 and 2026, Ricardo calculated the average annual growth rate to bridge the gap between MHD ZEV sales deployed as of 2021 and the projected MHD ZEV sales in 2027 by EPA. The sales forecast approach is presented in Figure 1.

The MHD ZEV adoption rate as of 2021 is estimated based on the number and mix of MHD zero-emission truck (ZET) deployed sales[3]. The annual growth rate is assumed to remain the same from 2022 to 2026.

[3] CALSTART (2022), Zeroing in on Zero-Emission Trucks, https://calstart.org/wp-content/uploads/2022/07/ZIO-ZETs-June-2022-Market-Update.pdf

Figure 1: 2022-2026 Sales Forecast Approach

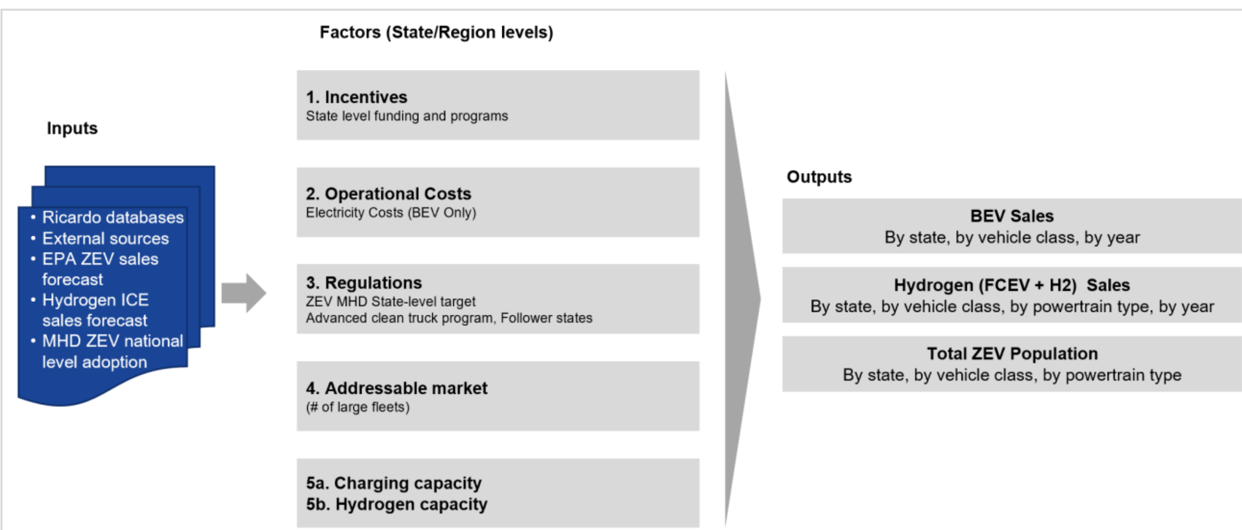


3.1.2 MHD ZEV Sales by State

As this study aims to assess the regional readiness of the ZEV-truck charging and hydrogen-refueling infrastructure and the hydrogen refueling stations, Ricardo estimated the MHD ZEV sales and adoption rate by state.

Technology costs, regulation, and charging infrastructure are the key barriers limiting MHD ZEV adoption. Thus, the projections modeled in this study are estimated based on national MHD ZEV data and five quantitative and qualitative parameters on the state level (Figure 2). Firstly, Ricardo estimated the state adoption rate compared to the national level based on the assessment of the five parameters shown below. Then, the ZEV-truck sales by state were calculated from the vehicle registration data and the state adoption rate.

Figure 2: Methodology of State Adoption Rate Estimation



Technology Costs

The capital costs and the operational costs are critical adoption-enabling factors.

1. **Incentives**
   The impact of state incentive programs is key to ZEV adoption rates. Incentives for upfront vehicle and infrastructure costs and charging or refueling costs will enable ZEVs to approach cost parity with conventional vehicles and encourage ZEV adoption.
2. **Electricity Costs**
   Electricity costs and hydrogen refueling costs are the major adoption-enabling factors affecting operational costs. Due to the limited availability of hydrogen refueling stations across the states, the costs of hydrogen refueling are not considered as significant as the costs of the necessary refueling infrastructure when considering key adoption enabling factors.

Regulation

The mandatory ZEV-sales regulations, purchase requirements, fuel economy, and emissions targets all create a regulatory framework for accelerating the growth of ZEV adoption.

Addressable Market

The size of the MHD vehicle market is a significant factor in the sale of MHD ZEVs at the state level.

Charging Infrastructure and Hydrogen Refueling Stations

ZEV adoption and the readiness of charging infrastructure or hydrogen refueling stations are the chicken-and-egg problems. The charging capacity and hydrogen refueling capacity could be either the accelerator or barrier to ZEV adoption.

The goal of the projections is to develop estimates of sales of MHD ZEVs and their share of new vehicle sales by state. States are assessed on the five quantitative and qualitative parameters (Table 2) to determine their relative adoption rates compared to national adoption rates.

Table 2: State Adoption Parameters

Parameter	Description
Incentives	MHD ZEV incentives on vehicle and infrastructure deployment (capital costs, installation costs), weight exemption and utility incentives, and programs of BEV charging costs (Time-of-Use, demand charge)
Electricity Price	Average state-level electricity price[4]
Regulations	ZEV mandates, GHG regulations, ZEV targets
Addressable Market	Number of top 500 fleets in the state[5]
Charging Infrastructure or hydrogen capacity	BEV: current number of charging stations in each state, including both private and public charging stations[6] Hydrogen FCEV/ H2-ICE: current and potential hydrogen production capacity, current number of hydrogens refueling stations, hydrogen transportation infrastructure (pipelines)

Ricardo designed a scorecard (dedicated scorecard to BEV and hydrogen FCEV/ H2-ICE) to reflect different adoption rates by state. An example of this assessment is shown in Figure 3.

Figure 3: Example of BEV Scorecard

	California	Texas	Washington
Incentives	1 • Highest number of MHD ZEV incentives/tax credits/grants	2 >3MHD ZEV incentives/tax credits/grants	2 >3MHD ZEV incentives/tax credits/grants
Electricity Price	3 Electricity price higher than average	2 Lower than average	2 Lower than average
Regulations	1 Adopted the Advanced Clean Trucks Rule Emission Target: 100% carbon-free by 2045	4 No Target	2 Adopted ACT 100% carbon-free electricity by 2045
# of top 500 fleets	1 Rank #5	1 Rank #1	3 Rank #24
Charging Infra	1 >30% of national capacity	2 > 5% of national capacity	2 >3% of national capacity
Overall	1	2	2

Relative Adoption Rates: Low - 4 … 1- High

[4] EIA, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=table_5_06_a
[5] FleetOwner, 2023, https://cdn.baseplatform.io/files/base/ebm/fleetowner/document/2023/01/FO_500_EQ_FEAT_FINAL_2023.63d945d138b05.pdf
[6] DOE, https://afdc.energy.gov/fuels/electricity_locations.html#/find/nearest?fuel=ELEC

3.2 Sales Forecast Results

This section details the results of the MHD ZEV sales forecast through 2032 by state, regulatory class, and use types.

3.2.1 MHD ZEV Sales by State

MHD ZEV sales through 2032 are expected to reach ~1.5 million BEVs and ~128 thousand FCEV and H2-ICE vehicles.

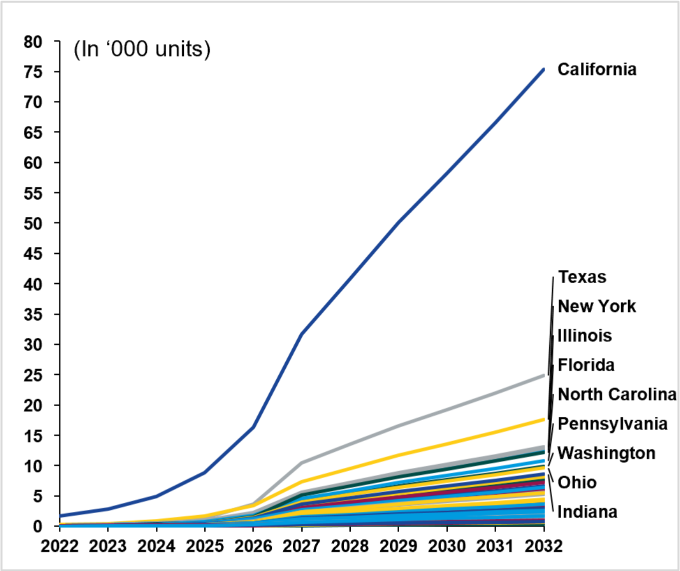
California is expected to continue to lead the pace of ZEV-truck adoption (see Figure 4 and Figure 5). California has established a wider portfolio of regulations, legislation, incentives, and processes to support the ZEV transition. The key mandates and incentives that accelerate MHD ZEV and charging or hydrogen refueling are highlighted below:

1. Mandates: Advanced Clean Trucks (ACT) Regulation, Innovative Clean Transit (ICT) regulation, Advanced Clean Fleet (ACF) Regulation
2. Incentives: Hybrid and Zero Emission Truck and Bus Voucher Incentive (HVIP), Low Carbon Fuel Standard (LCFS), California Electric Vehicle Infrastructure Project (CALeVIP), The Clean Off-Road Equipment Voucher Incentive Project (CORE), Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles (EnergIIZE)

In addition to the regulatory and incentives support, California also is leading the deployment of charging infrastructure and hydrogen refueling stations. More than 30% of Level 2 chargers and DC fast chargers (DCFC) are currently located in California. HD hydrogen refueling stations in the U.S. are primarily in California.

The ZEV sales between 2022-2026 make up less than 10% of total ZEV sales projected by 2032. Beyond 2026, the ZEV adoption ramp-up curve shows exponential growth, driven by the proposed "Phase 3" GHG standards and other incentives. Projected ZEV sales by the state are shown in Figure 4.

Figure 4: BEV Sales by State



Second to California, Texas is expected to be the next highest adopter of FCEV and Hydrogen ICE vehicles. Texas has significant advantages in hydrogen technology adoption, especially in production, storage, and transportation. Texas has access to renewables and natural gas and extensive oil and gas. The state also has hydrogen storage, salt caverns, and developed port infrastructure. Three of the four currently operational hydrogen storage facilities in the world are located in Texas. Texas also owns ~1,000 miles of hydrogen pipelines, representing 64% of the total mileage in the U.S. Projected FCEV and H2-ICE sales by state are shown in Figure 5. National ZEV sales are shown in Figure 6.

Figure 5: FCEV and H2-ICE Vehicles Sales by State

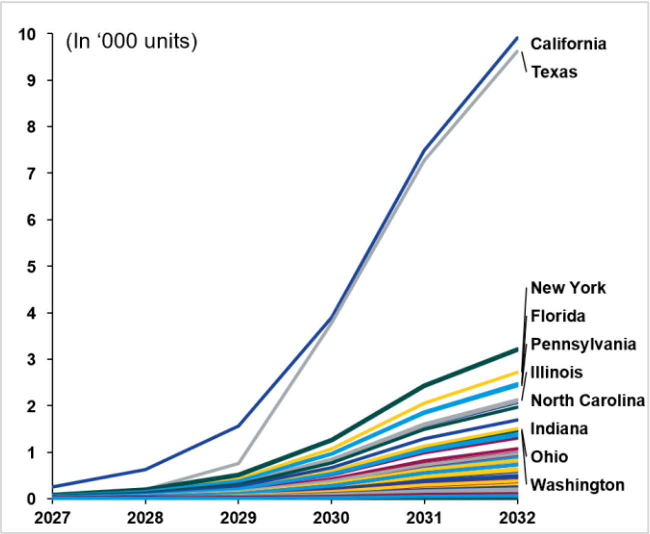
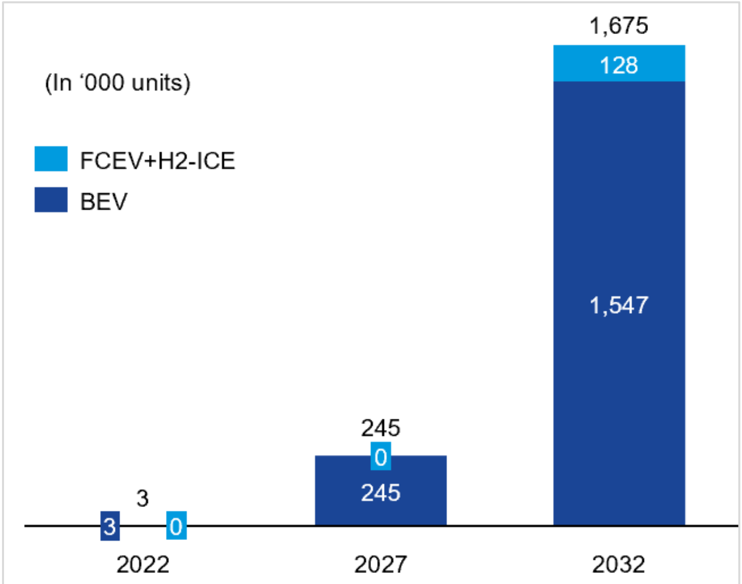


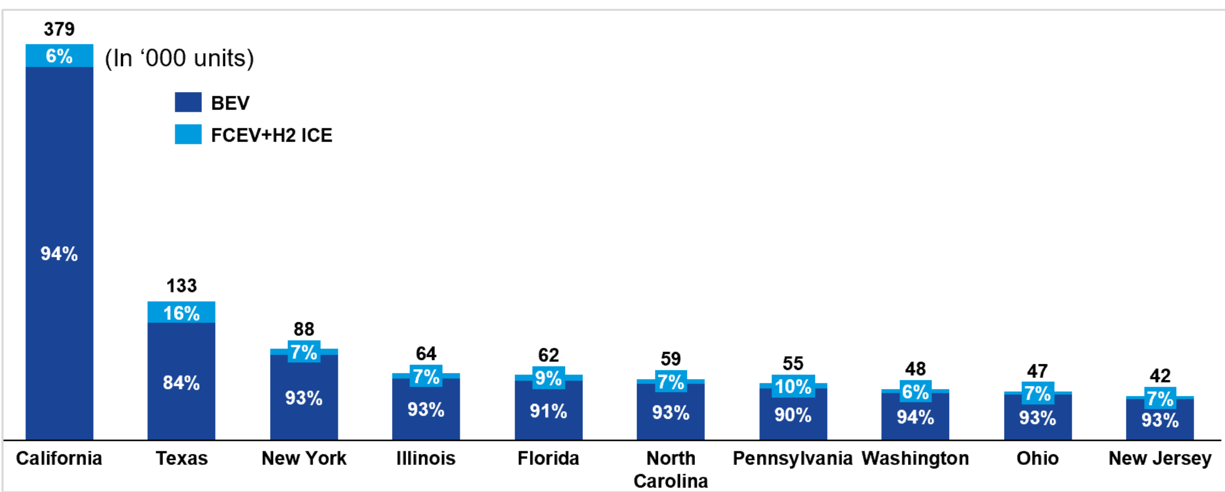
Figure 6: National Total ZEVs On the Road by 2032



As shown in Figure 7, the top 10 states for MHD ZEV sales represent over ~60% of total MHD ZEV sales, led by California, which accounts for ~23% of total sales followed by Texas, New York, Illinois, Florida, and North Carolina, which individually account for over 4% of total ZEV sales.

