Assessment of Alternative Fueling Infrastructure in the United States

Stephen Lommele, Ranjit R. Desai, Caley Johnson, Amy Snelling, Abby Brown, Mark Singer, Jesse Bennett, Jeff Cappellucci, Johanna Levene, and Christopher Hoehne

National Renewable Energy Laboratory

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NREL/TP-5400-88513
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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Foreword

This work was prepared by the National Renewable Energy Laboratory (NREL) under agreement IAG-20-16885 to support the National Highway Traffic Safety Administration (NHTSA) in its development and evaluation of Corporate Average Fuel Economy (CAFE) standards for light-duty vehicles and fuel efficiency standards for medium- and heavy-duty vehicles. This report assesses the current state of light-duty fueling infrastructure for biodiesel, electricity, ethanol (E85), hydrogen, and natural gas, and their impacts on the adoption of light-, medium-, and heavy-duty alternative fuel vehicles, as well as scenarios and considerations for the evolution of this infrastructure over time.

Acknowledgments

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List of Acronyms

AC	alternating current
ADOPT	Automotive Deployment Options Projection Tool
AFC	alternative fuel corridor
AFDC	Alternative Fuels Data Center
AFV	alternative fuel vehicle
BEV	battery-electric vehicle
BIL	Bipartisan Infrastructure Law
CAFE	Corporate Average Fuel Economy
CCAT	Connecticut Center for Advanced Technology
CCS	Combined Charging System
CNG	compressed natural gas
DC	direct current
DCFC	direct-current fast charging
DOE	U.S. Department of Energy
E85	ethanol
EIA	U.S. Energy Information Administration
EV	electric vehicle
EVSE	electric vehicle supply equipment
FCEV	fuel cell electric vehicle
FFV	flexible-fuel vehicle
FHWA	Federal Highway Administration
GGE	gasoline gallon equivalent
HEV	hybrid electric vehicle
IRA	Inflation Reduction Act
LNG	liquified natural gas
NACS	North American Charging Standard
NHTSA	National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
OEM	original equipment manufacturer
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
TEMPO	Transportation Energy & Mobility Pathway Options
ZEV	zero-emission vehicle

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1 Introduction

The National Renewable Energy Laboratory (NREL), owned by the U.S. Department of Energy (DOE) and operated by the Alliance for Sustainable Energy LLC, created the Alternative Fuels Data Center (AFDC) in 1991 in response to the Alternative Motor Fuels Act. The AFDC provides data, documents, online tools, and other resources to enable the implementation of alternative fuel and advanced vehicle technologies at the local and regional levels. The AFDC is a data hub for alternative fuel vehicle (AFV) fleets, infrastructure developers, and other stakeholders. NREL has unique insights into how the development of alternative fueling infrastructure relates to the adoption of AFVs. These unique insights come from NREL's work on the AFDC, along with collaboration with private industry (e.g., original equipment manufacturers [OEMs], fuel providers) and federal, state, and local governments.

At the time of writing, the National Highway Traffic Safety Administration (NHTSA) had finalized the fuel consumption standards for medium- and heavy-duty vehicles for model years 2014 through 2027 and beyond and finalized Corporate Average Fuel Economy (CAFE) standards through model year 2026. In completing these rulemakings, NHTSA has made a variety of estimates and assumptions regarding how vehicle manufacturers could meet future fuel economy and fuel efficiency requirements.

To support NHTSA in its development and evaluation of CAFE standards, the U.S. Department of Transportation's Volpe National Transportation Systems Center uses the CAFE model (i.e., the Volpe model) to analyze potential CAFE standards. The CAFE model analyzes the application of potential technologies to the current automotive industry vehicle fleet to determine the feasibility of future CAFE standards and the associated costs and benefits of the standards. The Volpe Center also assists NHTSA with developing the engineering and economic inputs to the CAFE model. While NHTSA is prohibited by statute from considering the fuel economy of alternative fuel vehicles when it sets fuel economy standards, NHTSA still seeks to be well-informed regarding the prevalence of alternative fuel vehicles that occur in the light-duty fleet for reasons other than CAFE compliance. Conversely, for medium- and heavy-duty fuel efficiency standards, NHTSA is permitted to consider the availability of alternative fuel vehicles, so having up-to-date information about their prevalence in those fleets and the infrastructure that fuels them is important.

This report analyzes the current state of alternative fueling infrastructure in the United States and its relationship to the light-, medium-, and heavy-duty AFV markets; explores the costs associated with alternative fueling infrastructure; investigates trends driving the deployment of alternative fueling infrastructure; explores how the adoption of various vehicle and fuel technologies may look in the future; and analyzes the evolution of alternative fueling corridors.

1.1 Analysis Limitations and Considerations

NHTSA requested that NREL explore the relationship between alternative fueling infrastructure development and AFV adoption, with a primary interest in understanding the relationships between electric vehicle (EV) charging stations and light-duty plug-in electric vehicles (PEVs), as well as hydrogen fueling stations and hydrogen fuel cell electric vehicles (FCEVs). For this reason, NREL leveraged its experience with alternative fuels to complete an in-depth analysis of the relationship between PEVs, FCEVs, and related infrastructure, described in Section 2. It is important to note that hydrogen, as of 2022, is almost exclusively a California alternative fuel. This is evident in the current trends around the adoption of FCEVs and the development of hydrogen fueling stations, which are not widely available outside of California.

The NREL analysis did not look specifically at the relationship between flexible-fuel vehicles (FFVs) and ethanol (E85) station locations. However, it is essential to mention that there were approximately 28 million FFVs registered in the United States in 2020 (NREL and Experian 2021), and there are currently 4,352 public and private station locations that provide E85 (AFDC 2021a). The number of FFV models offered by OEMs has been trending downward in recent years (AFDC 2020), and in 2022 there were a total of five FFV models available from Chevrolet, Ford, and GMC (AFDC 2022e). Having said that, E85 is still a significant alternative fuel source, representing about 10.2% of gasoline consumption (EIA 2022a).

Although light-, medium-, and heavy-duty diesel vehicles are not AFVs, all OEMs approve the use of B5, and many are approved up to B20. The 5 and 20 represent the percentage of biofuel content. As with FFVs and E85 stations, NREL did not conduct an in-depth analysis of light-duty diesel vehicles and biodiesel station locations, except to note that as of 2021, there were 741 public and private biodiesel station locations in the United States that sell B20 or higher biodiesel blends (AFDC 2021a).

The analysis of light-duty compressed natural gas (CNG) vehicles and CNG stations is also limited. While the Experian-derived data used in this report do not accurately represent light-duty CNG vehicles, NGVAmerica reports that more than 175,000 light-, medium-, and heavy-duty natural gas vehicles are on the road in the United States (NGVAmerica 2022). As of the first quarter of 2022, OEMs offer no light-duty CNG vehicles, and most of the OEM light-duty CNG vehicles on the road are legacy Honda Civics. Qualified service retrofitters can convert many light- and medium-duty vehicles for natural gas operation. Natural gas engines and fueling systems are also available for some heavy-duty vehicles. There are currently 1,505 public and private CNG station locations in the United States (AFDC 2021a).

The NREL analysis does not discuss the relationship between light-duty propane vehicles and propane stations in detail. Like CNG, the Experian-derived data used in this report do not accurately represent light-duty propane vehicles because propane vehicles are converted or retrofitted and not reregistered with a new fuel type. According to the Propane Education & Research Council, there are nearly 200,000 on-road propane vehicles (vehicle class not defined) with certified fuel systems in the United States (AFDC 2022g). Many are used in fleet applications, such as school buses, shuttles, and police vehicles. There are currently 1,239 public and private propane station locations in the United States, and another 1,594 station locations with propane available, but with limited vehicle fueling services (AFDC 2021a).

2 Alternative Fueling Infrastructure Development and Light-Duty AFV Adoption

According to the AFDC, more than a dozen alternative fuels are in production or under development for use in AFVs (AFDC 2021b). Common alternative fuels include biodiesel (B20 and above), CNG, electricity, E85, hydrogen, liquified natural gas (LNG), and propane.

As of January 2022, the AFDC Station Locator contained 57,448 station locations in the United States for all alternative fuel types combined (AFDC 2021a). Each station location represents a single geographic location or address, regardless of the number of fuel dispensers or electric vehicle supply equipment (EVSE) ports at that location.

For comparison, in 2019, there were 142,000 gasoline stations in the United States (VTO 2019). Figure 1 shows the approximate breakdown of public and private alternative fueling stations in the AFDC Station Locator by fuel type as of December 2021.

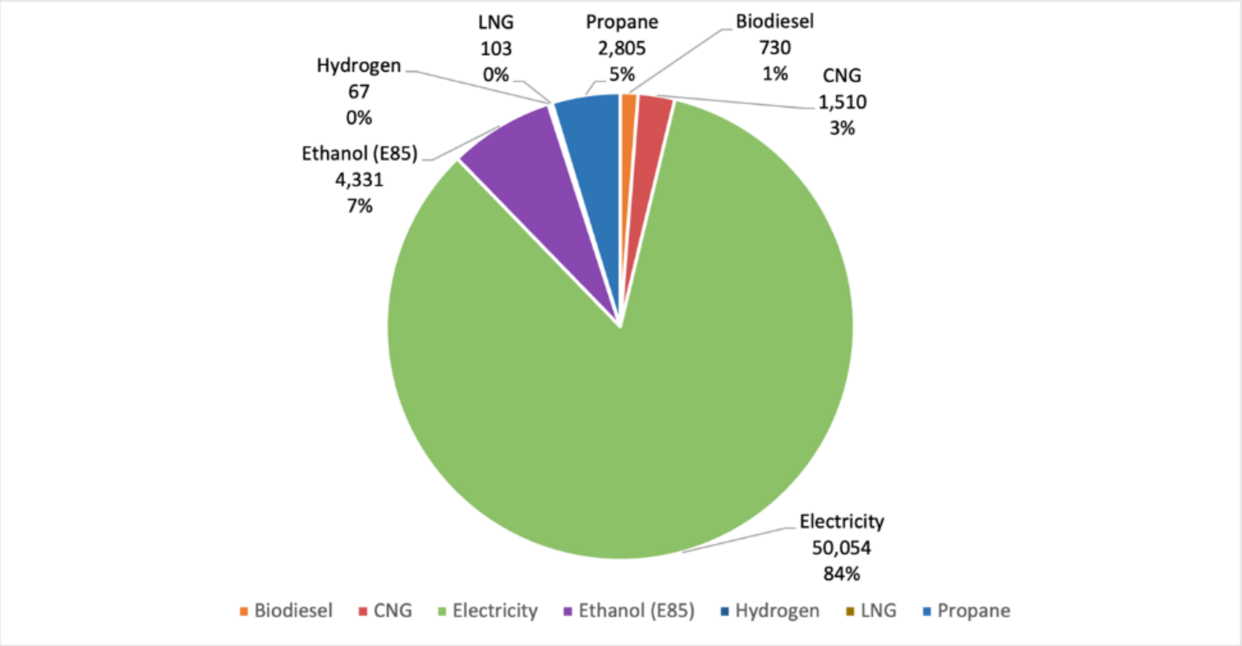

Figure 1. 2021 U.S. public and private alternative fueling stations by fuel type.

Data Source: AFDC Station Locator

Section 2.1 discusses in detail how alternative fueling infrastructure has developed over time.

As of Dec. 31, 2020, approximately 35 million light-duty AFVs were registered in the United States (NREL and Experian 2021). These registration counts are derived by NREL from Experian Information Solutions. For comparison, as per the Experian 2019 reports, there were approximately 276 million light-duty vehicles on the road in the United States in the first quarter of 2019 (Miller 2019). Figure 2 shows the approximate breakdown of AFVs registered in 2020.

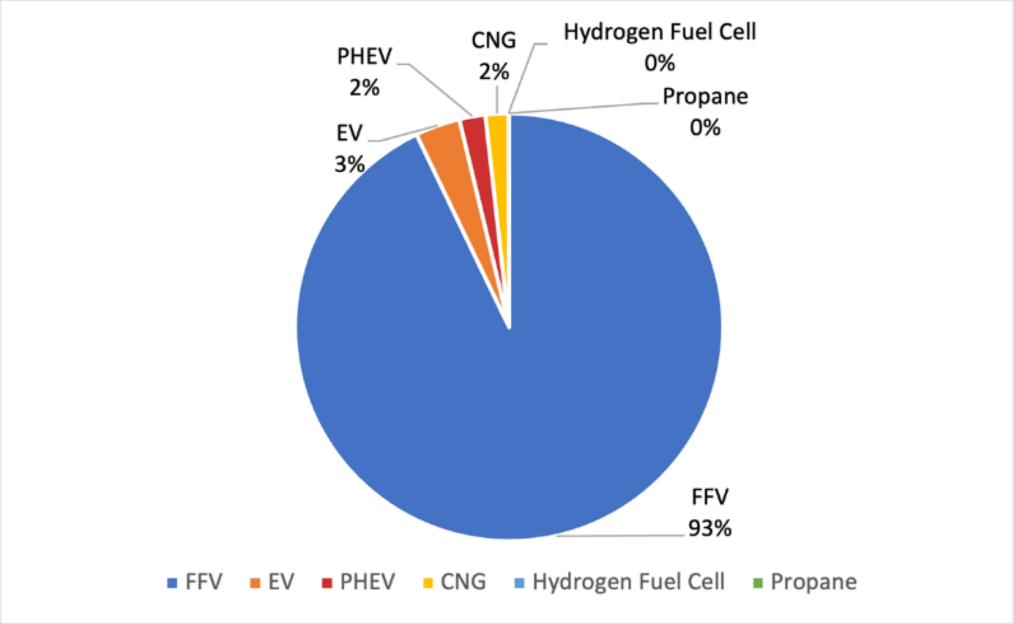

Figure 2. 2020 U.S. light-duty AFV registrations by fuel type.

Derived registration counts by NREL, Experian Information Solutions

As shown in Figure 2, 80% (or nearly 28 million vehicles) are FFVs. These vehicles can operate on regular gasoline up to E85, which comprises all ethanol/gasoline blends up to 83% ethanol. However, FFVs in the United States operate primarily on conventional gasoline and on E85 less than 2% of the time.[1]. PEVs, as the name suggests, plug into an external energy source and include two variations of electrified vehicles: battery-electric vehicles (BEVs), which are absent of an internal combustion engine, and plug-in hybrid electric vehicles (PHEVs), which have an internal combustion engine. Approximately 1,019,400 BEVs and 593,900 PHEVs were registered in 2020. Together, BEVs and PHEVs account for approximately 75% of the AFV population when excluding FFVs.

Light-duty propane and CNG vehicles are not correctly represented in the Experian data used in this report because most of those vehicles resulted from a converted or retrofitted fuel system (NREL and Experian 2021). Once a vehicle is converted to an alternative fuel, there is no requirement to update that vehicle registration's fuel type, making it difficult to track the vehicle population. CNG population values include conventional and converted vehicles that run on natural gas or gasoline.

Section 2.2 discusses in detail how AFV availability has evolved over time.

2.1 Alternative Fueling Infrastructure Development

It is helpful to explore the data contained in the AFDC Station Locator to understand alternative fueling infrastructure development in the United States. The AFDC has tracked alternative fueling and EV charging infrastructure in the United States since 1991. In 2017, NREL partnered

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[1] According to the U.S. Energy Information Administration's (EIA's) 2022 Annual Energy Outlook, less than one-quarter of 1% of light-duty vehicle energy use is E85. According to the data presented above, about 10% of vehicles are E85-capable. Based on these numbers, FFVs use alternative fuels roughly 2% of the time.

with Natural Resources Canada to expand the dataset to include infrastructure across Canada. The Station Locator database provides information on public and private nonresidential alternative fueling stations in the United States and Canada, including E85, biodiesel, CNG, EVSE, hydrogen, LNG, and propane. NREL is responsible for maintaining and enhancing the Station Locator, which serves as a primary resource for fleets, fuel providers, policymakers, Clean Cities and Communities coalitions, and others working to improve efficiency, cut costs, and reduce emissions in transportation (Brown et al. 2020). This section uses these data to discuss the growth in alternative fueling infrastructure over time, separating EVSE from the rest of the alternative fueling infrastructure for discussion and illustration purposes.

Data collected from the Station Locator and presented in Figure 3 show that E85 fueling infrastructure grew quickly and steadily between 2004 and 2021. Propane stations have reduced since their peak in 1998, although there was a rebound between 2008 and 2015. The increase in propane stations can be attributed to the Station Locator team's collaboration with the propane industry to source station data from providers like U-Haul that are primarily used for refilling propane tanks but open for vehicles as well. However, the number of propane stations has steadily decreased since 2016. A key reason for this decrease is that the industry has largely moved from independent, light-duty propane vehicles to large fleet vehicles that do not use small stations, such as U-Haul. CNG stations have shown overall growth since 2007 but a slight reduction since their peak in 2016. This reduction is partially due to station closures due to high repair and operating costs and fleets transitioning away from CNG (AFDC 2022h). LNG stations grew from 35 in 2007 to 140 in 2016 but have been trending down in recent years. The current number of LNG stations is 98. These trends are further illustrated in Figure 4 and Figure 5. The Station Locator only includes stations offering biodiesel blends of 20% (B20) and above for a certain period during the year, and these stations showed substantial growth in 2022. Figure 3 counts the geographic location of each alternative fueling station but does not include counts of how many individual dispensers or nozzles are on-site.

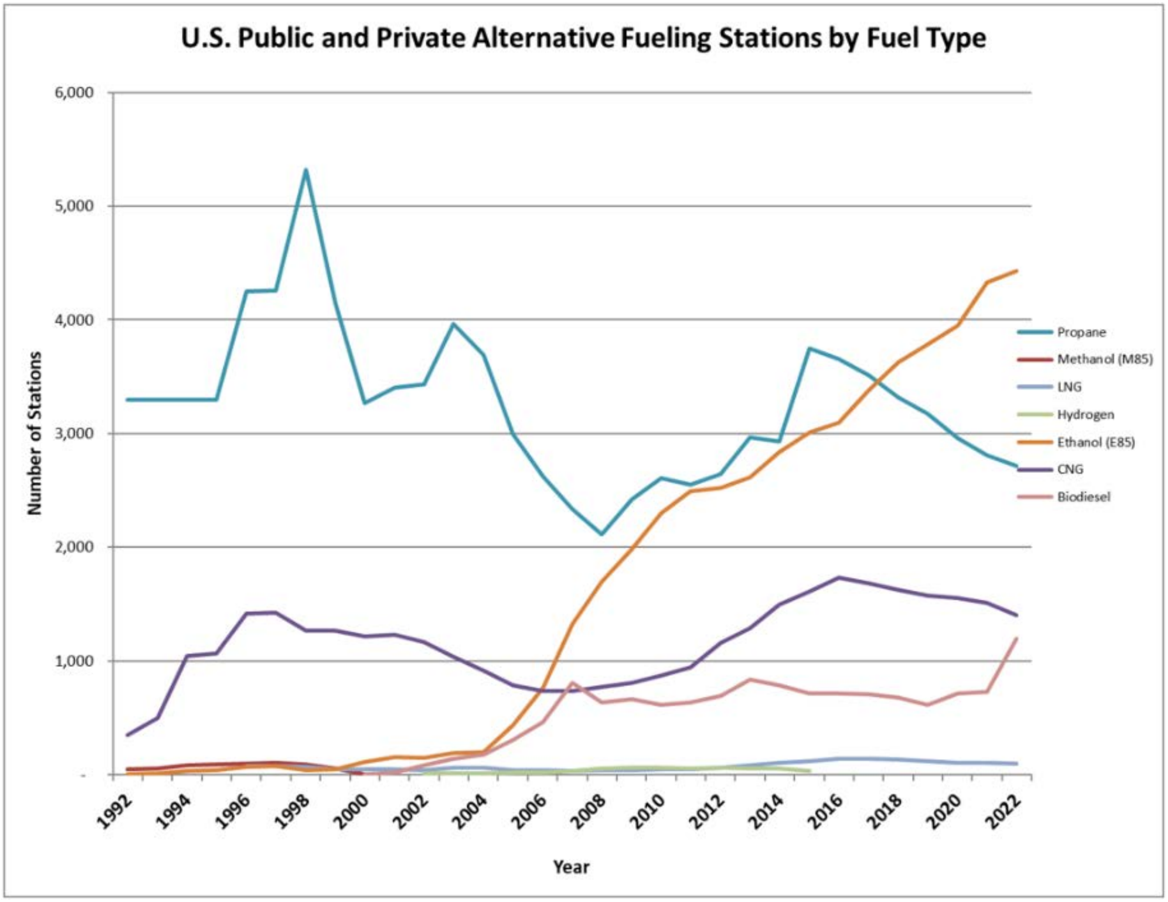


Figure 3. U.S. public and private alternative fueling station locations by fuel type.

Data Source: AFDC Station Locator.

Note: EV charging stations would distort the scale of this chart, so they are represented in Figure 6. Biodiesel blends less than B20 are only included in station count between 2005 and 2007.

The number of stations in operation is a balance of new stations opening and old stations closing, as illustrated in Figure 4 and Figure 5.

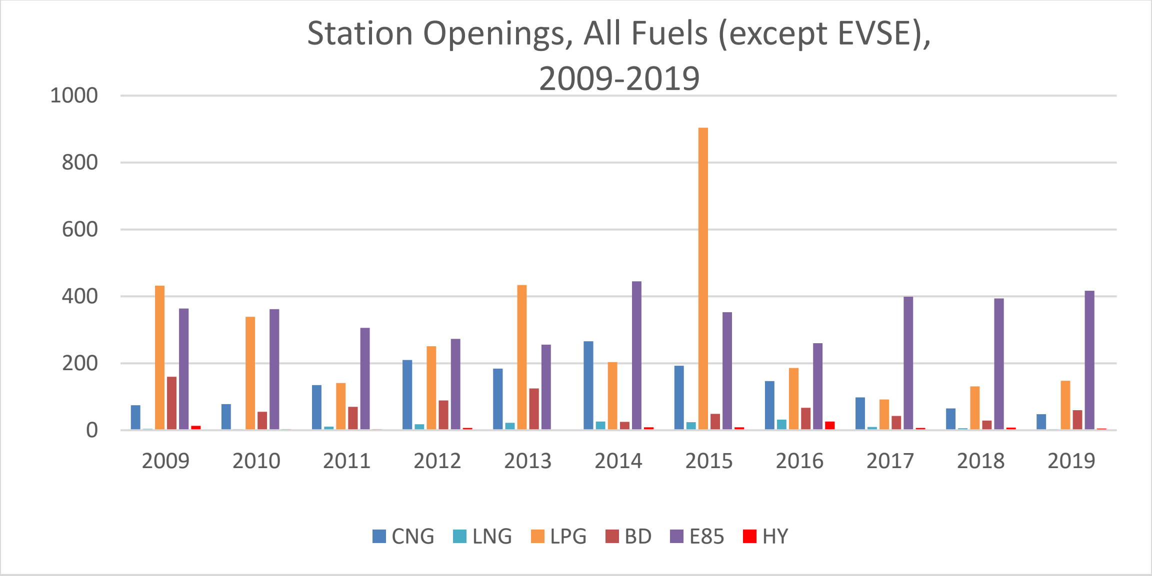


Figure 4. Station openings, all fuels (except EVSE) 2009–2019.

Data Source: AFDC Station Locator

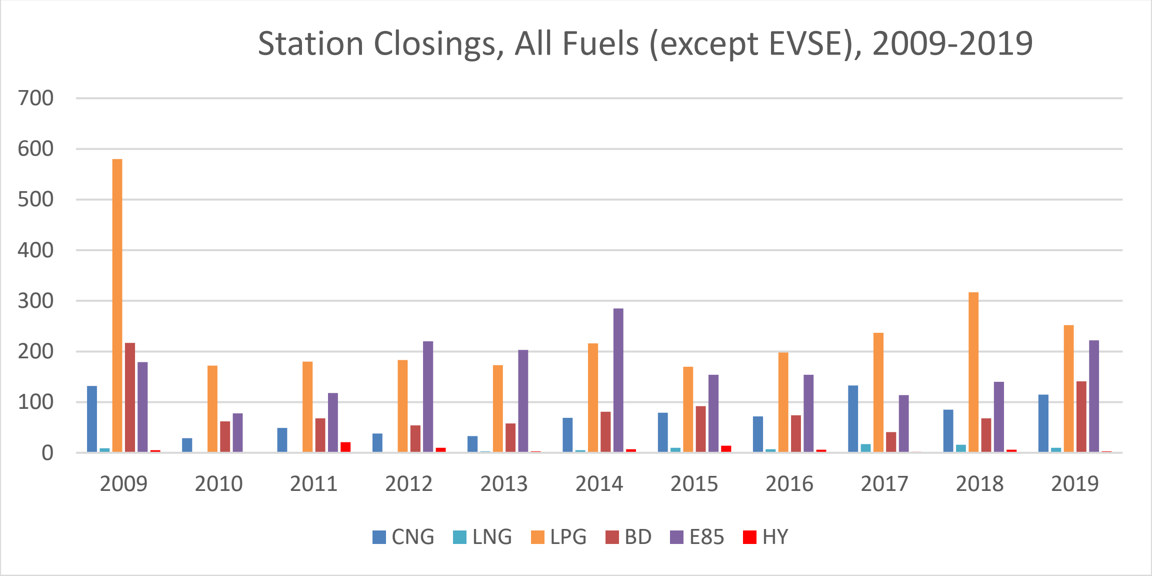


Figure 5. Station closings, all fuels (except EVSE), 2009–2019.

Data Source: AFDC Station Locator

As of July 28, 2021, there were 46,939 EV charging station locations in the United States, nearly 10 times the number of E85 stations represented in Figure 3. For this reason, data on EV charging are presented separately in Figure 6.

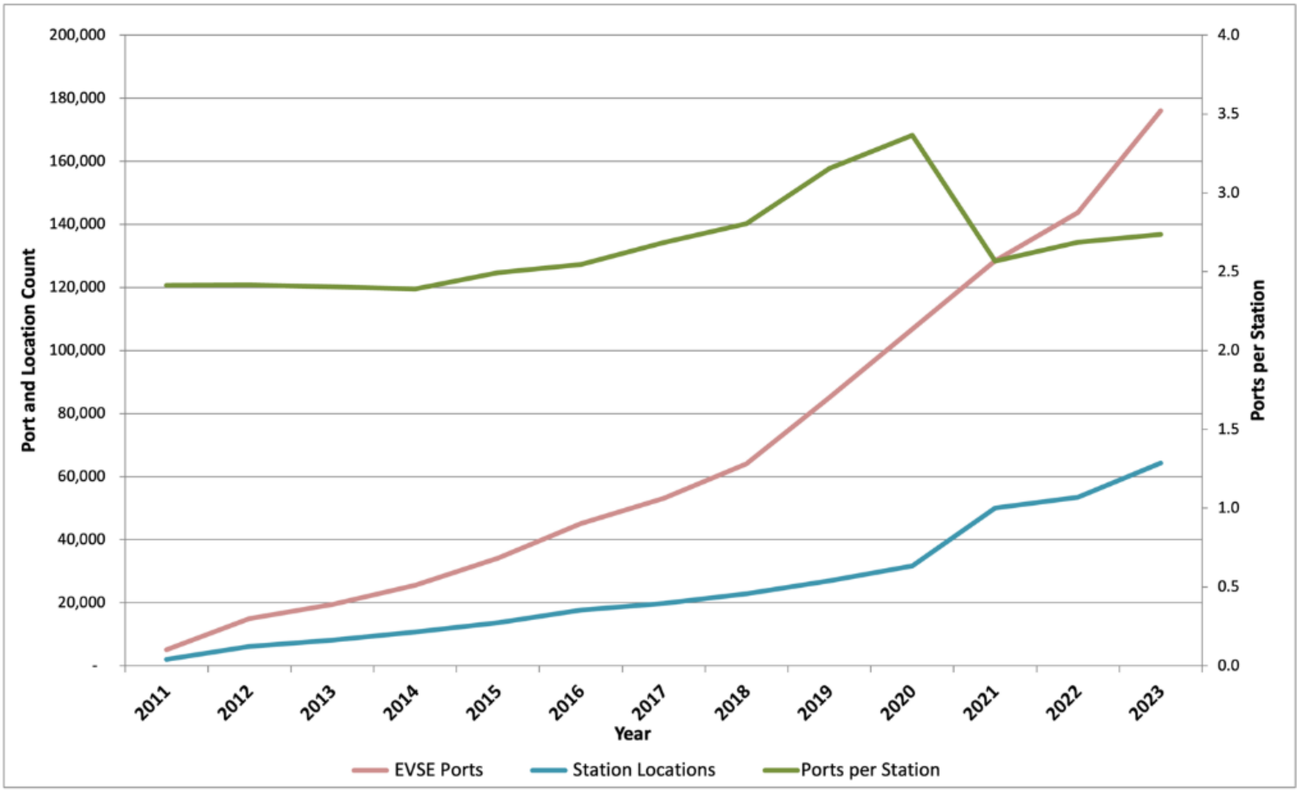


Figure 6. U.S. public EV charging station locations and ports.

Data Source: AFDC Station Locator

Figure 6 shows both unique EV charging station locations (Station Locations)—which can be compared to the counts of geographic locations for alternative fuels in the figure—as well as individual port counts (EVSE Ports), which are synonymous with the individual dispensers or nozzles on-site at other alternative fueling station locations. Data for Figure 6 were captured using the last data snapshot available for each calendar year. Between 2011 and 2013, the EV charging station counts are an estimate of the number of geographic locations (i.e., Station Locations) based on the number of EVSE ports because station number data were not collected during these years (AFDC 2021c). The average ports per location, as shown by the green line, gradually grows from 2.5 to nearly 3.5 by 2020, then drops back to 2.5 in 2021 as many new stations with fewer ports are added.

From 2011, the growth in EVSE accelerated following the 2010 increase of PEVs offered by major automakers and a federal investment through the American Recovery and Reinvestment Act. The number of EVSE ports has grown consistently, and the number of EV charging station locations has also increased. NREL started tracking the two figures separately in 2014. Since then, the ports-per-station ratio has stayed between 2.4 and 3.4. Between 2019 and 2022, the number of charging stations more than doubled. In 2022 alone, the number of charging stations grew by 16%. The number of EVSE ports is expected to increase as the population of PEVs continues to grow. Additional considerations for EVSE are discussed in Section 2.1.1.

Together, Figure 3 and Figure 6 show that alternative fueling infrastructure in the United States has grown with relative consistency. Figure 7 shows the percentage of growth by year and fuel.

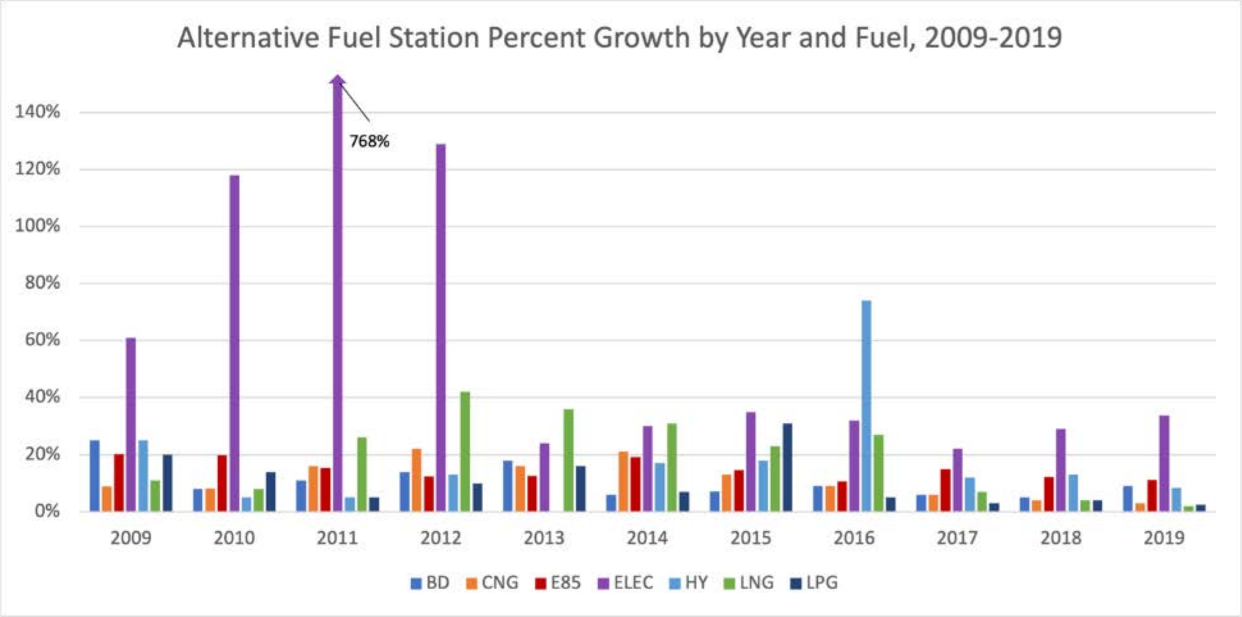


Figure 7. Alternative fuel station percentage of growth by year and fuel, 2009–2019.

Data Source: AFDC Station Locator

To put these station counts into perspective with gasoline, the *Transportation Energy Data Book: Edition 38* states that in 1972 nearly 290,000 public gasoline stations were serving 106 million vehicles nationwide. The number of public gasoline stations declined throughout the 1970s and 1980s. By 1990, 174,000 public gasoline stations were serving 179 million vehicles nationwide. Overall, the number of stations has continued its decline since 1990, and in 2019 there were 142,000 stations serving more than 276 million vehicles (VTO 2019). This represents an increase from approximately 366 vehicles per gasoline station in 1972 to approximately 1,944 vehicles per gasoline station in 2019 (VTO 2019).

2.1.1 EVSE

More than 60,000 stations are available in the United States as of 2023 (AFDC 2023d). Charging stations are being installed in critical areas throughout the country for consumers to use at public locations. These stations give consumers an alternative or supplementary option to workplace and residential charging to meet en route charging demands.

2.1.1.1 EVSE Definitions

According to the Station Locator (AFDC 2021a), the charging infrastructure industry has aligned with a common standard called the Open Charge Point Interface protocol with the following hierarchy for charging stations: location, EVSE port, and connector. The Station Locator uses the following charging infrastructure definitions:

Station location: A station location is a site with one or more EVSE ports at the same address. Examples include a parking garage or a mall parking lot.

EVSE port: An EVSE port provides power to charge only one vehicle at a time, even though it may have multiple connectors. The unit that houses EVSE ports is sometimes called a charging post, with one or more EVSE ports.

Connector: A connector is a device that is plugged into a vehicle to charge it. Connectors are sometimes referred to as plugs. Multiple connectors and connector types (such as CHAdeMO and Combined Charging System [CCS]) can be available on one EVSE port, but only one vehicle will charge at a time.

Further, charging equipment can be classified by the rate at which the batteries are charged:

Alternating-current (AC) Level 1 equipment (often referred to as Level 1) provides charging through a 120-V AC plug. Most, if not all, PEVs will come with a Level 1 cord set, so no additional charging equipment is required. On one end of the cord is a standard NEMA connector (e.g., NEMA 5-15, which is a common three-prong household plug), and on the other end is an SAE J1772 standard connector (often referred to simply as J1772). The J1772 connector plugs into the car's J1772 charge port, and the NEMA connector plugs into a standard NEMA wall outlet.