No H2-ICE vehicle sales forecast data were provided by EPA. Thus, Ricardo estimated the sales based on the IHS forecast and Ricardo's analysis. Because of the advantages in performance and range, major applications for hydrogen ICE vehicles are heavy-duty and long-haul. As a transition technology, hydrogen ICEs are estimated to be ~11% of FCEV in 2030 and are assumed to double in sales year-over-year from 2030 to 2032.

Figure 7: Top 10 States of ZEV on road by 2032



3.2.2 MHD ZEV Sales by Class and Use Types

This section discusses the projected MHD ZEV sales by class and uses types. See Figure 8[7].

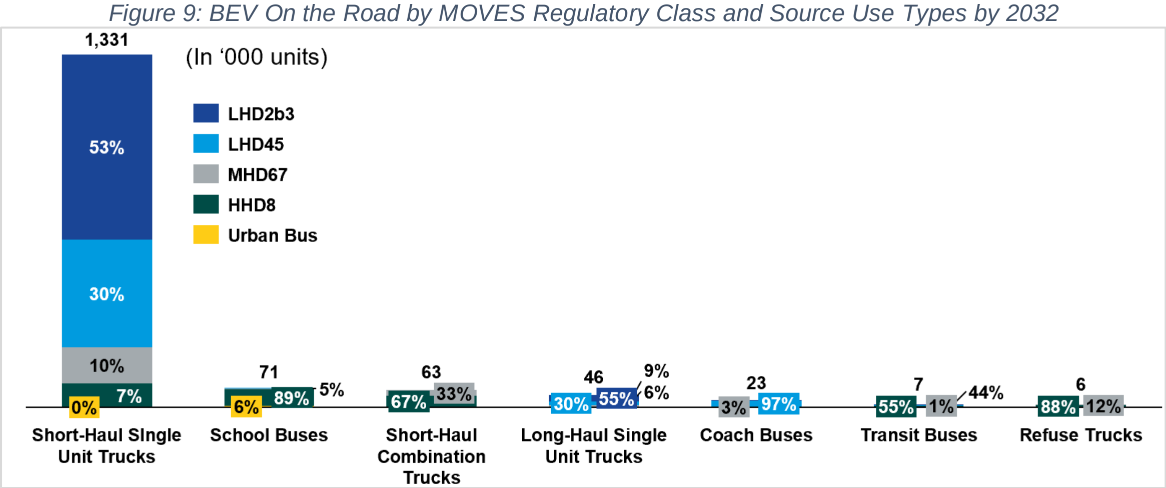
Figure 8: Matrix of Source Type – Regulatory Class Combinations in MOVES3

		Source Use Types												
		Motorcycles	Passenger Cars	Passenger Trucks	Light Commercial Trucks	Other Buses	Transit Buses	School Buses	Refuse Trucks	Short-Haul Single Unit Trucks	Long-Haul Single Unit Trucks	Motor Homes	Short-Haul Combination Trucks	Long-Haul Combination Trucks
Regulatory Classes		11	21	31	32	41	42	43	51	52	53	54	61	62
MC	10	X												
LDV	20		X											
LDT	30			X	X									
LHD2b3	41			X	X			X	X	X	X	X		
LHD45	42					X	X	X	X	X	X	X		
MHD67	46					X	X	X	X	X	X	X	X	X
HHD8	47					X	X	X	X	X	X	X	X	X
Urban Bus	48						X							
Gliders	49													X

The sales summarized in Figure 9 reflect the forecast accumulated BEV sales through 2032.

Over ~85% of BEVs are projected to be short-haul single-unit trucks (no trailer). Within short-haul applications, ~80% are medium-duty (MD) vehicles (class 2b-5). Based on the Daily Operational VMT in the HD TRUCS Model, the average daily range of MD short hauls is below 80 miles. The MD short-hauls are primarily used for freight deliveries (return-to-base) and delivery of various local services, including utility companies. Thus, based on the duty cycle (return-to-base and less than 80 miles daily mileage), the MD short-hauls are expected to dominate the BEV applications.

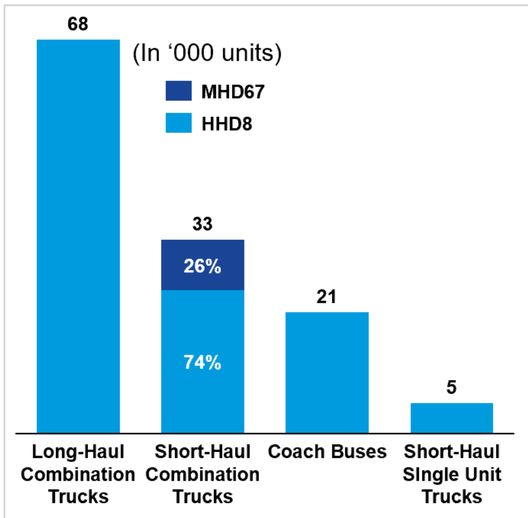
Figure 9: BEV On the Road by MOVES Regulatory Class and Source Use Types by 2032



[7] EPA's Heavy Duty Technology Resources Use Case Scenario tool https://www.epa.gov/system/files/other-files/2023-04/hd-tech-trucs-tool-2023-04.xlsm

Currently, over 90% of the Class 7 and Class 8 trucks have diesel engines (IHS[8]). As FCEV and Hydrogen ICE are still in the early demonstration stage, the adoption rate is not expected to ramp up until 2030.Approximately 50% of FCEV and hydrogen ICE are expected to be used for the multi-purpose long haul (200 miles daily mileage) and regional haul (420 miles daily mileage) (see Figure 10). Due to the constraints in hydrogen capacity (production, transportation) and relatively high fuel cost ($/kg), FCEV and hydrogen ICE vehicles are estimated to be ~10% of the total BEV sales by 2032 and will be limited to long-haul applications.

Figure 10: FCEV + H2 ICE On the Road by 2032 by Regulatory Classes and Use Types



3.3 Summary of Key Insights

MHD ZEV sales through 2032 are expected to reach ~1.5 million BEVs and ~128 thousand FCEV and H2-ICE vehicles.

California is expected to continue to lead the pace of ZEV adoption. Second to California, Texas is expected to be the next highest in FCEV and H2-ICE vehicle adoption.

Over ~85% of BEVs by 2032 are expected to be short-haul single-unit trucks (no trailer). Within short-haul applications, ~80% will be medium-duty (MD) vehicles (class 2b-5).

~50% of FCEV and H2-ICE are expected to be used for the multi-purpose long haul (200 miles daily mileage) and regional haul (420 miles daily mileage).

[8] IHS Insight, 2023

4 Charging Infrastructure and Electrical Demand Analysis

4.1 Methodology

To assess the peak electricity demand on the grid from MHDV-charging, we used the forecasted numbers of on-road MHDVs in 2032 along with specific charger size, type, and charging characteristic assumptions derived through MOVES.

4.1.1 Charging Characteristics

Charging behaviors were modeled to represent the average U.S. fleet for each MHDV segment. Refer to Table 23 in the Appendix, which lists charger location and charging characteristic assumptions by MOVES vehicle class and source use type. Except for 4 HHD8 use types, we assumed all fleets will use depot-based overnight charging to minimize the cost of charging[9]. The 4 HHD8 use-types will rely on highway-based opportunity charging.

We assume stationary wired charging only to reflect the industry development in the United States. The charger size and type used for charging are based on input from the HD TRUCS model. Table 3 below lists the characteristic charging inputs based on charger location.

Table 3: Charging Characteristic Inputs Based on Charger Location

Charger location	Charging type	Charger size and type	Total charging duration	Charger per vehicle	Charging sessions per day	Charging rate
Depot	Overnight	Based on input from the HD TRUCS model[10] 1. L2 19.2 kW 2. DCFC 50 kW 3. DCFC 150 kW 4. DCFC 350 kW	8 hrs.	1	1	Nominal power distributed over 8 hrs.
Highway	Opportunity		4 hrs.	0.16	6	Peak charger capability

[9] PG&E Business EV rate plans, https://www.pge.com/pge_global/common/pdfs/solar-and-vehicles/ev-charge-network/BusinessEVrate-fs.pdf

[10] EPA's Heavy Duty Technology Resources Use Case Scenario tool https://www.epa.gov/system/files/other-files/2023-04/hd-tech-trucs-tool-2023-04.xlsm

To simplify calculations and analyze the worst-case real-world scenario, we assume all depot-based, and highway vehicles are charging simultaneously during overnight charging, generating the peak electrical demand scenario for the electrical supply.

4.1.2 Peak Electrical Demand from Charging

To calculate peak electrical demand for each vehicle class, we use the following calculations:

4.1.2.1 Peak Electrical Demand for Charging / Vehicle at Depot

Calculation = (Vehicle battery size x 80% SOC) / 8 hrs. charge time

<u>Example 1 calculation:</u>

Vehicle class	LHD 4_5
Source use type	School bus
Charger location	Depot
Battery size	88 kWh
Benchmark vehicle	Bluebird G5
Usable SOC	80%
Charger size and type	L2 – 19.2 kW
Vehicles on road 2032	3559
Charger per vehicle	1

Peak electrical demand for charging / vehicle = (88 kWh x 0.80) / 8 hrs.= **8.8 kW**

4.1.2.2 Peak Electrical Demand for Charging / Vehicle On-Highway

Calculation = Peak charger rating

<u>Example 2 calculation:</u>

Vehicle class	HHD8
Source use type	Long Haul Single Unit
Charger location	Highway
Battery size	733 kWh
Benchmark vehicle	Nikola
Usable SOC	80%
Charger size and type	DCFC 350 kW
Vehicles on road 2032	2761
Charger per vehicle	0.16

Peak electrical demand for charging / vehicle = **350 kW**

4.1.2.3 Peak Electrical Demand for Vehicle Class

Calculation = Vehicles on the road 2032 x charger per vehicle x peak electrical demand for charging / vehicle

<u>Example 1</u>

Peak electrical demand School bus LHD 4_5 = 3559 x 1 x 8.8 = 31,321 kW or 31.3 MW

<u>Example 2</u>

Peak electrical demand Long Haul Single Unit HH8 = 2761 x 0.16 x 350 = 161,075 kW or 161 MW

Table 23 in the Appendix shows the breakdown of peak electrical charging demand for each vehicle by class and source use type in 2032.

4.2 Results

4.2.1 Charging Infrastructure Needs

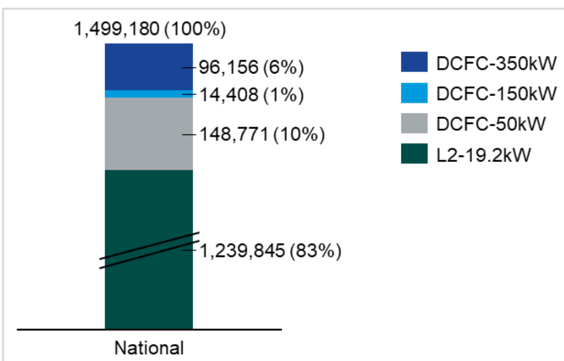
With the three inputs below, we determined national and state-level requirements for chargers in 2032.

1. 2032 national and state level MHDV ZEVs on road
2. Charging characteristics
    a. Charger location
    b. Charger size and type
    c. Charger per vehicle

4.2.2 National Level Charging Infrastructure Needs in 2032

Figure 11 below shows the national-level charger needs by each of the four charger types defined as per HD TRUCS[11] tool

Figure 11: National-level charger needs by charger size and type in 2032



[11] EPA's Heavy Duty Technology Resources Use Case Scenario tool https://www.epa.gov/system/files/other-files/2023-04/hd-tech-trucs-tool-2023-04.xlsm

Based on forecasted BEV MHDV adoption rates and charging characteristics, we project a need for ~1.5 million electric chargers to support on-road BEVs in 2032. Approximately 1.2 million (83%) of the chargers required are L2 19.2 kW depot-based chargers, along with ~100k (10%) 350 kW DCFC fast chargers. With ~98% of the total MHDV population expected to charge at depot-based chargers, only ~0.5% of total charger installations are required to be located on highways.

Table 4: Charger needs 2032 by location and charger size and type

Charger location	L2-19.2 kW	DCFC-50 kW	DCFC-150 kW	DCFC-350 kW	Total
Depot	1239845	148771	14408	86679	1489703
Highway				7477	7477

4.2.3 State-Level Charging Needs in 2032

Figure 12 below shows the total charger needs for the top 10 states in the U.S. California and Texas will need the largest numbers of chargers.