AC Level 2 equipment (often referred to as Level 2) offers charging through 240-V AC (typically used in residential applications) or 208-V AC (typically used in commercial applications) electrical service. This charging option can operate at up to 80 A and 19.2 kW of power. However, most residential Level 2 equipment operates at lower power. Many of these units use up to 30 A, delivering 7.2 kW of power. These units require a dedicated 40-A circuit. As of 2023, more than 75% of public EVSE ports in the United States were Level 2 (AFDC 2023d). Level 2 charging equipment uses the same J1772 connector that Level 1 equipment uses. All commercially available PEVs can charge using Level 1 and Level 2 charging equipment.

Direct-current (DC) fast charging (DCFC) equipment (typically 480-V AC three-phase input) enables rapid charging along heavy traffic corridors at installed stations. As of 2020, more than 15% of public EVSE ports in the United States were DC fast chargers. There are three types of DCFC systems, depending on the type of charge port on the vehicle: SAE CCS, CHAdeMO, and Tesla. The CCS connector (also known as the J1772 combo) is unique because a driver can use the same charge port when charging with Level 1, Level 2, or DC fast equipment. The only difference is that the DCFC connector has two additional bottom pins. Tesla vehicles have a unique connector that works for all their charging levels, including their fast-charging option, called the North American Charging Standard (NACS). Although Tesla vehicles do not have a CCS or CHAdeMO charge port, Tesla does sell adapters. The CCS connector is the most common in terms of locations while NACS has the most connectors (AFDC 2024o).

Charging the growing number of PEVs in use requires a robust network of stations for both consumers and fleets. Charging times vary based on how depleted the battery is, how much energy the battery is capable of holding at full capacity, the chemistry of battery, and charging equipment (i.e., charging level and power output). Depending on these factors, the charging time can range from less than 20 minutes (for 80% state of charge) to 20 hours or more.

2.1.1.2 Residential Charging

As discussed earlier, the Station Locator includes data on nonresidential alternative fueling stations. Unlike other alternative fuels addressed in this report, EV charging infrastructure can be installed where other fueling stations cannot, including at homes and workplaces. For PEV drivers, home may often be the most convenient and cost-effective charging location (for those who can establish access). Current research indicates PEV drivers primarily charge their vehicles at home, when possible, due to convenience and lower fuel costs (Smart and Salisbury 2015). While there is insufficient data on actual home charging infrastructure installed, "the current foundation of U.S. charging infrastructure has been built upon home charging at residential locations" (Ge et al. 2021). In 2019, the Station Locator team began tracking data on charging infrastructure installed in multifamily buildings available for resident use only. While data are currently limited, there was a 3.7% increase in EVSE ports at multifamily buildings in the second quarter of 2021 (Brown et al. 2021). A complete discussion of trends in charging in multifamily buildings can be found in NREL's EV charging infrastructure trends reports (AFDC 2022b).

For those with residential access, vehicle technology is progressing in a way that home will likely be the only place they need to charge regularly, except for long-distance road trips and emergencies. According to Ge et al. (2021):

> Projection results reveal that residential charging access is expected to remain high (78%–98%) while electric vehicles comprise a small share of the U.S. light-duty fleet (less than 10%), but that uncertainty increases as electrification penetrates the light-duty passenger fleet more broadly. Specifically, in a future where electric vehicles make up over 90% of the fleet, a range from as low as 35% to as high as 75% of electric vehicles are projected to have consistent residential charging access, depending on the scenario considered.

Multifamily buildings and rented single-family homes are the residences less likely to have access to vehicle charging (Ge et al. 2021). Aside from multifamily charging, the Station Locator data for EV charging are limited to nonresidential charging.

2.1.1.3 Workplace Charging

Those without residential access will be exclusively reliant on workplace and public charging.

> Workplace EV charging infrastructure includes charging stations that are private and designated for employee use only. The majority of private workplace EVSE ports in the Station Locator are Level 2, which is to be expected because employees use workplace chargers while they are parked at work for an extended period and therefore do not necessarily need rapid charging. As of the end of Q2 [2021], there were 9,998 workplace EVSE ports in the Station Locator […] The number of DC fast EVSE ports grew by the greatest percentage (12.0%) at workplaces in Q2 [2021], though this only represents the addition of six EVSE ports (Brown et al. 2021).

Workplace charging trends are also available in NREL's EV charging infrastructure trends reports.

2.1.1.4 Public Charging

Public charging can be broken into two use cases: en route (or highway corridor) and destination charging. Both public en route and destination charging continue to develop rapidly in the United States.

Public en route charging primarily comprises DCFC stations. As discussed earlier, the Station Locator includes data on connector type and maximum power output for DCFC stations. The NREL trends reports track growth on these characteristics. Most DCFC stations have a maximum power output of 300 kW or less. However, a growing number of higher-output fast charging stations operate up to 350 kW. While not all vehicles can currently charge at these higher power outputs, it is believed that most drivers will prefer to charge as fast as possible while using en route charging. Over time, higher-power chargers may make sense for larger vehicles as battery technology improves and a megawatt charging standard emerges. This en route charging is likely to be used on road trips, by transportation network companies, and in case of emergency. Routine use as a primary charging solution could make sense for some drivers, depending on price, convenience, and driver preference, all of which are challenging to track and therefore constitute significant unknowns at the time of this report.

Destination chargers entail EVSE that is available for customer use at places of business where a PEV would be parked for a significant period of time, such as a shopping mall or a restaurant. Currently, public destination charging primarily includes Level 2 but may also include DC 50–150 kW. Public destination charging has the potential to be a convenient option for PEV drivers and may serve to supplement or replace at-home charging. There are concerns about how it scales in high-demand environments and the potential scarcity of willing site hosts (Yong et al. 2023).

2.1.1.5 Fleet Charging

According to the Q2 2021 NREL trends report:

> In 2020, the Station Locator team began collecting data on whether stations are dedicated fleet charging stations, and if so, what types of vehicles charge at the station based on the Federal Highway Administration weight class (i.e., light-duty [LD], medium-duty [MD], or heavy-duty [HD] vehicles) […] The majority of [PEVs] on the road are LD vehicles, such as sedans, sport utility vehicles (SUVs), and pickup trucks; unsurprisingly, the majority of fleet charging EVSE ports are used to charge LD vehicles, and the majority of fleet charging EVSE ports are Level 2 (74.5%) (Brown et al. 2021).

2.1.1.6 EVSE Trends

Since 2020, NREL has published the aforementioned quarterly trends reports on available EV charging infrastructure in the United States. These reports on EVSE trends from the Alternative Fueling Station Locator provide snapshots of the state of EV charging infrastructure in the United States. Using data from the Station Locator, they break down the growth of public and private charging infrastructure by charging level, network, and location and assess the current state of charging infrastructure in the United States.

Here, we highlight significant elements from each quarterly trends report, but we recommend accessing the full reports for a complete picture. The full collection of quarterly trends reports is housed on the AFDC's Electric Vehicle Charging Infrastructure Trends page (AFDC 2022b).

As shown in Figure 8, EVSE infrastructure is experiencing rapid and consistent growth in the United States. In the most recent quarter of the time frame of this report, Q3 2023, the number of ports nationwide increased by 7.7%, or nearly 13,000 ports. Quarterly growth rates are indicated for public and private ports separately and noted between each quarter. Figure 8 also shows that a strong majority of these ports are publicly available, and the public subset is growing much more rapidly than the private subset.

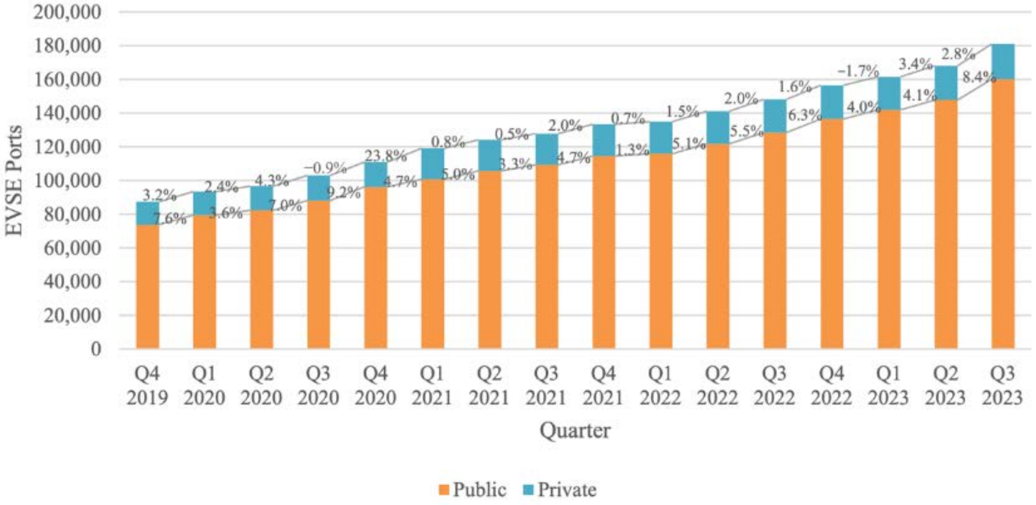


Figure 8. Quarterly growth of EVSE ports by access

Source: Brown et al. 2023c

Figure 9 shows the quarterly growth of public EVSE ports by charging level. The majority of EVSE ports in the Station Locator are Level 2, and this charging level saw the largest increase in public ports in Q3 2023. Still, the number of both public and private DCFC EVSE ports grew significantly in Q3, with an increase of 8.3% from the previous quarter, representing the addition of 2,696 DC fast ports.

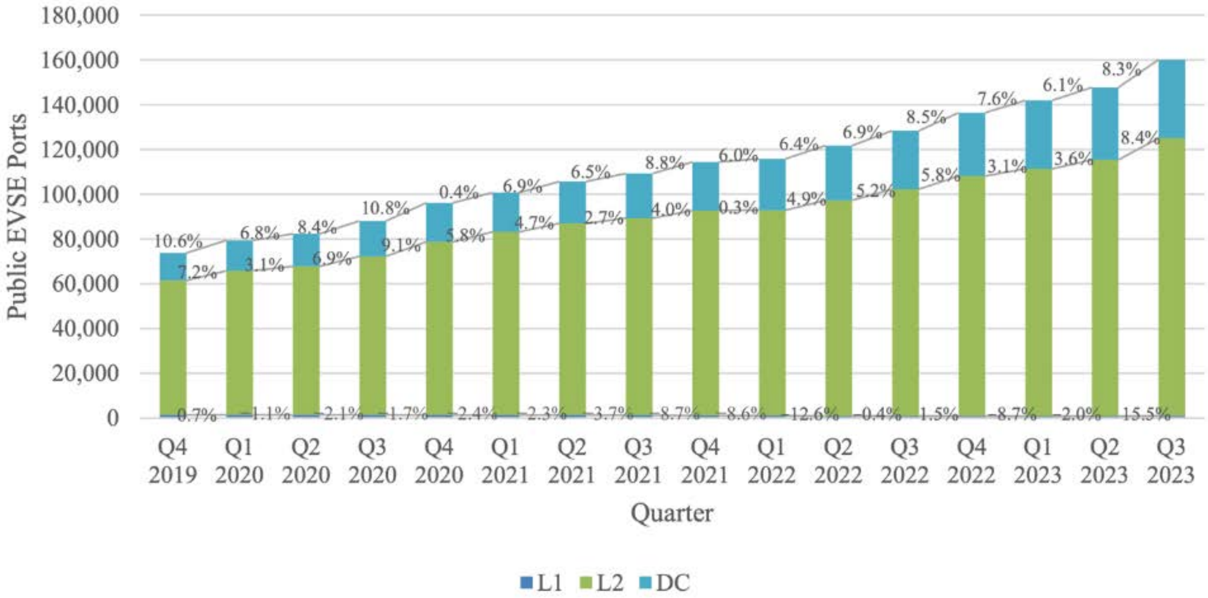


Figure 9. Quarterly growth of public EVSE ports by charging level

Source: Brown et al. 2023c

Of course, growth is not homogenous throughout the nation. California leads the country with more than a quarter (27%) of all public ports in the Station Locator. However, its share has gradually declined from its peak of 32% of public ports in Q1 2021. The Northwest region witnessed the most substantial growth in public charging infrastructure during Q3 2023, with a 13.0% increase in EVSE ports.

Another important trend to track is the power of public DCFC, as power (in kilowatts) is a major factor determining the speed at which vehicles charge and therefore the convenience penalty of driving a BEV. It is also a major factor in the impact that a DCFC will have on an electric grid. Figure 10 shows the growth of public DCFC ports by various power levels.

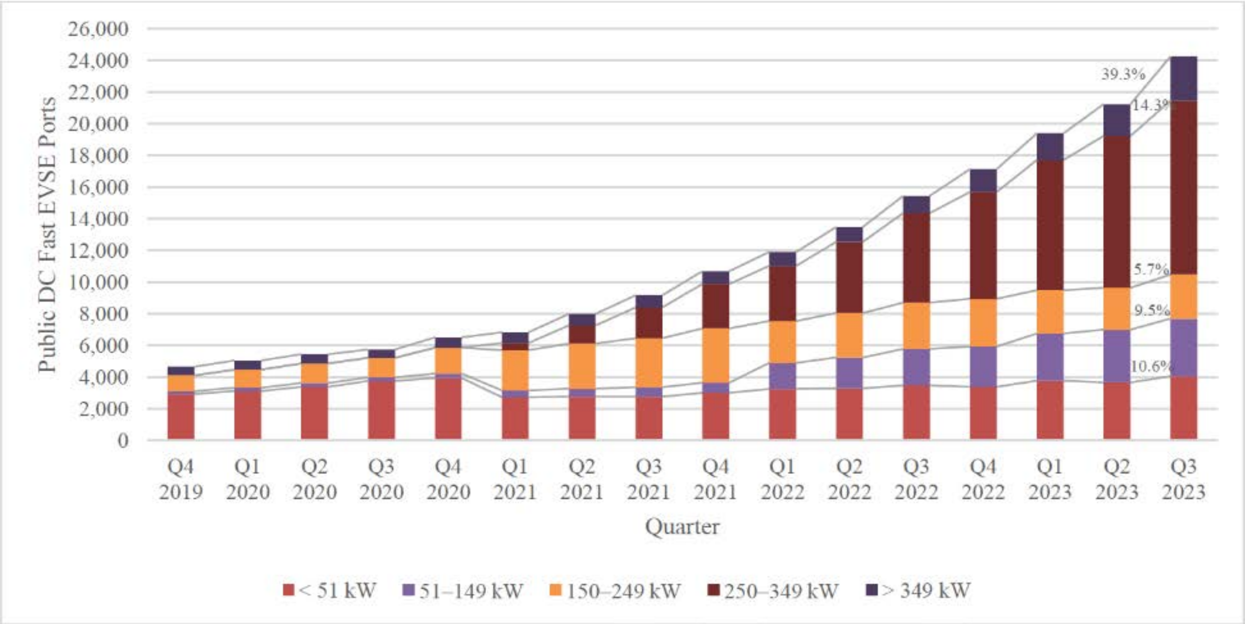


Figure 10. Quarterly growth of public DCFC ports by power (kW).

Source: Brown et al. 2023c

Figure 10 shows that DCFC with 250–349-kW power became the most numerous power segment built out in Q1 2022 and now comprises nearly half of all ports. This is at least partly due to the rollout of Tesla's 250-kW V3 Superchargers. The segment of DCFC with power >349 kW has recently surged, due in large part to the build-out of the EVgo network (350 kW).

2.1.2 Hydrogen Fueling Stations

At the end of 2023, 53 of 54 retail hydrogen fueling locations in the United States resided in California, where they have supported the light-duty FCEV market (AFDC 2023d). OEMs including Honda, Hyundai, and Toyota offer production FCEVs for sale or lease to customers in markets where hydrogen fuel is available, primarily in California. There is one additional retail hydrogen fueling location in Honolulu, Hawaii. There are a limited number of private (non-retail) hydrogen charging stations in other states, the details for which are outlined later in this section.

2.1.2.1 California

The California Energy Commission has expanded California's network of hydrogen fueling locations throughout California. There are 53 hydrogen fueling stations in California at existing gasoline stations covering regions in Northern California near San Francisco and Sacramento and Southern California near Los Angeles and San Diego. Additional connector and destination stations are on I-80 near Truckee and I-5 near Bakersfield. Figure 11 shows the geographic distribution of hydrogen fueling stations in California.

Figure 11. Public hydrogen fueling stations in California.

Data Source: AFDC Station Locator

At the time of this report, the California retail stations cannot currently fuel heavy-duty vehicles because they require a new fueling protocol, which is in development by an industry-led consortium.

Fourteen states outside of California have available or planned hydrogen fueling stations. Many of the hydrogen fueling stations in these states have been partially funded by grants from the state and/or federal government. The following subsections summarize hydrogen fueling station development outside of California, including funding mechanisms and information on the infrastructure development decision-making process, wherever available.

2.1.2.2 Hawaii

Hawaii's only public hydrogen fueling station is owned by Servco and was constructed without any grants or government funding (Bussewitz 2017). The other private fueling stations in the state have been funded through a combination of federal and state grants (Lauer 2021).

The Hawaii Center for Advanced Transportation Technologies director serves as the state hydrogen implementation coordinator. The director promotes hydrogen fuel by establishing hydrogen infrastructure and policies and chairs the Hawaii Hydrogen Implementation Working Group, which facilitates the establishment of infrastructure and policies across all state agencies to promote the expansion of hydrogen-based energy in Hawaii. The group submitted recommendations to the state legislature in 2015 (AFDC 2022d).

2.1.2.3 Connecticut

Air Liquide is planning three public hydrogen fueling stations in Connecticut: two in Hartford and one in New Haven. The installations are part of a collaboration with Toyota to install hydrogen infrastructure throughout the Northeast (Air Liquide 2024). It is our understanding that the stations in Connecticut are partially funded through grants from the state (Pilon 2018).

Connecticut state agencies work closely with the Connecticut Center for Advanced Technology (CCAT) to implement hydrogen strategies and grants. For example, the Connecticut Department of Transportation, in consultation with CCAT, developed the *Connecticut Hydrogen and Fuel Cell Deployment Transportation Strategy: 2011-2050* to identify strategies to expand the availability and use of hydrogen fuel and renewable energy sources (Connecticut Department of Transportation and Connecticut Center for Advanced Technology 2011). The strategy identifies specific locations for hydrogen fueling stations along state highways and other locations.

Additionally, the Connecticut Department of Energy & Environmental Protection and CCAT administer a hydrogen infrastructure grant program to support fueling stations in the greater New Haven area (CCAT 2024). Potential siting opportunities in the area have been developed to be consistent with a 2017 CCAT report, *Fuel Cell Electric Vehicle Fleet Deployment Plan* (CCAT 2017).

2.1.2.4 Massachusetts

Air Liquide also plans to install two public hydrogen fueling stations in Massachusetts as part of the collaboration with Toyota (Salomon 2016). According to Air Liquide, the sites in Massachusetts were chosen by the company after it "identified key strategic partnerships, both public and private entities, that have the necessary real estate and a large number of sites that would allow for us to expand our infrastructure rapidly."

The Massachusetts Bay Transportation Authority acquired funding for a hydrogen bus and private fueling infrastructure through the Federal Transit Administration's National Fuel Cell Bus Program (Nuvera Fuel Cells 2017). Another private hydrogen fueling station at Greentown Labs was primarily funded by a Massachusetts Clean Energy Center grant (Travaglini 2017).

2.1.2.5 Michigan

More than a decade ago, Ford Motor Company and BP partnered to install a private hydrogen fueling station in Dearborn, Michigan, which was funded through a DOE grant (Fleet Financials 2004).

2.1.2.6 New York

New York's only hydrogen fueling station is at the Department of Conservation and Waterways in Point Lookout (Green Car Congress 2009). The New York State Energy Research and Development Authority provided $900,000 in funding, and National Grid contributed $55,000. Additionally, the state's AFV fueling infrastructure tax credit contributed 50% of the total cost of the refueling station. The New York State Energy Research and Development Authority (NYSERDA) planned and prepared funding for the site as part of its Hydrogen Roadmap initiative (NYSERDA 2006).

As part of the Northeast station build-out, Air Liquide also plans to install two fueling stations in Hempstead and Brooklyn. The two stations will be partially funded by New York's Environmental Protection Fund (Air Liquide 2017).

New York's Climate Action Council is tasked under the state's climate law with developing a plan to create a "zero-emissions" electric grid by 2040 and reduce emissions 85% from 1990 levels by 2050.

While NYSERDA is still developing a hydrogen roadmap, that has not stopped the state from encouraging investments by companies with a hydrogen focus.

2.1.2.7 Ohio

The Stark Area Regional Transit Authority received grants from the Federal Transit Administration's Low or No Emission Grant Program and National Fuel Cell Bus Program, Ohio Department of Transportation, and Ohio Environmental Protection Agency's Diesel Emissions Reduction Program to purchase 10 hydrogen buses and a private fueling station (Eudy et al. 2019).

Several groups and councils in the state provide input and information on hydrogen decisions, such as the Fuel Cell Corridor and the Renewable Hydrogen Fuel Cell Collaborative (Ohio Fuel Cell & Hydrogen Coalition 2024; Renewable Hydrogen Fuel Cell Collaborative 2024).

2.1.2.8 Pennsylvania

Air Products owns the two hydrogen fueling stations located in Pennsylvania. One is located at their headquarters, and the other is at Pennsylvania State University. While we could not verify how the stations were funded, DOE may have supported the Penn State station (Larson Transportation Institute 2024).

2.1.2.9 Texas

The only hydrogen fueling station in Texas was funded by DOE grants and is located in Austin (University of Texas at Austin 2020, 2024).

2.2 AFV Adoption

No assessment of alternative fueling infrastructure can be complete without an assessment of AFV adoption and related trends. Various data sources can be used to understand AFV adoption trends, including vehicle registration data, vehicle sales data, and vehicle model availability.

2.2.1 AFV Registration Data

NREL purchased light-duty AFV registration data from Experian Automotive. Experian is a company that provides automotive industry data with databases on credit, vehicles, consumer marketing, and digital identity. The vehicle registration records are sourced from all 50 state Departments of Motor Vehicles, as well as the District of Columbia's. Experian has registration data for all vehicles in operation for model years 1967 to the present. These data are categorized into more than 80 primary data attributes. NREL has purchased the same or similar 14 data attributes relevant to this report for analysis since 2014. PHEVs and BEVs were not categorized separately in the Experian data until 2016. Per NREL's licensing agreement with Experian, granular data cannot be distributed or published outside the purchaser's use. Because of this, NREL cannot deliver granular data to avoid potential infringement of the agreement. Therefore, the data presented in this report are summarized at an aggregated level. This allows data sharing with third parties such as NHTSA, utilities, review boards, and other stakeholders or public parties.

Earlier, we discussed the percentage breakdown of light-duty AFVs registered in 2020. To provide additional context, the rough numbers are presented in Table 1. This provides a snapshot of the light-duty AFVs on the road as of 2020. As discussed previously, light-duty CNG and propane vehicles are not captured accurately in these data due to the widespread use of conversion kits, which do not update in Experian's dataset when installed on-vehicle. Focusing on a light-duty dataset also disproportionately understates the CNG and propane vehicles, which are largely medium and heavy duty.

Table 1. 2020 Light-Duty AFV Registrations

AFV Type	Approximate Vehicle Registrations
FFV	27,997,000
BEV	1,019,000
PHEV	594,000
CNG	522,000
Hydrogen fuel cell	14,000
Propane	~0

Derived registration counts by NREL, Experian Information Solutions

To explore recent trends associated with Experian registration data, NREL queried registration data for BEVs, PHEVs, FCEVs, and CNG vehicles for 2018–2020 (Figure 12). These figures show that from 2018 to 2020, registrations for PEVs have been trending upward, FCEVs have grown slightly, and registrations for CNG vehicles have trended downward. This is similar to trends for alternative fueling infrastructure for electricity, hydrogen, and CNG.

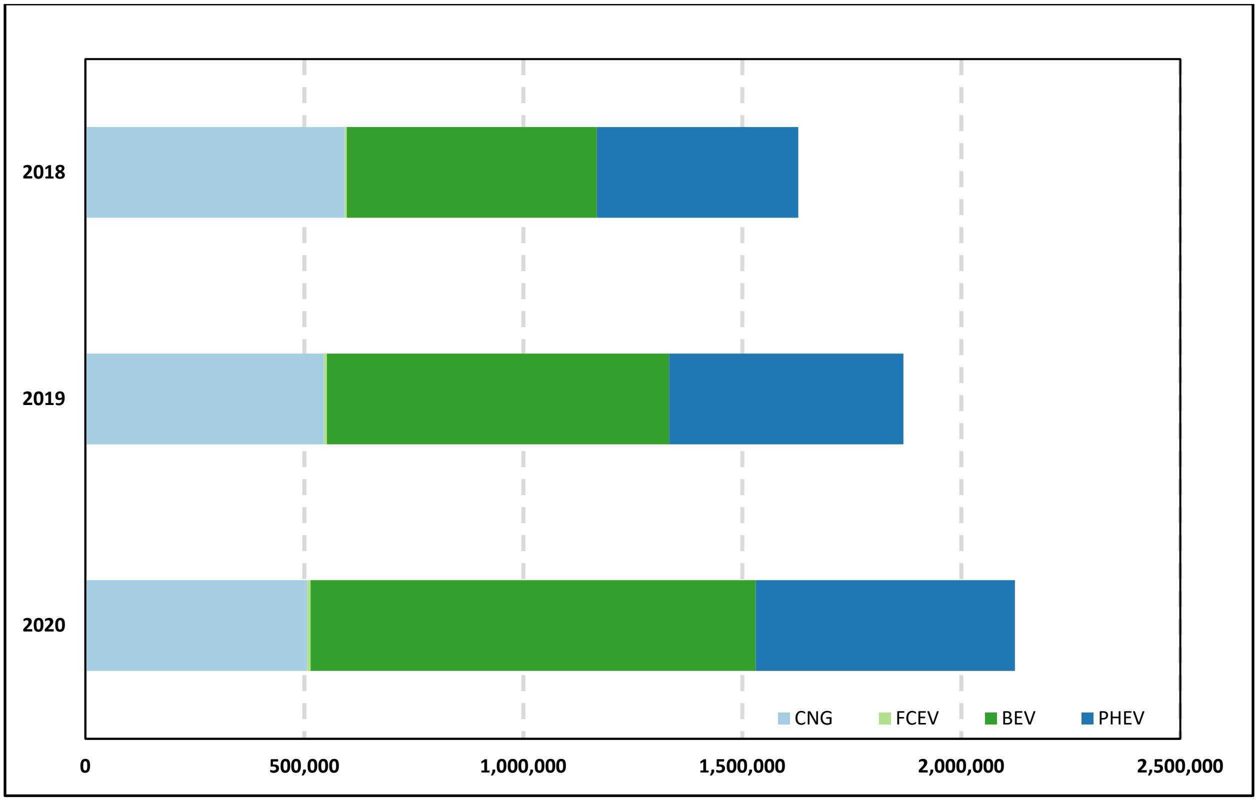


Figure 12. Alternative fuel light-duty vehicle registrations across the United States, 2018–2020.

Derived registration counts by NREL, Experian Information Solutions

Because California has such a significant share of all registered light-duty AFVs, we have also queried the data for California alone (Figure 13) and for the top 10 states excluding California (Figure 14).

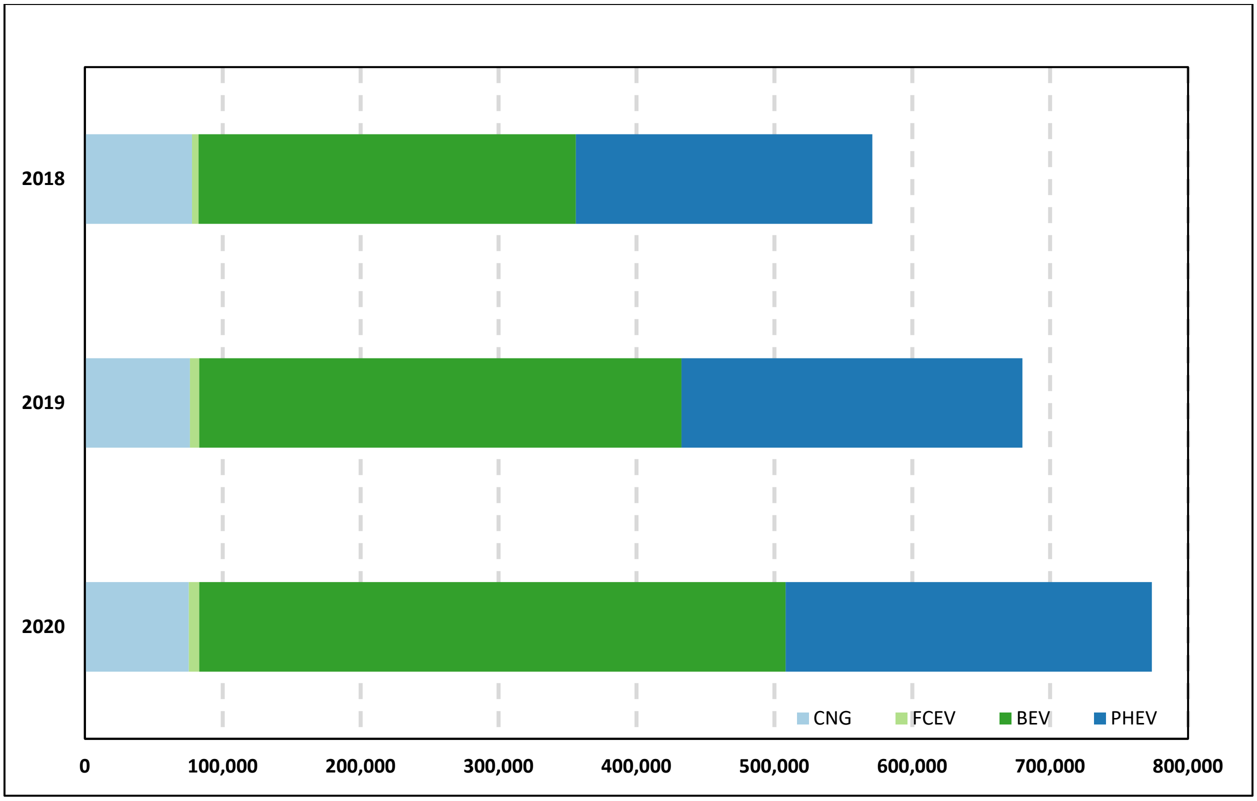


Figure 13. 2018–2020 California AFV registrations.

Derived registration counts by NREL, Experian Information Solutions

In Figure 13, we can see that BEVs are growing rapidly and becoming a larger portion of the overall PEV segment in California.

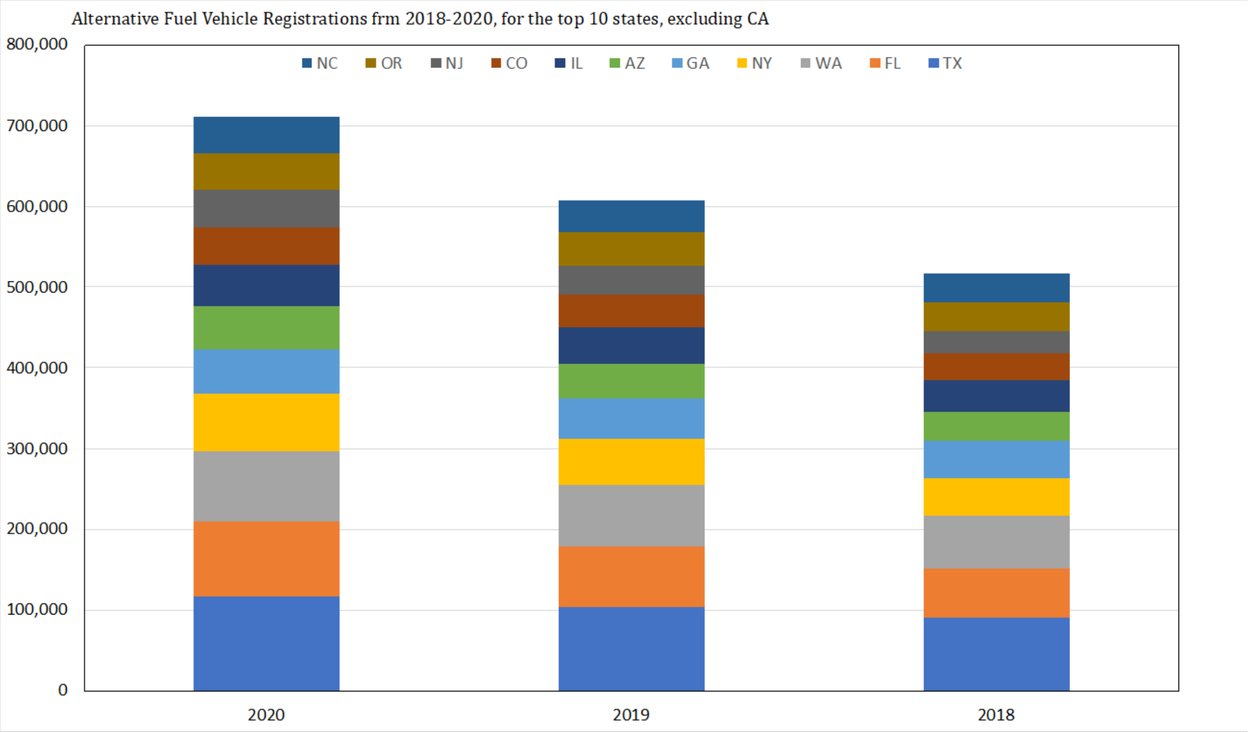
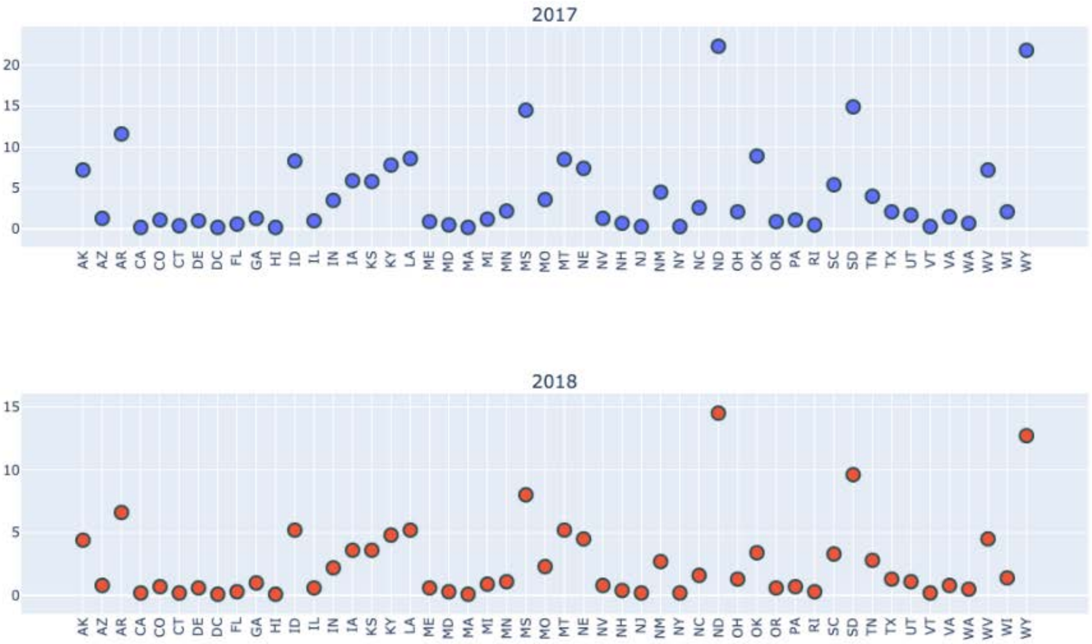


Figure 14. Alternative fuel light-duty vehicle registrations for the top 10 states, excluding California, 2018–2020.