Figure 12: State-level charger needs by charger size and type in 2032

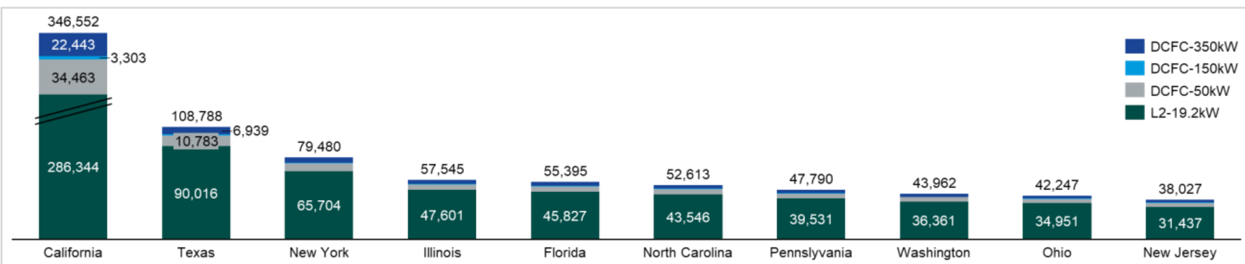


Table 5: List of national and state-level charger needs in 2032

State	DCFC-350kW	DCFC-150kW	DCFC-50kW	L2-19.2kW	% Of national charger needs
National	**94,867**	**14,299**	**147,140**	**1,227,459**	**100%**
California	21,875	3,255	33,744	280,889	23%
Texas	6,885	1,046	10,715	89,500	7%
New York	5,026	753	7,775	64,791	5%
Illinois	3,642	551	5,657	47,219	4%
Florida	3,506	531	5,449	45,491	4%
North Carolina	3,328	508	5,189	43,376	4%
Pennsylvania	3,025	457	4,698	39,209	3%
Washington	2,783	420	4,318	36,032	3%
Ohio	2,674	405	4,156	34,703	3%
New Jersey	2,405	360	3,721	31,012	3%

The top 10 states account for ~60% of the nation's charging needs. California accounts for the largest percentage share at 23%, 3X more than the next state Texas with ~110k total chargers.

4.2.4 Peak Electrical Demand from MHDV Charging

Electric supply in North America is managed by multiple regional utilities. Accordingly, for a thorough representation of peak electrical demand from MDHV charging, we calculate the state-level peak electrical demand.

4.2.4.1 State-Level Peak Electrical Demand from MHDV Charging

Figure 13 below shows the peak electrical demand (MW) from MHDV charging in 2032.

Figure 13: Top 10 states peak electrical demand (MW) from MHDV charging in 2032

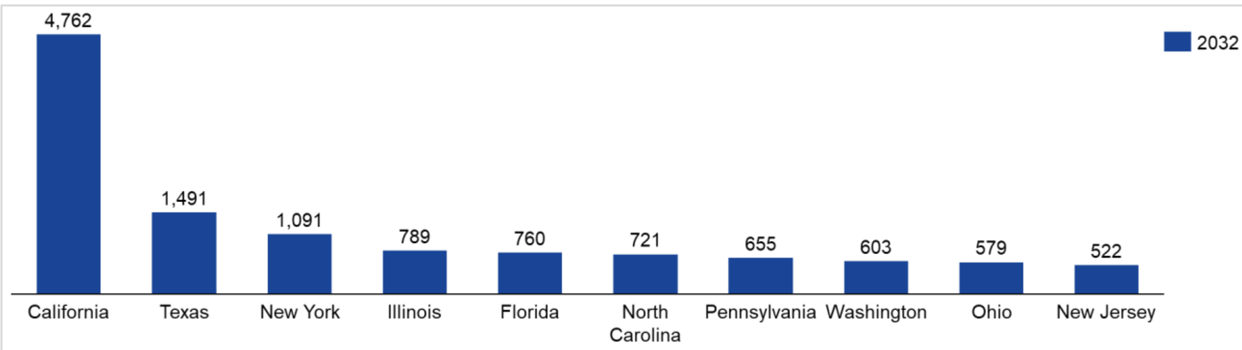


Table 6: List of national and state level peak electrical demand in 2032

State	Peak electrical demand from MHDV charging (MW)	% Of national peak electrical demand
National	**20568**	**100%**
California	4762	23%
Texas	1491	7%
New York	1091	5%
Illinois	789	4%
Florida	760	4%
North Carolina	721	4%
Pennsylvania	655	3%
Washington	603	3%
Ohio	579	3%
New Jersey	522	3%

The energy needs of MHDV charging are expected to grow most rapidly in the states with the most aggressive ZEV adoption policies. California, with the highest number of charger installations, is expected to have the highest peak electrical demand at 4762 MW (23%) ~3X that of Texas and New York. 10 states comprise approximately 60% of the energy consumption from MHDVs in 2032.

4.3 Summary of Key Insights

Charging characteristics of MHDV trucks will vary by class and use type. Approximately 98% of the MHDVs are expected to use depot-based overnight charging, requiring a nominal power demand through the 8-hour charging session using either a L2-19.2 kW, DCFC 50,150-, or 350-kW charger.

With every vehicle expected to have a dedicated charger connector at the depot, this translates to a need for ~1.49 million depot-based chargers and ~7.5k highway-based chargers.

The worst-case scenario of charging the entire population of MHDV simultaneously results in a nationwide peak electrical demand of 20,568 MW, with California representing 23% (4762 MW) of the national demand.

The high estimated number of L2 chargers is based on EPAs assumptions regarding the prevalence of depot-based charging, and the universal availability of overnight charging. If these assumptions are changed, the mix of chargers changes as well.

5 Electrical Supply Readiness

5.1 Methodology

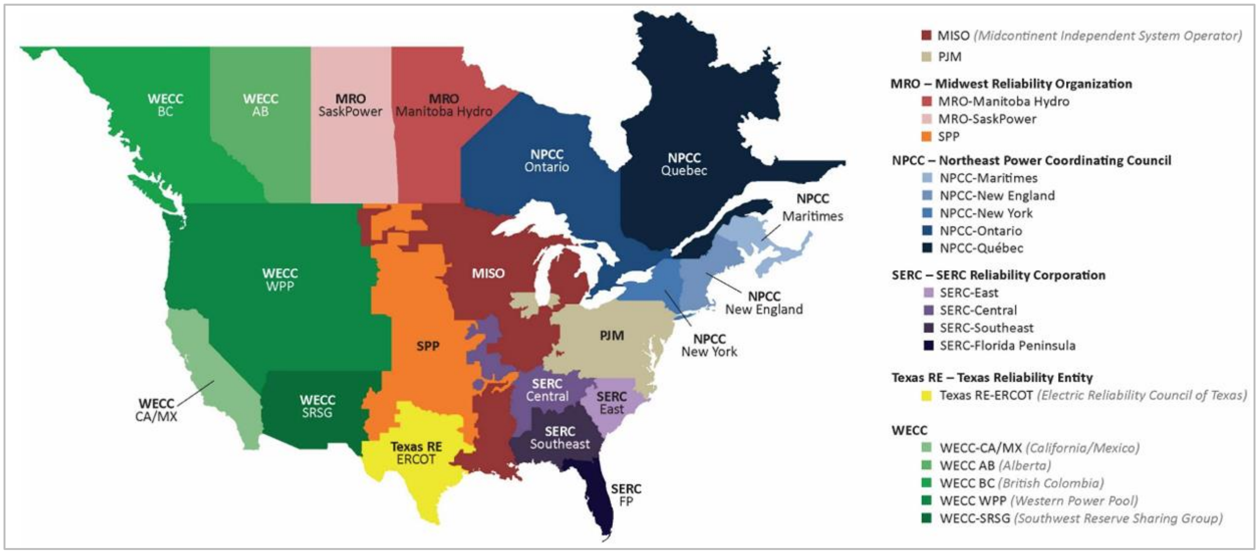
The electrical utility industry in North America employs a simple strategy for maintaining reliability: always have more supply available than may be required. The industry regularly monitors the supply situation by a measure called the “reserve margin”.Regional estimates of reserve margins are compared to pre-determined target levels to assess supply adequacy.

The North American Electric Reliability Corporation (NERC), along with regional entities, evaluates the long-term reliability of the North American Bulk power system while identifying trends, emerging issues, and potential risks including:

1. Electrification and Electric vehicle growth
2. Cryptocurrency impacts on loads and resources
3. Supply chain
4. 6G wireless connectivity

Figure 14 below shows an overview of regions managed by regional entities as published in the NERC long-term reliability assessment from December 2022[12]

Figure 14: Overview of Regions Managed by Regional Entities



Refer to

Table 24 in the Appendix details the state-level breakdown of regional entities. We used the following parameters published in the NERC long-term reliability assessment from

[12] NERC 2022 Long-Term Reliability Assessment, https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf

December 2022[13] as part of our analysis of electrical supply readiness in the U.S. to support peak electrical demand from MDHV charging.

Net demand:

1. Net demand: = Total internal demand - Amount of controllable and dispatchable demand response (Solar and Wind)
2. Total internal demand: This is the peak hourly load for the summer and winter of each year. Projected total internal demand is based on normal weather (50/50 distribution) and includes the impacts of distributed resources, energy efficiency, and conservation programs

Reference margin level:

1. System planners use this metric to quantify the amount of reserve capacity in the system above the forecasted peak demand that is needed to ensure sufficient supply to meet peak loads

Prospective margin level:

1. The number of prospective resources less net internal demand calculated as a percentage of net internal demand
2. Prospective resources include:
    a. Existing-other capacity includes capacity to serve the load demand during periods of peak demand from commercially operating generating units without firm transmission or other qualifying provisions specified in the market construct
    b. Tier 2 capacity additions: includes capacity that has been requested but not received approval for planning requirements
    c. Expected (non-firm) capacity transfers (imports minus exports): transfers without firm contracts but a high probability of future implementation
    d. Subtracting unconfirmed retirements

5.2 Results

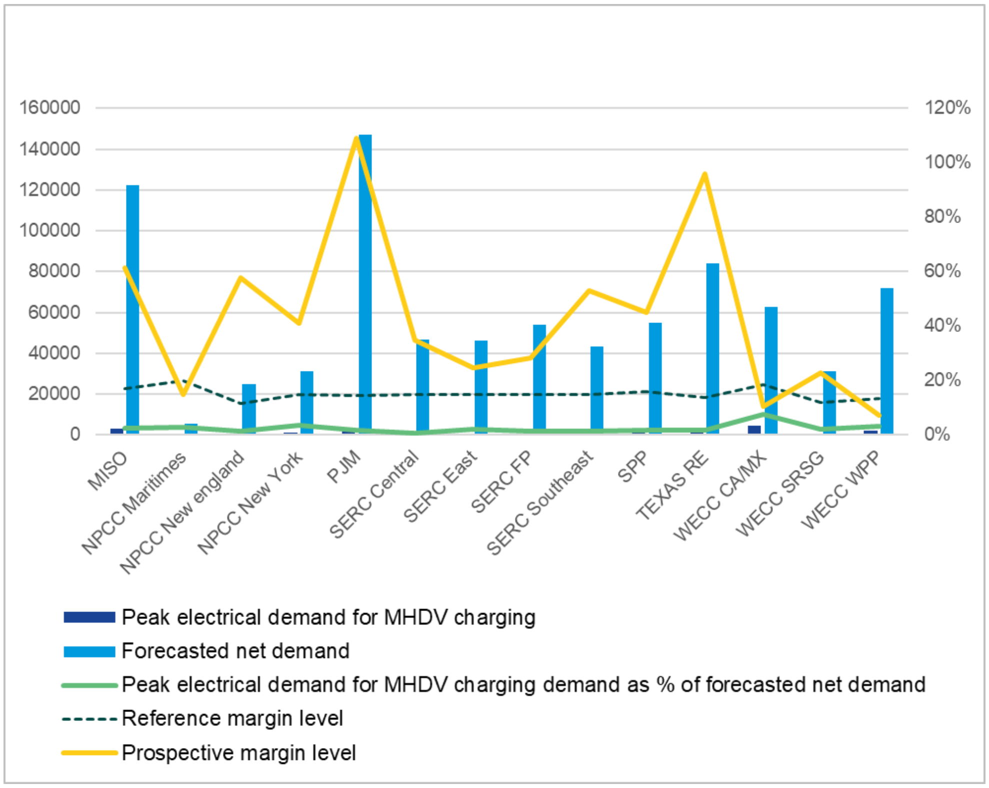
To assess the electrical supply readiness in the US to support peak electrical demand from MDHV charging, we used a similar approach to NERC to:

1. Ensure the combined peak electrical demand from the member states is higher than the forecasted net demand by each of the regional entities

[13] NERC 2022 Long-Term Reliability Assessment, https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf

2. Compare published reference margin levels and prospective margin levels to % impact from the peak electrical demand from MHDV charging vs. forecasted net demand.

Figure 15: Peak Electrical Demand for MHDV Charging vs. Forecasted Net Demand



The overall impact of MHDV charging demand on the grid is minimal and is well under forecasted prospective margins published in the NERC Long-Term Reliability Assessment from Dec 2022 [14]. As shown in Figure 15 and Table 7, California, Northwestern states and Northeastern coastal states are the only regions where the revised prospective margin level accounting for peak electrical demand from charging is lower than reference margin levels. California and WECC have the lowest (4%) prospective margin levels.

[14] NERC 2022 Long-Term Reliability Assessment, https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf

Table 7: Data Table for Peak Electrical Demand from MHDV Charging vs. Forecasted Net Demand - 2032

Regional Entity	Peak electrical demand from MHDV charging (MW)	Forecasted net demand	Max MHDV charging demand as % of peak grid demand (A)	Prospective margin level (B)	Prospective margin level after subtracting peak electrical demand from charging (B) - (A) = (C)	Reference margin level
MISO	3259	122300	2.7%	62%	59%	17.00%
NPCC Maritimes	161	5661	2.8%	15%	12%	20.00%
NPCC New England	329	24811	1.3%	58%	56%	11.50%
NPCC NY	1091	31402	3.5%	41%	37.5%	15.00%
PJM	2668	147141	1.8%	109%	107%	14.70%
SERC Central	354	46696	0.8%	35%	34%	15.00%
SERC East	931	46489	2.0%	25%	23%	15.00%
SERC FP	760	54099	1.4%	28%	26%	15.00%
SERC Southeast	697	43495	1.6%	53%	51%	15.00%
SPP	966	54898	1.8%	45%	44%	16.00%
TEXAS RE	1491	84114	1.8%	96%	94%	13.75%
WECC CA/MX	4762	62537	7.6%	11%	3%	18.70%
WECC SRSG	630	31032	2.0%	23%	21%	11.90%
WECC WPP	2399	72138	3.3%	7%	4%	13.50%

5.3 Summary of Key Insights

The electrical utility industry in North America employs a simple strategy for maintaining reliability: always have more supply available than may be required. The industry regularly monitors the supply situation by a measure called the reserve margin. Regional estimates of reserve margins are compared to pre-determined target levels to assess supply adequacy on an annual basis.