Derived registration counts by NREL, Experian Information Solutions

The same trend for the growing popularity of BEVs outside of California is also evident.

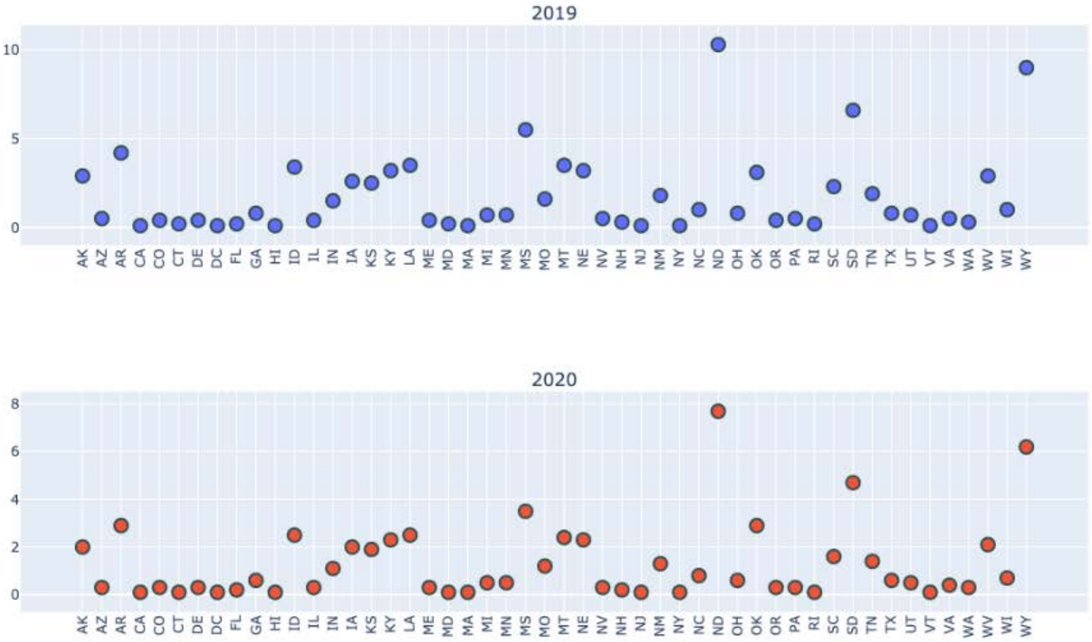
Figure 15 and Figure 16 compare the overall ratio of CNG vehicles to PEVs in each state for each year from 2017 to 2020. During this period, the overall number of CNG vehicles outweighed that of PEVs. However, the number of PEVs has continually increased from 2017 onward. As evidenced by the y-axis scale in each of the charts, the overall ratio of PEVs to CNG vehicles continues to decrease each year, showing the relative rise in PEV popularity over time compared to another alternative fuel. We used CNG vehicles because they are generally registered in every state. Note that CNG vehicle makes and models have decreased over time, and PEV model offerings have increased over time.


2017

2018

Figure 15. Ratio of PEV to CNG vehicle registrations in 2017 and 2018.

Derived registration counts by NREL, Experian Information Solutions


2019

2020

Figure 16. Ratio of PEV to CNG vehicle registrations in 2019 and 2020

Derived registration counts by NREL, Experian Information Solutions

2.2.2 Data Source: Argonne AFV Sales Data

Another valuable source of information for showing trends in AFV adoption is vehicle sales data. Argonne National Laboratory maintains monthly light-duty vehicle sales updates, including hybrid electric vehicles (HEVs), PEVs, and FCEVs. To provide some current numbers, the most recent update from Argonne National Laboratory, which includes data through February 2024, states that “in total, 4,934,884 PHEVs and BEVs have been sold since 2010.” (Argonne National Laboratory 2024). A recent report by the lab examines trends from 2010 to 2020 based on these data (Gohlke and Zhou 2021).

While not directly derived from sales, EIA publishes annual estimates of alternative fuel highway vehicles made available. These data are summarized from 2004 to 2018 in Table 6.1 of the *Transportation Energy Data Book* (Davis and Boundy 2022). Estimates for PEVs made available in model year 2021 are also available in Tables 6.7 and 6.8 in the same report.

2.2.3 AFV Model Availability

AFVs are available from a variety of automakers. Figure 17 shows the number of light-duty AFVs offered by vehicle manufacturers in the United States from 2009 to 2019. FFVs capable of using E85 (up to 83% ethanol, 17% gasoline) represented the largest share of models offered from 2003 until 2017, when PEVs overtook them. This was mainly because the technology required for E85 vehicles is comparatively inexpensive and compatible with gasoline use. 2015 was the first quantitative decrease in the number of new AFV models offered after 5 years of steady increases. Contributing factors to this decrease could be a reduction in gasoline prices and the phase-out of CAFE credits for FFVs (Johnson et al. 2021). PEVs increasingly cover the losses from the E85 offering reduction since 2016, leading to overall growth in AFV models since then.

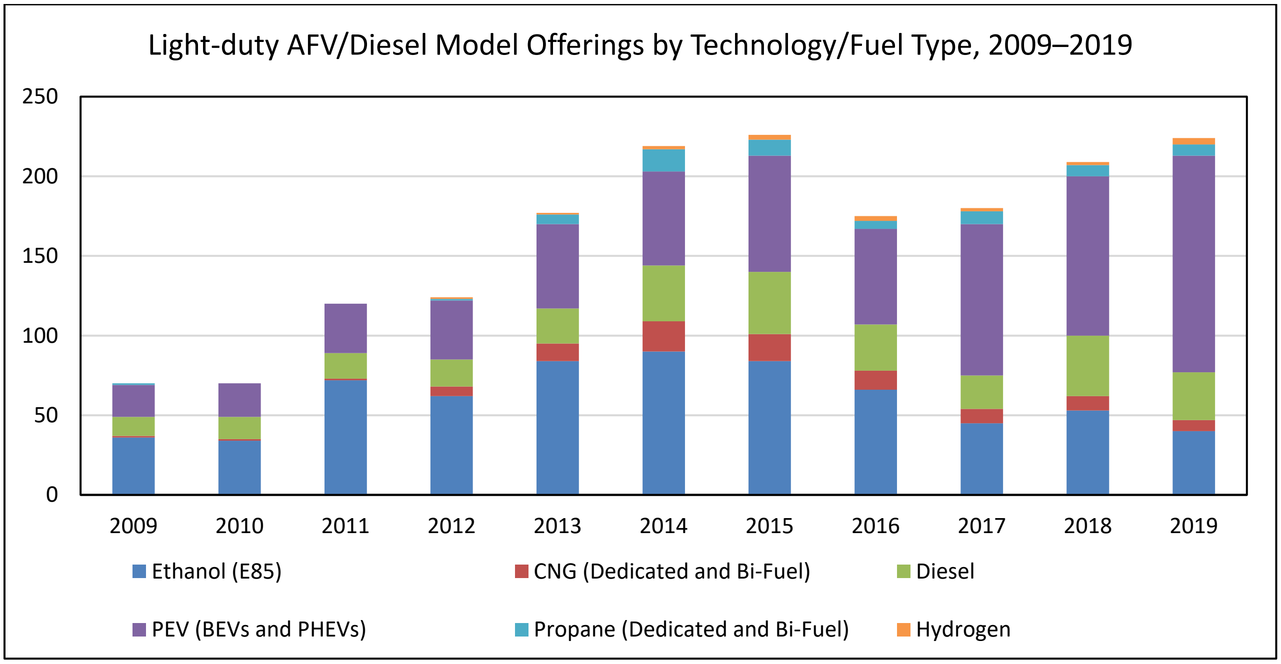
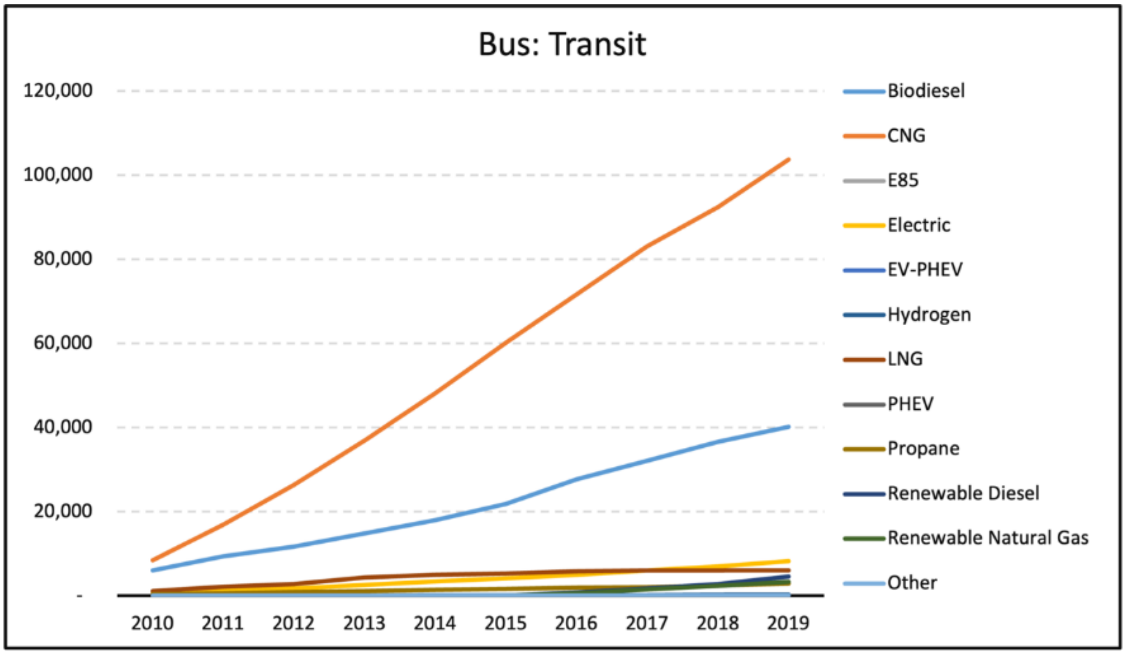


Figure 17. Light-duty AFV model offerings, 2009–2019.

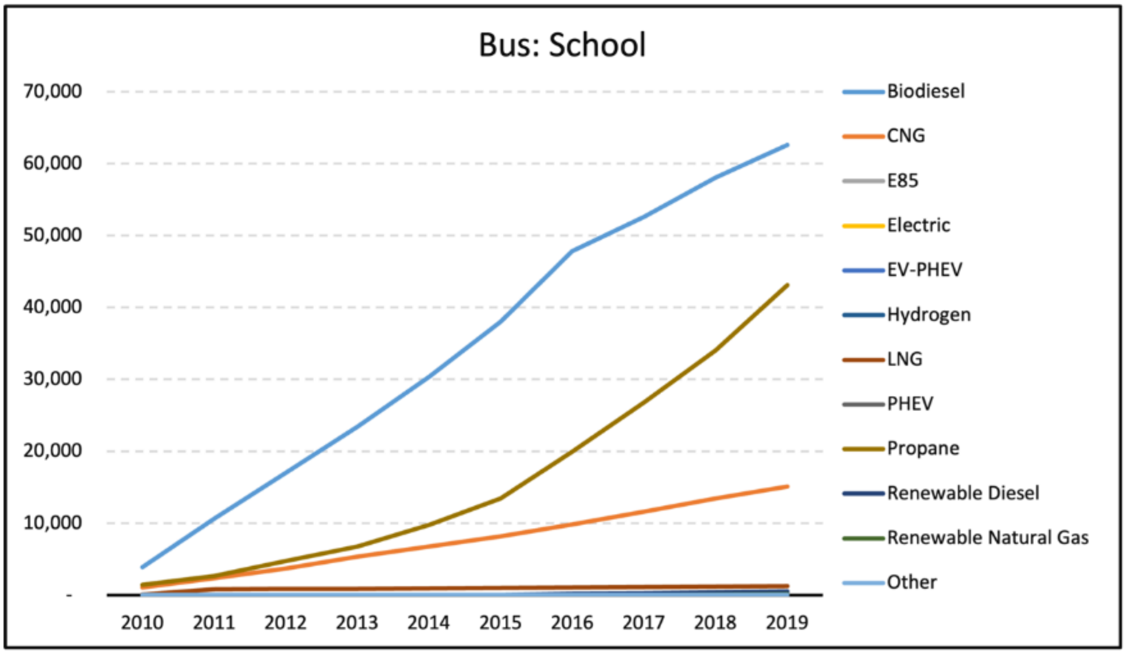
Data source: AFDC

2.2.4 Heavy-Duty AFVs

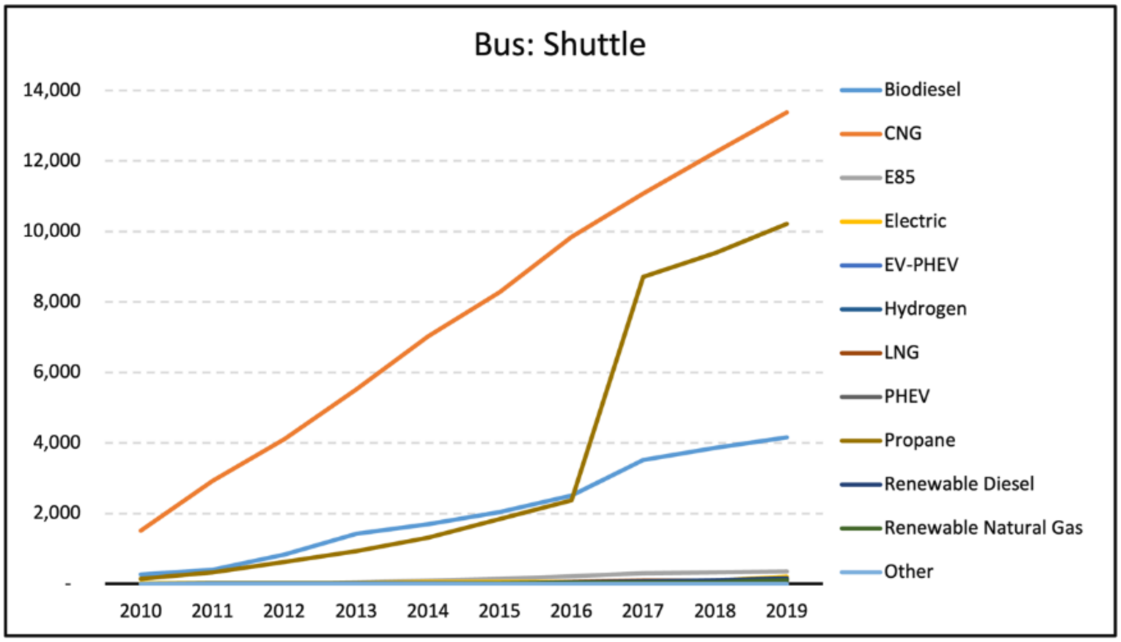
The biggest challenge with adopting heavy-duty AFVs is the lack of availability of the right vehicle models that utilize the desired alternative fuel. NREL compiled some data from the Clean Cities and Communities program regarding AFV populations for heavy-duty vehicles such as buses and trucks based on data reported in Clean Cities and Communities coalitions annual activity reports (AFDC 2024r). Figure 18 and Figure 19 show trends in vehicles by fuel type report by Clean Cities and Communities coalitions. Note that for biodiesel, Clean Cities and Communities coalitions can report vehicles utilizing any level of biodiesel content.



A. Transit buses



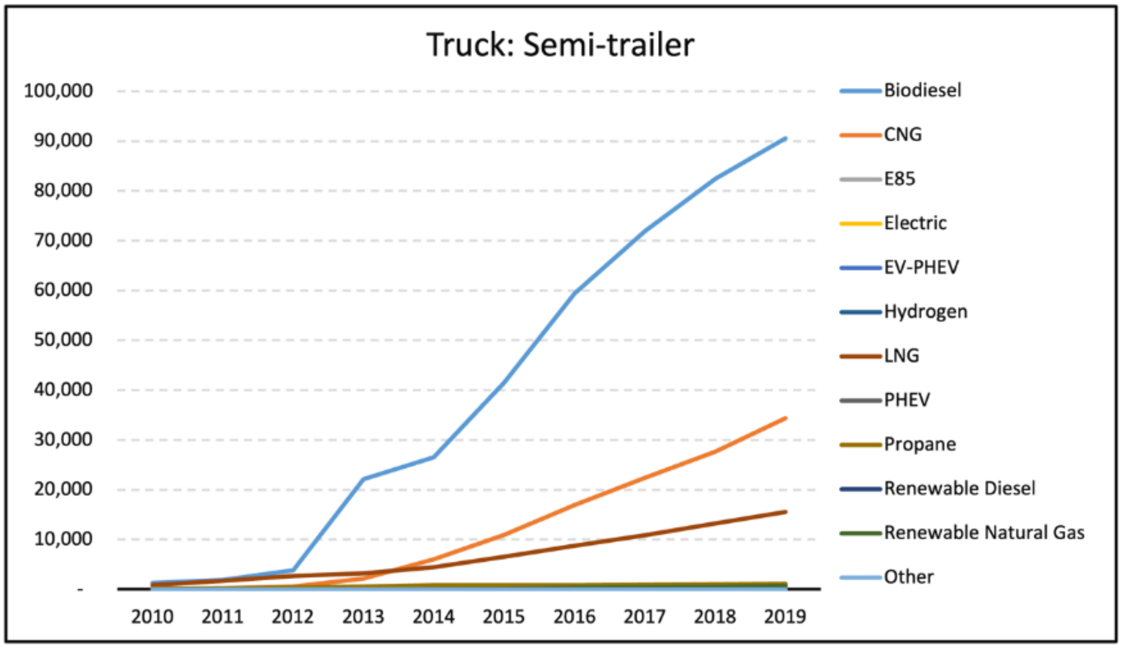
B. School buses



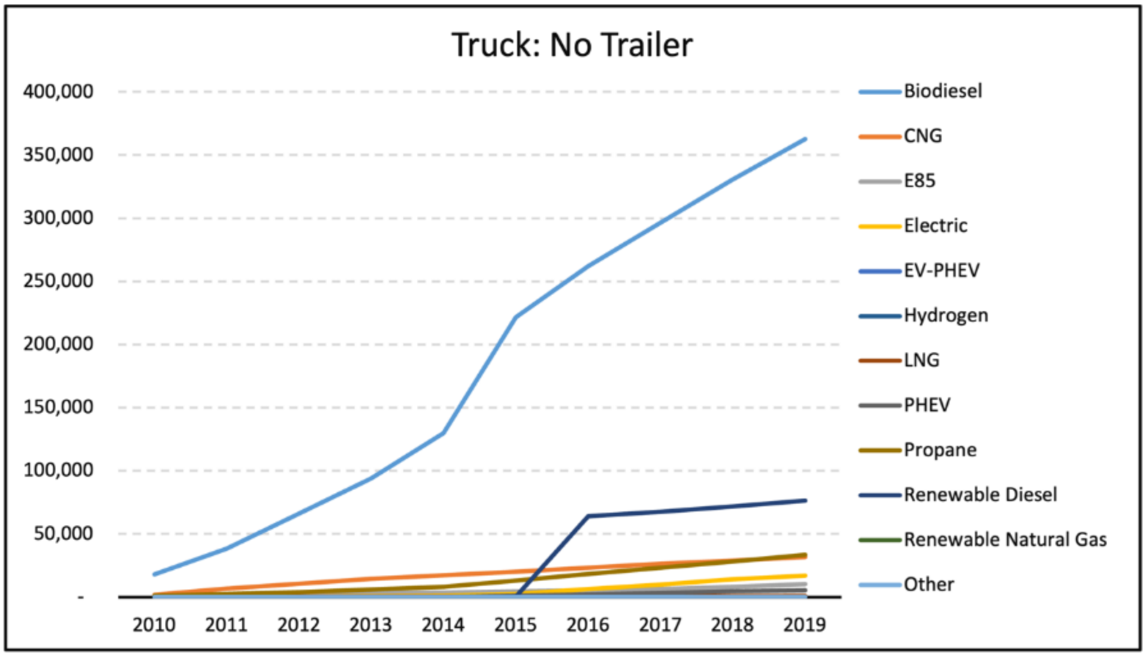
C. Shuttle buses

Figure 18. Alternative fuel buses (transit buses, school buses, and shuttle buses) as reported by Clean Cities and Communities coalitions at the end of 2019.

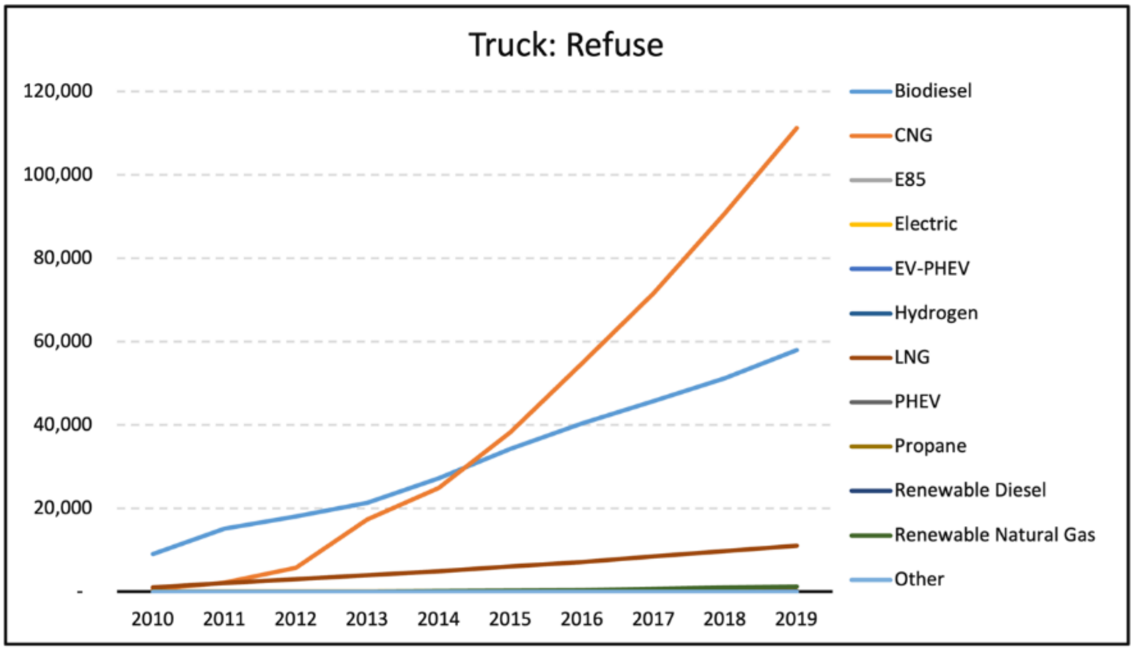
Source: Clean Cities and Communities Annual Reporting Tool



A. Truck: Semi-trailer



B. Truck: No trailer



C. Truck: Refuse

Figure 19. Alternative fuel trucks (semi-trailers, no trailers, and refuse) reported by Clean Cities and Communities coalitions at the end of 2019.

Source: Clean Cities and Communities Annual Reporting Tool

2.2.5 EVs

Having a variety of vehicle models available, and therefore choices in vehicle types, is critical to market growth (Bui, Slowik, and Lutsey 2021). A number of light-, medium-, and heavy-duty PHEVs and BEVs are available from a variety of automakers, although not all PEV models are necessarily available in every state or region. The number of light-duty PEV vehicle models offered by automakers has grown significantly since 2012, as shown in Figure 20.

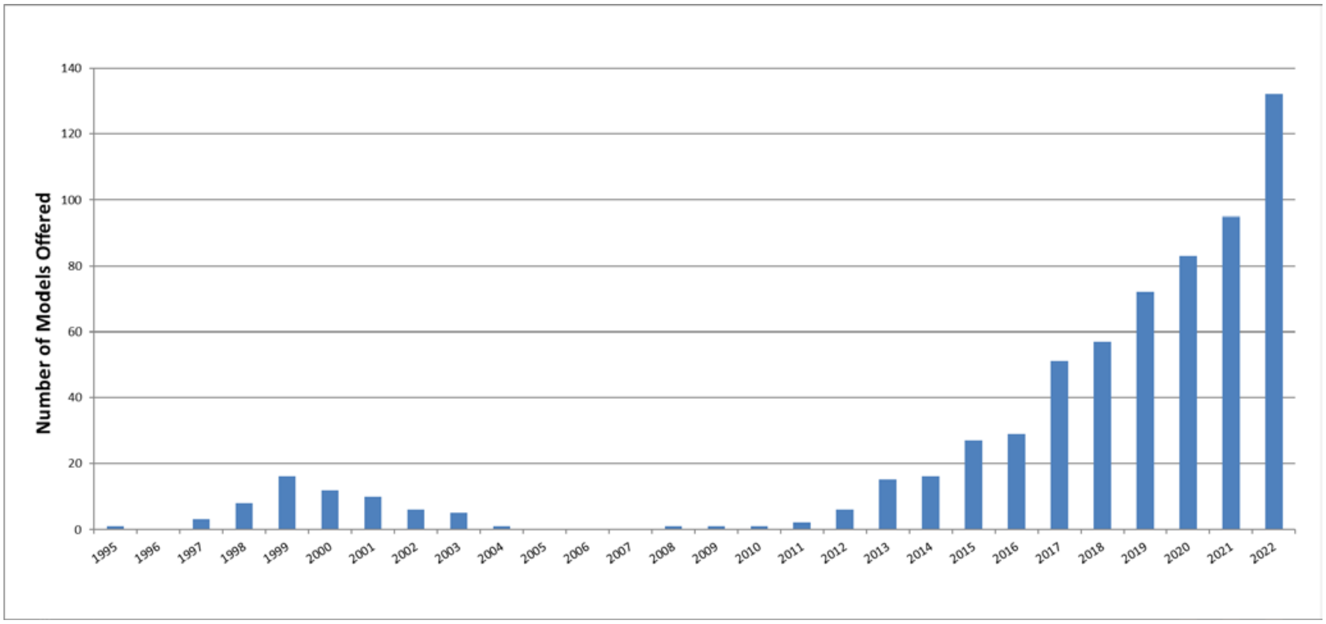


Figure 20. Available light-duty PEV models.

Source: AFDC Maps and Data website

As new model offerings grew, so did PEV sales. As shown in Figure 21, PEV sales had consistent growth between 2011 and 2018. They then plateaued in 2019 and 2020 due to global supply chain issues. In 2021, PEV sales nearly doubled to 608,000 vehicles as supply chain issues were resolved and manufacturing capacity increased. They then more than doubled again between 2021 and 2023 as additional vehicle options became available, range increased, charging infrastructure expanded, and new purchase incentives became available.

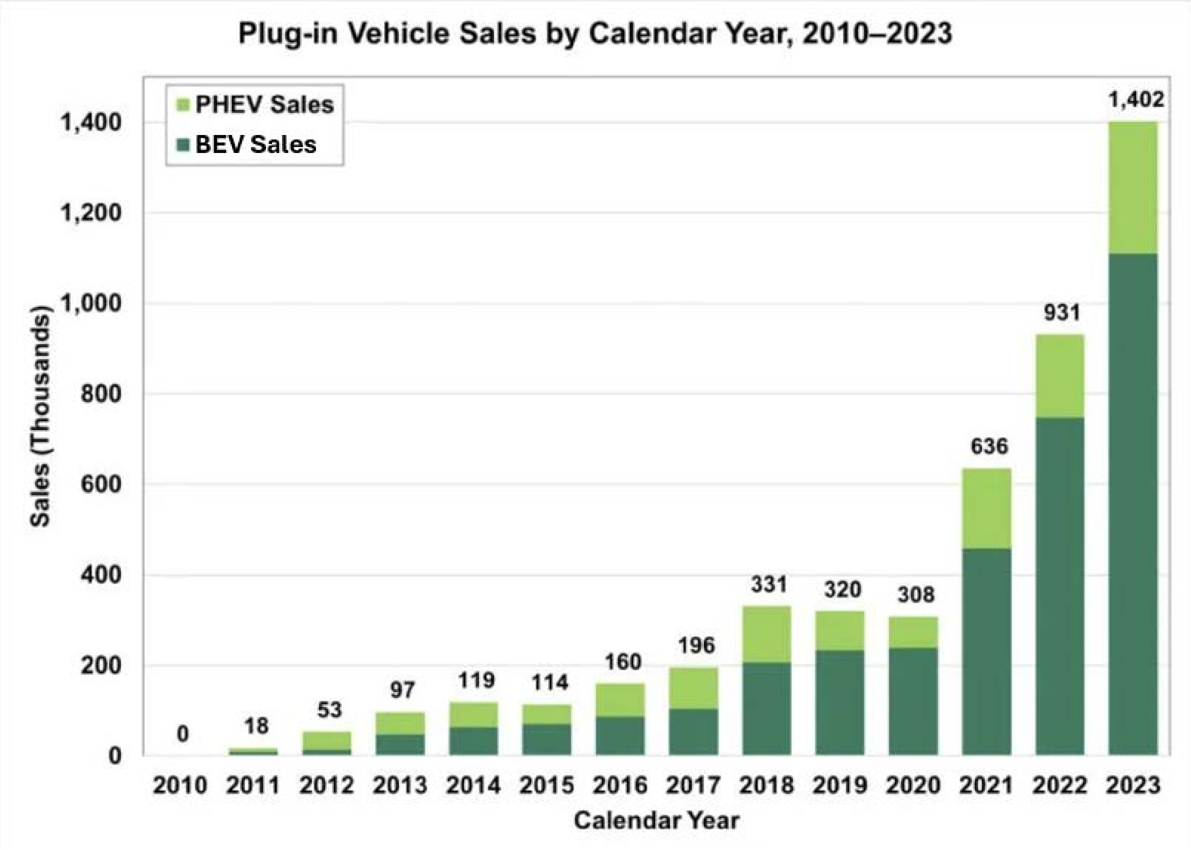


Figure 21. U.S. PEV sales by type.

Source: Argonne National Laboratory 2024

EVs are increasingly being adopted by transportation network companies in the light-duty market. In 2020, both Uber and Lyft announced zero-emission platform commitments. Uber's goal is to operate as a "zero-emission mobility platform" by 2030 across the United States, Canada, and Europe, with the further goal of having 100% of rides globally in zero-emission vehicles (ZEVs) or via micro-mobility or transit by 2040 (Uber 2024). Lyft announced a commitment to 100% ZEVs on their platform by 2030 (Lyft 2023). Both companies offer a "green" option, for which users can elect to use a PEV or HEV for their ride.

All PHEVs and BEVs in the United States can be charged using Level 1 or Level 2 charging equipment using either an SAE J1772 connector, a North American Charging Standard (NACS) connector, or adaptor. Depending on the vehicle model, three different types of connectors may be used for DCFC: CCS, CHAdeMO, or Tesla. Historically, CHAdeMO chargers were mainly used by Asian manufacturers, including Nissan, Mitsubishi, and Toyota, while North American and European manufacturers used CCS chargers. However, moving forward, the trend in the North American market appears to be the adoption of CCS chargers by most automakers, regardless of origin region. Tesla fast chargers have historically been proprietary and available only for Tesla vehicles; however, in November 2022 Tesla opened its charging standard for other companies to manufacture and renamed it the NACS. SAE International is testing equipment and standardizing it as SAE J3400. Most PEV manufacturers selling in the U.S. market have now announced that they will fit their EVs with the J3400 connector (Manthey 2023).

Figure 22 shows the vehicle registrations for PEVs by state as of Dec. 31, 2020. Generally speaking, the states with the highest registration counts are also those with the largest populations. Still, the PEV adoption relationship does not appear to be directly related to the population alone. For example, the state of Washington has a similar number of PEV registrations as Texas, despite having a significantly smaller population (Economic Research Service 2023). Both Texas and Florida also offer significant incentives for PEV adoption (AFDC 2024c).

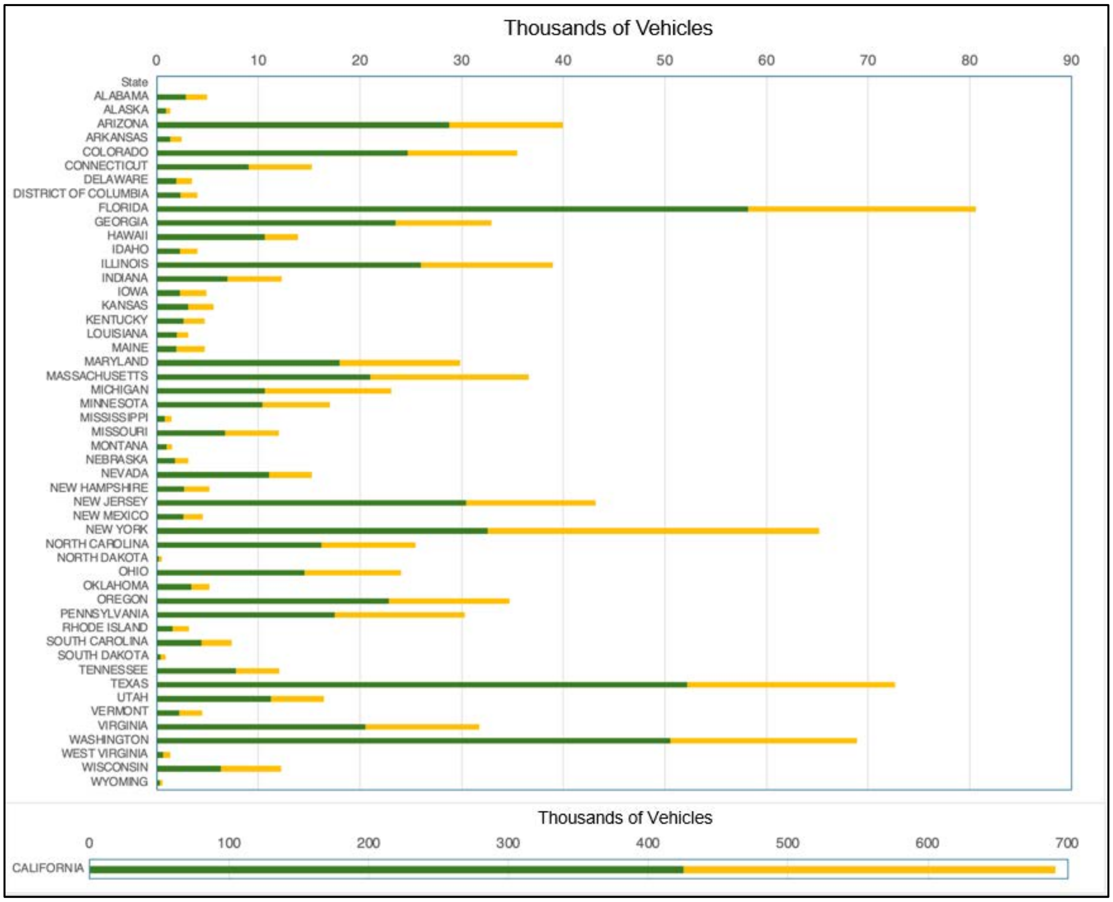


Figure 22. PEV Registrations by State at End of 2020.

Derived registration counts by NREL, Experian Information Solutions. This chart shows each state's vehicle registration counts of PEVs as of Dec. 31, 2020. California (on separate subplot) has the highest number of PEVs, approximately 42% of PEVs nationwide. Florida has the second-highest count, followed by Texas.