The prospective margin levels from the NERC long-term reliability assessment of December 2022 were used as key metrics to assess the % impact from peak electrical demand from MHDV charging.

The prospective reserve margin levels from regional entities are inclusive of expected increase in energy demands due to the following:

1. Electrification and Electric vehicle growth
2. Cryptocurrency impacts on loads and resources
3. Supply chain
4. 6G wireless connectivity

Except for California, Northwestern and Northeastern coastal states, all other regions currently have a prospective margin level in excess of the reference margin levels.

6 Charging Infrastructure Readiness

This section discusses the current MD/HD charging infrastructure and the gaps between the current charging infrastructure and the infrastructure demand by 2032. In addition, Ricardo has provided recommendations to achieve the necessary charging infrastructure development to meet the EPA-proposed ZEV vehicle adoption targets.

6.1 Current Charging Infrastructure

6.1.1 LDV vs. MHDV

As compared to LDVs, MHDVs require larger battery packs to support the applications' range requirements. This, in turn, results in increased charging time and/or charger capacity requirements for charging MHDV vehicles. Table 23 in the Appendix lists the average battery size for MHDVs by sales class and use type.

LDV charging sites are not designed to accommodate pull-through spaces, turning radii, or ingress/egress requirements for MHDV vehicles, so LDV sites will provide little benefit for the majority of MHDV vehicles.

The difference in battery pack size, charger requirements, and charging site infrastructure between LDVs and MHDVs drives very limited interoperability between LDV and MHDV charging infrastructures, which necessitates dedicated MHDV charging infrastructure solutions.

6.1.2 Current Installations

The current charging infrastructure in the United States is primarily focused on LDV charging with ~160,650[15] charger ports nationwide, with 125,400 (~78%) ports being L2-19.2 kW charging ports and 35,200 (~22%) being DC fast chargers.

With only ~3000[16] BEV MHDVs on-road in 2022, current MHDV charging infrastructure is limited primarily to private depot-based installations nationwide. Table 8 below shows an example of 15 of the largest private MHDV BEV fleet size and depot-based charger installations based on published public domain information.

[15] https://afdc.energy.gov/stations/#/analyze?fuel=ELEC

[16] Figure 6: National Total ZEVs On the Road by 2032

Table 8: Top 15 Truck and Tractor Fleets Nationwide

Fleet name	Installed charging station	Planned installations	Current Fleet size[17] [18] (2022)	BEV fleet size (2022)	Planned BEV fleet size	BEV fleet % of the total fleet
FedEx	56	500	120491	150	2000	0.001%
UPS	6	-	104751	100	NA	0.001%
Pepsi co.	8	36	33899	8	36	0.0005%
Sysco	40	-	10281	40	2800	0.003%
Walmart	-	1300	9305	NA	4500	0%
Halliburton	-	-	8564	-	-	-
Reyes Holdings	0	60	7107	0	60	-
US Foods	30	-	6402	30	NA	0.005%
PFG	1	-	6305	1	NA	0%
McLane	-	-	4169	-	-	-
Patrick Ind.	-	-	3530	-	-	-
Brinks	5	NA	3261	5	NA	0.001%
UniGroup	3	NA	3037	3	NA	0.001%
Quality Carriers	-	-	2292	-	-	-
R+L Carriers	-	-	1662	-	-	-

Given the low adoption of BEV MHDVs, the charging infrastructure at fleet depots is limited to meeting the ongoing pilot program requirements. It is important to point out two key observations:

1. The percentage of BEV vehicles in the current 2022 trucking fleet is ~ 0.001%
2. Several large fleets (highlighted yellow in Table 8) have not published any guidance on future fleet electrification plans or pilot programs

[17] https://pages.ttnews.com/rs/905-BBW-876/images/tt100Private22.pdf

[18] https://cdn.baseplatform.io/files/base/ebm/fleetowner/document/2023/01/FO_500_EQ_FEAT_FINAL_2023.63d945d138b05.pdf

6.2 Charging Infrastructure Investment Requirements by 2032

Using the forecasted number of chargers required to support the forecasted BEV population on the road in 2032, we estimated the total investment needed to develop the charging infrastructure using a unit cost metric, "Project cost per connector." The costs are estimated from CaleVIP[19] (1057 Level 2 and 377 DCFC installations) and ICCT-published data sources from prior installations and industry research. The project cost per connector is inclusive of the following costs:

1. Labor
2. Materials (charger port, electrical equipment for grid connection, etc.)
3. Permits
4. Taxes

Table 9 below shows the cost for each charger type along with forecasted cost reductions (based on ICCT data)[20] primarily due to the economics of scale advantage from higher future EV adoption rates across all vehicle segments.

Table 9: EV Charger Installation Project Cost per Connector

Charger type	No. of connectors per project 2022	Project cost per connector 2022	% Forecasted cost reduction	No. of connectors per project 2032	Project cost per connector 2032	Project cost per connector 2022 data source
L2 19.2 kW	8	$ 9,139	25 %	16+	$ 6,854	CaleVIP (2022)
DCFC 50 kW	4	$ 28,401	35 %	8+	$ 18,460	ICCT (2019)
DCFC 150 kW	4	$ 104,443	25 %	8+	$ 78,332	CaleVIP (2022)
DCFC 350 kW	4	$140,000	35 %	8+	$ 91,000	ICCT (2019)

[19] https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program/california-electric-vehicle
[20] https://theicct.org/wp-content/uploads/2021/06/ICCT_EV_Charging_Cost_20190813.pdf

6.3 Results

Table 10 below shows the total investment required to develop the charging infrastructure to support the forecasted MHDV vehicles on the road in 2032.

Figure 16: Investment Required to Develop Charging Infrastructure to Support Forecasted MHDV Vehicles on road in 2032

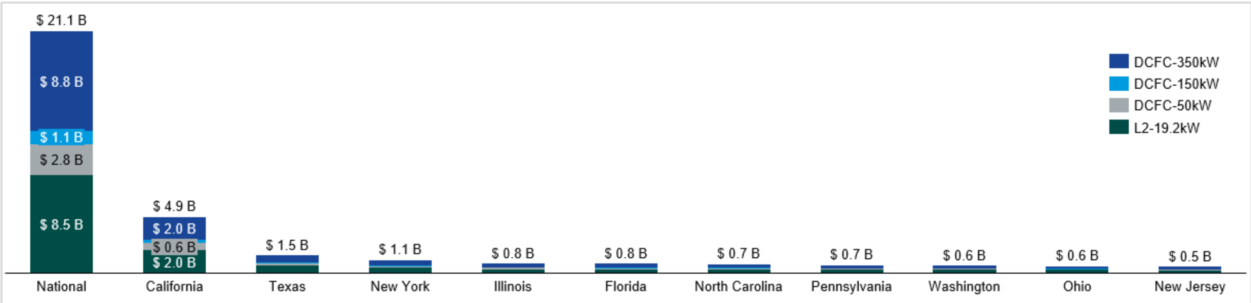


Table 10: Investment Required to Develop Charging Infrastructure to Support Forecasted MHDV Vehicles on road in 2032

State	DCFC-350kW	DCFC-150kW	DCFC-50kW	L2-19.2kW	The total investment needed ($ Billion)	% National Investment	No. of charge connectors
National	8.75	1.13	2.75	8.50	21.1	100%	1483765
California	2.04	0.26	0.64	1.96	4.9	23%	339763
Texas	0.63	0.08	0.20	0.62	1.5	7%	108146
New York	0.47	0.06	0.15	0.45	1.1	5%	78345
Illinois	0.34	0.04	0.11	0.33	0.8	4%	57069
Florida	0.32	0.04	0.10	0.31	0.8	4%	54977
North Carolina	0.30	0.04	0.10	0.30	0.7	3%	52401
Pennsylvania	0.28	0.04	0.09	0.27	0.7	3%	47389
Washington	0.26	0.03	0.08	0.25	0.6	3%	43553
Ohio	0.25	0.03	0.08	0.24	0.6	3%	41938
New Jersey	0.22	0.03	0.07	0.22	0.5	3%	37498

The estimated investment required to develop the necessary charging infrastructure to support forecasted MHDV vehicles on the road in 2032 is ~$21.1 billion. That investment would support the installation of ~1.5 million charger ports nationwide.

The estimated investment is promised on EPA's assumptions regarding the prevalence of depot-based charging and the universal availability of overnight charging. If those assumptions are changed, the need for higher-power DC fast chargers increases, which would increase the estimated investment substantially.

6.4 State and Federal Charging Infrastructure Incentives and Funding

Table 11 below shows a summary of available state and federal charging infrastructure incentives and funding programs.

Table 11: Summary of State and Federal Incentives and Funding Eligible for MHDV Charging Infrastructure

Program	Public MHDV charging infra.	Private MHDV was charging infra.	Public vehicles	Private fleet vehicles	Eligibility Restrictions	Cumulative funding and duration
Grants for buses and bus facilities program[21]	X		X		None	**$2 billion** (5 yrs.)
Clean heavy-duty truck program[22]	X	X	X	X	None	**$1 billion** (10 yrs.)
Expansion of EV charging in underserved communities[23]	X				Justice40 underserved areas	NA
Alternative fuel infra. tax credit[24]	X	X			Low-income and non-urban communities with at least 20% poverty	NA (10 yrs.) 30% of equipment cost to the max of $100,000
CUPC – California public utilities[25]	X	X	X	X	70% percent toward MHDV charging	**$1 billion** (5 yrs.)

Federally funded programs like the grants for buses and bus facilities program, expansion of EV charging in underserved communities, and alternative infrastructure credit have restrictions that only support a specific vehicle class or limit nationwide eligibility.

[21] https://www.transit.dot.gov/bus-program
[22] https://www.epa.gov/inflation-reduction-act/clean-heavy-duty-vehicle-program
[23] https://www.energy.gov/articles/biden-harris-administration-announces-funding-zero-emission-medium-and-heavy-duty-vehicle
[24] https://afdc.energy.gov/laws/10513
[25] https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-adopts-transportation-electrification-program-to-help-accelerate-electric-vehicle-adoption

We consider these programs to have minimal impact on supporting MHDV charging infrastructure installations at private depots across the country.

Clean heavy-duty truck and CUPC programs are the only programs with funding eligible for private fleet vehicles to install charging infrastructure at private depots with a total of $2 billion dollars of cumulative program value.

As allocated in the CUPC program, we assumed 70% ($1.4B) of the total available $2.0 B will be available for the development of MHDV charging infrastructure in the next 5 yrs.

6.5 Summary of Key Insights

The necessary MHDV vehicle charging infrastructure has limited interoperability with LDV charging infrastructure primarily due to the following:

1. Larger battery size in MHDVs
2. Charging site requirements
    a. Drive-thru
    b. Turning radius
    c. Ingress/Egress

The primary differences between LDV and MHDV charging infrastructure requirements warrant a separate dedicated MHDV charging infrastructure to support the forecasted on-road MHDV population in 2032.

Current nationwide charging installations are catered to support LDV charging, with most of them located for public access. Charger installations at MHDV fleet depots are currently limited to supporting ongoing BEV pilot programs.

The estimated investment required to develop the charging infrastructure to support the forecasted numbers of MHDVs on the road in 2032 is ~$21.1 billion. That investment would support the nationwide installation of ~1.5 million charger ports through 2032.

State and federal incentives and funding programs are constrained to supporting specific vehicle classes and regions. The CUPC program in California and the Clean Heavy-duty Truck Program from the Inflation Reduction Act of 2022 are the only programs that directly support MHDV charging infrastructure development, with $1.4B in eligible funding.

An additional investment of $ 19.7 B in private and public investment will be required to address the shortfall and develop a sufficient charging infrastructure dedicated to MHDV charging at depots and highways.

7 BEV Charging Infrastructure Deployment Recommendations

Dedicated federal funding for MHDV charging infrastructure

The upfront costs of MHDV charging stations are significant when considering large installations required by MHDV fleet operators. However, fewer incentives or funding programs are currently available for charging infrastructure due to the earlier stage adoption of BEV MHDVs. Based on Table 11, there are only two ZEV incentives or funding programs eligible for BEV charging infrastructure. Similar to the NEVI[26] , which has allocated $7.5 billion to develop a nationwide network of 500,000 chargers to accelerate LDV adoption, a dedicated MHDV charging infrastructure program would facilitate the deployment of MHDV charging infrastructure, driving adoption to meet EPAs Phase 3 GHG emission targets.

FHWA guidance on MHDV charging standard

Based on EPA's Phase 3 GHG emission standards, the adoption of BEV MHDVs is expected to grow to 17% of new vehicle sales by 2027, and the number will increase even further up to 47% of new vehicle sales by 2032. To support a steady adoption rate over the next 5 years, the FHWA should work with truck OEMs, fleet operators, charging service providers, utilities, and other stakeholders to develop guidance for MHDV charging standards. This will help provide stakeholders an opportunity to address specific needs as well as share their development experience to develop a standardized MHDV charging standard.

Ongoing technological innovation for MHDV charging is anticipated, e.g., megawatt charging which is likely to be used for charging Class 8 BEV trucks at highway-based charger installations. However, based on the adoption rate targets set in the EPA Phase 3 GHG emission standards, short-haul single-unit trucks are forecasted to have the highest BEV adoption rates. Those are vehicles that will primarily return to the depot for overnight charging.

We recommend FHWA consider a two-phased approach for issuing guidance for depot-based charging installations to support vehicle applications that return to the home base every day, followed by a second phase for issuing guidance for highway-based charging installation standards.

[26] https://www.fhwa.dot.gov/environment/nevi/

Charging site design recommendations

Larger sizes of MHDVs present accessibility constraints. Listed below are a few factors which need to be considered when designing an MHDV charging site:

1. Drive-thru accessibility
2. Turning radius
3. Ingress/egress
4. Longer dwell times

We recommend FHWA include charging site design considerations as part of the development of MHDV charging standards.

Government needs to take necessary steps to drive utilities and fleet operator collaboration

To manage the forecasted increase in electrical demand from electrical charging infrastructure, utilities need to develop programs to leverage the existing smart charging and fleet management software based on unique fleet use cases and sizes. This will help utilities:

1. Plan their load profiles and develop custom service contracts with individual customers
2. Manage a more certain load forecast, eventually benefitting fleet customers TCO
3. Utilize efficient workforce planning and training

While helping fleet operators to:

1. Understand any potential supply chain issues that will impact the fleet electrification road map
2. Plan investments for fleet electrification and associated infrastructure costs

As part of MHDV charging standards and grant program prerequisites, we recommend that the federal government take the necessary steps to ensure that utilities and fleet operators collaborate to plan and develop efficient charging infrastructure solutions leveraging smart-charging technology.

8 Hydrogen Demand Analysis

MHD BEVs are being developed for a range of applications. However, electrification has been considered a challenge for higher-mileage and heavier-load vehicle applications. FCEVs and H2-ICEs are expected to be used for a significant share of HD regional and long-haul applications. As FCEVs and H2-ICEs are at a pre-commercial stage, EPA projected the FCEVs ramp-up to begin in 2030.

This section discusses the hydrogen demand to meet the projected FCEV and H2-ICE sales from 2030 to 2032.

8.1 Methodology

Ricardo calculated the hydrogen demand for both FCEVs and H2-ICEs based on EPA's projection (national FCEV sales) and Ricardo's forecast (state FCEV sales, national and state H2-ICEs sales) and the duty cycle parameters. Ricardo multiplied the total volume of FCEVs and H2-ICEs between 2030 and 2032 by the daily mileage, fuel efficiency, and annual working days to calculate the hydrogen demand.

An example of calculation procedures for determining the national hydrogen demand for multi-purpose long-haul and regional haul is shown in Table 12.

Table 12: Example of Hydrogen Demand Estimation

Parameters	MOVES Source TypeID	Long-Haul Combination Trucks	Long-Haul Combination Trucks
	MOVES RegClassID	HHD8	HHD8
	Vehicle ID	78Tractor_SC_Cl8_MP	79Tractor_SC_Cl8_R
Daily Operational VMT (miles per day)		200	420
Fuel Efficiency(kWh/mile)		3.57	3.56
FCEV Fuel Efficiency (H2 kg/mile)		0.11	0.11
Annual Average Working Days (number of days)		260	260
Annual Hydrogen Demand per FCEV (H2 kg)		**5,641**	**11,826**
National FCEV Sales by 2032		16,729	43,016
Total FCEV Hydrogen Demand (H2 kg)		**94,369,410**	**508,696,245**

The values of daily mileage and fuel efficiency (kWh/mile) were obtained from the HD TRUCS Model. The values used for estimating hydrogen demand are shown in Table 13 by source type, regulatory class, and vehicle ID.

Table 13: Values from HD TRUCS Model

MOVES Source TypeID	MOVES RegClassID	Vehicle ID	Daily Operational VMT (miles per day)	Fuel Efficiency (kWh/mile)
41 Other Buses - Coach Bus	47 HHD8	17B_Coach_Cl8_R	158	3.13
41 Other Buses - Coach Bus	47 HHD8	18B_Coach_Cl8_MP	158	3.13
62 Long-Haul Combination Trucks	47 HHD8	78Tractor_SC_Cl8_MP	200	3.57
62 Long-Haul Combination Trucks	47 HHD8	79Tractor_SC_Cl8_R	420	3.56
52 Short-Haul Single Unit Trucks	47 HHD8	80Tractor_DC_Cl8_HH	106	5.17
61 Short-Haul Combination Trucks	46 MHD67	81Tractor_DC_Cl7_R	120	2.88
61 Short-Haul Combination Trucks	47 HHD8	82Tractor_DC_Cl8_R	216	3.51
61 Short-Haul Combination Trucks	47 HHD8	84Tractor_DC_Cl8_U	216	3.51

Ricardo converted the fuel efficiency from kWh/mile to kg/mile according to DOE conversion factors[27].

1. GGE = Electricity kWh x 0.031
2. GGE = H2 kg x 1.019

The fuel efficiency of H2-ICE is estimated to be ~19% better than FCEV between 2030 and 2032 [28] due to the performance advantages in heavy vehicles.

8.2 Results

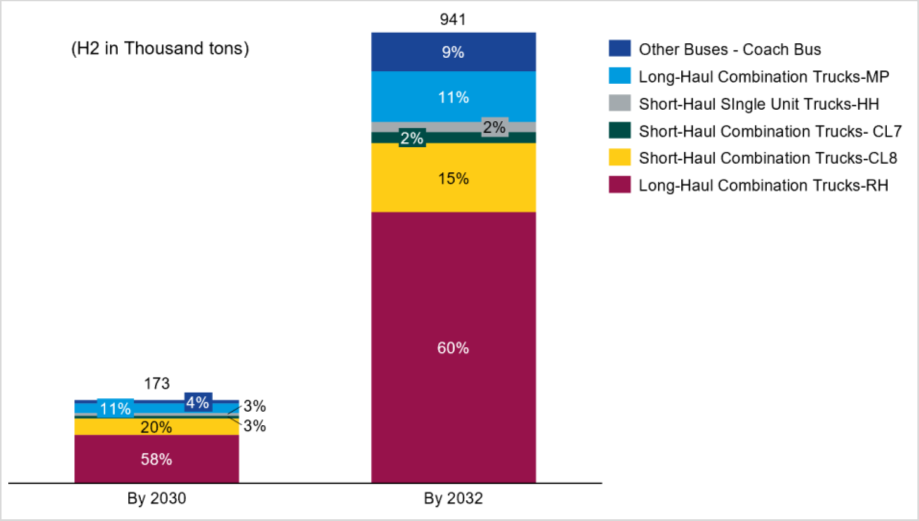
To achieve the target adoption of FCEVs and H2-ICEs (Figure 6), the estimated hydrogen demand is 0.2 M tons/year by 2030 and 0.9 M tons/year by 2032 (Figure 17). Regional-haul applications comprise over ~50% of total hydrogen demand, followed by class 8 short-haul combination (with trailer) applications, which make up ~15% of the total share.

The daily range of both regional-haul and class 8 short-haul combination exceed 200 miles. As discussed in MHD ZEV Sales by Class and Use Types, FCEVs and H2-ICEs are expected to take a significant share of higher-mileage and heavier-load applications.

The demand analysis results by each state, source type, and class are shown in Figure 18.

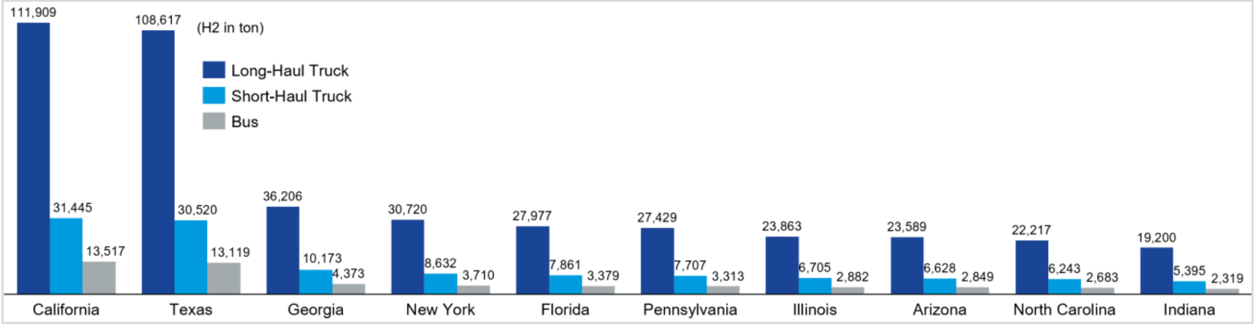
[27] DOE, https://epact.energy.gov/fuel-conversion-factors
[28] 43rd International Vienna Motor Symposium, 2022, https://mobilitynotes.com/h2-ice-truck-cost-of-ownership-vs-diesel-and-fuel-cell-vehicles/

Figure 17: Annual Hydrogen Demand



California and Texas lead the hydrogen demand as California is pushing the decarbonization of HD vehicles. Texas has a large HD truck market and significant advantages in hydrogen resources to promote hydrogen adoption.

Figure 18: Top 10 States of Annual Hydrogen Demand by 2032



8.3 Summary of Key Insights

The hydrogen demand is expected to be 0.9 M tons/year by 2032. Regional-haul applications will comprise over ~50% of total hydrogen demand. California and Texas are projected to be the dominant players to drive hydrogen demand.

9 Hydrogen Infrastructure Readiness

This section discusses the hydrogen infrastructure capacity and the gap between the current hydrogen infrastructure capacity and the hydrogen demand projected by 2032. In addition, Ricardo has provided recommendations to help accelerate the adoption rate for the hydrogen market.

9.1 Hydrogen Infrastructure Capacity

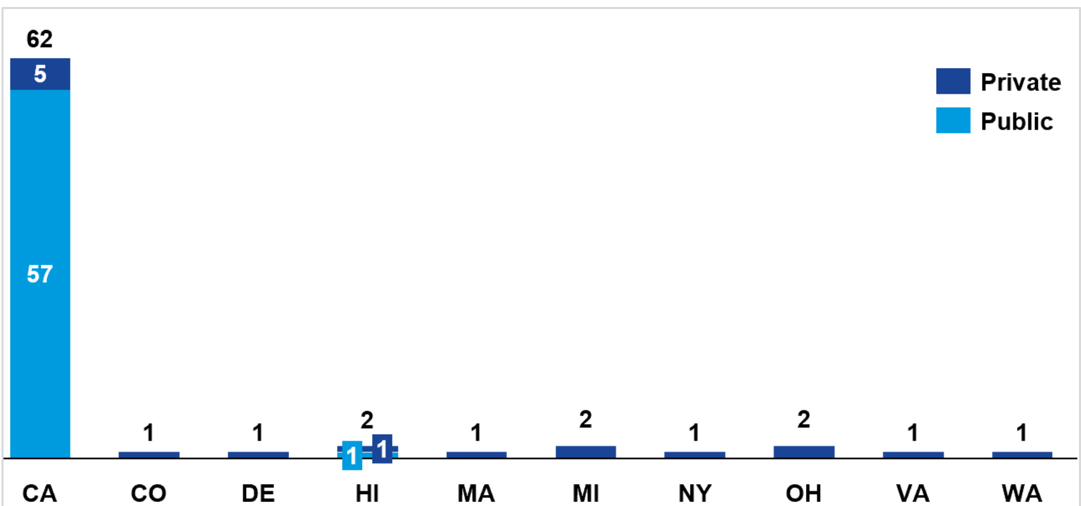
9.1.1 Current LDV Hydrogen Infrastructure Capacity

Hydrogen infrastructure is a critical element of MHD FCEV and H2-ICE adoption. Although light-duty (LD) FCEVs are commercialized, less than 80 refueling stations are open nationally as of May 2023[29]. More than ~85% of LDV refueling stations are located in California.

LDV refueling stations are typically sited at gas stations (~80% of LDV hydrogen stations are in gas stations). Other key facility types are shown below:

1. Public: Convenience store, college campus, dealer, office building
2. Private: Fleet garage

Figure 19: Hydrogen Refueling Station - LDV



[29] DOE, May 2023, https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/hydrogen-refueling

9.1.2 HDV Infrastructure Requirements Compared to LDV

Due to constraints in storage capacity and fueling rate, an LD hydrogen refueling station is not expected to dispense the volume or rate that an HD FCEV or H2-ICE requires. Thus, the capacity of LD hydrogen refueling stations is not included in this study. The two main constraints of LD refueling stations are noted below:

Storage Capacity

Current LDV stations do not have enough storage capacity to fuel MHDVs at scale. A high-volume refueling operation may cause the LDV station to terminate fueling, as the system may consider this volume to be a leak in the tank or some other fault. Standards for LDV fueling are generally not compatible with HDVs. SAE J2601 (for LDVs) only allows fueling for tanks that have a maximum storage capacity of 10 kg, but HD trucks are expected to have a larger tank system (40–100 kg).

Fueling rate

SAE J2601 (LDVs) only allows for fueling at a maximum rate of ~3.6 kg per minute. HD FCEVs require an average rate of ~8-10 kg per minute, which is the diesel-equivalent fueling rate for a Class 8 truck DOE's interim target for 2030 is 8 kg per minute.

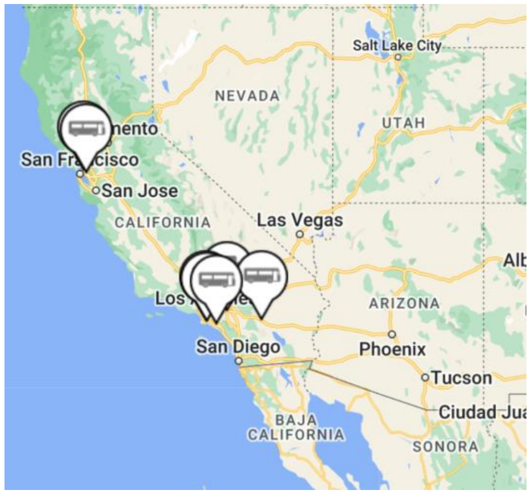
9.1.3 HDV Infrastructure Capacity

As HD FCEVs and H2-ICEs are in earlier stages of development than LDVs, very few HD hydrogen refueling stations have been deployed. Six HD refueling stations are deployed in California (Figure 20[30]).Three of them were deployed for HD fuel cell electric buses (FCEB), and the other three are at Shell stations for HD trucks.

Other than the deployed HD hydrogen refueling stations, another 13 stations have been funded by California Energy Commission (CEC) as of end of 2022 and are to be deployed in California in the future (deployment dates unknown). The capacity of the funded stations range from 2000 kg to 6000 kg.