Of interest is the fact that Florida and Texas are third and fourth in the nation with respect to the number of public chargers available (preceded only by California and New York). This will be investigated in a 2024 report as part of the NHTSA/NREL research partnership.

Figure 23 shows the ratio of BEVs to PHEVs in each state for 2018, 2019, and 2020. These figures show that over time, BEVs are becoming more common than PHEVs. Hawaii has the highest BEV/PHEV ratio, possibly because its geography limits the required driving range, therefore making PHEVs less appealing.

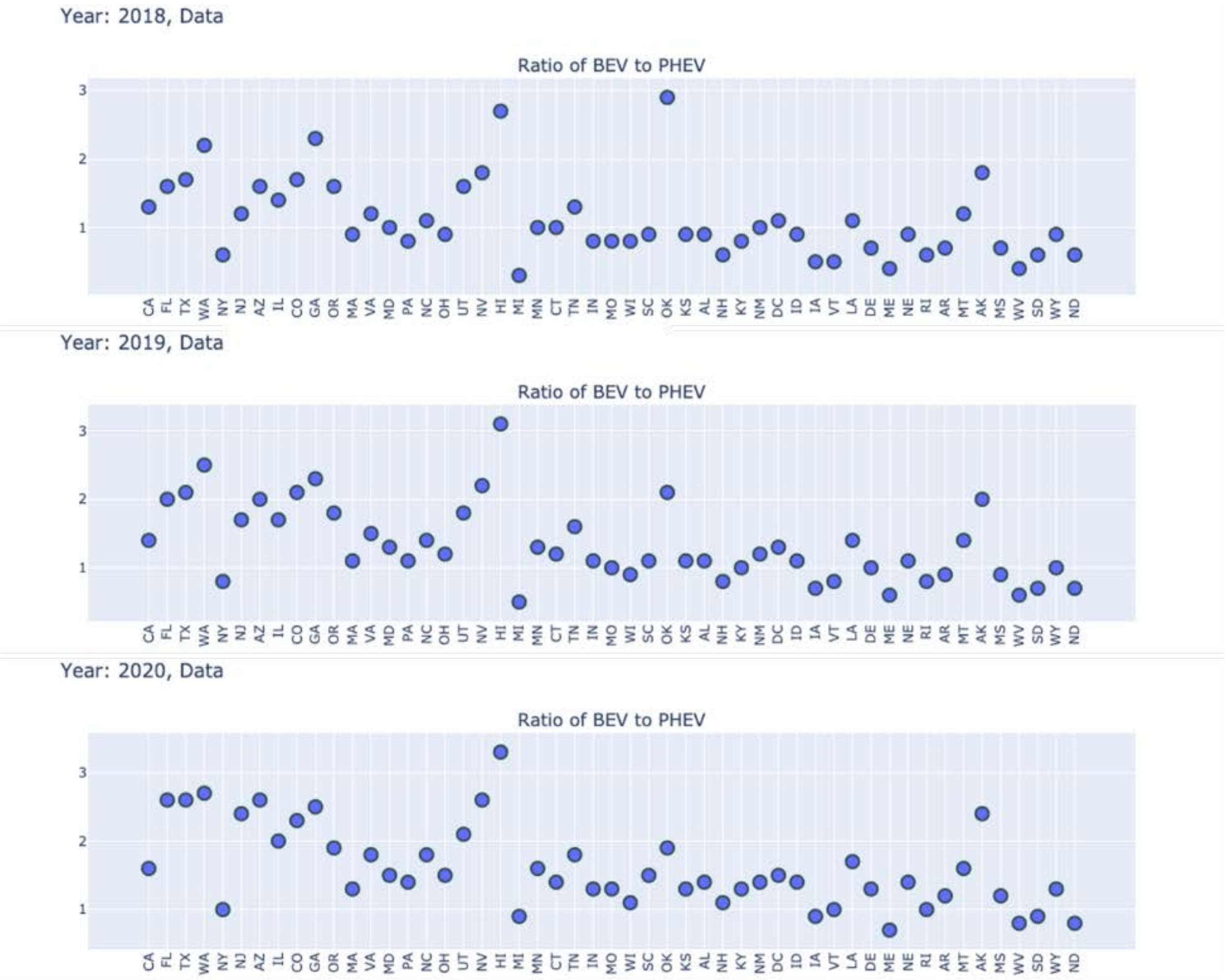


Figure 23. Ratio of light-duty BEV to PHEV registrations for each U.S. state, 2018–2020.

Derived registration counts by NREL, Experian Information Solutions

2.2.6 Hydrogen FCEVs

Several vehicle manufacturers have begun making light-duty hydrogen fuel cell vehicles available in select markets like Southern and Northern California, where there is access to hydrogen fueling stations (DOE 2024). Test vehicles are also available in limited numbers to select organizations with access to hydrogen fueling stations. Heavy-duty tractors have hydrogen options available on a demonstration basis, and hydrogen buses are in the early stages of deployment.

The California Energy Commission's *Joint Agency Staff Report on Assembly Bill 8* reports progress toward establishing a hydrogen fueling network that provides the coverage and capacity to fuel vehicles requiring hydrogen fuel that are being placed into operation in the state (Baronas and Achtelik 2020). Through the Clean Transportation Program, the California Energy Commission is investing in an initial network of 100 public hydrogen stations across California. Since 2010, the program has invested nearly $166 million in hydrogen infrastructure to support the FCEV market. As of Dec. 1, 2020, there were 45 open retail hydrogen refueling stations capable of supporting nearly 20,000 light-duty hydrogen FCEVs. California estimates system capacity by using 0.7 kilograms as the average amount of fuel used per FCEV per day. As of 2020, nearly 8,000 FCEVs were registered in California. This suggests there is an immediate capacity to add more vehicles.

While hydrogen fuel cell vehicle adoption is directly tied to—and for practical purposes limited by—fuel availability, the existence of infrastructure, by itself, may not be the only limiting factor for FCEV growth, as California's example suggests. Specifically, the number of vehicles that can be supported by infrastructure depends on the FCEV model itself, geographical distribution relative to station locations, hydrogen price, FCEV driver habits, vehicle miles traveled, and routes traveled. These stations are limited to fueling light- and medium-duty vehicles.

3 Costs for Alternative Fueling Infrastructure

The cost to develop alternative fueling infrastructure varies and impacts how and where stations are developed. The impact of station development costs on retail fuel prices depends on many factors; however, in general, the primary drivers for a fuel's retail price are the cost of the acquisition, production, refinement, and distribution of the fuel; marketing costs and profits; and taxes.

Th*e Clean Cities Alternative Fuel Price Report (*AFDC 2022c) provides regional alternative and conventional fuel prices for biodiesel, CNG, E85, hydrogen, propane, gasoline, and diesel. The report is a snapshot in time of retail fuel prices. Alternative fuel fleets can obtain significantly lower fuel prices than those reported by entering into contracts directly with local fuel suppliers.

Figure 24 shows average monthly retail fuel prices in the United States from 2000 to 2021. The price of petroleum fuels (gasoline and diesel fuel) is the primary driver of liquid fuel (E85 and biodiesel) prices. This is because the liquid fuels are used in non-dedicated AFVs and can be substituted with petroleum fuels if their price rises too high, decreasing demand until the price drops close to that of the petroleum fuel. However, natural gas and electricity prices have been buffered from this driver because transportation only constitutes a tiny portion of their markets. LNG was first tracked in July 2016, and prices for electricity started in 2011 when the availability of commercial vehicles and charging stations became significant in the market.

Pairing these fuel price data with historical station cost data could be a way to identify any correlations between station development cost and retail fuel prices; however, there is not a good source of data for historical alternative fueling infrastructure costs. This section details the general costs for electric, natural gas, hydrogen, and propane fueling infrastructure.

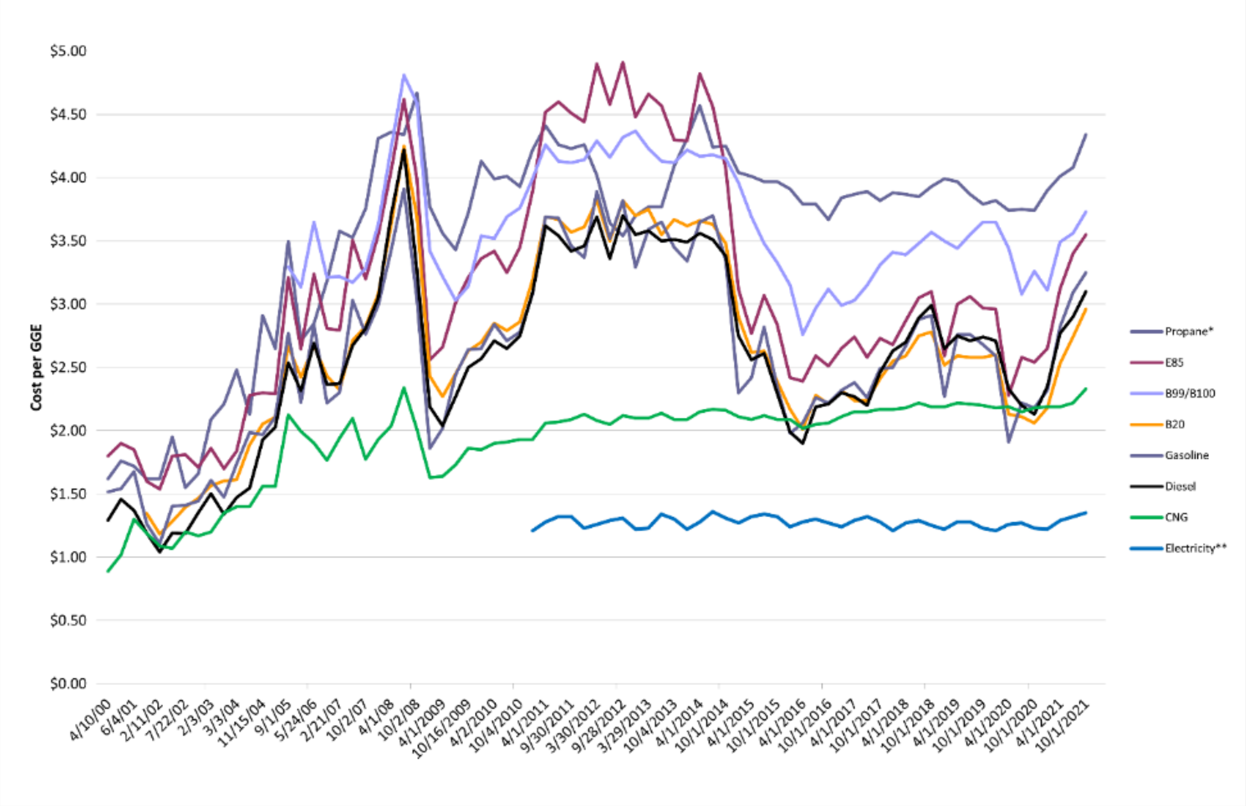


Figure 24. Average retail fuel prices in the United States (not adjusted for inflation).

* Propane prices reflect the weighted average of primary and secondary stations. Primary stations have dedicated vehicle services and tend to be less expensive. Secondary stations are priced for the tanks and bottles market and tend to be more expensive.

** Electricity prices are reduced by a factor of 3.54 because electric motors are 3.54 times more efficient than internal combustion engines (per AFDC Maps and Data page) and converted to gasoline gallon equivalents (GGE) at a rate of 33.7 kWh/GGE (per AFDC Fuels Comparison).

Source: AFDC 2022c

3.1 EVSE

NREL is currently assessing the "soft costs" of EVSE such as communications between the utility and providers, permitting processes, easement processes, and future-proofing. For this project, researchers have been going through approximately 3,500 invoices from New York, Colorado, and Texas state governments. The study will be published in Q4 2024, and this section will be updated after publication.

Accurate and representative cost data on the procurement, installation, and operations and maintenance of charging equipment continue to be elusive. A number of reports summarize major costs for EV charging. Organizations like the Center for Sustainable Energy manage many state and utility incentive programs and have proprietary cost data for each program. There are a variety of inputs that impact the cost to develop EV charging infrastructure, including equipment, installation, and operations and maintenance (including electricity, demand charges, and annual charging network fees). The burden for these costs depends on station ownership, which plays out in various financial scenarios for station site hosts (Satterfield and Nigro 2020). Charging station ownership typically falls into one of two categories: site host owned or third-party owned (e.g., owned by a charging network), though there are other possible arrangements. Charging infrastructure owned by the site host is purchased, installed, and maintained by the site host, which allows for complete control over the station and the ability to keep all revenue from the station (if applicable). In this scenario, site hosts are responsible for all associated costs, including maintenance or payment transaction fees. Charging infrastructure owned by a third party is installed and maintained by the third party, minimizing responsibility to the site host. In some cases, the site host may earn revenue by leasing the space occupied by the charging infrastructure to the third party.

3.1.1 Equipment

Equipment costs may vary based on factors such as application, location, charging level, and type. According to the Rocky Mountain Institute (Nelder and Rogers 2019), the three most significant drivers of equipment costs are:

- Power rating of the chargers or the total power requirements of a site with multiple chargers.
- Existing grid power capacity at the site.
- Location of the chargers within a site.

As part of the 2030 National Charging Network analysis, NREL compiled EVSE capital cost estimates for EVSE to use as model inputs. The compilation is listed in Table 2.

Table 2. EVSE Capital Costs from Wood et al. 2023

Charger Hardware		Unit Cost per Port	Install Cost per Port [a]	References
L1 residential	Low: High:	$0 $0[b]	$100 $1,000	(Fixr.com 2022; Courtney 2021; HomeAdvisor 2022)
L2 residential	Low: High:	$400 $1,200	$500 $1,700	(Borlaug et al. 2020; Fixr.com 2022; Courtney 2021; HomeAdvisor 2022)
L2 commercial	Low: High:	$2,200 $4,600	$2,200 $6,000	(Nicholas 2019; Nelder and Rogers 2019; Borlaug et al. 2020; Bloomberg New Energy Finance 2020; Pournazeri 2022)
DC 150 kW	Low: High:	$66,400 $102,200	$45,800 $94,000	(Nicholas 2019; Nelder and Rogers 2019; Borlaug et al. 2020; Bloomberg New Energy Finance 2020; Borlaug et al. 2021; Gladstein, Neandross & Associates 2021; Bennett et al. 2022)
DC 250 kW	Low: High:	$91,400 $134,800	$54,750 $105,950	Inferred from DC 150-kW and 350-kW costs
DC 350+ kW	Low: High:	$116,400 $167,400	$63,700 $117,900	(Nicholas 2019; Bloomberg New Energy Finance 2020; Borlaug et al. 2021; Gladstein, Neandross & Associates 2021; Bennett et al. 2022)

[a] These ranges do not span the set of all possible situations. They are meant to be plausible optimistic (low) and pessimistic (high) estimates for assessing network capital costs at scale. In some cases, it was not possible to verify exactly what was included within each study's estimate for installation costs, thus some discrepancies may be present across sources.

[b] L1 chargers tend to be included with the purchase of a PEV and are thus excluded as an infrastructure cost from this analysis. Networked charging infrastructure is connected to the internet and sends data, such as information on the frequency of use, to a network services provider (i.e., charging network) and the site host. The site must have access to a wired or wireless internet connection or cellular service to install a networked station. Non-networked charging infrastructure is not connected to the internet and provides basic charging capabilities without advanced utilization monitoring or payment capabilities. Costs for networking vary by network service provider.

3.1.2 Installation

Installation costs can vary based on factors including the number and type of charging infrastructure, geographic location, site location and required trenching, existing wiring and required electrical upgrades to accommodate existing and future needs, labor costs, and permitting. Based on these factors, reasonable installation costs can range from \$100 up to \$1,000 for Level 1, \$500 to \$6,000 for Level 2, and \$45,800 to \$117,900 for DCFC, as shown in Figure X. Local permitting and inspection fees may also apply. Federal, state, local, and utility incentives may be available to offset costs.

3.1.3 Other Considerations

Depending on the station, there may be other costs, including utility upgrades, on-site storage, and on-site generation. Utility costs are another element with a lot of uncertainty and variation by utility, depending on line-extension policies and make-ready programs.

EVSE is commonly installed in locations where other alternative fueling infrastructure cannot be installed, including residential (single family and multifamily), workplace, fleet, and public locations. Most PEV drivers charge their vehicles overnight at home using Level 1 or Level 2 charging equipment (Ge et al. 2021). This is the most cost-effective way for most PEV drivers to charge, with an average price of electricity for the residential sector in the United States of 14.11 cents per kilowatt-hour in October 2021 (EIA 2022b). Most Level 1 charging is provided through a standard 120-V AC plug, and most, if not all, PEVs will come with a Level 1 cord set, so no additional charging equipment is required for residential installations. In some cases, Level 1 EVSE may be installed at workplaces or public parking areas to control access. Simple wall-mounted Level 1 EVSE units that plug into an outlet or can be hardwired to the electrical system cost around \$300–\$600. On the higher end of the Level 1 EVSE price range, a pedestal unit with access control costs about \$1,500 (Smith 2016). On average, installation of a Level 2 charger at a single-family home may cost between \$400 and \$1,000. Still, this cost may vary significantly depending on equipment, labor, and the need for any electrical upgrades (City of Fort Collins 2022).

Charging stations in multifamily buildings, such as condos or apartments, face unique considerations related to installation and use, ranging from parking and electrical service access to billing and legal concerns. Equipment costs vary based on the features provided and can range from less than \$1,000 to more than \$6,000 (California Plug-In Electric Vehicle Collaborative 2013). Some units with network capability may require upfront activation fees, licensing fees, or monthly access fees. In addition to equipment costs, there may be permitting costs, installation costs, electricity metering costs, and ongoing operations and maintenance. A 2019 AFDC case study indicates that Green Rock Apartments in Minneapolis, Minnesota, installed Level 2 charging units at the cost of $600 per unit and paid an additional $400 per unit for installation (AFDC 2019). Financial recovery models vary and depend on the technology solutions employed (California Plug-In Electric Vehicle Collaborative 2013).

Costs associated with nonresidential EVSE vary widely depending on the use case and equipment. These costs are also difficult to track based on the complexity of EVSE and its relationship to the grid and built environment. The installed cost of Level 2 fleet EVSE is generally the lowest, followed by workplace charging, and public sites typically demand the highest costs (Electric Power Research Institute 2013). A 2019 Rocky Mountain Institute report (Nelder and Rogers 2019) includes updated detailed DCFC EVSE cost by power level (including 150–350-kW chargers), with a range of $20,000–$35,800 for 50 kW, $75,600–$100,000 for 150 kW, and $128,000–$150,000 for 350 kW.

The Rocky Mountain Institute report further breaks down costs to deploy charging equipment into procurement, requirements, and soft costs:

- Procurement:
    - Charger hardware
    - Managed charging capability
    - Contracts
    - Software
    - Grid hosting capacity
    - Make-ready infrastructure.
- Requirements:
    - Payment system
    - Measurement standards compliance
    - Americans with Disabilities Act compliance and parking requirements
    - Dual-plug types for DCFC
    - Cost standards.
- Soft costs:
    - Communication between utilities and providers
    - Future-proofing
    - Easement processes
    - Complex codes and permitting processes.

The addition of on-site storage introduces additional cost and complexity for which there are currently insufficient cost data.

Another way of looking at this is to explore the approach taken in NREL’s article, *Levelized Cost of Charging Electric Vehicles in the United States* (Borlaug et al. 2020):

> The cost to charge a PEV (i.e., the PEV "fuel" cost) depends on many factors, including the retail price of electricity, capital cost of charging or [EVSE], the cost of installation and maintenance of this equipment, and, for dedicated charging stations, additional business and operational expenses. Each factor is further dependent on the type of EVSE used—AC Level 1 (L1), AC Level 2 (L2), or [DCFC]; charging site—home residence, workplace, or public station; charging profile; and geographic region. This complexity produces a wide range of possible EV charging costs. Despite this, many studies assume the cost of EV charging to be equivalent to the average residential cost of electricity (often the price reported by the [EIA]) or the average levelized cost of electricity generation. These simple assumptions fail to capture essential variations in the cost of EV charging associated with the factors described previously.

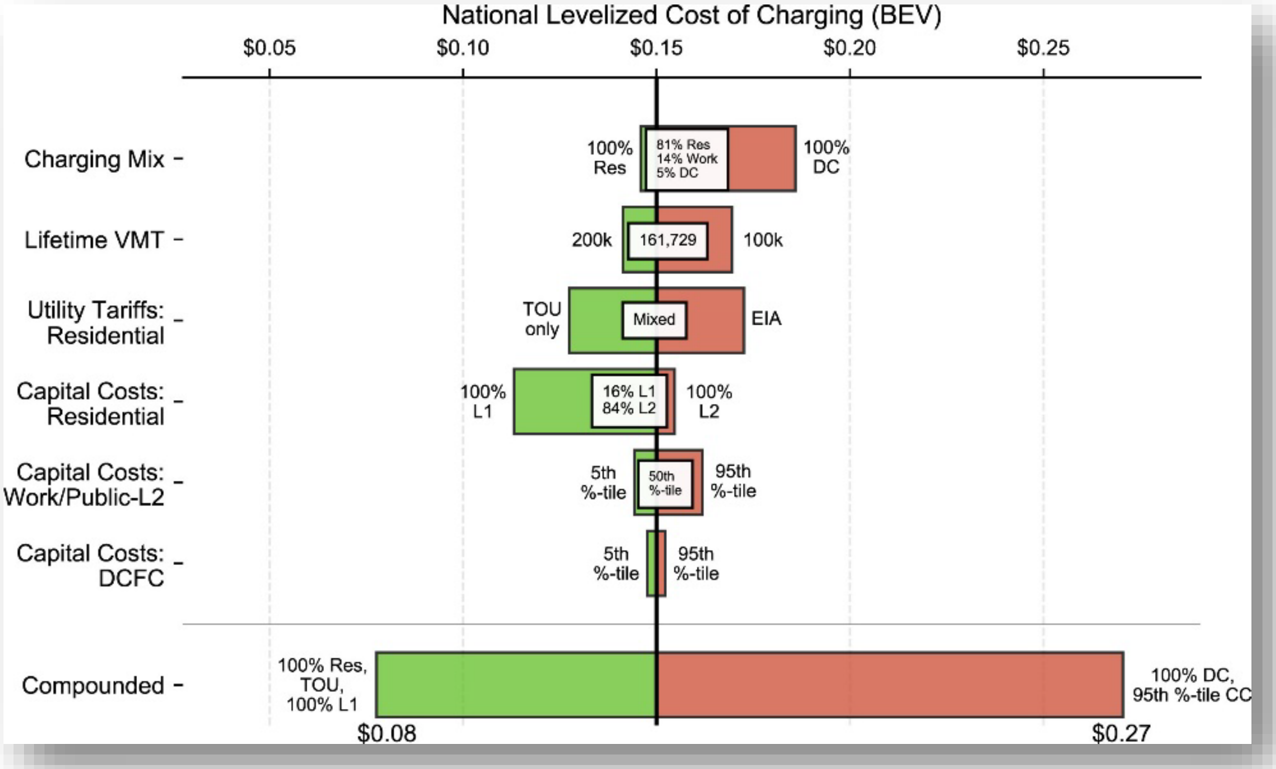


Figure 25. National levelized cost of charging (BEVs).

Source: Borlaug et al. 2020.

Note: VMT is vehicle miles traveled and TOU is time of use.

3.2 Natural Gas Fueling Infrastructure Costs

Costs for CNG and LNG stations vary considerably. CNG stations require more equipment and configuration, while LNG stations require less equipment but more safety precautions during fueling. As discussed in Section 4.3, the number of CNG and LNG stations have both trended down since 2016.

The cost of installing natural gas infrastructure is influenced by station size, capacity, type of natural gas (LNG, CNG, or both) dispensed, and how natural gas is dispensed (fast fill or time fill). The costs for installing a CNG fueling station can range up to $1.8 million, depending on the size and application. Smaller fueling units average $10,000, including installation. LNG fueling station costs are highly variable, ranging from approximately $1 million up to several million dollars (Smith and Gonzales 2014). Costs are dependent on factors such as storage capacity, station design, and the services needed to build the station.

NREL developed the Vehicle and Infrastructure Cash-Flow Evaluation Model (NREL 2014) to help fleet managers assess the financial soundness of converting their fleets to run on CNG. The model's station cost assumptions vary by vehicle type, application, and station capacity.

Table 2 shows cost data collected from Clean Cities and Communities coalitions. The minimum and maximum ranges listed here require more investigation to understand factors that impacted final station costs.

Table 2. Cost Data for CNG Stations

CNG Station Cost Data	Average	Minimum	Maximum	Stations Reporting
Dispenser	$53,517	$40,000	$100,000	27
Storage	$170,521	$14,400	$1,050,000	27
Compressor (per unit)	$274,209	$100,000	$791,866	30
Compressor (per horsepower)	$1,225	$343	$3,000	30
Dryer	$103,820	$5,000	$500,000	23
Total equipment costs	$1,400,502	$60,117	$5,604,603	39
Total installation costs	$860,894	$9,000	$2,900,000	30
Total station costs	$1,890,986	$173,000	$5,604,603	54
Incentive	$1,005,832	$173,000	$4,897,000	2

3.3 Hydrogen Infrastructure Costs

The costs and trends related to development of public hydrogen fueling stations in California are well documented. The California Air Resources Board publishes an Annual Hydrogen Evaluation that provides regular updates on the population of hydrogen-fueled vehicles in the state, as well as new fueling infrastructure, an evaluation of current and future fueling capacity, and updates to relevant standards, protocols, and regulations (CARB 2023a). Specific to cost, for planned future hydrogen refueling stations in California, a recent DOE report found that "an average hydrogen station has capacity of 1,240 kg/day (median capacity of 1,500 kg/day) and requires approximately $1.9 million in capital (median capital cost of $1.9 million)" (DOE 2020).

The capital costs of hydrogen stations vary substantially (between $1,200 and $3,000 per kilogram per day [DOE 2020]) largely due to several variables. Hydrogen can arrive at the station in gaseous or liquid form. If it arrives as a liquid, the station requires additional equipment to store liquid, convert it to gas, and efficiently buffer the pressures down to what the vehicle can accept. The daily fueling capacity and number of dispensers are also very influential drivers of cost. In addition to the cost drivers per DOE (2020), a significant driver is whether hydrogen is produced on-site, and if so, whether it is produced by steam methane reforming or hydrolysis.

3.4 Propane Infrastructure Costs

Cost data collected from Clean Cities and Communities coalitions specific to propane station installations are shown in Table 3. Note the wide range in costs for both the equipment and installation, with the reported total station costs ranging from $3,500 to $500,000 and an average station cost of $55,335. Note also that propane fueling infrastructure for vehicles can be as simple as adding a stand-alone propane tank with a pump.

Table 3. Cost Data for Propane Stations

Station Data Costs	Average	Minimum	Maximum	Stations Reporting
Storage tank (per gallon)	$7.18	$0.33	$37.88	19
Storage tank (per tank)	$37,883	$2,000	$150,000	19
Pump	$6,287	$2,000	$50,000	25
Dispenser [a]	$13,096	$2,000	$25,000	14
Card reader	$8,500	$5,000	$12,000	2
Total equipment	$47,946	$3,000	$500,000	31
Total installation	$22,324	$1,000	$88,546	27
Total station	$55,335	$3,500	$500,000	48
Incentive	$19,843	$1,500	$50,000	16

[a] Two stations reported a cost of $1 and another two stations reported $250; these values were not included.

4 Emerging Trends in Alternative Fueling Station Technology and Development

This section explores trends (technical, market, and policy) in alternative fueling station technologies and some of the critical drivers of infrastructure development. We focus primarily on electricity and hydrogen for light-duty vehicles.

4.1 Alternative Fueling Infrastructure Laws and Incentives

The AFDC's maps and data page for laws and incentives provides some high-level charts on AFV policy trends. In particular, Figure 26 shows trends in laws and incentives related to alternative fuels and advanced vehicles, enacted in all 50 states and the District of Columbia, from 2002 to 2022 (AFDC 2023c). Note that these data are not specific to alternative fueling infrastructure.

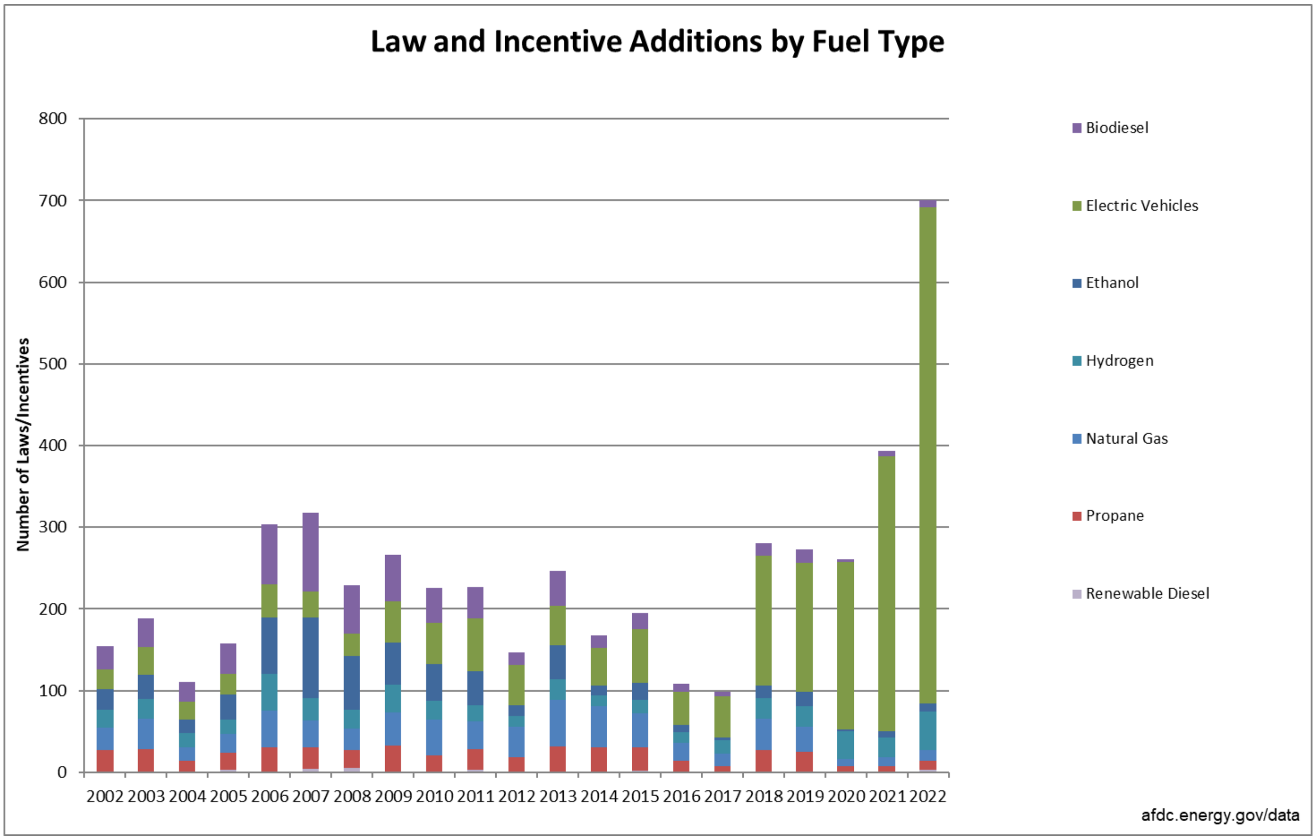


Figure 26. Law and incentive additions by fuel type.

Data Source: AFDC laws and incentives database

Overall, the number of new federal, state, and utility activities related to alternative fuels, advanced vehicles, and other strategies have increased in recent years. In fact, activities in 2022 exceeded all previous years in the AFDC's 21-year record, as shown in Figure 26. The growth in state alternative fuel actions follows unprecedented federal actions and builds on momentum from state agency, private, and utility investment in ZEVs and infrastructure in recent years.
To address the climate crisis, the Biden administration set targets to build a national network of 500,000 public EVSEs and have at least 50% of new U.S. passenger car and light truck sales as

ZEVs by 2030 (The White House 2021a). To help meet these goals, in November 2021, President Biden signed the Bipartisan Infrastructure Law (BIL), enacted as the Infrastructure Investment and Jobs Act of 2021 (Congress.gov 2021). The BIL supports a variety of AFVs and advanced vehicle technologies through grant programs, studies, technology standards, loans, research and development, fleet funding, and other measures. It includes provisions to increase investment in EV charging equipment, alternative fuel infrastructure, PEV batteries, electricity grid upgrades, and light-, medium-, and heavy-duty ZEVs.

Provisions in the BIL mark the largest investment by the U.S. government in EV charging infrastructure in history. Specifically, the BIL provides $5 billion over 5 years (Fiscal Years 2022–2026) in formula funding to states that will help build a convenient, affordable, reliable, and equitable nationwide network of public EV charging infrastructure. This funding under the National Electric Vehicle Infrastructure Formula Program is directed to designated Alternative Fuel Corridors (AFCs) for PEVs to build out this national network, with EV charging stations spaced no more than 50 miles apart and within 1 mile of an interstate exit or highway. When the national network is fully built out, states may use allocated funding to develop EV charging stations on any public road or in other publicly accessible locations.

The BIL also includes $2.5 billion, through two distinct discretionary grant programs, to support EV charger and alternative fuel infrastructure deployment along corridors and in communities. The Corridor Grant Program and Community Grant Program will strategically deploy publicly accessible EV charging and hydrogen, propane, and natural gas fueling infrastructure along designated AFCs and in communities.

To further support the nation’s climate goals, President Biden signed the Inflation Reduction Act (IRA) in August 2022, which includes $370 billion in investments to deliver an equitable clean energy future and put the United States on a path to achieving net-zero emissions by 2050 (Congress.gov 2022). The passage of the IRA designates the most significant action taken on clean energy and climate change in the nation’s history. It builds on the foundational investments in the BIL to support a variety of AFV and infrastructure technologies through tax credits, grant programs, and loan programs. Additionally, it advances the Justice40 Initiative, which directs 40% of the overall benefits of federal investments to disadvantaged communities (The White House 2023b).

In particular, the IRA extends through 2032 the AFV Refueling Tax Credit, which provides a tax credit for qualified AFV fueling and EV charging infrastructure in low-income and rural areas (AFDC 2023c). A new provision to this tax credit extends it to tax-exempt entities such as state, local, and tribal governments, which can elect to receive these tax credits in the form of direct payments (The White House 2023a).