[30] Hydrogen Fuel Cell, https://h2fcp.org/stationmap

Figure 20: HD Hydrogen Refueling Stations in California



Although more than 200 fuel cell electric buses (FCEB)[31] have been deployed, most of the FCEB fleets have less than five hydrogen buses and use hydrogen refueling stations with coordinated on-site production[32]. The hydrogen refueling stations with on-site production are for private purposes and with lower capacity compared to HD refueling stations. Thus, the capacity of small FCEBs fleets (less than 5 FCEBs) with on-site production is not included in the capacity estimation.

Based on a CALSTART California hydrogen market assessment report [33], the hydrogen refueling capacity in California's truck clusters is estimated to be ~11 thousand tons/year. Adding the capacity of buses (Table 14), California's total hydrogen refueling capacity is ~12 thousand tons/year. That refueling capacity is projected to be less than half of the annual demand by 2030. A gap of over ~140 thousand tons/year will need to be filled by 2032.

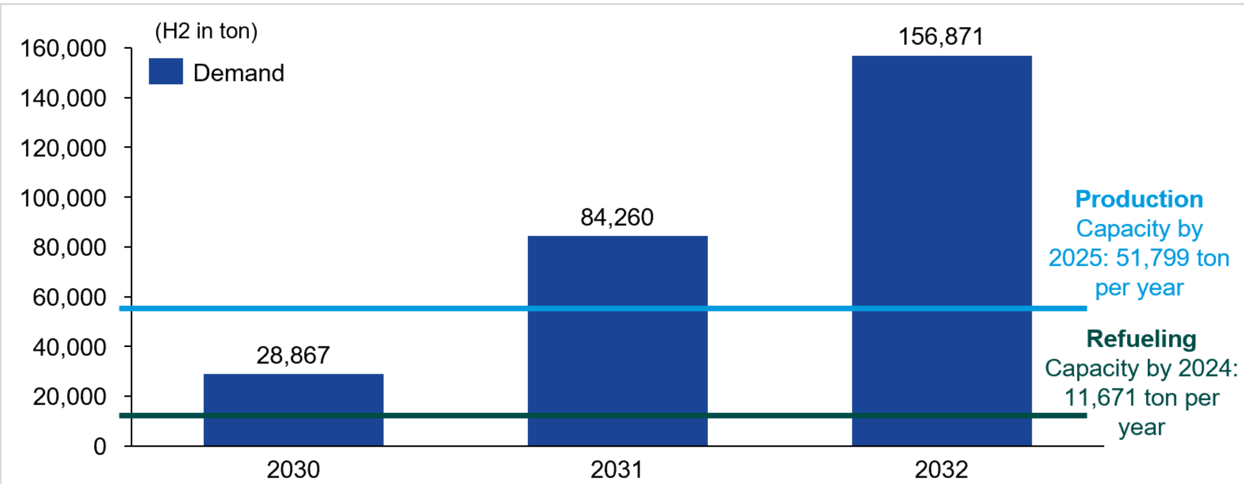
[31] CALSTART, Feb 2023, Zeroing on ZEBs, https://calstart.org/wp-content/uploads/2023/02/Zeroing-in-on-ZEBs-February-2023_Final.pdf
[32] NREL, https://www.nrel.gov/hydrogen/fuel-cell-bus-evaluation.html

[33] CALSTART, Mar 2023, Roadmap to Fuel Cell Electric Truck Commercialization

Table 14: Refueling Capacity of Large FCEB Fleets

Fleet	Capacity
California	
AC Transit (California)	~6,000 kg[34] (storage capacity) Estimated ~910 kg/day (dispense capacity)
Orange County Transportation Authority (California)	~4,800 kg[35] (storage capacity) Estimated ~730 kg/day (dispense capacity) based on ~50 FCEB daily capacity
SunLine Transit (California)	~900 kg/day[36] (production capacity)
Estimated Total Annual Refueling Capacity	**~0.7 thousand tons/year**
Ohio	
Stark Area Regional Transit Authority (Ohio)	~4,000 kg[37](storage capacity) Estimated ~610 kg/day (dispense capacity)
Estimated Total Annual Refueling Capacity	**~0.2 thousand tons/year**

Figure 21: Hydrogen Refueling and Production Capacity by Funded Projects



Ricardo conducted public domain research on the planned and funded hydrogen refueling stations from various sources (e.g., industry and state governmental agencies). However, only a few states have developed roadmaps for hydrogen infrastructure. It is unclear what total refueling capacity is included in funded projects. Thus, Ricardo estimated the

[34]AC Transit https://www.actransit.org/zeb#:~:text=Our%20Zero%20Emission%20Bus%20(ZEB,9%2C000%20gal%20hydrogen%20storage%20tank.

[35] NREL, March 2021, Orange County Transportation Authority Fuel Cell Electric Bus Progress Report, https://www.nrel.gov/docs/fy21osti/78250.pdf

[36] CARB, https://ww2.arb.ca.gov/lcti-sunline-fuel-cell-buses-hydrogen-onsite-generation-refueling-station-pilot-commercial#:~:text=Turn%2Dkey%20provision%20by%20Nel,renewable%20electrolysis%20hydrogen%20fueling%20station.

[37] https://www.cantonrep.com/story/news/2022/08/12/sarta-gets-federal-grant-to-cover-cost-of-two-no-emission-buses/65400943007/

number of HD hydrogen refueling stations required to meet the 2032 target based on the hydrogen demand by 2032. Except for California and Ohio, the number of stations is calculated based on the difference between hydrogen demand and the refueling capacity.

9.2 Hydrogen Infrastructure Needs by 2032

696 HD hydrogen refueling stations will need to be developed to meet the 2032 FCEV and H2-ICE targets. 219 stations will need to be deployed in Texas and California. The estimated hydrogen refueling infrastructure needs by state are summarized in Table 15.

Table 15: Hydrogen Refueling Station Needs by 2032 by State

State	# Of Stations Needs by 2032	State	# Of Stations Needs by 2032
Texas	116	Oklahoma	10
California	103	Connecticut	9
Georgia	38	Alabama	9
New York	34	Louisiana	9
Florida	30	Oregon	7
Pennsylvania	30	Kansas	7
Arizona	25	Idaho	5
Illinois	25	Nebraska	5
North Carolina	24	Nevada	3
Indiana	20	South Carolina	3
Washington	19	Kentucky	3
Ohio	19	New Hampshire	3
New Jersey	16	Iowa	3
Colorado	16	Maine	3
Missouri	16	Arkansas	3
Michigan	13	New Mexico	1
Maryland	11	Montana	1
Tennessee	11	Mississippi	1
Wisconsin	11	West Virginia	1
Virginia	10	South Dakota	1
Utah	10	Wyoming	1
Minnesota	10	North Dakota	1

High-capacity hydrogen refueling stations (estimated ~5,000 kg daily capacity) are expected to be developed for HD FCEVs and H2-ICEs in our study between 2030 to 2032. The annual capacity per refueling station is estimated to be 1.3 M tons (5000 kg/day X 260 days/year).

An example of calculation procedures for determining California's hydrogen station needs is shown in Table 16.

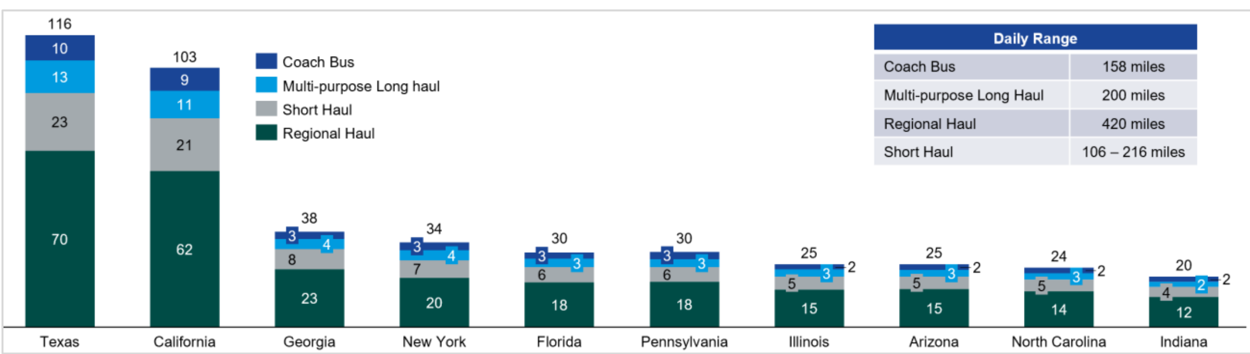
Table 16: Example of Hydrogen Infrastructure Needs Analysis

Annual gaps between hydrogen demand and capacity - California	134 M tons
Daily station capacity	5,000 kg
Annual hydrogen refueling station capacity per station	1.3 M tons
# Of stations needed	103

Over ~60% of hydrogen refueling stations are expected to be deployed for regional-haul applications. Due to the duty cycle (420 miles daily mileage), regional haul applications may be heavily reliant on public hydrogen refueling networks. Across the U.S., California and Texas are expected to lead the infrastructure deployment. Approximately 130 stations are required to be installed in the hydrogen refueling network in or connected to California or Texas (stations in California, Texas, Oregon, Nevada, and New Mexico).

Approximately 40% of the hydrogen refueling stations will be to be installed for return-to-base applications. With daily operations ranging from 106 miles (heavy haul) to 216 miles, these HD applications may require a mix of depot refueling and public refueling networks.

Figure 22: Top 10 States by Hydrogen Refueling Stations Required by 2032



9.3 Hydrogen Infrastructure Investment Requirements by 2032

9.3.1 Methodology

In this study, Ricardo estimated the total investment needs based on capital cost per station and the number of stations required. The capital costs for hydrogen refueling station deployment are estimated from the published capital costs of HD refueling stations. The capital costs primarily refer to the equipment costs, but in some projects, installation and commissioning could be included. The hydrogen transportation infrastructure (pipeline) is not included in the capital costs.

As there are only a few HD hydrogen refueling stations deployed as of this writing, limited cost data is available. An average cost per daily capacity of ~$2600/kg was estimated based on available data points. Table 17 summarizes the costs and key characteristics of stations.

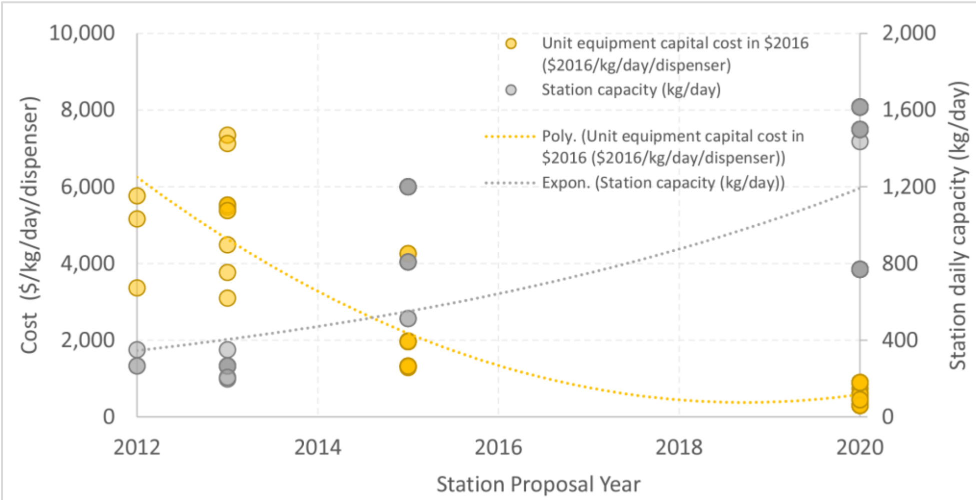
Table 17: Hydrogen Refueling Station Costs per Capacity

Project	Daily Capacity	Refueling Station Specs	Liquid or Gaseous	Estimated Costs (Total funding)
Shell[38]	5000 kg	3X350 bar and 3X750 bar fueling positions	Gaseous fuel delivery	$6.8M
Orange County Transportation Authority	4,536 kg	350 bar	Not Available	$6M
First Energy's NorCal Zero station	1,610 kg	700 bar	Liquid hydrogen delivery	$8.2M
Alameda-Contra Costa Transit -Emeryville Facility[39]	1,750 kg	Not Available	Not Available	$4.4M
Average cost per dispensed capacity (daily capacity)				**~$2600/kg**

HD hydrogen refueling station costs are expected to follow the cost reduction path of LDV hydrogen refueling stations due to anticipated economies of scale. The cost of LDV stations decreased ~80% from 2012 to 2020 and ~45% from 2016 to 2020 (Figure 23). As the current HD hydrogen market seems to be at a similar stage (early commercialization) as LD FCEV in 2016 based on the comparison of cumulative sales, the HD hydrogen refueling station costs are expected to reduce by ~45% by 2032.

[38] Oregon Department of Transportation, 2022, Hydrogen Pathway Study
[39] AC Transit, 2021, https://www.actransit.org/sites/default/files/2021-06/0604-20%20Report-ZEB%20Perf_FNL_062321.pdf

Figure 23: Capital Cost of LDV Hydrogen Refueling Station[40]



9.3.2 Results

Based on the estimated infrastructure cost and number of stations needed to meet the EPA target by 2032, the upfront investment in hydrogen refueling station infrastructure is required to be ~$5.3 billion, as shown in Table 18. Close to $3 B of this investment is needed to serve the longer-range regional haul applications in the refueling network.

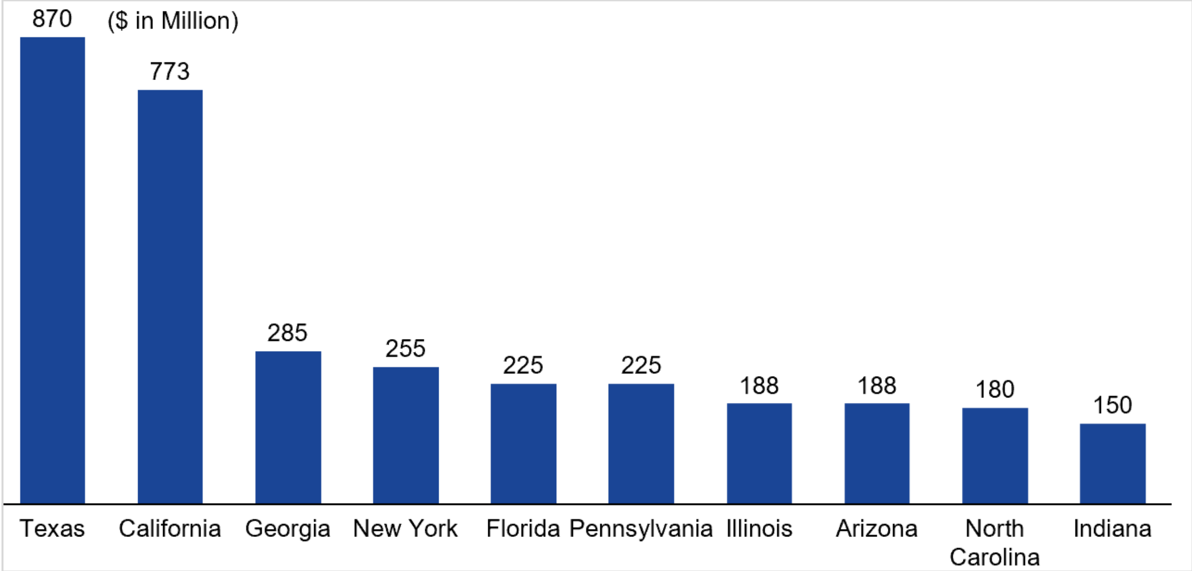
Table 18: Estimated Hydrogen Refueling Station Investment Requirements

Use Case	# Stations	Total Capital Cost
Coach Bus	59	$0.4 B
Multi-purpose Long-Haul	74	$0.6 B
Regional Haul	422	$3.2 B
Short Haul	141	$1.1 B
Total Investment	696	**$ 5.3 B**

Approximately $1.6 B in investments are required to serve FCEV and H2-ICE in California and Texas, as shown in Figure 24.

[40] DOE, 2020, https://www.hydrogen.energy.gov/pdfs/21002-hydrogen-fueling-station-cost.pdf

Figure 24: Top 10 States by Investments Required for Hydrogen Refueling Stations by 2032



9.4 Federal and State Hydrogen Infrastructure Incentives and Funding

With an estimated total of $0.8B in available funding, the required investment is $5.3B - $0.8B =$4.5B (Table 19). Estimated funding or incentives for hydrogen refueling stations are shown in Table 19. For incentives and funding not dedicated to hydrogen technology, it is assumed that 30% of the funding could be allocated to hydrogen refueling station projects.

The key available funding or incentives are shown in Table 27 in Appendix.

Table 19: Estimated Funding for Hydrogen Refueling Station

Federal / State	Program	Estimated Funding for Hydrogen Refueling Station
Federal	IIJA Charging and Fueling Infrastructure	$750 M
California	EnergIIZE	$20 M
Texas	Governmental Alternative Fuel Fleet (GAFF); Alternative Fueling Facilities Program (AFFP)	$3 M
New York	ZEV Rebate and ZEV Fueling Infrastructure Grant for Municipalities	$17 M
Pennsylvania	EV Charging Station and Hydrogen Fuel Cell Infrastructure Grants	$15 M

9.5 Summary of Key Insights

The required investment for HD refueling stations is estimated to be $4.5B. This estimate is based on the forecast and estimate of HD refueling stations' needs, the capital cost of HD refueling stations, and federal and state incentives and funding

1. **HD hydrogen needs**
   696 HD hydrogen refueling stations will need to be developed to meet the 2032 FCEV and H2-ICE target. 219 stations are expected to be deployed in Texas and California.
2. **Capital costs**
   The estimated capital cost is the ~$1.3M for a hydrogen refueling station with a dispensed capacity of 5000kg/day
3. **Federal and state funding**
   ~$0.8B estimated funding is available for hydrogen refueling stations.

10 Hydrogen Infrastructure Deployment Recommendations

Accelerate deployment of hydrogen refueling corridors and hydrogen public refueling stations in truck clusters

As over ~70% of FCEVs and H2-ICEs are expected to be deployed for longer mileage applications (>200 daily miles), the majority of hydrogen applications may not return to base daily. Thus, access to public hydrogen refueling network is required to support the deployment of FCEVs and H2-ICEs. Additionally, the deployment of public refueling stations can save the upfront costs for truck fleets and support FCEV and H2-ICE adoption.

1. **Hydrogen Corridors development**
   Under the Alternative Fuels Corridors (AFC) program of the Federal Highway Administration (FHWA), several interstate highways and state highways are designated as hydrogen AFCs. However, most of the designated AFC is still pending (no refueling station or not at the right frequency)[41]. As of May 2023, only two segments of corridors in California are ready (I-10: Between Santa Monica and the I-10/I-710 interchange in Los Angeles; I-405 between the I-405/I-5 split in San Fernando and the I-405/I-5 merge in Irvine[42]). It is unclear whether the hydrogen refueling stations in those two segments of corridors are HD refueling stations or LD refueling stations. Thus, investment and support are needed to build up/accelerate HD hydrogen refueling corridors.
2. **Public refueling stations in truck clusters**
   Fuel cell trucks and H2-ICE trucks make up ~90% of projected hydrogen demand. Thus, it is important to build hydrogen infrastructure in the truck clusters, such as ports, airports, railroads, warehouses, and freight hubs.

Dedicated funding for HD hydrogen refueling stations

The upfront costs of an HD hydrogen refueling station are much higher than for a charging station (both level 2 and DC fast chargers). However, fewer incentives or funding programs are currently available for hydrogen refueling infrastructure, which is due to the earlier stage of commercialization of hydrogen technology compared to BEVs. Based on Table 27 in the Appendix, none of the key ZEV infrastructure incentives or funding programs are dedicated to hydrogen infrastructure.

Thus, we recommend a dedicated hydrogen refueling infrastructure program to facilitate the deployment of the hydrogen refueling infrastructure. The NEVI Program of EV charging infrastructure is an example of how a dedicated funding program can accelerate transitions to new technology.

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[41] Frequency: Public hydrogen stations no greater than 150 miles between one station and the next on the corridor, and no greater than 5 miles off the highway

[42] DOT,https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/previous_rounds/round_5/#ready

Extend incentives for HD refueling station

Since the capital cost of HD hydrogen refueling stations is higher than that of a charging station or LD refueling station, the incentives should be designed to reflect the difference. However, in the ZEV infrastructure program of some states, the technology difference is not considered. For example, a ZEV infrastructure grant of up to $0.5M is offered in NY and Pennsylvania. That amount is ~7% of the hydrogen refueling infrastructure capital cost (~$0.5M for ~$7.5M) compared to ~50% of EV fast charging infrastructure (~$1M DC fast charger capital cost).
Similarly, Hydrogen Refueling Infrastructure (HRI) credits in California can only be awarded up to 1,200 kg per day at maximum capacity. Since a HD refueling station is estimated to have a ~5000 kg daily capacity, that creates a limit on the amount of HRI credits that HD stations can earn.

HD FCEV and H2-ICE demonstration and pilot projects in California and Texas

It is beneficial for refueling infrastructure providers to deploy their products in fleet applications and monitor performance, issues, and successes. Pilot and demonstration projects can lead to an improved generation of FCEV, H2-ICE, and hydrogen refueling stations that are well-accepted by the fleets. Pilot and demonstration projects also provide fleets an opportunity to gain experience with deploying and operating a new technology and provide valuable feedback. The benefits extend beyond the participating entities and provide valuable information to state agencies and the industry.
The priority for demonstration and pilot projects should be in California and Texas due to their forecasted high hydrogen demand. California is already accelerating efforts to develop its hydrogen refueling infrastructure. Compared to California, Texas has more hydrogen resources but is at an earlier deployment stage in FCEV and H2-ICEs. Pilot and demonstration deployment projects in Texas are recommended for providing insights and feedback to accelerate adoption based on lessons learned from real-world experiences.

11 Acronyms and Abbreviations

ACF	Advanced Clean Fleet
ACT	Advanced Clean Trucks
ICT	Innovative Clean Transit
BEV	Battery electric vehicle
CALeVIP	California Electric Vehicle Infrastructure Project
CARB	California Air Resources Board
CEC	California Energy Commission
CORE	Clean Off-Road Equipment Voucher Incentive Project
CUPC	California Public Utilities Commission
DCFC	Direct current fast charger
EnergIIZE	Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles
EPA	Environmental Protection Agency
FCEV	Fuel cell electric vehicle
FHWA	Federal Highway Administration
GHG	Greenhouse gas emissions
H2-ICE	Hydrogen ICE vehicle
HD	Heavy-duty
HVIP	Hybrid and Zero Emission Truck and Bus Voucher Incentive
LCFS	Low Carbon Fuel Standard
LD	Light-duty
MD	Medium-duty
MHD	Medium- and heavy-duty
MHDVs	Medium- and heavy-duty vehicles
NERC	North American Electric Reliability Corporation
NEVI	National Electric Vehicle Infrastructure
SOC	State of charge
ZET	Zero-emission truck
ZEV	Zero-emission vehicle

Appendix A

Table 20: BEV On the Road by 2032 – Buses and Refuse Trucks

MOVES Source Use Types	Other Buses	Other Buses	Transit Buses	Transit Buses	Transit Buses	School Buses	School Buses	School Buses	Refuse Trucks	Refuse Trucks
MOVES Regulatory Classes	LHD45	MHD67	LHD45	MHD67	HHD8	LHD45	MHD67	HHD8	MHD67	HHD8
California	5,240	162	743	11	875	828	14,846	909	172	1,323
Texas	1,594	51	229	3	289	261	4,573	286	57	412
New York	1,189	37	169	3	204	190	3,383	209	40	303
Illinois	849	27	122	2	151	138	2,429	151	30	218
Florida	816	26	117	2	146	133	2,335	145	29	210
North Carolina	766	24	110	2	141	126	2,204	138	28	199
Pennsylvania	705	22	101	2	125	115	2,018	125	25	181
Washington	650	20	93	1	115	105	1,859	115	23	167
Ohio	622	20	89	1	111	101	1,780	111	22	160
New Jersey	568	18	81	1	98	91	1,618	100	19	145
Indiana	557	18	80	1	99	91	1,593	99	19	143
Colorado	552	17	79	1	95	89	1,572	97	19	141
Virginia	521	17	75	1	96	86	1,498	94	19	135
Arizona	510	16	73	1	94	84	1,467	92	18	133
Georgia	490	15	70	1	86	79	1,401	87	17	126
Michigan	472	15	68	1	84	77	1,351	84	16	121
Oregon	424	13	61	1	77	70	1,216	76	15	110
Missouri	425	13	61	1	74	68	1,210	75	14	108
Tennessee	378	12	54	1	69	62	1,084	68	13	98
Wisconsin	361	11	52	1	65	59	1,034	65	13	93
Oklahoma	351	11	51	1	64	58	1,010	63	13	91
Minnesota	345	11	50	1	62	57	990	62	12	89
Iowa	275	9	39	1	50	45	789	49	10	71
Alabama	259	8	37	1	47	42	743	46	9	67
Maryland	255	8	37	1	46	42	732	46	9	66
Connecticut	242	8	35	1	44	40	694	43	9	63
Kansas	246	8	35	1	43	39	700	43	8	63
Utah	238	7	34	1	41	38	678	42	8	61
Louisiana	229	7	33	1	42	38	659	41	8	59
South Carolina	222	7	32	0	41	37	640	40	8	58
Idaho	194	6	28	0	36	32	559	35	7	51
Nebraska	183	6	26	0	33	30	525	33	6	47
Arkansas	181	6	26	0	33	30	519	32	6	47
Montana	163	5	23	0	29	27	468	29	6	42
New Mexico	163	5	23	0	28	26	465	29	5	42
Nevada	127	4	18	0	23	21	363	23	5	33

MOVES Source Use Types	Other Buses	Other Buses	Transit Buses	Transit Buses	Transit Buses	School Buses	School Buses	School Buses	Refuse Trucks	Refuse Trucks
MOVES Regulatory Classes	LHD45	MHD67	LHD45	MHD67	HHD8	LHD45	MHD67	HHD8	MHD67	HHD8
Kentucky	120	4	17	0	22	20	346	22	4	31
North Dakota	108	3	15	0	19	18	308	19	4	28
Maine	95	3	14	0	17	16	273	17	3	25
Mississippi	83	3	12	0	15	14	239	15	3	22
South Dakota	57	2	8	0	10	9	162	10	2	14
New Hampshire	58	2	8	0	9	9	163	10	2	14
Massachusetts	57	2	8	0	9	9	161	10	2	14
West Virginia	52	2	7	0	9	8	149	9	2	13
Wyoming	51	2	7	0	9	8	145	9	2	13
Hawaii	43	1	6	0	7	7	123	8	1	11
Vermont	43	1	6	0	7	7	122	8	1	11
Alaska	35	1	5	0	6	6	101	6	1	9
Rhode Island	35	1	5	0	6	6	101	6	1	9
Delaware	23	1	3	0	4	4	66	4	1	6

Table 21: BEV On the Road by 2032 – Short-haul and Long-haul Trucks

MOVES Source Use Types	Short-Haul Single Trucks	Short-Haul Single Trucks	Short-Haul Single Trucks	Short-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	LHD2b3	LHD45	MHD67	HHD8	LHD2b3	LHD45	MHD67	HHD8	MHD67	HHD8
California	162,112	92,697	31,806	20,709	5,829	3,138	988	643	4,857	9,761
Texas	50,831	29,432	9,952	6,397	1,823	986	308	203	1,524	3,047
New York	37,165	21,342	7,287	4,724	1,335	720	226	148	1,114	2,234
Illinois	26,894	15,531	5,268	3,396	965	521	163	107	806	1,614
Florida	25,888	14,962	5,070	3,265	929	502	157	103	776	1,553
North Carolina	24,578	14,265	4,810	3,084	881	477	149	98	737	1,472
Pennsylvania	22,336	12,897	4,375	2,820	801	433	135	89	669	1,340
Washington	20,548	11,854	4,025	2,598	737	398	125	82	616	1,233
Ohio	19,743	11,413	3,866	2,490	708	383	120	79	592	1,184
New Jersey	17,781	10,214	3,486	2,259	639	344	108	71	533	1,069
Indiana	17,646	10,192	3,456	2,227	633	342	107	70	529	1,059
Colorado	17,289	9,938	3,389	2,195	621	335	105	69	518	1,039
Virginia	16,713	9,705	3,270	2,096	599	324	101	67	501	1,001
Arizona	16,356	9,492	3,201	2,053	586	317	99	65	490	980
Georgia	15,472	8,920	3,031	1,957	555	300	94	62	464	929
Michigan	14,959	8,638	2,930	1,889	537	290	91	60	448	898