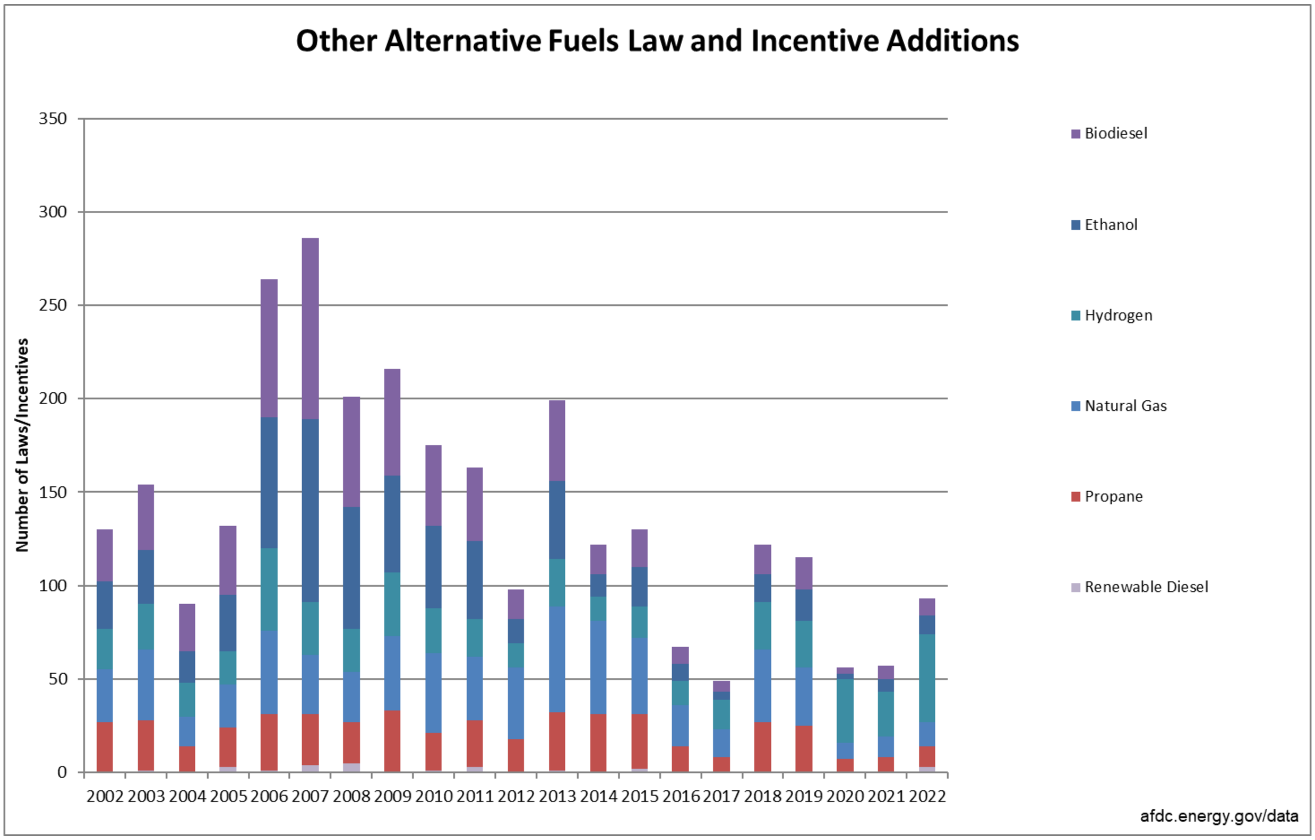


Figure 27. Other alternative fuels laws and incentives additions.

Data Source: AFDC laws and incentives database

At the state level, the alternative transportation fuel receiving the most attention from state governments, utilities, and other entities in 2022 was electricity, as shown in Figure 26. Figure 27 shows trends for other alternative fuel types (excluding electricity). As shown in Figure 27, attention to hydrogen grew at the state level, particularly for incentives, which marked the highest number of hydrogen-related incentives in the 21-year record. Additionally, it shows that state attention on other alternative fuels, including biodiesel, E85, natural gas, and propane, also increased slightly in 2022 after declining in recent years.

The large number of electricity actions in recent years is partially attributed to the 2016 Volkswagen Environmental Mitigation Trust funding state incentive programs (EPA 2024). The trust allows states to commit up to 15% of their allocation to fund light-duty EV charging infrastructure. Most states opted to allocate a portion of funding to support the installation of EV charging infrastructure. For example, Iowa and Oklahoma provide grant programs funded by their portion of the Volkswagen Environmental Mitigation Trust for publicly accessible Level 2 and DCFC stations (AFDC 2024e, 2024h). Pennsylvania provides grants for the acquisition, installation, operation, and maintenance of publicly available DCFC stations and hydrogen fueling infrastructure (AFDC 2023h). States such as Alabama (AFDC 2024j) and Colorado (AFDC 2024b) are building on the momentum from Volkswagen-funded programs as they implement EV charging programs funded by the BIL.

Further, state investment in alternative fuel programs may have been spurred by state or multistate goals to support the adoption of ZEVs, deployment of fueling or charging infrastructure, and reduction of greenhouse gas emissions. Through the Advanced Clean Cars II regulation, California requires an increasing percentage of light-duty ZEVs in new vehicle sales that reaches 100% by model year 2035 (AFDC 2024s). At the time of writing, eleven other states have adopted the Advanced Clean Cars II regulation, with additional states in the rulemaking process. Other states have set their own targets, such as North Carolina, which established a goal to increase the share of new passenger vehicle sales to 50% ZEVs by 2030 (AFDC 2024r). Expanding beyond the light-duty sector, California and six other states adopted standards for Advanced Clean Trucks, requiring all new medium- and heavy-duty vehicles sold in California to be ZEVs by 2045 (AFDC 2024a). Sixteen states and the District of Columbia joined California by signing a memorandum of understanding requiring all new medium- and heavy-duty vehicles sales in the signatory states to be ZEVs by 2050 (Northeast States for Coordinated Air Use Management 2022).

Over the past several years, state legislatures began excluding EV charging equipment owners from the definition of a public utility, thereby allowing for the deregulated sale of electricity at public EV charging stations. Currently, 46 states, as well as the District of Columbia, have deregulated EV charging stations, allowing owners to charge for electricity by the kilowatt-hour rather than by session or duration of charge (AFDC 2024c). This helps standardize charging payment calculation methodologies nationwide. The remaining four states (Michigan, Nebraska, Tennessee, and Wisconsin) are required to deregulate EV charging stations by the end of 2023 to remain in compliance with National Electric Vehicle Infrastructure Final Guidance (FHWA 2023a).

State governments, utilities, and other entities increasingly set income-level criteria for electric-drive and AFV incentives or offer additional funding for AFV projects in environmental justice communities. Approximately 30 states have more than 150 laws or incentives that include low-income or underserved community considerations. For example, in Illinois, additional rebates are available for EV charging stations deployed in underserved and environmental justice communities (AFDC 2024i).

Ten states, including New Jersey and Hawaii (AFDC 2024k, 2024l), set policies to reduce barriers to installing EV charging equipment at housing associations and condominiums, expanding EV charging access to individuals. In New Jersey, condominium associations may not prohibit or restrict the installation or use of EV charging stations in a homeowner’s designated parking space. This and other right-to-charge laws provide residents at multifamily dwellings, condominium owners associations, and homeowners associations with the right to install an EV charging station for personal use. Some states and local governments, including Oregon and Massachusetts (AFDC 2024g, 2024f), have enacted EV charging building codes to advance “EV readiness” by requiring new construction to support EV charging. For example, in Massachusetts, at least one parking space in any new commercial construction with more than 15 parking spaces must be made-ready for EV charging stations.

Utilities and private organizations often support PEV readiness through make-ready programs and other incentives that reduce costs associated with EV charging installations, PEVs, and electricity rates for EV charging. These incentives encourage customers to adopt new and alternative technologies while increasing customer engagement and promoting sustainable load growth. Rocky Mountain Power in Utah offers custom grants to nonresidential customers to help cover the upfront costs for electrical infrastructure and installation of PEV projects (AFDC 2024p). Most New York utilities offer a variety of incentive programs to customers, from make-ready programs to EV charging station incentives and time-of-use rates (AFDC 2024n).

Forty-eight states and the District of Columbia joined the National Electric Highway Coalition, committing to create a network of DCFC stations connecting major highway systems from the Atlantic to the Pacific coasts of the United States (Edison Electric Institute 2024). Utility members agree to ensure efficient and effective fast charging deployment plans that enable long-distance BEV travel, avoiding duplication among coalition utilities and complementing existing corridor DCFC sites.

4.2 EVSE

The BIL includes a $7.5-billion investment for deploying EV charging equipment and other alternative fueling infrastructure nationwide through the National Electric Vehicle Infrastructure Formula Grant Program and Community Charging and Fueling Grants. These funds will help states and communities expand public charging networks and will drive technology and development trends for EV charging stations. In addition to increases in federal investment and attention on EV charging equipment, recent technology trends include faster higher-power charging, interoperability, reliability, and diversification of charging options. Development trends include the build-out of a convenient, affordable, reliable, and equitable national network of EV charging equipment.

4.2.1 EVSE Technology

Building out the country's network of public DCFC is critical to supporting BEV adoption in the United States. As BEVs become more popular, the demand for faster and more robust charging infrastructure continues to grow. This is especially apparent in the deployment of public charging stations. Of public EVSE ports, DCFC ports continue to increase by the greatest percentage in recent years (Brown et al. 2023a). While DCFC is estimated to be a relatively small part of the national network in terms of number of total ports, it is vital to enabling future growth by assuring drivers they will be able to charge quickly whenever they need or want (Wood et al. 2023).

However, as discussed earlier, the majority of all charging happens at home or at work due to cost and convenience, likely on AC Level 1 or AC Level 2 charging (Wood et al. 2023). For public charging, the preference for faster-power EVSE represents the public desire to reduce the time it takes to charge their vehicles while away from home. However, the overall cost of energy for using DCFC, most of which operates at power outputs of 50 or 250 kW, can be nearly four times as expensive compared to the average cost of energy for home charging (Brown et al. 2023a; Voelcker 2023). This increased cost is necessary to support the expensive infrastructure required for DCFC. It is likely more valuable to consumers using public charging on road trips or in the middle of the day when the vehicle dwell period needs to be relatively short.

Although a 150-kW DCFC station is an order of magnitude more powerful than the most common AC Level 2 stations, manufacturers continue to develop EVSE and BEVs with even greater capabilities (Bennett et al. 2019; Brown et al. 2023a). The number of DC fast EVSE ports at higher power levels is steadily increasing, and advances in battery technology are expected to stimulate demand for higher-power chargers (Brown et al. 2023a; Wood et al. 2023). Analyzing data from the AFDC Station Locator, the average power for U.S. ports is approximately 190 kW, with a median of 250 kW. Power output data from the AFDC Station Locator are only available for approximately 63% of public DC fast EVSE ports in the database (Brown et al. 2023a). As almost all the ports with missing power data in this dataset are Tesla Superchargers, NREL is able to fill the data gap by assuming that any Tesla Superchargers installed before March 6, 2019, are 150 kW and any installed after that date are 250 kW (Tesla 2019).

This trend in the growth of higher-power DC fast EVSE ports is reflected in Figure 1Figure 28. The number of EVSE ports with a power output between 250 and 349 kW and greater than 349 kW grew by the largest percentage, based on Station Locator 2023 data (Brown et al. 2023a). This growth is largely driven by new Tesla Supercharger installations with a power output of 250 kW and new EVgo installations with a power output of 350 kW (Brown et al. 2023a, 2023b). It is estimated that by 2030, DCFC rated for at least 350 kW will be the most prevalent technology across the national fast charging network (Wood et al. 2023).

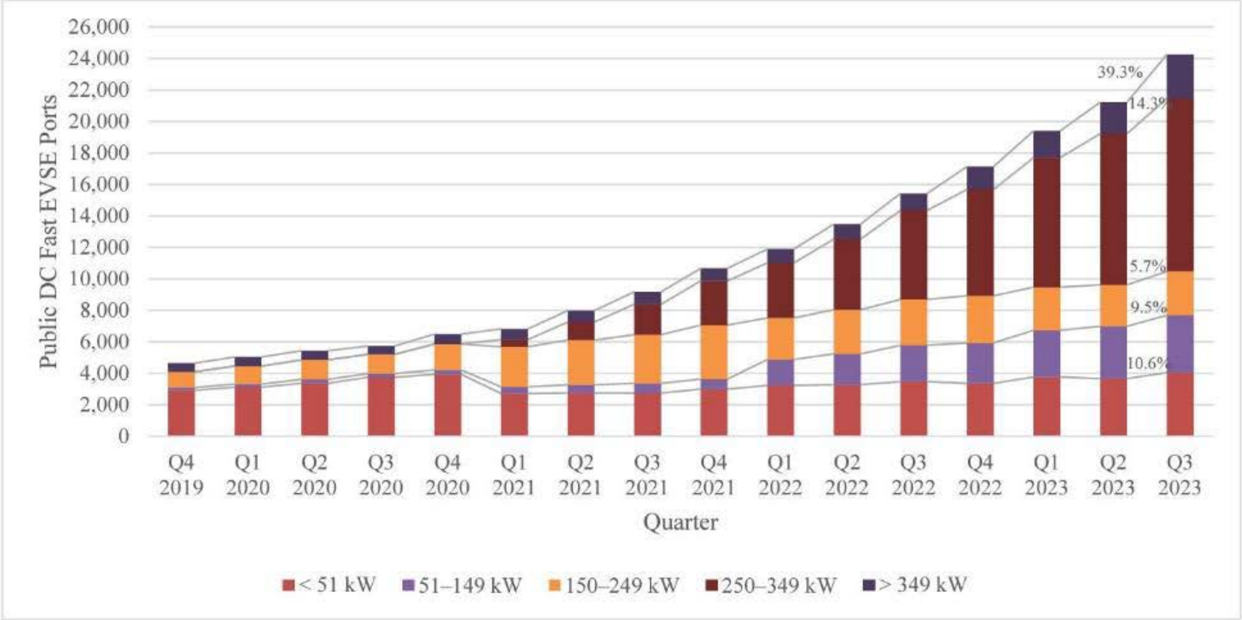


Figure 28. Quarterly growth of public DC fast EVSE ports by power output.

Source: Brown et al. 2023c

Attention to improving the reliability of EV charging equipment technology, as well as investments to address uptime issues, has increased over the past few years. In 2021, Ford Motor Company launched its Charge Angels project to find and fix nonworking charging stations within its FordPass Charging Network (Martinez 2021). While Ford does not operate charging stations, its partners' networks include more than 12,000 charging stations (Ford Motor Company 2020). In 2022, the University of California, Berkeley, published "Reliability of Open Public Electric Vehicle Direct Current Fast Chargers" (Rempel et al. 2022), one of the first reports that brought attention to the station reliability issue. Subsequently, the Federal Highway Administration (FHWA) established a requirement for all EV charging stations funded with federal funds that each charging port must have an average annual uptime greater than 97%

(FHWA 2023b). To build on the foundation for charging reliability established by the minimum standards, the Joint Office of Energy and Transportation established the National Charging Experience Consortium to address EV charging challenges (Joint Office of Energy and Transportation 2023). Furthermore, to ensure more reliable public EV charging equipment, the EV Charger Reliability and Accessibility Accelerator Program was established to provide up to $100 million in federal funding to repair and replace existing but nonoperational EVSE (FHWA 2023a). Station reliability, including progress toward meeting 97% uptime requirements, will be elaborated on in upcoming NREL reports.

Station-vehicle compatibility or interoperability is also an area of focus. In 2015, 40% of all DCFC connectors were CHAdeMO, which declined to 26% in 2018 and to 18% in 2023 (AFDC 2023c). Conversely, in 2015, 7% of all DCFC connectors were CCS, which increased to 22% in 2018 and to 31% in 2023 (AFDC 2023e).

The NACS connector was originally developed by Tesla, and until recently, only Tesla vehicles could charge with its proprietary connector. However, in November 2022, Tesla announced that it would open their EV connector design (Tesla 2022) for use among non-Tesla EVs. FHWA's National Electric Vehicle Infrastructure Standards and Requirements Final Rule establishes a requirement that to receive federal funding, each DCFC port must have a CCS Type 1 connector or a non-proprietary connector (FHWA 2023b). As such, to be eligible for funding, Tesla's NACS connector went through the rigorous standards development process and interoperability testing to become the SAE J3400 charging standard (Klein and Lommele 2023). An open or non-proprietary connector helps pave the way for PEVs to charge at the greatest number of charging stations and maintain a reliable and consistent baseline experience for all PEV drivers (Klein and Lommele 2023). Most vehicle manufacturers, including Ford Motor Company, General Motors, and Nissan, have announced adopting the NACS connector as early as 2025, which will allow non-Tesla EVs to charge at Tesla stations with the NACS connector Stafford 2024). Tesla DCFC connectors have historically made up the largest share of connectors, capturing approximately 50% of all DCFC connectors since 2015 (AFDC 2023b). Additionally, Tesla's charging network has much greater reliability than non-Tesla public charging stations (Blanco 2023).

Diversification of charging options is another emerging trend. Beyond the traditional plug-in chargers, other emerging technologies that may influence charging infrastructure trends include advances in wireless (static and dynamic) and overhead charging. Wireless inductive charging uses floor-mounted receiver pads that are charged wirelessly through a transmitter embedded into the ground (DOT 2023). Static wireless charging would occur at a stationary location, while dynamic wireless charging could happen while a vehicle drives, with cables buried in the roadway. On-route inductive charging stations extend the range of in-service buses. Overhead conductive (pantograph) charging requires a connection between the charger and the onboard battery through a pantograph apparatus or overhead wires (DOT 2023). Similarly, this allows in-service electric buses to charge through the pantograph charging system while stationary for short periods of time. In-motion charging utilizes overhead catenary wires, allowing the bus to charge at low power while moving along the bus route, providing a cost-effective way to extend the bus range while utilizing a smaller battery (DOT 2023). Both inductive and conductive charging require high capital and construction costs (Lepre, Burget, and McKenzie 2022).

Inverted pantograph dispensers mounted on overhead structures can help fleets streamline their operations as the pantograph initiates or ends the charging session without an operator having to plug or unplug a charger, which is particularly useful as fleets scale up deployments (Lepre, Burget, and McKenzie 2022). Recently, a few transit agencies in the United States began efforts to pilot overhead charging systems for their bus operations. In 2022, San Diego Metropolitan Transit System began construction on an overhead charging system, which was the first of its kind to be installed in North America (Wanek-Libman 2022). In 2023, the Metropolitan Transportation Authority in New York started construction on a total of 67 overhead and cabled dispensers across five locations to prepare for new electric buses expected to arrive starting in 2024 (Governor's Press Office 2023).

Research institutions, government, and industry are still investigating the requirements and feasibility of these emerging charging technologies. One effort to support the development of these technologies is DOE's Electric Vehicles at Scale (EVs@Scale) Lab Consortium. The consortium is conducting research to optimize charging to meet consumer demands, integrate EV charging networks with the grid, advance and validate wireless charging technologies, and enable charging options for PEVs while defending internet-connected EV charging equipment against cyberattacks (VTO 2023a). For example, the consortium is exploring high-power dynamic wireless power transfer technologies to enable PEVs to be charged as they are driven at highway speeds (VTO 2023a).

4.2.1.1 PEV Battery Considerations for EV Charging Equipment

While this report does not investigate battery technology in detail, it is important to briefly discuss some of the relationships between battery technology and EV charging equipment. The charging speed is affected by many factors, including the EVSE charger manufacturer, condition, and age; air temperature; vehicle age and condition; and vehicle battery-pack and on-board charging equipment (DOT 2023). Even if DCFC can provide 350 kW, a PEV's maximum charging capacity will be the limiting factor in how much power it can actually accept (DOT 2023). Another variable impacting how fast a PEV battery charges is the battery size. Even if two PEVs can accept the same power flow, that does not mean they will have the same charging time (Tucker 2023). In addition to its size, the battery itself has a significant impact on charge rates—its chemistry, materials, layout, temperature (including battery conditioning), and other battery technology elements are all contributing variables. Manufacturers are continuously changing and improving these variables to meet consumer needs for cost and performance. Battery advancements increase the charging speed and decrease the charging time. As of 2023, the most impressive charging speeds belong to the Lucid Air, Kia EV6, Hyundai Ioniq 5 and 6, and Genesis Electrified GV70 and GV60, all of which can charge at 350 kW (Moore 2023).

Declining battery prices are making an increasing array of medium- and heavy-duty vehicles cost-effective, in addition to benefitting light-duty vehicles. The cost of a PEV lithium-ion battery pack declined 89% between 2008 and 2022 (VTO 2023b). As battery costs scale with size, PEVs in general are becoming cost-competitive over life cycle costs in vehicles with small batteries first and large batteries later (Slowik and Lutsey 2017; Wolfram and Lutsey 2016; Desai, Hittinger, and Williams 2022). A study from Argonne National Laboratory finds that a light-duty HEV is the vehicle powertrain with the lowest total cost of ownership over a 15-year span, and a light-duty BEV with the highest all-electric range in the study with 300 miles has the highest total cost of ownership (Burnham et al. 2021). The comparatively high costs for a BEV with 300-mile range comes from assumed higher battery costs. Across all powertrains, the total cost of ownership depends on the size of the vehicle, as larger vehicles tend to be more expensive and less fuel-efficient (Burnham et al. 2021). Upcoming NREL reports will explore medium- and heavy-duty ZEV trends and their relationships with charging and fueling infrastructure.

4.2.2 EVSE Development Trends

In a 2021 Executive Order, the Biden administration set goals to have PEVs make up at least 50% of new vehicle sales by 2030 (The White House 2021a). Recent years have seen rising commitments from OEMs to the EV transition, with most companies focusing investment in research, development, equipment, and production plants for vehicle electrification (Bloomberg New Energy Finance 2022). In 2020, none of these automakers had formally announced an internal combustion engine phase-out pledge; within a few years, more than a dozen automotive brands announced internal combustion engine phase-out targets committing to become ZEV-only manufacturers, ranging from 2030 to 2040, depending on the automaker (Bloomberg New Energy Finance 2022).

Using NREL's Transportation Energy & Mobility Pathway Options (TEMPO™) model, and consistent with multiple 2030 scenarios from third parties, NREL estimates that 30–42 million PEVs will be on the road by 2030 (Wood et al. 2023); NREL also prepared an assessment of the charging infrastructure needed to support the millions of PEVs on the road by this time frame. *The 2030 National Charging Network: Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure* report projects that a national network in 2030 could be composed of 26–35 million ports to support 30–42 million EVs. Specifically, the United States would require 26.8 million private AC Level 1 and AC Level 2 charging ports at single-family homes, multifamily properties, and workplaces; 182,000 public DCFC ports along highway corridors and in local communities; and 1 million public Level 2 charging ports near homes and workplaces (including in high-density neighborhoods, at office buildings, and at retail outlets) to support a scenario of 33 million PEVs (Wood et al. 2023). Based on this analysis, the number of public DCFC and AC Level 2 EVSE ports currently available is 7.0% and 10.4%, respectively, of the way toward meeting projected 2030 requirements (Brown et al. 2023a).

Based on AFDC Station Locator data, there are approximately 64,000 public and private electric charging stations and more than 176,000 charging ports across the United States (AFDC 2021a). The number of charging ports has grown consistently, and the number of EV charging station locations has also increased steadily, as shown in Figure 29. Between 2019 and 2023, the number of charging ports more than doubled. The annual growth rate in ports has averaged 25% for the past decade. Figure 29 also shows that the ports per station grew steadily from 2.5 to nearly 3.5 between 2014 and 2020, and then dropped back to 2.5 as there was a surge in new, smaller charging stations brought online in 2021.

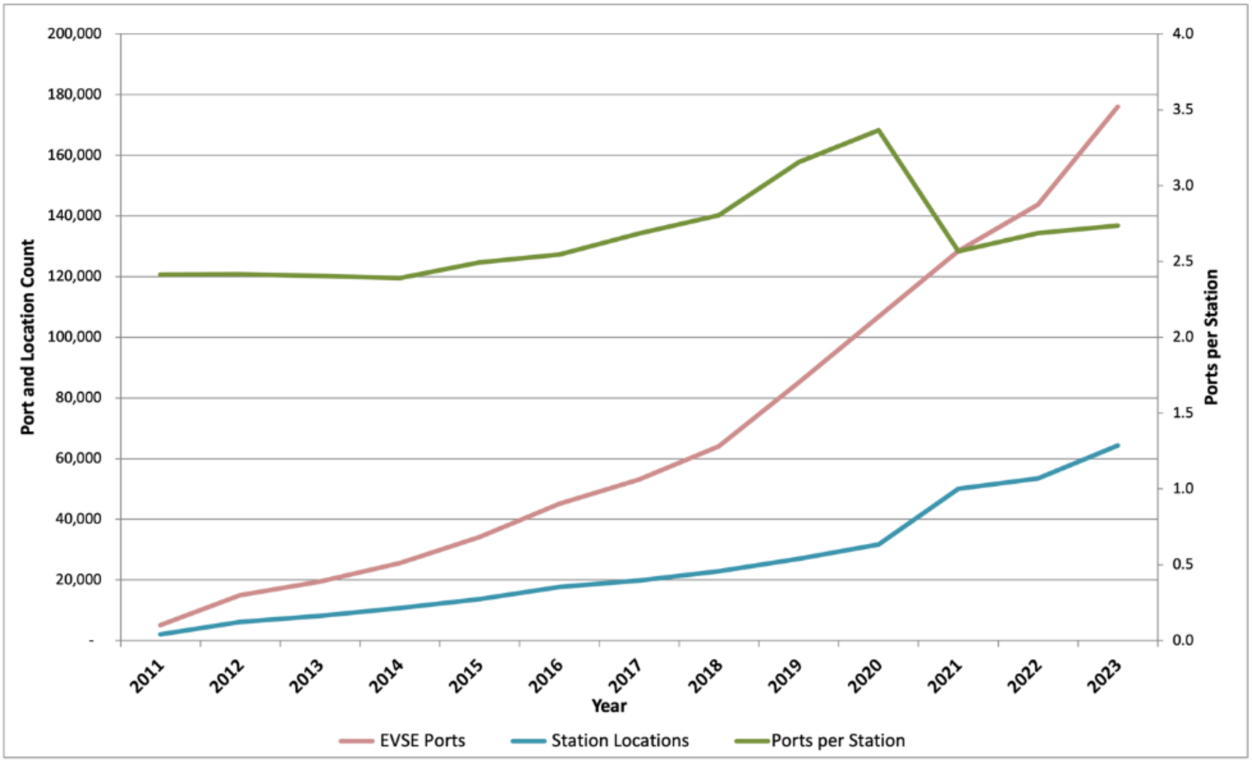


Figure 29. U.S. public and private EV charging infrastructure.

Data Source: AFDC Station Locator

Home is likely the most convenient and cost-effective charging location (for those with access) (Wood et al. 2023). As such, NREL's assessment maximizes the use of residential charging as a first priority, and Level 2 EVSE will be an effective solution in communities when colocated with activities with sufficiently long dwells (typically workplaces). Finally, DCFC will meet the needs of drivers that do not have access to home charging and do not exhibit dwell time compatible with Level 2 charging speeds (such as long-distance road trips) (Wood et al. 2023).

While the current foundation of U.S. charging infrastructure relies on residential charging, it is uncertain how effectively home charging can meet charging needs as the country transitions to an electrified light-duty fleet. In a 100% light-duty vehicle electrification scenario, analysis from NREL estimates that at least 25% of individuals will not have access to residential charging (Ge et al. 2021). This highlights an equity issue to address by improving charging access as the market expands beyond early adopters to mainstream consumers (Ge et al. 2021). An emerging deployment strategy in communities throughout the country is using utility poles and streetlights to mount chargers to provide convenient and reliable charging (Werthmann and Kothari 2021). Charging infrastructure solutions for households without consistent access to overnight home charging may include workplace charging, public right-of-way charging (such as a highway, street, alley, or sidewalk), curbside charging, or streetlight charging (Clean Cities Coalition Network 2023).

Funding from federal programs will support deployment of public EV charging infrastructure along designated AFCs and in communities, expanding light-duty EV charging access in rural and historically underserved communities. Equitable EV charging is another EVSE development trend. Since 2021, federal funding to deploy EV charging equipment focuses on filling gaps to facilitate access, with a particular focus on underserved and disadvantaged communities (Chu et al. 2023). Federal investments support the Justice40 Initiative, which directs 40% of the overall benefits of federal investments to disadvantaged communities (The White House 2023b). A priority consideration for public EVSE development is planning, siting, and operating chargers to help remedy historical inequities of benefits and burdens from the transportation and energy systems for underserved communities (Zhou et al. 2022). Engaging communities and incorporating input from underserved communities throughout the entire process is essential to ensuring that EV chargers placed in disadvantaged communities benefit residents. National laboratories, the Joint Office of Energy and Transportation, and the White House Council on Environmental Quality, among others, provide several tools, resources, and guiding principles to help states and communities installing EV charging equipment maximize the benefits for underserved communities.

Another driver of EVSE development trends is PEV adoption. In conversations with ChargePoint, NREL learned that a current trend for investment is for charging networks to install EVSE where there is high PEV adoption or where demographics indicate there is likely to be future PEV adoption. Along these lines, the national network is expected to vary dramatically by community (Wood et al. 2023). Densely populated areas will require significant investments to support those without residential access, while more rural areas are expected to require DCFC along highways to support travelers from urban areas passing through on long-distance travel (Wood et al. 2023).

With $7.5 billion in federal investment to install EV charging and alternative vehicle fueling infrastructure in communities and along designated AFCs, it is likely that these sites will drive infrastructure development trends for years to come. However, continued investments in U.S. charging infrastructure are necessary to build out a national network of EV chargers. To support a mid-adoption scenario of 33 million PEVs on the road by 2030, it is estimated that a $31–$55-billion cumulative capital investment in publicly accessible charging infrastructure is needed (Wood et al. 2023). As of March 2023, NREL estimates that $23.7 billion of capital has been announced for publicly accessible light-duty EV charging infrastructure through the end of the decade, including from private firms, the public sector (including federal, state, and local governments), and electric utilities (Wood et al. 2023).

Federal and state requirements for deployment of medium- and heavy-duty vehicles are expected to drive charging infrastructure investments to support their electrification. In recent years, requirements were set for federal agencies to acquire 100% medium- and heavy-duty ZEVs by 2035, and numerous states set requirements for medium- and heavy-duty vehicles sold to be ZEVs by 2045 or 2050 (The White House 2021b; DOE 2023b; AFDC 2023f). With these goals, the national stock of medium- and heavy-duty ZEVs could reach 41% by 2050 (Ledna et al. 2022). For the most part, medium- and heavy-duty PEVs will be charged at private fleet facilities with return-to-base operations. However, with funding from the BIL and private sector investments, movement is expected concerning alternative fueling infrastructure build-out for on-route heavy-duty vehicles. Such projections will be explored in upcoming NREL reports.

Under the federal National Electric Vehicle Infrastructure Program, states are encouraged to future-proof charging station designs and power levels to support medium- and heavy-duty EV charging (FHWA 2023a). To accommodate medium- and heavy-duty vehicles, charging stations must allocate a larger space for vehicles. Portland General Electric and Daimler Trucks North America have pioneered one of the first public EV charging stations able to accommodate Class 8 trucks (Ligouri and Ey 2021). The station, in Portland, Oregon, is designed to have a "drive-thru" format and offers up to 5 MW of capacity and eight vehicle charging stations. Press materials state that the station was designed to be able to adapt to future charger equipment upgrades, including megawatt-plus charging capabilities (Lambert 2021; Ligouri and Ey 2021).

Daimler Trucks announced a joint venture with NextEra Energy Resources LLC and BlackRock Renewable Power to design, develop, install, and operate a nationwide U.S. charging network for medium- and heavy-duty electric and hydrogen fuel cell vehicles. The announcement went on to add that the planned infrastructure will begin build-out in 2023 and includes "a network of charging sites on critical freight routes along the east and west coasts and in Texas by 2026" (Daimler Truck 2022). As another example, Volvo Group and Pilot Company announced intent to support public charging for medium- and heavy-duty PEVs at select Pilot and Flying J travel centers across the United States (Volvo Group 2022). However, these investments will require power grid restructuring and collaboration between fleets, the utility sector, and fuel retailers. As PEVs are one of the largest sources of new load, minimizing the impacts of vehicles on the grid through effective vehicle-grid integration will be essential (Office of Energy Efficiency & Renewable Energy 2023).

4.3 Hydrogen Fueling Infrastructure

The U.S. market for hydrogen as a transportation fuel is in its infancy and in localized regions, although government and industry are working toward more widespread use. As of 2023, less than 18,000 light-duty FCEVs have been sold or leased in California, and by extension, the United States (Hydrogen Fuel Cell Partnership 2023; AFDC 2022i). California is leading the nation in building hydrogen fueling stations for light- and heavy-duty FCEVs. As of 2023, nearly all hydrogen stations open to the public in the United States were in California, with one public station in Hawaii (AFDC 2023e). California invests in light- and heavy-duty public hydrogen fueling infrastructure through its Clean Transportation Program, and has set a goal of 200 hydrogen fueling stations by 2025 (AFDC 2023l). As of mid-2023, California has 65 light-duty retail fueling stations and 6 heavy-duty fueling stations operational, with 35 planned light-duty stations and 9 heavy-duty-capable planned stations (California Energy Commission 2023). In the past decade, the hydrogen fueling station growth rate has been variable, but the past few years it has been consistently positive (Figure 30). According to AFDC Station Locator data, nearly all hydrogen fueling stations in the United States are public, retail fueling stations (AFDC 2023e).

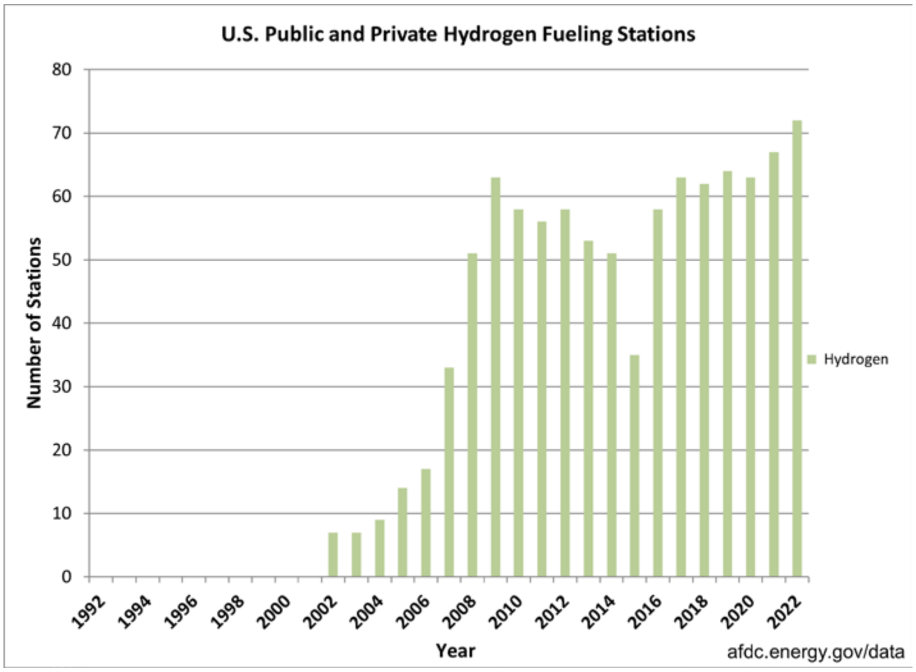


Figure 30. U.S. public and private hydrogen fueling stations as of 2022.

Data Source: AFDC Alternative Fueling Station Locator

While infrastructure development is not even throughout the United States, efforts are also underway to expand public hydrogen fueling locations in Hawaii and across the East Coast, with other markets expected to develop as consumer demand increases (AFDC 2023i). Additionally, states throughout the country are coordinating to build out a continuous public hydrogen fueling infrastructure at strategic locations along major national highways through the FHWA AFC program. FHWA-designated hydrogen-pending corridor networks are shown in Figure 31. Private hydrogen fueling stations—those used by government, commercial, or other fleets—may also be available in states throughout the country. In particular, with funding from the Federal Transit Administration's Low or No Emission Grant Program for the purchase or lease of zero- and low-emission transit buses and acquisition, construction, and leasing of required supporting facilities, the number and network of private hydrogen fueling stations will likely expand.