MOVES Source Use Types	Short-Haul Single Trucks	Short-Haul Single Trucks	Short-Haul Single Trucks	Short-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Long-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	LHD2b3	LHD45	MHD67	HHD8	LHD2b3	LHD45	MHD67	HHD8	MHD67	HHD8
Oregon	13,528	7,839	2,648	1,701	485	262	82	54	406	811
Missouri	13,327	7,667	2,612	1,690	479	258	81	53	399	801
Tennessee	12,060	6,988	2,361	1,516	432	234	73	48	361	723
Wisconsin	11,488	6,650	2,249	1,446	412	223	70	46	344	689
Oklahoma	11,246	6,521	2,201	1,413	403	218	68	45	337	674
Minnesota	11,000	6,370	2,154	1,384	394	213	67	44	330	659
Iowa	8,763	5,073	1,716	1,103	314	170	53	35	263	525
Alabama	8,265	4,788	1,618	1,040	296	160	50	33	248	495
Maryland	8,133	4,710	1,592	1,023	292	158	49	32	244	487
Connecticut	7,709	4,460	1,509	971	276	150	47	31	231	462
Kansas	7,708	4,433	1,511	978	277	149	47	31	231	463
Utah	7,465	4,295	1,463	947	268	145	45	30	224	448
Louisiana	7,334	4,253	1,435	921	263	142	44	29	220	439
South Carolina	7,156	4,160	1,400	896	256	139	43	29	215	428
Idaho	6,251	3,633	1,223	783	224	121	38	25	187	374
Nebraska	5,825	3,371	1,140	734	209	113	35	23	175	349
Arkansas	5,764	3,335	1,129	726	207	112	35	23	173	346
Montana	5,193	3,004	1,017	654	186	101	31	21	156	311
New Mexico	5,102	2,929	1,000	649	183	99	31	20	153	307
Nevada	4,045	2,344	792	509	145	78	24	16	121	242
Kentucky	3,863	2,243	756	485	138	75	23	15	116	231
North Dakota	3,415	1,972	669	431	123	66	21	14	102	205
Maine	3,030	1,754	593	381	109	59	18	12	91	182
Mississippi	2,661	1,543	521	334	95	52	16	11	80	159
South Dakota	1,782	1,026	349	226	64	35	11	7	53	107
New Hampshire	1,751	989	344	227	63	34	11	7	52	106
Massachusetts	1,745	990	343	225	63	34	11	7	52	105
West Virginia	1,637	942	321	208	59	32	10	7	49	98
Wyoming	1,596	918	313	202	57	31	10	6	48	96
Hawaii	1,358	781	266	172	49	26	8	5	41	82
Vermont	1,337	769	262	170	48	26	8	5	40	80
Alaska	1,109	638	217	141	40	21	7	4	33	67
Rhode Island	1,109	637	217	141	40	21	7	4	33	67
Delaware	723	414	142	92	26	14	4	3	22	44

Table 22: FCEV and H2-ICEs by Road by 2032

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
California	3,499	11,352	880	1,464	4,117
Texas	3,396	11,018	854	1,421	3,996
Georgia	1,132	3,673	285	474	1,332
New York	961	3,116	242	402	1,130
Florida	875	2,838	220	366	1,029
Pennsylvania	858	2,782	216	359	1,009
Illinois	746	2,421	188	312	878
Arizona	738	2,393	186	309	868
North Carolina	695	2,254	175	291	817
Indiana	600	1,948	151	251	706
Ohio	532	1,725	134	223	626
Washington	515	1,669	129	215	606
Colorado	489	1,586	123	205	575
Missouri	480	1,558	121	201	565
New Jersey	463	1,502	117	194	545
Michigan	377	1,224	95	158	444
Tennessee	343	1,113	86	144	404
Wisconsin	343	1,113	86	144	404
Maryland	326	1,057	82	136	383
Utah	309	1,002	78	129	363
Virginia	292	946	73	122	343
Oklahoma	292	946	73	122	343
Minnesota	274	890	69	115	323
Alabama	257	835	65	108	303
Louisiana	257	835	65	108	303
Connecticut	223	723	56	93	262
Oregon	206	668	52	86	242
Kansas	172	556	43	72	202
Idaho	137	445	35	57	161
Nebraska	137	445	35	57	161
New Hampshire	120	390	30	50	141
Iowa	111	362	28	47	131
Nevada	103	334	26	43	121
South Carolina	94	306	24	39	111
Kentucky	86	278	22	36	101
Maine	86	278	22	36	101
Arkansas	86	278	22	36	101
Mississippi	69	223	17	29	81
Montana	60	195	15	25	71

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
New Mexico	43	139	11	18	50
West Virginia	34	111	9	14	40
South Dakota	34	111	9	14	40
Wyoming	26	83	6	11	30
North Dakota	26	83	6	11	30
Massachusetts	17	56	4	7	20
Vermont	17	56	4	7	20
Delaware	17	56	4	7	20
Rhode Island	17	56	4	7	20
Alaska	17	56	4	7	20
Hawaii	9	28	2	4	10

Appendix B

Table 23: Battery size, Charger type, Charging characteristics and Peak electricity demand by truck Use and Class type

Truck Use Type	Truck Class Type	Battery size (kWh)	Charging location	Charging sessions per day	No. of chargers per vehicle	Charger type	Charger capacity	Nominal charging demand (kW)	Total BEV MDHV on road 2032	Peak demand from MHDV charging 2032 (kW)
Other Buses	LHD2b_3	105	Depot	1	1	L2	19.2	10.50	3	30
Other Buses	LHD4_5	129	Depot	1	1	L2	19.2	12.90	22,223	286676
Other Buses	MHD6_7	160	Depot	1	1	DCFC	50	16.00	699	11186
Other Buses	HHD8	313	Highway	6	0.16	DCFC	350	350.00	0	0
Transit Buses	LHD2b_3	105	Depot	1	1	L2	19.2	10.50	2	21
Transit Buses	LHD4_5	129	Depot	1	1	L2	19.2	12.90	3,177	40979
Transit Buses	MHD6_7	160	Depot	1	1	DCFC	50	16.00	48	768
Transit Buses	HHD8	313	Depot	1	1	DCFC	150	31.30	3,908	122309
School Buses	LHD2b_3	88	Depot	1	1	L2	19.2	8.80	5	41
School Buses	LHD4_5	88	Depot	1	1	L2	19.2	8.80	3,593	31616
School Buses	MHD6_7	155	Depot	1	1	L2	19.2	15.50	63,461	983647
School Buses	HHD8	155	Depot	1	1	L2	19.2	15.50	3,935	60991
Refuse Trucks	MHD6_7	211	Depot	1	1	DCFC	50	21.10	766	16170
Refuse Trucks	HHD8	281	Depot	1	1	DCFC	50	28.10	5,696	160055
Short Haul Single Unit	LHD2b_3	68	Depot	1	1	L2	19.2	6.80	700,783	4765323
Short Haul Single Unit	LHD4_5	127	Depot	1	1	L2	19.2	12.70	403,929	5129896
Short Haul Single Unit	MHD6_7	141	Depot	1	1	DCFC	50	14.10	137,306	1936020
Short Haul Single Unit	HHD8	420	Depot	1	1	DCFC	350	42.00	88,680	3724541
Long Haul Single Unit	LHD2b_3	68	Depot	1	1	L2	19.2	6.80	25,153	171039
Long Haul Single Unit	LHD4_5	127	Depot	1	1	L2	19.2	12.70	13,583	172510
Long Haul Single Unit	MHD6_7	141	Depot	1	1	DCFC	50	14.10	4,255	59999
Long Haul Single Unit	HHD8	733	Highway	6	0.16	DCFC	350	350.00	2,788	162627

Truck Use Type	Truck Class Type	Battery size (kWh)	Charging location	Charging sessions per day	No. of chargers per vehicle	Charger type	Charger capacity	Nominal charging demand (kW)	Total BEV MDHV on road 2032	Peak demand from MHDV charging 2032 (kW)
Short Haul Combination Truck	MHD6_7	264	Depot	1	1	DCFC	150	26.40	21,002	277225
Short Haul Combination Truck	HHD8	420	Highway	6	0.16	DCFC	350	350.00	42,074	2454332
Long Haul Combination Truck	HHD8	733	Highway	H2	1	H2	350	0	0	0

Table 24: US States and Corresponding Regional Entities as per NERC

Regional Entity	**Member states**								
MISO	Illinois	Indiana	Michigan	Missouri	Wisconsin	Minnesota	Louisiana	Arkansas	Mississippi
NPCC Maritimes	Maine	Vermont	Rhode Island						
NPCC New England	Connecticut	Massachusetts	New Hampshire						
NPCC New York	New York								
PJM	Pennsylvania	Ohio	New Jersey	Virginia	Maryland	Kentucky	West Virginia	Delaware	
SERC Central	Tennessee								
SERC East	North Carolina	South Carolina							
SERC FP	Florida								
SERC Southeast	Georgia	Alabama							
SPP	Oklahoma	Iowa	Kansas	North Dakota	South Dakota				
TEXAS RE	Texas								
WECC CA/MX	California								
WECC SRSG	Arizona	New Mexico							
WECC WPP	Washington	Colorado	Oregon	Utah	Idaho	Nebraska	Montana	Nevada	Wyoming

Appendix C

Table 25: Annual National Hydrogen Demand (H2 tons)

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
Hydrogen Demand By 2030	7,668	119,418	5,908	5,666	34,540
Hydrogen Demand By 2032	81,100	671,453	22,121	23,311	143,238

Table 26: Annual Hydrogen Demand by 2032 by State (H2 tons)

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
California	13,516	111,909	3,687	3,885	23,873
Florida	3,380	27,977	922	971	5,968
Texas	13,120	108,618	3,578	3,771	23,171
Washington	1,988	16,457	542	571	3,510
New York	3,710	30,720	1,012	1,067	6,553
New Jersey	1,788	14,812	488	514	3,160
Arizona	2,850	23,588	777	819	5,032
Colorado	1,888	15,635	515	543	3,336
Illinois	2,882	23,863	786	828	5,090
Georgia	4,374	36,206	1,193	1,257	7,724
Virginia	1,126	9,325	307	324	1,989
Massachusetts	66	549	18	19	117
Oregon	796	6,583	217	229	1,404
Pennsylvania	3,312	27,429	904	952	5,851
Maryland	1,258	10,423	343	362	2,223
North Carolina	2,684	22,218	732	771	4,740
Ohio	2,054	17,006	560	590	3,628
Michigan	1,458	12,069	398	419	2,575
Nevada	398	3,291	108	114	702
Utah	1,192	9,874	325	343	2,106
Minnesota	1,060	8,777	289	305	1,873
Hawaii	34	274	9	10	59
Connecticut	862	7,131	235	248	1,521

MOVES Source Use Types	Other Buses	Long-Haul Combination Trucks	Short-Haul Single Trucks	Short-Haul Combination Trucks	Short-Haul Combination Trucks
MOVES Regulatory Classes	HHD8	HHD8	HHD8	MHD67	HHD8
Tennessee	1,326	10,972	361	381	2,341
Indiana	2,320	19,200	633	667	4,096
Missouri	1,856	15,360	506	533	3,277
Wisconsin	1,326	10,972	361	381	2,341
South Carolina	364	3,017	99	105	643
Oklahoma	1,126	9,325	307	324	1,989
Alabama	994	8,229	271	286	1,756
Kansas	662	5,485	181	190	1,170
Kentucky	332	2,743	90	95	585
New Mexico	166	1,372	45	48	293
New Hampshire	464	3,840	127	133	819
Iowa	430	3,566	117	124	761
Idaho	530	4,389	145	152	936
Vermont	66	549	18	19	117
Louisiana	994	8,229	271	286	1,756
Maine	332	2,743	90	95	585
Delaware	66	549	18	19	117
Nebraska	530	4,389	145	152	936
Rhode Island	66	549	18	19	117
Arkansas	332	2,743	90	95	585
Montana	232	1,920	63	67	409
Mississippi	266	2,194	72	76	468
Alaska	66	549	18	19	117
West Virginia	132	1,097	36	38	234
South Dakota	132	1,097	36	38	234
Wyoming	100	823	27	29	176
North Dakota	100	823	27	29	176

Table 27: Major Funding Programs

Federal							
Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	ZEV Vehicle	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station

Inflation Reduction Act	Tax credit equal to 30% of capital cost						
IIJA Charging and Fueling Infrastructure	$2.5 B			X		X	X
Hydrogen Demonstration Project	$400M in 2022		X			X	X
Regional Clean Hydrogen Hubs	$7 B		X		X	X	X
ZEV Infrastructure and Advanced Vehicle Grants							

California

Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	ZEV Vehicle	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station
Hydrogen Refueling Infrastructure (HRI) credits		Awarded up to 1,200 kg per day				X	X
EnergIIZE	$69M in 2022; 30% allocated to hydrogen			X			X
Assembly Bill 8	$20 M					X	

Texas

Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	ZEV	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station
Governmental Alternative Fuel Fleet (GAFF)	$3.9M in total		X	X		X	X
Alternative Fueling Facilities Program (AFFP)	$6M in total			X		X	X

New York							
Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	Vehicle	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station
Zero Emission Vehicle (ZEV) Rebate and ZEV Fueling Infrastructure Grant for Municipalities	Up to $0.5M per refueling station			X		X	X
Pennsylvania							
Program	Funding or Incentives ($) to Capital Cost	Funding or Incentives ($) to Operational Cost	Vehicle	EV Charging Infrastructure	Hydrogen Production, Pipeline	LDV Hydrogen Refueling Stations	HD Hydrogen Refueling Station
EV Charging Station and Hydrogen Fuel Cell Infrastructure Grants	Up to $0.5M per refueling station			X		X	X