Figure 31. FHWA hydrogen corridors as of Oct. 10, 2023.

Source: FHWA 2023b

Solid line: corridor ready; dashed line: corridor pending.

Hydrogen and fuel cells offer significant near-term opportunities for applications requiring long driving ranges, fast fueling, and large or heavy payloads (Hunter et al. 2021). Large, long-range vehicles such as buses and trucks can be decarbonized through hydrogen, and transitioning trucks to zero-emission technology can significantly reduce greenhouse gas emissions in the transportation sector. With California's ZEV mandate to transition public transit agencies to 100% zero-emission bus fleets by 2040 and all medium- and heavy-duty vehicles sold to be zero-emission by 2045, installation of hydrogen fueling infrastructure is essential for enabling deployment (CARB 2023c). California transit agencies are transitioning some vehicles to hydrogen and are installing fueling infrastructure to support these vehicles. However, electric buses are currently growing faster than FCEVs, with nearly 600 electric buses in operation, compared to the approximately 100 hydrogen fuel cell buses that are in operation in California transit agency fleets (CARB 2023b).

As fleet size increases, hydrogen may become a more viable fuel than electricity for these transit agencies and others outside of California. However, industry feedback reveals that to be cost-competitive, the total cost to the end user, including infrastructure, must reach about $5/kg (DOE 2023b). Operational data from California show that delivered cost of hydrogen to fueling stations, including compressing and dispensing, can be more than $13/kg (DOE 2023b). Reducing the produced and delivered cost of clean hydrogen will help expand the market beyond early adoption.

Hydrogen also has a strong value proposition in the trucking sector, particularly for fleets with heavy-duty vehicles, long-distance (>500-mile) routes, or multi-shift operations that require rapid fueling (DOE 2023b). Unlike the public consumer stations for FCEVs that need multiple locations to cover wherever the consumer may travel, private fleet fueling stations require fewer locations or even just a central location to meet a specific fleet's needs. Investing in clusters of dedicated infrastructure for these fleet applications can reduce the risk of stranded assets and ensure the utilization of the developing hydrogen fueling infrastructure (DOE 2023b). While there is much discussion about FCEVs in heavy-duty trucking, there has been limited infrastructure deployed to date to support these heavy-duty vehicles. The rollout of heavy-duty hydrogen trucks, such as line-haul trucks, will necessitate very large stations compared to light-duty needs. As part of DOE's H2@Scale initiative, industry stakeholders and national laboratory researchers are working to advance hydrogen fueling infrastructure (Hydrogen and Fuel Cell Technologies Office 2023).

Another opportunity for early market adoption for hydrogen is material handling equipment. In particular, hydrogen fuel cell electric forklifts are increasingly being used throughout the country, with more than 60,000 in operation in the United States (DOE 2023b). These applications can be competitive at higher hydrogen fuel costs due to faster fueling times, higher operational throughput, and less space required compared to electric forklifts (DOE 2023b).

A strategy to develop the nascent hydrogen market is to simultaneously develop hydrogen-related industries. The BIL-established Regional Clean Hydrogen Hubs Program (H2Hubs) allocates up to $8 billion to develop regional clean hydrogen hubs across America (Congress.gov 2021). H2Hubs will kickstart a national network of clean hydrogen producers, consumers, and connective infrastructure while supporting the production, storage, delivery, and end use of clean hydrogen (DOE 2023a). In 2023, seven H2Hubs were selected to accelerate the commercial-scale deployment of low-cost clean hydrogen (DOE 2023a). The H2Hubs selected include Appalachian, California, Gulf Coast, Heartland, Mid-Atlantic, Midwest, and Pacific Northwest Hydrogen Hubs, and each hub is associated with specific aims, such as green production or decarbonizing certain sectors (DOE 2023a). As the current national leader in hydrogen fueling for transportation, the California Hydrogen Hub in particular aims to provide a blueprint for decarbonizing public transportation, heavy-duty trucking, and port operations (DOE 2023a). H2Hubs will enable infrastructure development, drive scale, and facilitate market liftoff (DOE 2023b).

The increase in production and distribution of hydrogen for fueling stations could improve efficiency and utilization of expensive capital equipment, leading to lower fuel costs per kilogram, benefiting both heavy- and light-duty customers. This includes existing refining and ammonia production plants. Hydrogen applications in the first deployment wave will be jump-started by markets with access to hydrogen and compatible end uses (DOE 2023b). Industrial clusters that collocate large-scale production with end use for such applications can help drive down costs and create the infrastructure that could be leveraged for other markets in subsequent phases.

4.4 Natural Gas Fueling Infrastructure

CNG and LNG fueling stations vary considerably. CNG stations require more equipment and configuration, while LNG stations require less equipment but more safety precautions during fueling (AFDC 2022f). The three types of CNG stations are based on the way natural gas is dispensed: fast fill, time fill, and a combination of the two. The type of CNG station needed depends on the application (AFDC 2022f). Typically, public fueling stations offer fast fill, and fleets that have central fueling and the ability to fill overnight use time fill, taking advantage of smaller, less expensive compression equipment. LNG stations operate like gasoline and diesel stations because they deliver liquid fuel to the station via tanker trucks. LNG dispensers deliver fuel to vehicles at pressures of 30 to 120 psi. Because LNG is stored and dispensed as a supercooled liquefied gas, protective clothing, face shields, and gloves are required when fueling a vehicle, and personnel must also be trained on fueling procedures (AFDC 2022f).

Three options exist for LNG fueling: mobile, containerized, and permanent large stations. In mobile fueling, LNG is delivered by a tanker truck that has onboard metering and dispensing equipment. A containerized station, or starter station, includes a storage tank, dispensing equipment, metering, and required containment. A permanent station has greater storage capacity and is tailored to meet fleets' needs (AFDC 2022f).

Based on AFDC Station Locator data, there are approximately 800 public natural gas stations across the United States, including approximately 750 offering CNG and 50 offering LNG (AFDC 2023e). Private CNG and LNG fueling stations expand the natural gas fueling network with more than 600 private CNG and nearly 50 private LNG stations throughout the country (AFDC 2023e). The growth rate of natural gas fueling stations has slowed in recent years, as shown in Figure 32. The decline in natural gas fueling infrastructure in recent years is attributed, in part, to declines in gasoline prices. However, other market drivers, including more stringent emissions regulations, may lead to a growth in natural gas bus and truck fleet adoption. Compared to conventionally fueled vehicles, natural gas vehicles can produce lower amounts of some harmful air pollutants and greenhouse gas emissions, depending on vehicle type, drive cycle, and engine calibration (Cai et al. 2015). Fueling vehicles with renewable natural gas offers additional emissions benefits. Specifically, renewable natural gas qualifies as a renewable fuel under the federal Renewable Fuel Standard and provides at least a 60% life cycle greenhouse gas reduction (EPA 2023a).

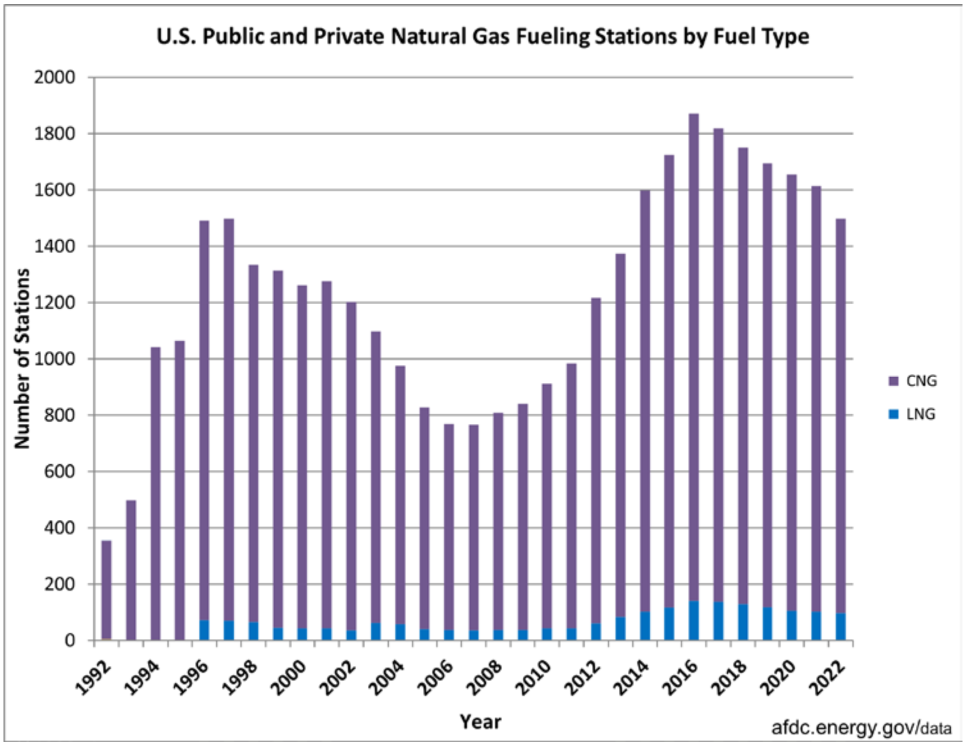


Figure 32. U.S. public and private natural gas fueling stations by fuel type.

Data Source: AFDC Station Locator

The build-out of the public natural gas fueling network is concentrated along highways and interstates. States throughout the country are coordinating to build out a continuous public natural gas fueling infrastructure at strategic locations along major national highways through the

FHWA's AFC program. FHWA-designated CNG corridor networks and LNG corridor networks are shown Figure 33 and Figure 34, respectively (FHWA 2023b). Private natural gas fueling stations at depots—those used by government, commercial, or other fleets—will also contribute to the development of natural gas fueling stations in the United States.

Figure 33. FHWA CNG corridors as of Oct. 10, 2023.

Source: FHWA 2023b.

Solid line: corridor ready; dashed line: corridor pending.

Figure 34. FHWA LNG corridors as of Oct. 10, 2023.

Source: FHWA 2023b.

Solid line: corridor ready; dashed line: corridor pending.

5 Alternative Fueling Infrastructure Growth Scenarios

NREL has developed multiple scenarios of how alternative fueling infrastructure could grow into the future. They are all exploratory, but valuable lessons can be learned by assessing the relationships between refueling infrastructure and vehicles that are fundamental in these scenarios and by analyzing two of NREL's analytical tools that develop such scenarios.

5.1 Relationship Between Refueling Infrastructure and Vehicles

Before exploring the models and AFV projections, it is important to define general aspects of the relationships between refueling infrastructure and vehicles. This relationship differs greatly depending on fuel type.

5.1.1 PEVs

Refueling a PEV deviates from gasoline, CNG, and hydrogen vehicles in a few fundamental ways.

Unlike other fuels, PEVs can ***refuel at home or work***. In fact, 50%–80% of charging events occur at home, 15%–25% at work, and less than 10% at public stations (Hardman et al. 2018). This creates a unique dynamic in which public stations are needed at more locations to provide coverage to compensate for a PEV's reduced range, yet that reduced range does not necessarily translate into increased demand for public stations.

The ***range of the average BEV*** on the road (sales weighted) in 2022 was 291 miles (Randall 2023), which was only 71% of the 412-mile median distance of gasoline light-duty vehicles available for sale in 2016 (VTO 2016). This means that along highways and rural areas, EVSE must be installed with shorter gaps between them (as compared to other fuels) so that BEVs can complete long road trips. The shorter range of BEVs also leads to "range anxiety," which can be reduced when EVSE are numerous, well placed, and highly visible. This is one mechanism by which EVSE infrastructure build-out increases PEV purchases. On average in the United States, each additional charging station per population of 100,000 has led to (3 months later) a 7.2% increase of BEVs purchased and 2.6% increase of PHEVs purchased (Narassimhan and Johnson 2018). Causality was inferred by staggering the data and looking for a change in the relationship, which was strongest when vehicle sales were delayed one quarter after infrastructure data. However, it is uncertain how this trend applies to market subsets (such as demographics or vehicle type) and how it will evolve in future years as PEV adoption moves past its nascent stages.

Currently, it takes longer to charge a PEV than to refuel a gasoline vehicle. At the time of this report, the fastest that most PEVs on the road today can charge is less than 250 kW (per Figure 35), although an increasing number can charge faster. At that charging power, when adjusted for battery management, it takes a Tesla sedan 15 minutes to add 200 miles of range (Tesla 2024). Gasoline, conversely, flows through a dispenser at up to 10 gallons per minute (EPA 1996). Therefore, a car with an average fuel economy of 24.1 mpg could gain that same 200-mile range in 1.2 minutes.

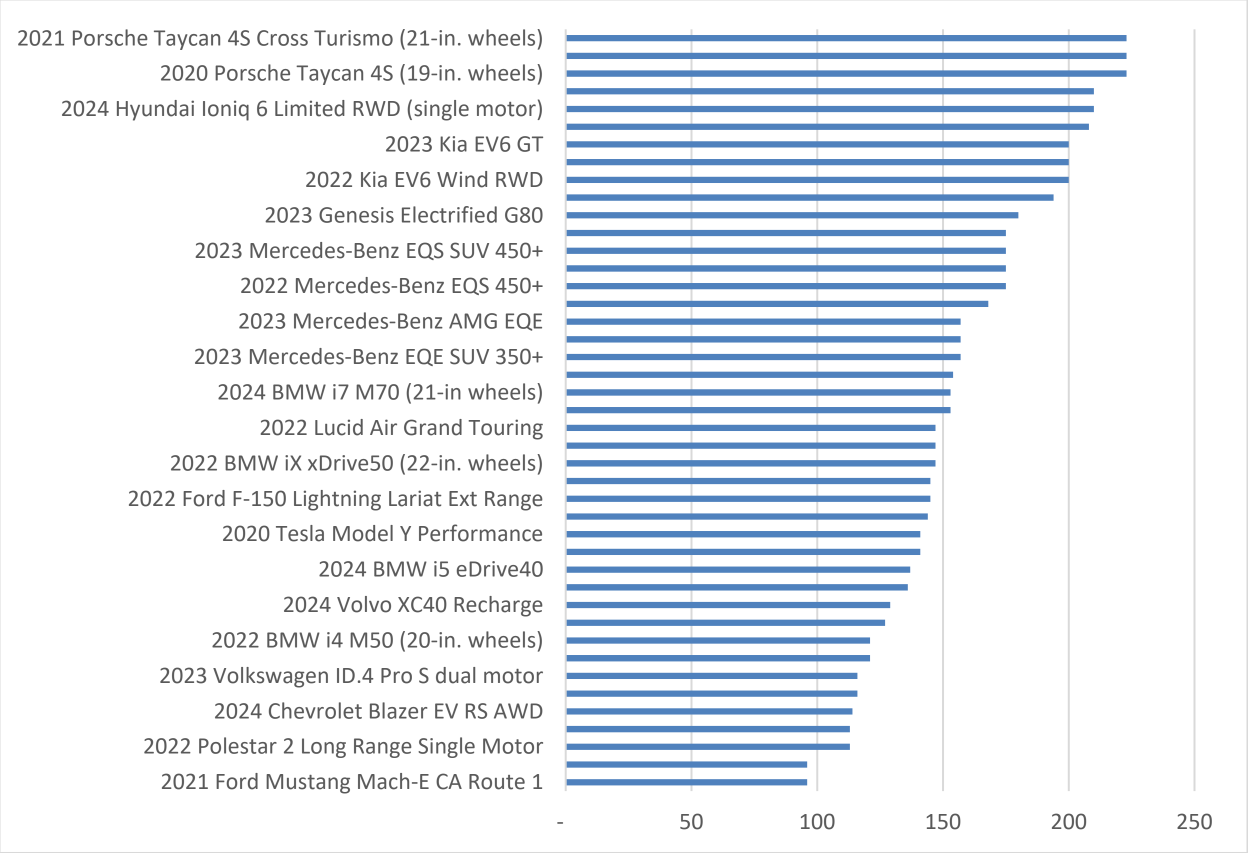


Figure 35. Edmunds Tested Average Charging Power (kW from 10-80% state of charge).

Data Source: Elfalan 2024.

PEV stock is growing faster, in percentage terms, than any other fuel category. This means that they will require the most infrastructure build-out into the foreseeable future—a need addressed in part by the BIL. PEVs are majority-owned by independent drivers—their ratio of EIA-reported fleet EVs compared to IHS Markit's Vehicles in Operation database was 3:100 in 2017 (EIA 2019b; S&P Global Mobility 2024).[2] The capability for using gasoline changes the relationship between driver and refueling infrastructure in important ways that is discussed in the model-specific sections below.

5.1.2 Natural Gas Vehicles

Natural gas vehicles are operated as part of a **fleet** more often than conventional fuels, EVs, or hydrogen. Approximately 15% of the 175,000 natural gas vehicles in operation in the United States have been reported as part of a federal agency, state agency, transit agency, or fuel-providing company, including electric and natural gas utilities (NGVAmerica 2022). These reported fleets do not include refuse collection companies or school districts, which have many natural gas vehicles and would surely raise the percentage of fleet vehicles. Furthermore,

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[2] EIA's fleet vehicle counts include heavy-duty and light-duty vehicles in federal agencies, state agencies, transit agencies, and fuel-providing companies, including electric and natural gas utilities. Polk numbers include light-duty vehicle registrations. Therefore, the ratio of fleet vehicles to registrations should not be taken as a direct "percentage of total."

because fleet vehicles tend to drive more miles and refuel more often, an even greater percentage of refueling events are performed by fleet vehicles. Fleets tend to have more predictable drive cycles and are more likely to influence (through investments or fuel purchase contracts) the number, location, and size of refueling stations in their proximity. Therefore, fleets can make refueling convenient regardless of the total number of refueling stations.

Despite the large number of fleet natural gas vehicles, there are still many independent natural gas vehicles. Some of these are dual-fuel that can also use conventional fuels much like their electric PHEV counterparts. Natural gas can be dispensed as either LNG or CNG. Because LNG stations are much rarer and used largely by long-haul trucks, the remainder of this report focuses on CNG.

CNG fueling speed depends largely on station type. Time-fill stations are used almost entirely at fleet parking lots and garages or homes. In this way, they are similar to home or depot chargers for electricity. All public CNG stations have a “fast-fill” option, meaning that they have storage tanks and can therefore fill a vehicle faster than the compressors can compress the CNG. Fast-fill stations dispense CNG at similar rates as gasoline—less than 5 minutes to fill a 20-GGE tank. However, these stations are more expensive than time fill and might not be able to fill vehicles back-to-back without taking time to replenish their storage tanks between vehicles. There are 844 public CNG stations and 688 private CNG stations in the United States (AFDC 2023a).

5.1.3 Hydrogen FCEVs

In total, as of February 2024, there have been 18,102 light-duty FCEVs sold or leased in the United States since 2014, and 48 FCEV buses are in operation (Argonne National Laboratory 2024; Hydrogen Fuel Cell Partnership 2023). Hydrogen infrastructure has an outsized impact on fuel cell vehicle adoption because the vehicles are only sold or leased in select areas with hydrogen refueling infrastructure. Ninety-eight percent of light-duty FCEVs are registered in California, where 47 of the nation’s 48 publicly available hydrogen stations are located (AFDC 2023a). The remaining public station is in Hawaii, with 19 private stations in Arizona, California, Colorado, Connecticut, Delaware, Hawaii, Massachusetts, Michigan, New York, Ohio, Virginia, and Washington. Hydrogen fuel is not as readily available as electricity, natural gas, and petroleum. For most stations in California, hydrogen is produced off-site and trucked to the fueling station, creating a constraint on the locations where a hydrogen refueling station can be operated.

Hydrogen has a refuel time similar to gasoline, with an average light-duty vehicle fueling time of less than 4 minutes (AFDC 2024d). However, the high pressures and small molecular size of hydrogen require expensive, well-maintained equipment to avoid leakage.

5.2 Examples of Insights from NREL Analytical Tools

NREL has developed a portfolio of analytical tools and methods to explore various facets of the adoption of AFVs and related infrastructure. These integrated modeling and analysis tools are designed to overcome technical barriers and accelerate the development of advanced transportation technologies and systems that maximize energy savings and on-road performance. For a complete list of tools and information, visit: www.nrel.gov/transportation/data-tools.html.

In the following sections, we include some example results from ongoing research using some of these tools to highlight the kinds of results and insights that are being generated. These preliminary results are meant to portray what factors need to be considered when modeling vehicle adoption.

5.2.1 Example 1: ADOPT

Developed by NREL, the Automotive Deployment Options Projection Tool (ADOPT) is a light-duty vehicle consumer choice and stock model (NREL 2024a). ADOPT estimates vehicle technology improvement impacts on future U.S. light-duty vehicle sales, energy use, and emissions. Estimating sales requires modeling the most important factors and confirming its functionality with validation. ADOPT captures the key aspects required to estimate vehicle sales. It starts simulations with a realistic representation of vehicle options by starting with the more than 700 makes, models, and trim levels available. This ensures that even vehicles containing uncommon features in the baseline fleet are represented, which allows the model to recognize and adopt vehicle elements in future years that a less granular model utilizing composite or average feature sets may miss. It endogenously creates future options using the Future Automotive Systems Technology Simulator (FASTSim™), a fully integrated vehicle powertrain model. New options are created for the best-selling powertrain in each income bin. Their component sizes, such as the battery size for a BEV, are optimized for sales under the market conditions (fuel prices, incentives, and technology prices) of that year.

The process of model creation is repeated at different income levels to capture the different preferences by income (the value of performance and size increase with income) and the differences in the best-selling powertrain for that income (new BEV options so far are aimed at the luxury and sports vehicle market). During the historically simulated period, it results in endogenously created options that are similar to the best-selling BEV, the Tesla Model Y. In the projected simulated period, it matches historically increasing power (and acceleration) trends.

ADOPT also captures details of the CAFE and greenhouse gas standards, IRA purchase incentives, and regional market conditions. Simulations are generally run at a state level to accurately capture the combined influence of local fuel prices, electricity prices, incentives, and household income distributions. Sales are based on the most important attributes to the consumer including price, fuel cost, acceleration, size, and range. BEV sales have demonstrated the especially important attribute of acceleration with sales not taking off until quick-accelerating options came to market. Capturing these key modeling factors enables ADOPT to validate with historical vehicle option evolution and sales. Select visualizations of this historical validation are shown in Figure 36 and Figure 37; additional validation figures can be found in Figure A-1 through Figure A-4 of the appendix.. An example application can be found in Brooker et al. (2021). Many details on model functionality from an early version of the model can be found in Brooker et al. (2015). Over the course of its 20-year development, ADOPT has been used and funded by many entities including the Vehicle Technologies Office, Hydrogen and Fuel Cell Technologies Office, Bioenergy Technologies Office, California Energy Commission, Environmental Protection Agency, and Shell.

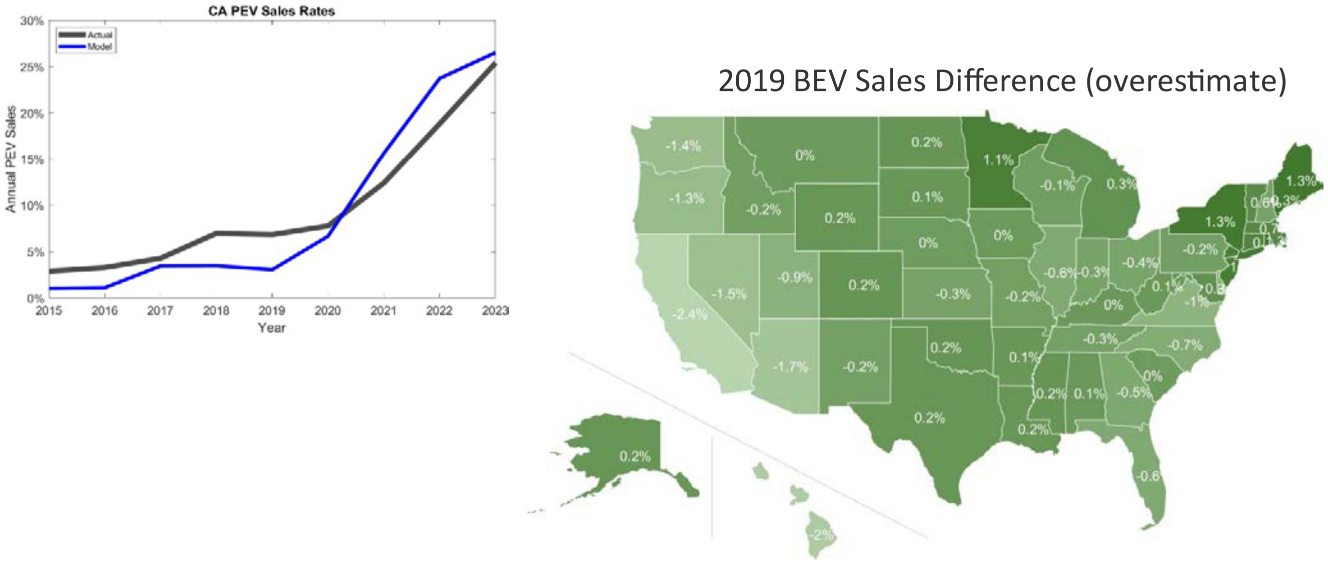

Figure 36. ADOPT validation of regional sales

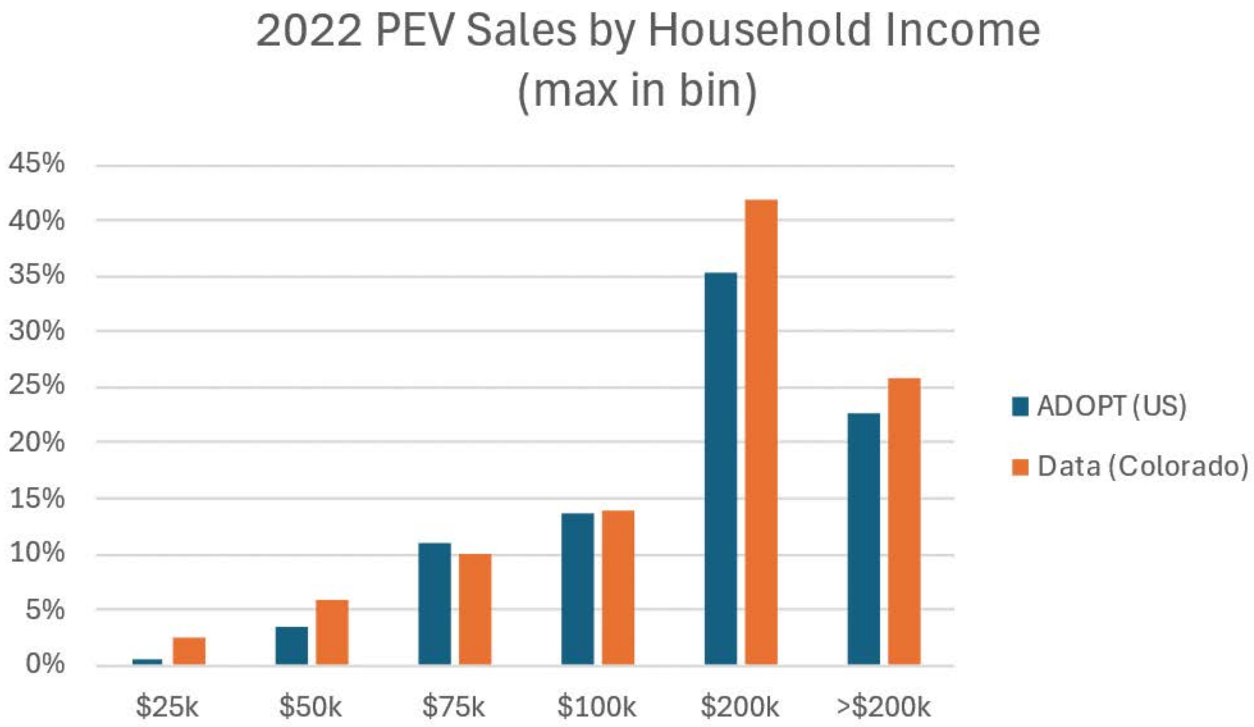

Figure 37. ADOPT validation of PEV sales by income

ADOPT includes two approaches for exploring the impact of public charging infrastructure on PEV adoption. Each approach is detailed in the following sections.

5.2.1.1 ADOPT Approach 1: Long-distance travel inconvenience penalty

In the first approach, a preference penalty is added to BEVs for their more inconvenient long-distance travel. The penalty goes to zero as BEV range, refueling time, and refueling infrastructure availability along long-distance corridors approach parity with that of gasoline vehicles. This approach is based on two assumptions.

The first assumption is that consumers will only purchase a BEV if they have charging near their dwelling that is similarly reliable, inexpensive, and convenient as home charging, such that long-distance travel is the only disadvantage. The case to choose a BEV is much stronger with home charging because it is reliably available, inexpensive, and convenient. Something resembling home charging could include chargers in garages close to home or workplace charging.

The second assumption this approach relies on is how BEV range has increased enough that only long-distance charging is needed. When BEVs first came to market, most had much shorter range than today. The best-selling option in 2011, the Nissan Leaf, had only 73 miles of range (Randall 2023). Based on travel distribution data from the 2017 National Household Travel Survey, shown in Figure 38, 73 miles would frequently not be enough for a traveler's daily driving. Since then, the average range of a new BEV model has increased to 305 miles for model year 2022 (EPA 2023d), enough for more than 98% of daily driving, mitigating the need for public charging outside of long-distance trips. These trends support the approach of only using a penalty for long-distance trips, which fades as the vehicles and long-distance infrastructure reach parity with conventional vehicles.

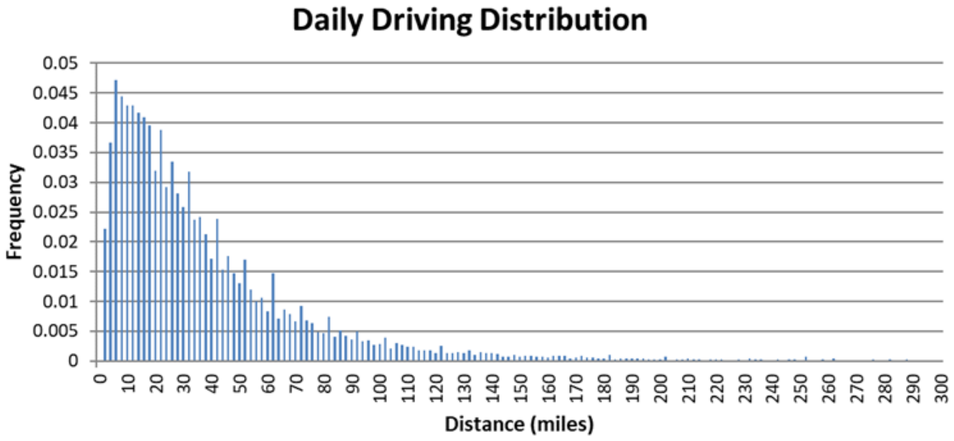

Figure 38. Distribution of daily driving

5.2.1.2 ADOPT Approach 2: Tangible value of public charging infrastructure

In the second approach, we integrated equations quantifying the tangible value of public charging infrastructure for PEV owners into ADOPT's consumer choice modeling framework. These equations are documented in Greene et al. (2020a, 2020b), and the process of integrating them into ADOPT is documented in Ledna et al. (2022). For BEV owners, willingness to pay a premium for public charging infrastructure (assumed to be public DCFC) is defined as the discounted value of travel enabled by public infrastructure, minus the time costs of accessing scarce infrastructure and time spent recharging. For PHEV owners, willingness to pay a premium for public charging infrastructure (assumed to be public Level 2) is defined as the discounted fuel cost savings from switching from gasoline to electric miles. Both quantities are discounted over the lifetime of the vehicle and considered at the point of vehicle purchase.

In ADOPT, these relationships are translated into penalties for insufficient public infrastructure for BEVs based on the extent to which the vehicle's ability to travel is limited by the public infrastructure network and the extent to which the time spent recharging exceeds the time required to refuel a conventional vehicle. Penalties for insufficient infrastructure diminish as vehicle range, infrastructure availability, and charging power and speed increase. For PHEVs, public Level 2 is translated into a monetary benefit for prospective buyers and assigned a value of 0 in the absence of a public Level 2 network. Infrastructure availability in ADOPT is expressed on a scale of 0% to 100% and corresponds to sufficient chargers available for a PEV fleet to enable charging without excessive queueing or additional time traveling to sparse stations. We use three metrics of infrastructure availability in ADOPT: public Level 2 availability (for PHEVs), intraregional public DCFC availability (for BEVs, defined as the chargers located within urban areas), and interregional public DCFC availability (also for BEVs, defined as the chargers available along rural and interregional highways).

Similar to approach 1, a key assumption of this framework is that all vehicles have access to overnight (home) or workplace charging infrastructure. Surveys on home charging availability in the United States suggest that under scenarios of widespread PEV adoption, a substantial fraction of drivers will be reliant solely on public or workplace charging (Traut et al. 2013). Research is currently underway to determine the value of public charging to consumers that do not have overnight charging, but this consumer segment is not considered in this analysis of the impact of public charging on PEV adoption.

5.2.1.3 Insights From Updated ADOPT

While forthcoming work will more fully document the relationships between vehicle adoption projected by ADOPT and infrastructure availability, some preliminary insights are discussed below from analysis using the second approach mentioned above for modeling the value of infrastructure. These insights may be contingent on other technology and policy assumptions and interactions in ADOPT scenarios, but generally emerge from the structure of the equations integrated from Greene et al. (2020). These include:

1. **High levels of access to public DCFC infrastructure incentivize BEV adoption.** This emerges from the theoretical framework quantifying consumer willingness to pay for public DCFC for BEVs, which accounts for the value of enabled travel minus the time costs of recharging and accessing public charging. Greene et al. (2020) estimate the present value of willingness to pay for fully available public DCFC to translate to around \$3,000–\$4,000 for a ~200-mile range BEV driving intraregionally in California, with values decreasing with vehicle range. The value of interregional (corridor) travel is an additional \$1,000 for a ~200-mile range BEV but increases substantially for shorter-range vehicles. In ADOPT, these "willingness to pay" values are translated into equations that estimate the monetary cost of travel limitations and charging speed, disadvantaging BEVs relative to other vehicles in scenarios that lack adequate infrastructure. General findings suggest a modest but consistent increase in BEV sales when comparing scenarios with high infrastructure access vs. low access.

2. **Increased infrastructure modestly incentivizes increased sales of lower-range BEVs.** BEVs with higher vehicle range rely less on public charging infrastructure to complete required travel, as reflected by the relationships between infrastructure, vehicle miles

traveled, and vehicle range calibrated in Greene et al. (2020). As a result, in ADOPT, we observed modest shifts toward sales of lower-range BEVs (below 200 miles in range) when more public charging infrastructure was available. Future research to explore the implications of these shifts for vehicle affordability should be considered.

3. **The value of public charging may be affected by the availability of other types of charging, which is a high priority for future work.** Estimates of the value of public charging infrastructure that are currently implemented in ADOPT assume that all vehicles have consistent and reliable access to private charging, whether at home or a workplace. However, it is expected that without access to home or workplace charging, the value of public charging to consumers will increase, particularly for BEV owners. Incorporating this consumer segmentation in infrastructure availability may substantially affect future scenarios modeling BEV and PHEV adoption and is a key priority for research.

5.2.1.4 CNG and Hydrogen in ADOPT

For CNG and hydrogen, ADOPT uses the stated preference results from Melaina, Bremson, and Solo (2012) to monetize the penalty of reduced refueling availability and adding that penalty to the purchase price of the vehicle. Fueling penalties are monetized at the local (urban area), on medium-distance trips (within 150 miles of an urban area), and on long-distance trips to other urban areas. Figure 39 shows the results of the stated preference survey at the urban area level in comparison to a clustering method for deriving the same cost penalties.

Key takeaways from the ADOPT model are combined and compared with those from the TEMPO model in Section 5.3 below.

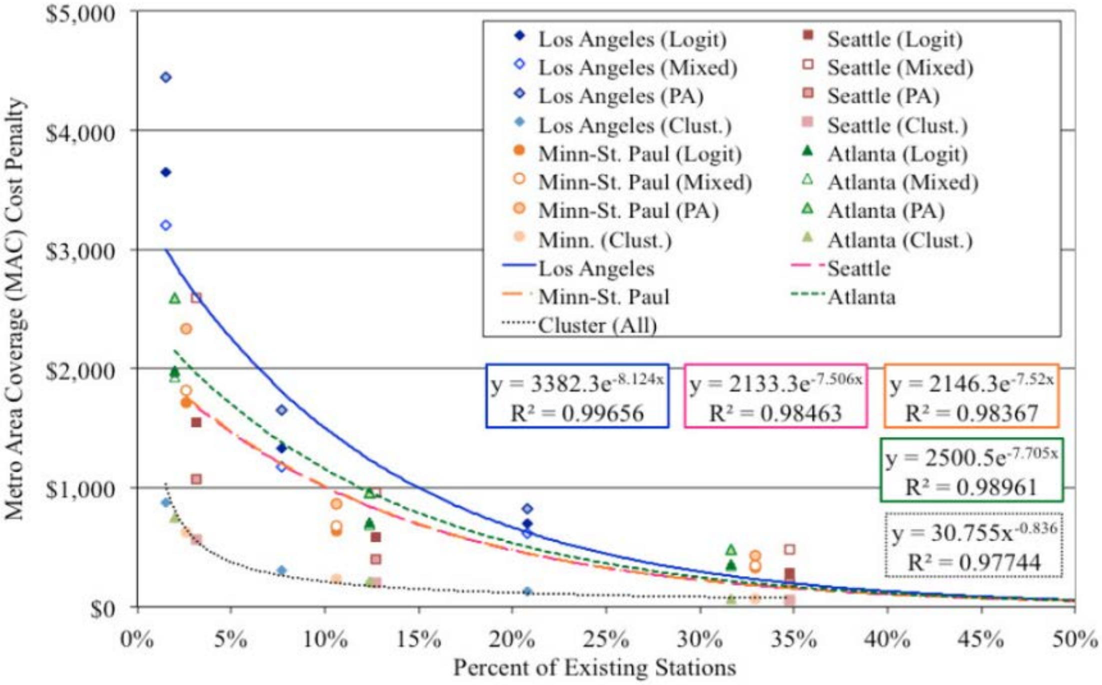

Figure 39. Cost penalties of reduced refueling availability at the urban level, as revealed by stated preference survey and compared to clustering algorithms.

Source: Melaina, Bremson, and Solo 2012

5.2.2 *Example 2: TEMPO*

The TEMPO model is an all-inclusive transportation demand model that covers all passenger and freight travel modes for the entire United States (NREL 2024b). TEMPO models the heterogeneity of travel decisions, including household-level activity-based travel demand, vehicle ownership, and mode/tech choice based on technology attributes and consumer preferences. TEMPO models the domestic passenger and freight transportation needs for the whole nation or at the state or county level. For simulating the whole nation at once, TEMPO uses an implicit spatial resolution that captures the heterogeneity in passenger travel needs across different urban densities, household incomes, and household sizes (for passenger) and across different commodities by distances (for freight). TEMPO can simulate passenger travel at granular resolutions (e.g., county) and requires data on regional household travel trends and options. This includes the number and distribution of households by urbanity and income, trends in local vehicle ownership, and availability of transit options. Freight scenarios can only be modeled at the national level due to less granular available data.

To illustrate the ability of TEMPO to accurately project future scenarios and represent the key elements that determine future energy use, a base case TEMPO scenario was developed that closely matched the EIA's Annual Energy Outlook 2019 Reference Scenario (EIA 2019a) in energy use by fuel, mode, and technology. The Annual Energy Outlook provides comprehensive and widely accepted projections of energy supply and demand including fuel prices, travel demand, vehicle stock, and energy use in the United States through 2050 based on the EIA's National Energy Modeling System. Projections of vehicle costs, fuel prices, fuel economies, and technology choice were used as inputs in TEMPO to represent the same evolution of technology.

This TEMPO scenario is used as the "base case" to serve as a reference point of comparison for sensitivity and uncertainty analyses. For more details on this comparison to the Annual Energy Outlook, see Muratori et al. (2021).

5.2.2.1 Factors Impacting Regional Passenger AFV Adoption in TEMPO

Simulating regional differences in household travel needs can illuminate broader causes of PEV adoption. This section discusses the major factors that account for different PEV adoption rates and how these may differ across regions. This section focuses on factors TEMPO considers when simulating passenger travel using granular representation of passenger travel demand (by 60 household types) supported by National Household Travel Survey data (FHWA 2022). The factors impacting AFV adoption in TEMPO fall into three categories, as described below.

Differing regional travel demand profiles: Households in more urban regions typically have higher frequencies of short-distance trips, which may be more suitable to PEVs with short or medium range. Higher density of development typically increases the probability of nearby public charging options. On the other hand, very dense urban regions where single-family homes and personal garages are rare (e.g., Manhattan) may require higher levels of public and workplace charging infrastructure to enable high adoption due to less access to overnight home charging. Finally, while urban trips skew toward shorter distances on average, higher lifetime vehicle miles traveled in areas where vehicles are driven more (typically rural areas) may support PEV adoption because the lifetime cost of ownership decreases; marginal costs for PEVs are lower due to higher efficiencies and less maintenance.

Income and financial incentives: The upfront cost of competing technologies is often described as a very influential factor in PEV adoption. Household incomes differ across regions, with cities and large job centers attracting higher concentrations of educated workers, producing higher proportions of high-income households. Higher-income households are more likely to be PEV adopters, especially during more nascent technological stages, as they have more financial independence (Narassimhan and Johnson 2018). Different regions also have different financial incentives such as tax rebates that may increase adoption. As discussed in Section 5.2.2.4, TEMPO did not model PEV rebates in this analysis.

Vehicle ownership trends: While BEV ranges are increasing and therefore becoming less restrictive, vehicle use patterns for multi-vehicle households can impact adoption decisions. It is common that households with multiple drivers concentrate use to one dominant vehicle. For certain households (more urban, higher income), this may increase the likelihood of switching to a BEV for the primary vehicle. On the other hand, if the primary vehicle is used more often for longer-distance trips, a secondary or tertiary household vehicle may be more feasible as a BEV. Lastly, vehicle class needs (e.g., SUVs vs. compact cars) or preferences (e.g., luxury vs. economy) may impede PEV adoption in some regions. More rural and agricultural regions have higher penetrations of pickup trucks and medium-duty personal vehicles, which are currently less cost-competitive than their internal combustion engine vehicle counterparts. A lack of competitive options in these vehicle classes may slow adoption.

5.2.2.2 Assumptions for Refueling Infrastructure and AFVs

For passenger travel, TEMPO estimates light-duty vehicle ownership and mode choice decisions explicitly at the household level based on the utility (expressed in terms of perceived and actual monetary cost) of options available. Households make annual ownership decisions to minimize the total cost of ownership across all expected trips for a year. Households make trip-by-trip mode choices based on the trip-level utility (marginal cost). Refueling access is defined as a refueling option existing within the vehicle range during a trip, and this access is represented in TEMPO as a continuous probability between 0% and 100% and varies by five categories of urbanicity (urban, suburban, second city, small town, and rural). For more details on TEMPO's use and classification of urbanicity, see Yip et al. (2023). A binomial sampling approach is used to determine the fractions of trips with access to refueling infrastructure. For example, if a group of households has a 50% probability of refueling access across five trips, the probability that they'll have access to fuel on at least one of those five trips is 96.9%.[3]

PEV technologies have the option for home charging, workplace AC Level 2, or DCFC, whereas non-BEV technologies must rely on public refueling options. When computing the utility to adopt a vehicle, costs for charging are included and differ by type based on inputs (this includes additional costs for upgrading home charging to Level 2). Additionally, if a household has access to residential charging, it incurs no extra time penalty for the proportion of trips that recharge at home. A time penalty for public refueling is incurred for all trips needing public refueling in utility calculations, and the penalty varies by three household income bins, which have different values of time that increase with income. Trips require public charging when no household charging is available or if the trip length exceeds the vehicle range. With this approach, TEMPO does not consider the spatial distribution of refueling options to a household (i.e., proximity to refueling options) and how this impacts local adoption. Rather, it models the probability that a household has access to residential EV charging and public refueling. These probabilities are exogenous inputs that can be altered to examine the sensitivity of implicit local access of charging options to trends in household PEV adoption. This differs from other adoption approaches that consider explicit proximity and density of charging options relative to a traveler.

For freight technology adoption, as explained in Ledna et al. 2024, the density of refueling infrastructure and a refueling time penalty are the only refueling factors considered. The share of ton-miles by freight mode depends on the total cost and time of travel, in addition to the capacity and load factors for the given mode. As a result, it is expected that vehicle costs, infrastructure growth, and significant policy changes (e.g., carbon tax or internal combustion engine ban) will be the most impactful factors for AFV adoption in TEMPO's freight module. More work in this area is needed. For a full overview of the methodology and underlying data sources, see Muratori et al. (2021).

5.2.2.3 Sensitivity and Uncertainty of National AFV Adoption

A key feature of TEMPO is its ability to evaluate sensitivities of AFV adoption and other outcomes of interest under different assumptions of technology progress, policies, and travel behavior. In this section, we discuss the sensitivity of future AFV adoption out to 2050 under preliminary simulations of TEMPO scenarios that vary a selection of input variables: fuel and electricity prices; refueling availability (hydrogen and electricity only); efficiencies of new vehicles (e.g., internal combustion engine vehicle vs. BEV vs. FCEV); assumptions about

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[3] $X \sim B(n,p),\ P(x) = \frac{n!}{x!(n-x)!} p^x (1-p)^{n-x} = X \sim B(5, 0.5),\ P(x \geq 1) =$

$$1 - P(x=0) = 1 - \frac{5!}{0!\,(5-0)!} 0.5^0 (1-0.5)^5 = 1 - 0.031 = 0.969$$

vehicle retirement rates; changing vehicle ownership patterns; changing travel needs (demand); the value of time when charging/refueling (i.e., higher time penalty); and impacts of system efficiency, vehicle occupancies, and availabilities of other modes (e.g., more transit, cheaper mobility as a service). Results from this section are derived from Hoehne et al. (2023). Scenarios for vehicle cost projections utilize NREL's Annual Technology Baseline study (Sertac et al. 2020). TEMPO can evaluate two types of sensitivities: single-variable (isolated) impacts and multivariable impacts. The former approach allows for understanding the impacts of a single specific variable on outcomes in isolation (e.g., vehicle cost impact to BEV adoption), while the latter focuses on understanding the full spectrum of outcomes to explore uncertainty of future adoption trends (e.g., impacts of fuel prices, vehicle costs, and infrastructure availability combined).

Figure 40 exemplifies preliminary relative impacts on BEV stock share in 2050 for individual variables (x-axis) across multiple input categories (each black dot with connecting lines). The most impactful scenario in isolation are ZEV sales mandates (including PHEVs); doing so in 2030 results in 59% of light-duty stock being BEVs by 2050. Another impactful scenario is vehicle cost reductions with battery costs of $40/kWh by 2050, resulting in 45% of vehicles being BEVs by 2050. This scenario requires substantial progress in battery manufacturing capabilities and availability of necessary minerals. Changes to fuel prices (environmental carbon prices, increased fossil fuel prices) or impacts to refueling trends (lower value of time while charging, increased home charging availability, higher public DCFC power) would accelerate BEV adoption in isolation. For every 2.9% increase in residential charging availability there is a 1% increase in BEV stock by 2050.

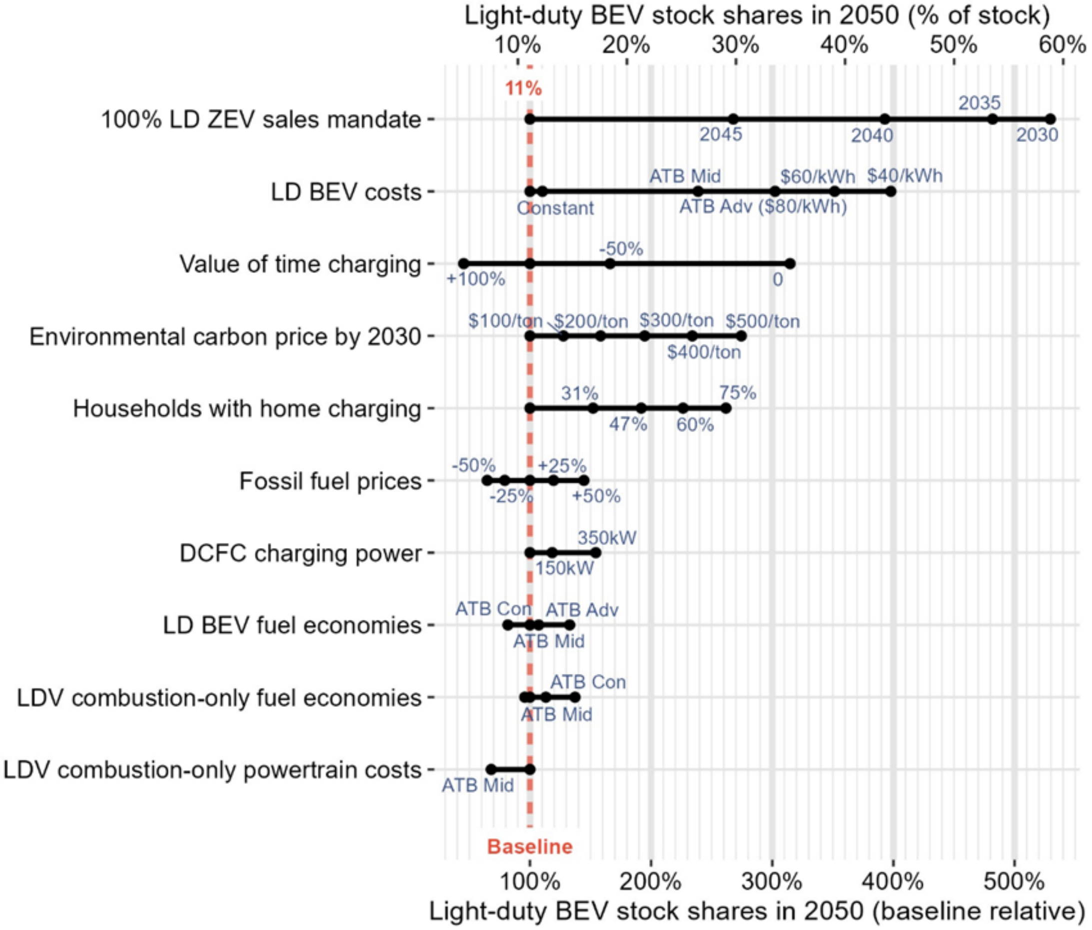

Figure 40. Isolated variable impacts on light-duty BEV stock shares in 2050.

Input categories (y-axis) are ranked by greatest to least absolute impact. Scenarios with stock shares that changed less than 20% relative to the baseline are excluded. For electricity price scenarios, “res” and “com” refer to residential and commercial prices, respectively. Environmental carbon prices are per metric ton CO_2 equivalent. BEV costs and fuel economies are based on the 2020 Annual Technology Baseline study (Sertac et al. 2020), with ATB “Con,” “Mid,” and “Adv” referring to the constant, mid, and advanced scenarios, respectively, with two additional scenarios of battery cost reduction assumptions ($60 kWh^{-1} and $40 kWh^{-1} by 2050).

Figure 41 shows the same results from sensitivity simulations for PHEVs. Similar to BEVs, ZEV sales mandates and vehicle cost reductions are potentially very impactful, while fuel/electricity costs have smaller impacts on adoption. PHEVs are also less likely to be adopted in isolation when BEV costs decline; however, current simulations did not translate the impacts of battery cost reductions to PHEVs (primarily because their ranges and batteries are smaller, so the impact is expected to be small; future work will incorporate this).

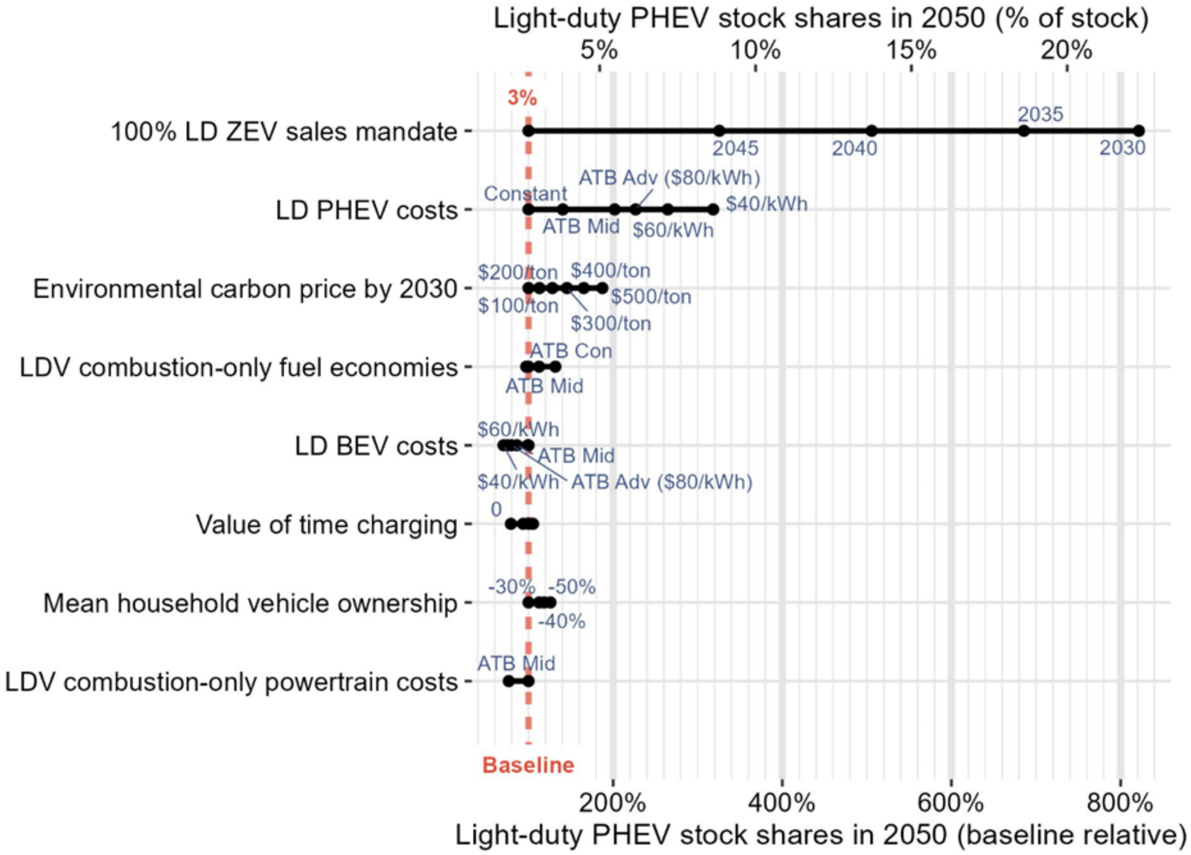

Figure 41. Isolated variable impacts on light-duty PHEV stock shares in 2050.

Input categories (y-axis) are ranked by greatest to least absolute impact. Scenarios with stock shares that changed less than 20% relative to the baseline are excluded. For electricity price scenarios, “res” and “com” refer to residential and commercial prices, respectively. Environmental carbon prices are per metric ton CO_2 equivalent. BEV costs and fuel economies are based on the 2020 Annual Technology Baseline study (Sertac et al. 2020), with ATB “Con,” “Mid,” and “Adv” referring to the constant, mid, and advanced scenarios, respectively, with two additional scenarios of battery cost reduction assumptions ($60 kWh^{-1} and $40 kWh^{-1} by 2050).

Simulations in the freight sector indicate that medium- and heavy-duty freight BEV adoption is only impacted in isolation by ZEV sales mandates and reductions in vehicle costs; a 2035 ZEV sales mandate for freight vehicles results in 71% BEV stock share by 2050, and vehicle cost reductions with $40/kWh batteries result in 41% BEV stock share by 2050. All other variables tested in isolation had no impacts on medium- and heavy-duty vehicle stock shares by 2050 (including fuel prices, vehicle payback sensitivity, carbon prices, fuel economies, and changing trends in freight shipment distances).

Broad FCEV adoption in both the light- and heavy-duty sectors did not occur under any scenario in isolation that was evaluated. FCEV cost reductions (nearly 50% reduction from current) lead to 540,000 freight FCEVs by 2050. When only changing one in isolation at a time, FCEV sales are projected to remain very limited, even under the most optimistic assumptions to individual variables (e.g., increasing availability to hydrogen refueling is not enough without other levers such as reductions in costs or hydrogen prices). Natural gas technologies are also tracked in TEMPO, but this analysis did not evaluate any natural-gas-specific scenarios; therefore, no significant adoption occurred.

To understand the uncertainty of AFV adoption, more than 2,000 TEMPO simulations were run, with each simulation varying between dozens of input variables by using a quasi-uniform sampling approach. The results in this section *do not indicate the probability or likelihood of any outcomes*, but instead help shed light on the uncertainty under a broad array of future scenarios. In other words, they are *possibilistic* but not *probabilistic*. For more details on this scenario design, see Hoehne et al. (2023).

Figure 42 shows the uncertainty of passenger and freight BEV adoption with a large range of potential outcomes for BEV adoption in both the light-duty and heavy-duty vehicle sectors. However, no scenarios exist in which BEVs reach >20% adoption in the next decade in freight and accelerating passenger adoption in the next decade requires many simultaneous levers that usually include ZEV sales mandates phasing in sooner rather than later. Scenarios that are most favorable to achieving high light-duty BEV adoption by 2050 include aggressive battery cost reductions (at least \$80/kWh down to \$40/kWh) and policy impacts such as high carbon taxes or banning internal combustion vehicles.

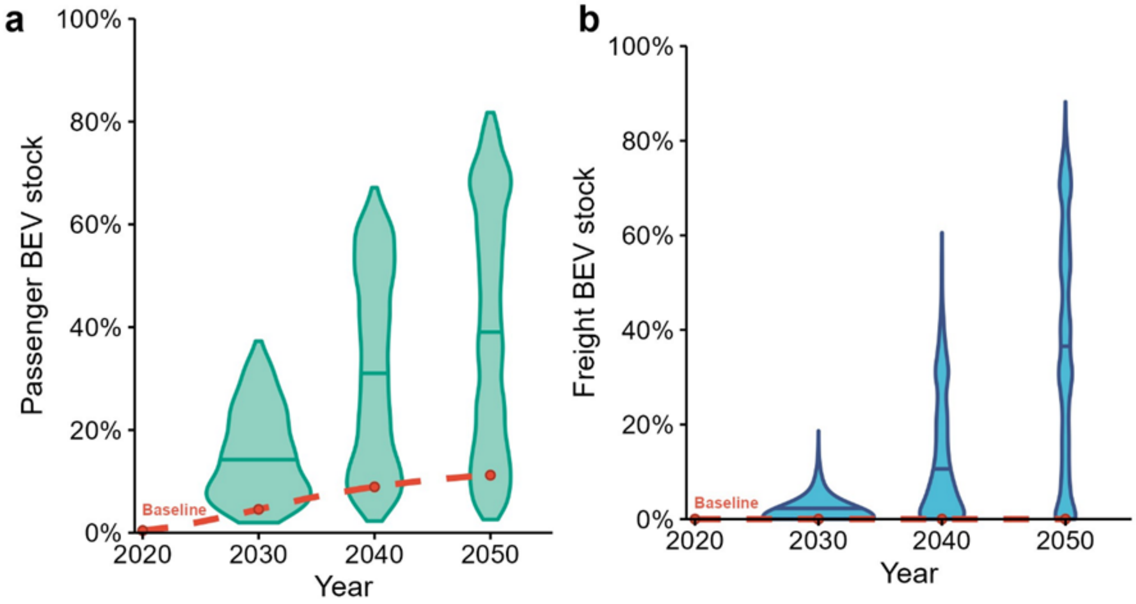

Figure 42. Uncertainty of (a) passenger light-duty and (b) freight medium- and heavy-duty BEV stock shares across 2,000 multivariable TEMPO simulations

A narrow range of scenarios have high penetrations of FCEVs (light or heavy duty). Hydrogen refueling availability was evaluated at 50% or 100%. For passenger light-duty FCEVs, 100% household access to hydrogen refueling leads to a mean of 10% light-duty FCEV stock by 2050 when combined with pessimistic assumptions for BEVs and at least one of the following: lower consumer hydrogen prices (as low \$3.40 kg^{-1} via \$1 kg^{-1} for production), lower FCEV costs, or improved FCEV fuel economies. For freight medium- and heavy-duty vehicles, 100% fleet access to hydrogen refueling results in a mean of 36% FCEV stock by 2050 when also assuming pessimistic assumptions for BEVs alongside at least one of the following: lower hydrogen prices, lower FCEV costs, or improved FCEV fuel economies.

5.2.2.4 Potential Improvements and Opportunities for Future Research

TEMPO is considered a “living model” and is still under active development. Some features are planned, and others are desired based on future funding and staffing. This section highlights opportunities for improvements in the TEMPO model and opportunities for future research on this topic.

A better understanding and representation of purchase decisions relating to non-monetary impacts of charging availability is needed. TEMPO currently only captures impacts such as range anxiety through calibrated preference variables and does not capture the impacts of the density of available stations (just whether options are available). A potential solution is to estimate local and national density of charging infrastructure by urbanity and household type to model refueling options as a more complex probability function that considers nearby density of charging stations, minimum distance from household to nearest public refueling, workplace availability, etc. This would help overcome limitations around the implicit assumption of refueling availability. Additionally, with a density of options and vehicles, there should be consideration of wait times for public refueling, as this will have impacts when the demand for public refueling is higher than supply.

While TEMPO is primarily aimed at national-scale modeling, it is also able to simulate down to county-level passenger travel. However, this requires data with much higher resolution and additional calibration and validation against local travel trends and preferences. Understanding the impacts of different household characteristics could be further explored for applications at the county or state level. For example, TEMPO can evaluate the sensitivity of AFV adoption for a specific county or state by incorporating regional household data, regional availability of travel options (e.g., more granular availability of transit, refueling options, AFV rebates, or other financial incentives) to identify pathways to decarbonization given regional socioeconomic characteristics, infrastructure, and policy. Current work is underway to understand regional impacts, but to date, TEMPO analyses have focused only on PEV adoption to understand impacts to regional energy demand (Yip et al. 2023).

This application of TEMPO did not consider trip purpose (e.g., work vs. leisure) or trip chaining (e.g., work to grocery store to home in two connected trips) constraints. Recent model developments are addressing these limitations to understand the impacts of trip purpose, long-distance charging and refueling, and more resolved workplace charging/refueling availability.

Due to less granular data on freight and heavy-duty vehicles, as well as the interregional nature of freight travel, TEMPO focuses on modeling freight travel at the national level. Fleet operator decision-making is not well understood, especially how it may differ across regions due to differing demand for goods across differing compositions of highway, rail, and water routes. Currently, TEMPO relies on a couple of key data sources for the freight sector: the 2019 Annual Energy Outlook, the 2001 Vehicle Inventory and Use Survey, the Freight Analysis Framework, and airline data from the Bureau of Transportation Statistics. Matching aggregate projections from the Annual Energy Outlook helps TEMPO verify its freight sector approach, but a lack of recent and higher-fidelity data (akin to the passenger data from NHTSA) for truck and rail freight modes makes it difficult to model trade-offs between competing and emerging technologies in the sector. Better-quality data sources (including the upcoming Vehicle Inventory and Use Survey) could help improve the granularity of freight sector simulations to better understand the uncertainty and sensitivity of freight AFV adoption to factors such as fuel prices, infrastructure availability, and shifts in how freight is demanded across the United States.

Some key assumptions regarding the freight module include exogenous demand growth, no use of DCFC, and no feedback of technology choice and infrastructure growth. TEMPO assumes exogenously set growth rates for total freight demand but could be linked with a macroeconomic model to endogenize the evolution of freight demand. More work is needed to understand how the freight sector might invest in fleet DCFC and general infrastructure for refueling.

5.3 Conclusions and Model Comparisons

The TEMPO and ADOPT models have different scopes and boundaries, but they both include representations of private light-duty vehicle adoption. There are, however, key distinctions in how they model consumer vehicle purchase decisions, both in scope and level of detail. It is therefore useful to compare the two tools so that NHTSA might be equipped to determine which aspects are most applicable in their models. ADOPT segments consumer markets into six income bins (spanning household incomes of less than $25,000/year to more than $200,000/year), while TEMPO's market segmentation is more highly resolved by household composition (household size and number of drivers), income (only three bins between $50,000/year and $125,000/year), and urbanity (urban, suburban, second city, small town, and rural).

TEMPO has more coarse representation of available technology options, while ADOPT has higher granularity and realism of the scope of powertrains available. ADOPT simulates the creation of new vehicle models in response to consumer demand, endogenously choosing features such as vehicle range, engine power, and acceleration. TEMPO assumes more general and static categories of options (PHEV 25- and 50-mile electric ranges, and 100- and 300-mile BEV ranges) and leverage exogenous vehicle evolution trends for other models. ADOPT also endogenously evolves the cost and performance attributes of existing vehicle models in response to changes in technology costs and attributes and policy conditions. Consumer preferences are also more highly resolved in ADOPT versus TEMPO, with consumers weighing preferences for vehicle and fuel cost, range, volume, acceleration, and infrastructure availability among other factors when making adoption decisions in ADOPT. TEMPO consumers adopt light-duty vehicles based on total cost of driving decisions, which do not include attributes such as vehicle internal volume and acceleration. However, TEMPO also considers a broader scope than ADOPT, with consumers making vehicle purchase decisions based on household-level needs and the costs and availability of alternative modes of travel, such as public transportation and mobility as a service. This means that total vehicle sales are an endogenous output of TEMPO, whereas they are an exogenous input in ADOPT. Table 4 summarizes other key differences across these models.

Table 4. Comparison of Key Assumptions in ADOPT and TEMPO Models

Assumption Description	ADOPT Value/Source	TEMPO Value/Source
BEV/battery Cost	Set exogenously.	Set exogenously.
Starting vehicle representation	Starts with all existing makes, models, and trims for a realistic representation to capture the nonrepresentative performance of the best-selling HEVs and BEVs. Endogenously creates new options based on market conditions for different levels of income.	Based on current stock and energy statistics.
Future vehicle attributes	Based on endogenously created options optimized for sales based on market conditions for consumers of different income levels. Matches historical trends of increasing acceleration.	Exogenous.
CAFE/greenhouse gas standards	Captures the footprint size-based standards using all the existing vehicle platforms. Models pricing trade-offs used to meet the regulations.	Vehicle attributes and projected changes are set exogenously.
Purchase incentives	Captures the IRA (and previous) incentives including the price limits by size and household income limits.	This analysis did not consider IRA impacts, but TEMPO has recently expanded the capacity to consider specific IRA polices.
Vehicle sales	Estimates sales by make, model, and trim. Aggregated by powertrain, size, and other attributes. Total sales are set exogenously and follow the consistent growth trends since 1970.	Modeled endogenously; baseline is calibrated to match the Annual Energy Outlook 2019 Reference Case.
Consumer preferences	Captures the value of key vehicle attributes including price, fuel cost, size, and range, but also acceleration, which has helped BEVs compete in the luxury/sports vehicle market.	Total cost of ownership based on heterogenous household mobility needs.
PEV range	Modeled endogenously based on market conditions (lower battery prices tend to produce longer-range BEVs).	100- and 300-mile BEVs; 25- and 50-mile PHEVs (more options can be added based on exogenous vehicle inputs).
DCFC charging speed	Exogenous scenarios.	Baseline assumes 25% 50-kW chargers and 75% 150-kW chargers. Sensitivity analysis includes (1) a linear transition to 2030 of 100% 150-kW chargers and (2) a

Assumption Description	ADOPT Value/Source	TEMPO Value/Source
		linear transition to 2030 of 100% 350-kW chargers.
Charging availability	Range of scenarios with public Level 2 and DCFC availability ranging from 0% to 100%. Home and workplace charging assumed to be fully available.	Baseline assumes 11% availability in residential charging with sensitivity up to 75% (Ge et al. 2021). Public workplace Level 2 is assumed 50% and varied to 0% or 100%. DCFC availability is not constrained (assumed 100%) but incurs time and convenience penalties.
Calibration	ADOPT's consumer preferences were calibrated in 2008 based solely on attributes and remain unchanged for subsequent years. No general calibration factor (alternative specific constant) is used or changed by year to match sales.	TEMPO's technology choice is calibrated to Annual Energy Outlook's 2019 Reference Case, and mode choice is calibrated to the 2017 National Household Travel Survey.
Model validation	Matches historical sales distributions by fuel economy, acceleration, size, price, and powertrain. Matches number of vehicle options and sales by powertrain since 2015. Matches BEV sales by household income.	TEMPO matches Annual Energy Outlook energy consumption by mode and technology and matches National Household Travel Surbey mode shares. For more details see Muratori et al. (2021).

ADOPT and TEMPO both model future PEV adoption using logit methods (a weighting function for different attributes) but differ in representation of options that influence purchase decisions. ADOPT focuses more on individual consumers and their preferences with greater detail in vehicle technology options, while TEMPO focuses more on household travel decisions more heavily informed by heterogenous travel needs and their influence on total cost of ownership.

6 Evolution of Alternative Fueling Infrastructure Corridors

In 2016, FHWA first requested AFC designations from states. These nominations were intended to identify sections of the National Highway System that had enough alternative fuel to provide reliable transport. The five alternative fuel station types that are part of the AFC program are EV charging, hydrogen, propane, CNG, and LNG. The first round of corridors was designated in 2017, and the fifth round was designated in 2021.

The designations classified nominated roadways into three categories: AFC ready, AFC pending, and undesignated. AFC-ready corridors have fueling stations along the nominated roadways that meet FHWA requirements. AFC-pending corridors have some fueling stations, but not enough density, or stations that do not meet the FHWA requirements. Undesignated corridors have neither the density of stations nor stations that meet FHWA requirements. As the program evolved, the FHWA AFC requirements were occasionally adjusted, but for round five, the requirements for all fuels were as follows:

1. Public fueling station
2. Station not more than 5 miles off the highway.

Table 5. Fuel-Specific Requirements

Fuel	Mileage Between Stations	Fuel-Specific Station Requirements
EV charging	50	DCFC with J1772 combo (CCS) and CHAdeMO connectors
Hydrogen	100	None
Propane	150	Primary propane stations
CNG	150	Fast fill; 3,600 psi
LNG	200	None

Nominations are made by states for each fuel. After five rounds of designation, Table 6 shows which states have either pending or ready AFC and for which fuels.

Table 6. States With AFCs Ready or Pending

State	CNG	Electric	Hydrogen	LNG	Propane
Alabama	Yes	Yes	No	Yes	Yes
Alaska	No	Yes	No	No	No
Arizona	Yes	Yes	Yes	Yes	Yes
Arkansas	Yes	Yes	No	No	Yes
California	Yes	Yes	Yes	Yes	No
Colorado	Yes	Yes	Yes	Yes	Yes
Connecticut	Yes	Yes	Yes	Yes	Yes
Delaware	No	Yes	No	No	No
District of Columbia	No	Yes	No	No	No
Florida	Yes	Yes	Yes	Yes	Yes
Georgia	Yes	Yes	No	Yes	Yes
Hawaii	No	Yes	No	No	No
Idaho	Yes	Yes	No	No	Yes
Illinois	Yes	Yes	Yes	Yes	Yes
Indiana	Yes	Yes	Yes	Yes	Yes
Iowa	Yes	Yes	Yes	Yes	Yes
Kansas	Yes	Yes	No	Yes	Yes
Kentucky	Yes	Yes	No	Yes	Yes
Louisiana	Yes	Yes	No	Yes	Yes
Maine	No	Yes	No	Yes	No
Maryland	Yes	Yes	No	Yes	Yes
Massachusetts	Yes	Yes	No	No	No
Michigan	Yes	Yes	No	No	Yes
Minnesota	No	Yes	No	No	No
Mississippi	Yes	No	No	No	No
Missouri	Yes	Yes	Yes	Yes	Yes
Montana	No	Yes	No	No	No
Nebraska	Yes	Yes	No	No	Yes
Nevada	Yes	Yes	No	Yes	Yes
New Hampshire	Yes	Yes	No	No	Yes
New Jersey	Yes	Yes	Yes	Yes	Yes
New Mexico	Yes	Yes	No	Yes	Yes
New York	Yes	Yes	Yes	Yes	Yes
North Carolina	Yes	Yes	No	Yes	Yes
North Dakota	No	Yes	No	No	Yes
Ohio	Yes	Yes	Yes	Yes	Yes
Oklahoma	Yes	Yes	No	No	No
Oregon	Yes	Yes	Yes	Yes	Yes
Pennsylvania	Yes	Yes	Yes	Yes	Yes
Rhode Island	Yes	Yes	Yes	No	No
South Carolina	Yes	Yes	No	No	Yes
South Dakota	No	No	No	No	No
Tennessee	Yes	Yes	Yes	Yes	Yes
Texas	Yes	Yes	Yes	Yes	Yes
Utah	Yes	Yes	No	Yes	Yes
Vermont	Yes	Yes	No	No	Yes
Virginia	Yes	Yes	No	No	Yes
Washington	Yes	Yes	Yes	Yes	Yes
West Virginia	Yes	Yes	No	No	Yes
Wisconsin	Yes	Yes	Yes	Yes	Yes
Wyoming	Yes	Yes	No	No	No
Total with AFCs	**42**	**49**	**19**	**29**	**37**
Total without AFCs	**9**	**2**	**32**	**22**	**14**

While the overall coverage of both pending and ready AFCs shows which fuels have widespread coverage (CNG and electric charging) and which fuels have limited coverage (hydrogen), only ready AFCs have reliable fueling infrastructure. Pending AFCs indicate locations where states have interest in infrastructure build-out to complete corridors. The next series of maps and charts show where ready AFCs exist across the country. These maps can be compared to Table 6 to understand what states have available infrastructure (ready AFCs) and what states are more appropriate for infrastructure build-out considerations (pending AFCs).

6.1 Historic AFC Build-Out

Each of the five AFCs were built out differently by region and over time. The following maps and graphs display the designation of each fuel's ready corridors.

6.1.1 CNG

As of 2021, CNG had 21,800 miles of ready-designated AFCs. Half of the mileage was designated in Round 1 (11,000 miles), and each round of designation had fewer miles. Overall, 9.8% of the National Highway System is designated as a CNG-ready AFC. This is the second-highest level of coverage by an alternative fuel, behind electric charging. California has the highest number of designated miles (3,500), followed by Texas (2,100) and Oklahoma (1,800). Eleven states do not have any designated AFCs, which can be seen in Figure 43 and Figure 44. The average mileage per state with ready corridors is 540 miles.

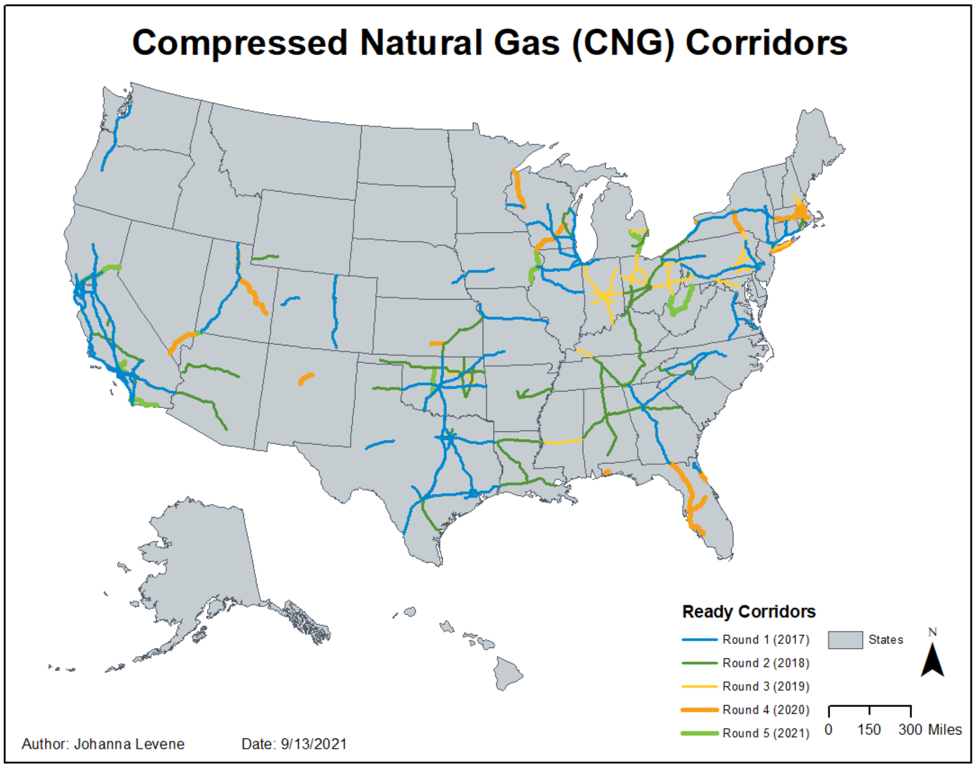

Figure 43. CNG corridors

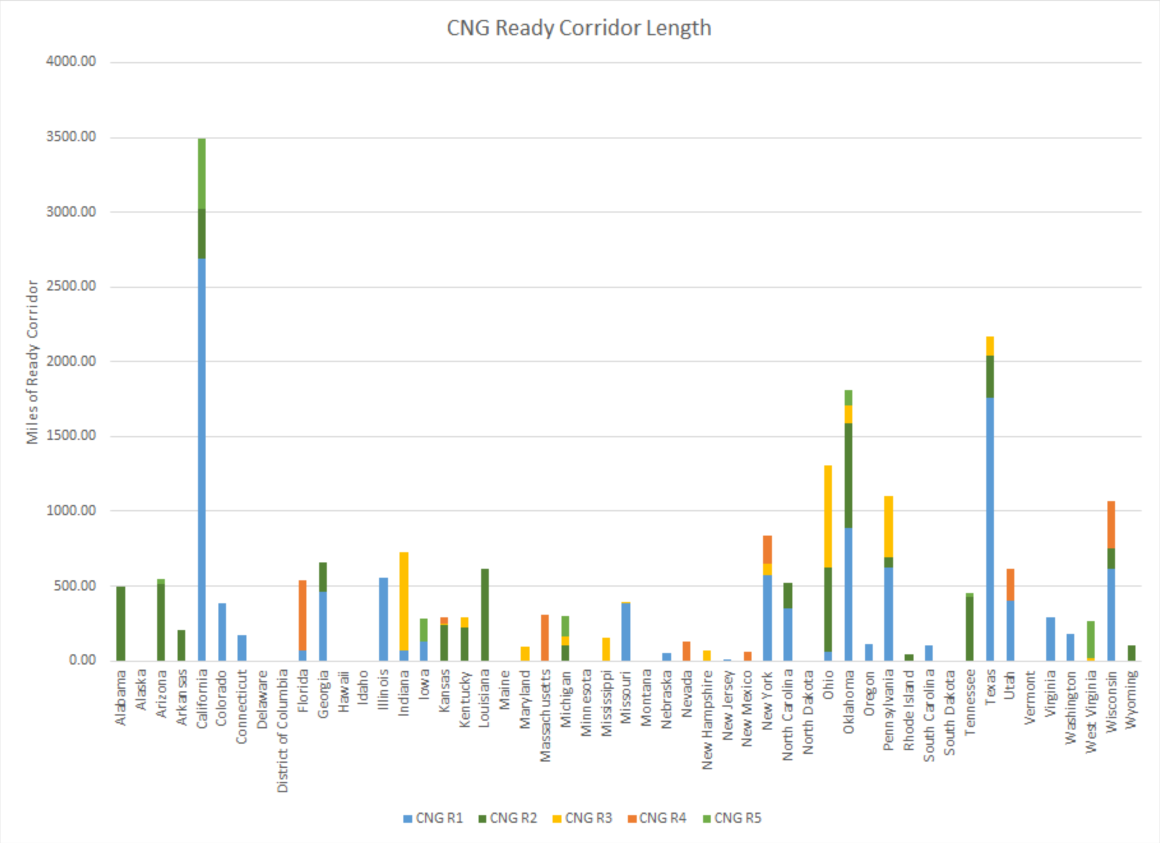

Figure 44. CNG-ready corridor length

6.1.2 Electric Charging

As of 2021, electric charging had 21,900 miles of ready-designated AFCs. Most of the mileage was designated in Round 1 (12,000 miles), with the second-most mileage designated in Round 5 (4,900 miles). Overall, 9.9% of the National Highway System is designated as an electric-charging-ready AFC. This is the highest level of coverage by an alternative fuel. California has the highest number of designated miles (4,000), followed by Virginia (1,200), Ohio (1,100), and New York (1,100). Eight states do not have any designated electric charging AFCs, as can be seen in Figure 45 and Figure 46. The average mileage per state with ready corridors is 510 miles. The number and distance of electric corridors is being rapidly increased through the National Electric Vehicle Infrastructure Formula Program (AFDC 2024m). This program provides federal funding to states to strategically deploy EV charging stations.

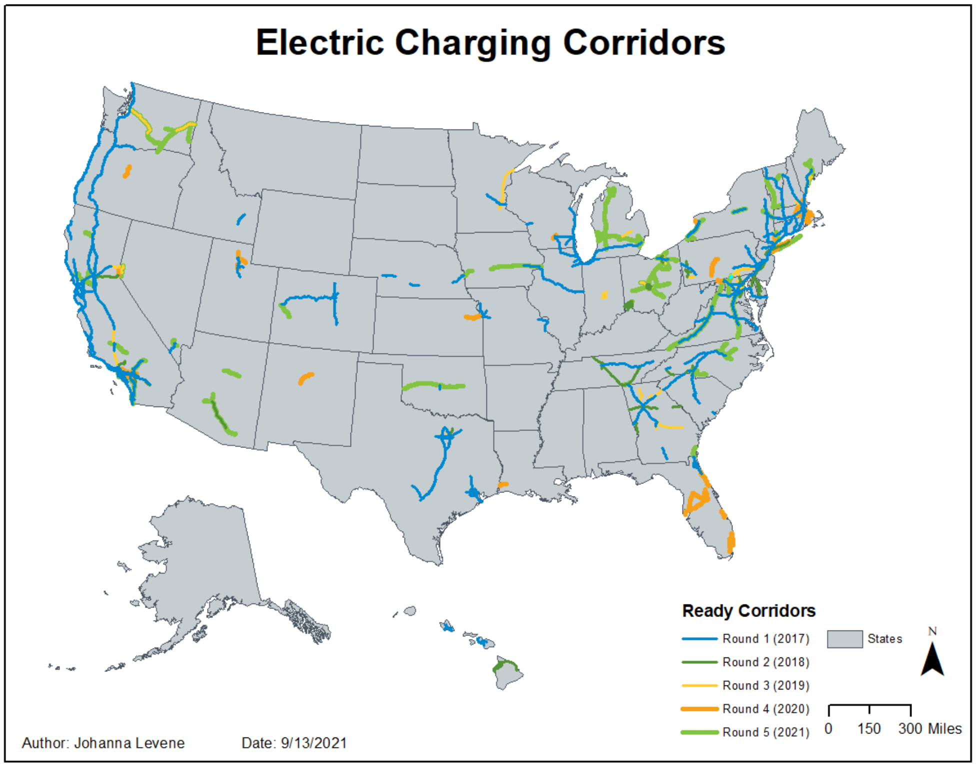

Figure 45. Electric charging corridors

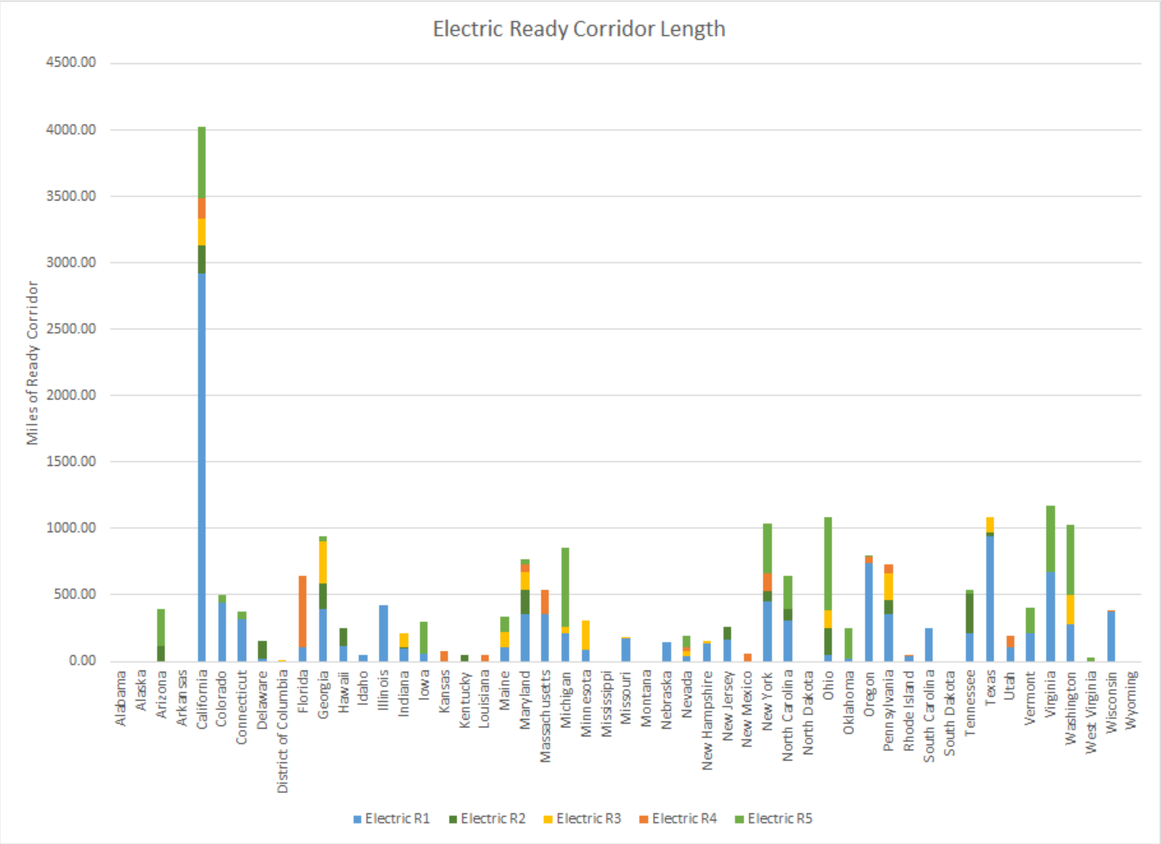

Figure 46. Electricity-ready corridor length

6.1.3 Hydrogen

As of 2021, hydrogen had 900 miles of ready-designated AFCs. Most of the mileage was designated in Round 1 (700 miles), with the second-most mileage designated in Round 5 (93 miles). Overall, 0.4% of the National Highway System is designated as a hydrogen-ready AFC. This is the lowest level of coverage by an alternative fuel. California is the only state with designated miles. The other 50 states (including the District of Columbia) do not have any ready-designated hydrogen AFCs, as can be seen in Figure 47 and Figure 48.

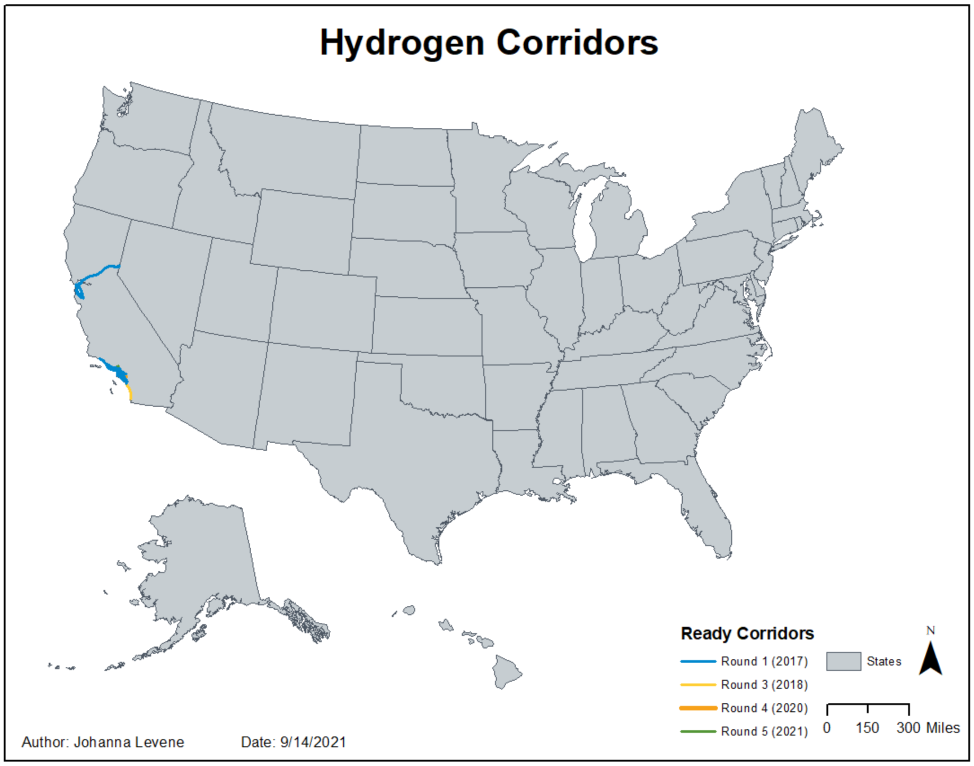

Figure 47. Designated hydrogen corridors

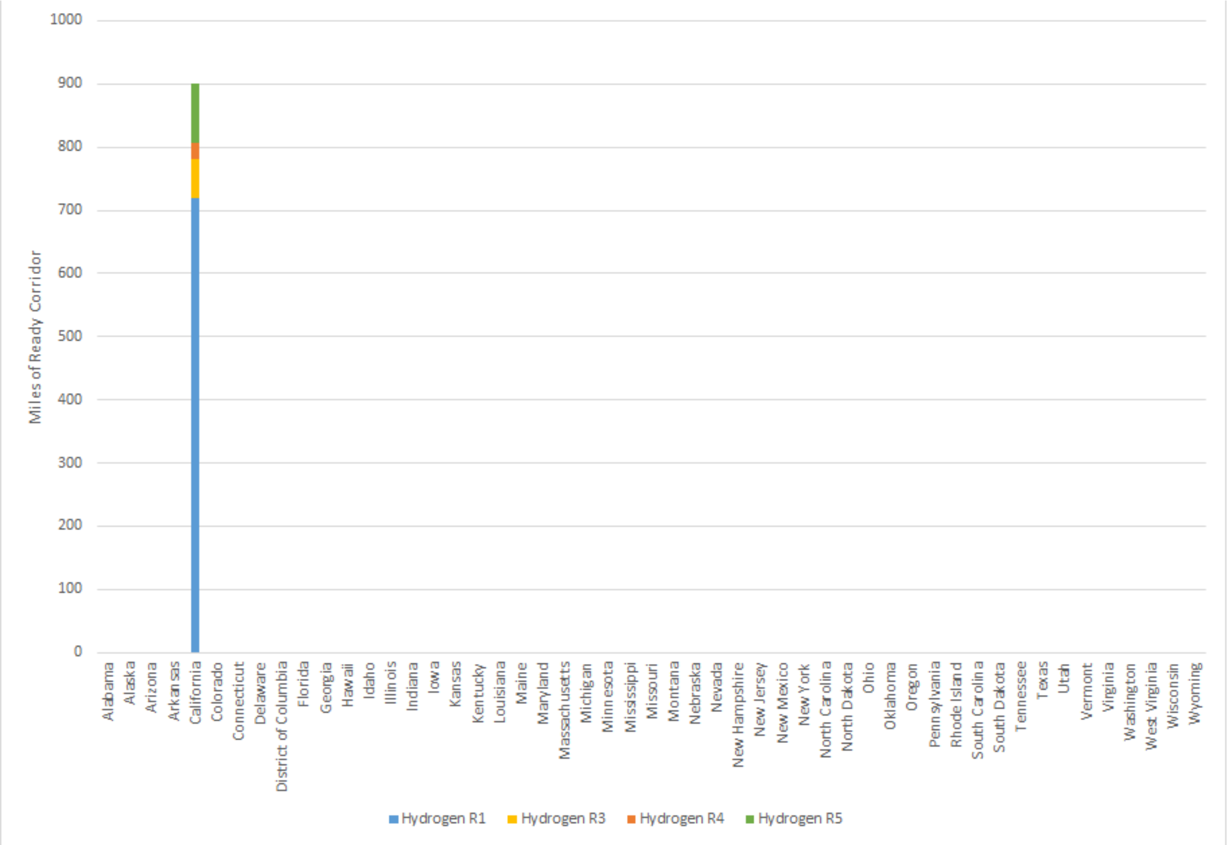

Figure 48. Length of hydrogen-ready corridors

6.1.4 LNG

As of 2021, LNG had 3,700 miles of ready-designated AFCs. Most of the mileage was designated in Round 1 (2,800 miles), and the second-most mileage designated in Round 2 (500 miles). Overall, 1.6% of the National Highway System is designated as an LNG-ready AFC. This is the second-lowest level of coverage by an alternative fuel. Only 10 states have ready-designated miles. Neither the other 40 states nor the District of Columbia have any designated LNG AFCs, which can be seen in Figure 49 and Figure 50. California has the most mileage (1,400), and Texas is second with 950 miles. The average mileage per state with ready corridors is 950 miles.

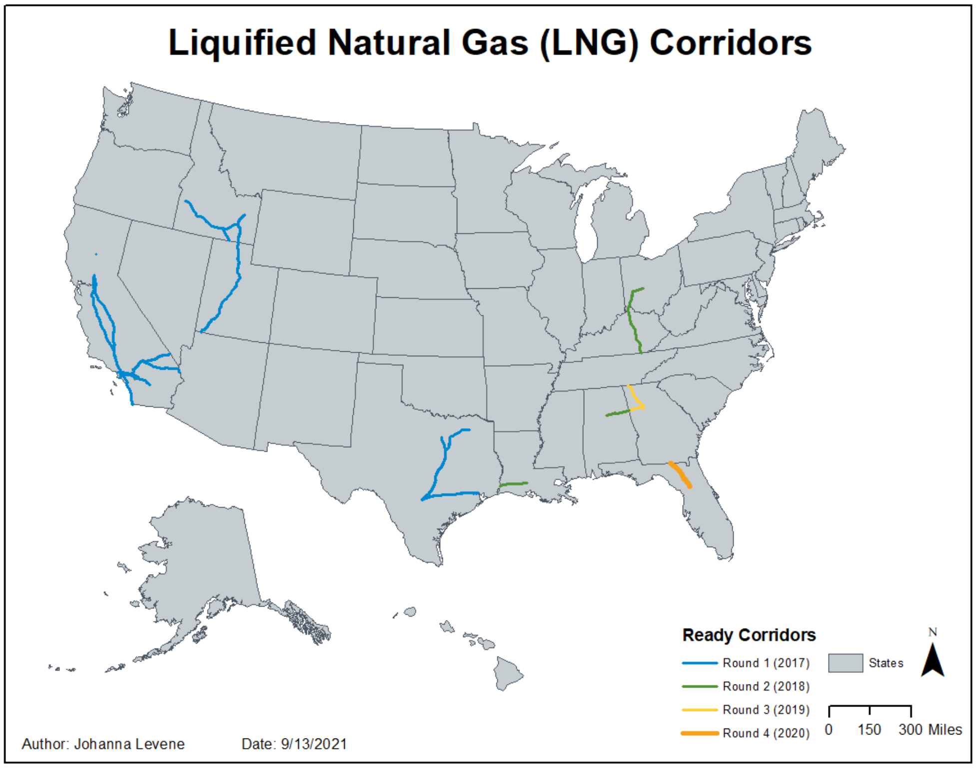

Figure 49. LNG corridors

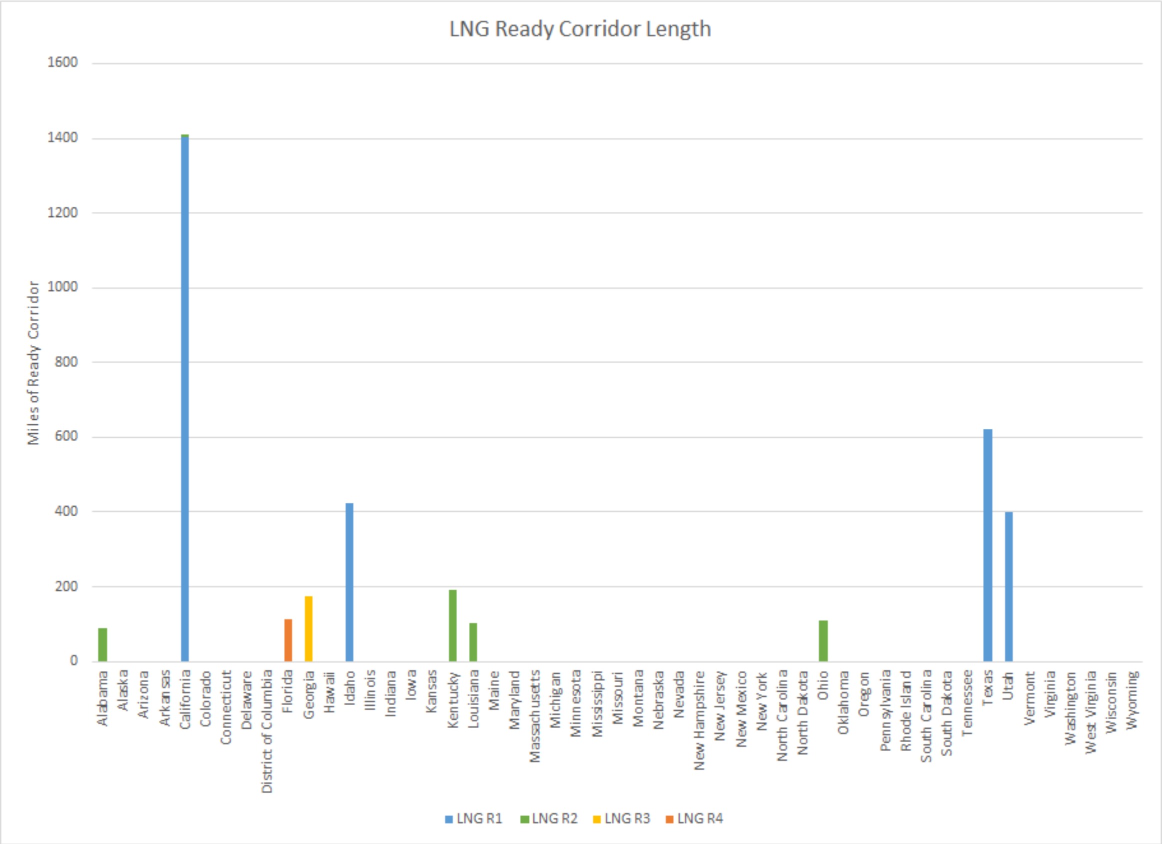

Figure 50. LNG-ready corridor length by state

6.1.5 Propane

As of 2021, propane had 16,000 miles of ready-designated AFCs. Most of the mileage was designated in Round 5 (5,900 miles), and the second-most in Round 1 (4,000). Overall, 7.1% of the National Highway System is designated as a propane-ready AFC. This is the third-highest level of coverage by an alternative fuel, behind electric charging and CNG. New Mexico has the highest number of designated miles (1,200), followed by Texas (1,100) and Illinois (1,100). Sixteen states do not have any designated AFCs, which can be seen in Figure 51 and Figure 52. The average mileage per state with ready corridors is 450 miles.

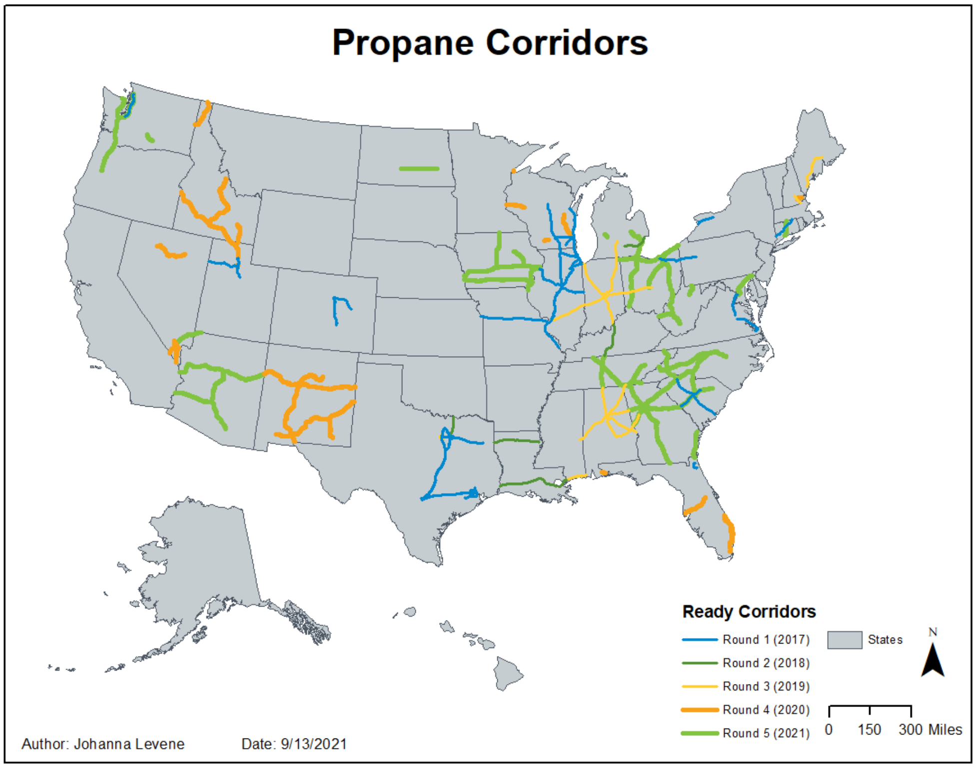

Figure 51. Propane corridors as of September 2021

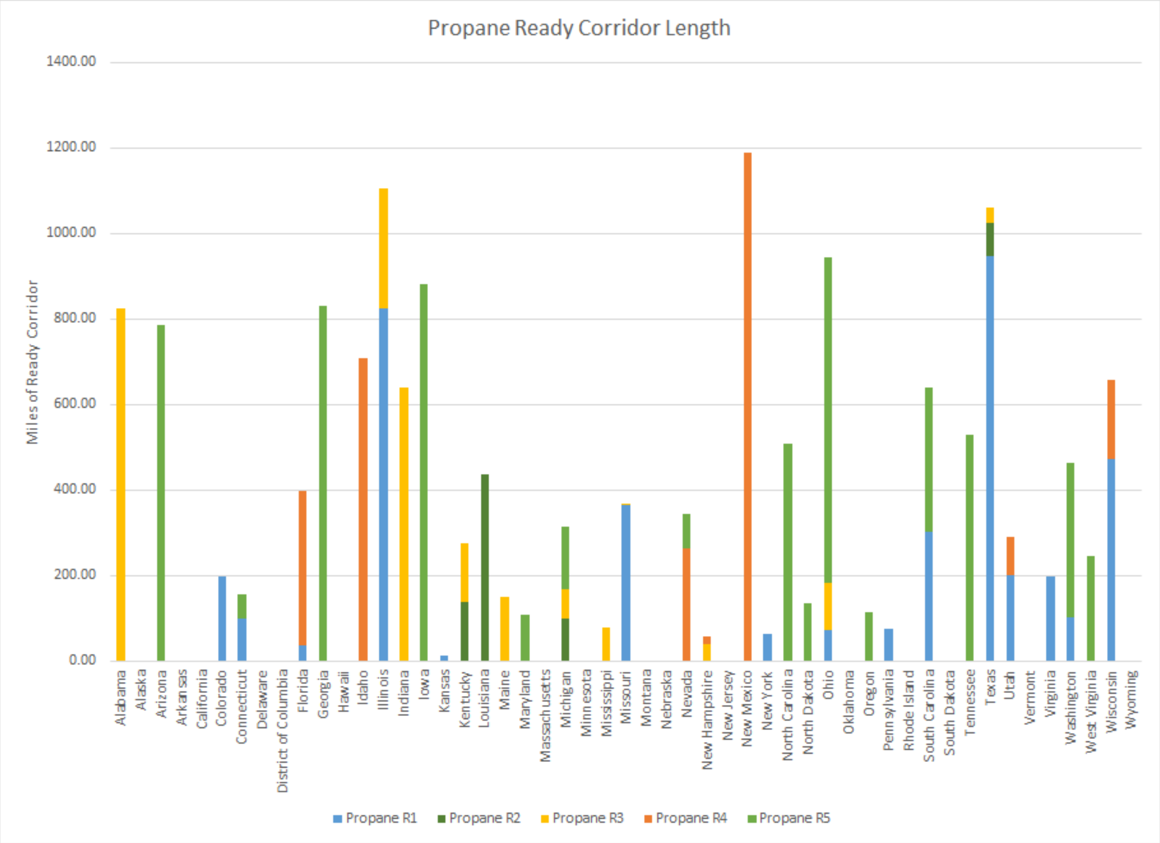

Figure 52. Propane-ready corridor length by state

6.2 Current Alternative Fuel Station and Corridor Coverage

The national build-out of alternative fuel stations determines the designation of pending or ready AFCs. Each state has their own progression toward their goal of complete AFC coverage. This section of the report used the National Highway System dataset to find alternative fuel stations that meet the AFC criteria within 5 miles. Counts of these stations were aggregated by state and categorized in the bottom, middle, and top tercile of station implementation.

States with many stations of a given fuel type may still have low total coverage of AFCs compared to the other states due to AFC criteria not being met for some or many of the stations. The second set of maps show each state's corridor coverage as a percentage of their total highway length (interstates, national highways, and state highways). Note that some states may consider other roads part of their corridor-eligible highway system due to special circumstances, but only interstates, national highways, and state highways were considered as part of this analysis.

6.2.1 CNG

CNG shows considerable coverage across the United States, with seven states having no stations, but many being in the upper tercile of adoption. Figure 53 shows the statewide implementation of CNG stations.

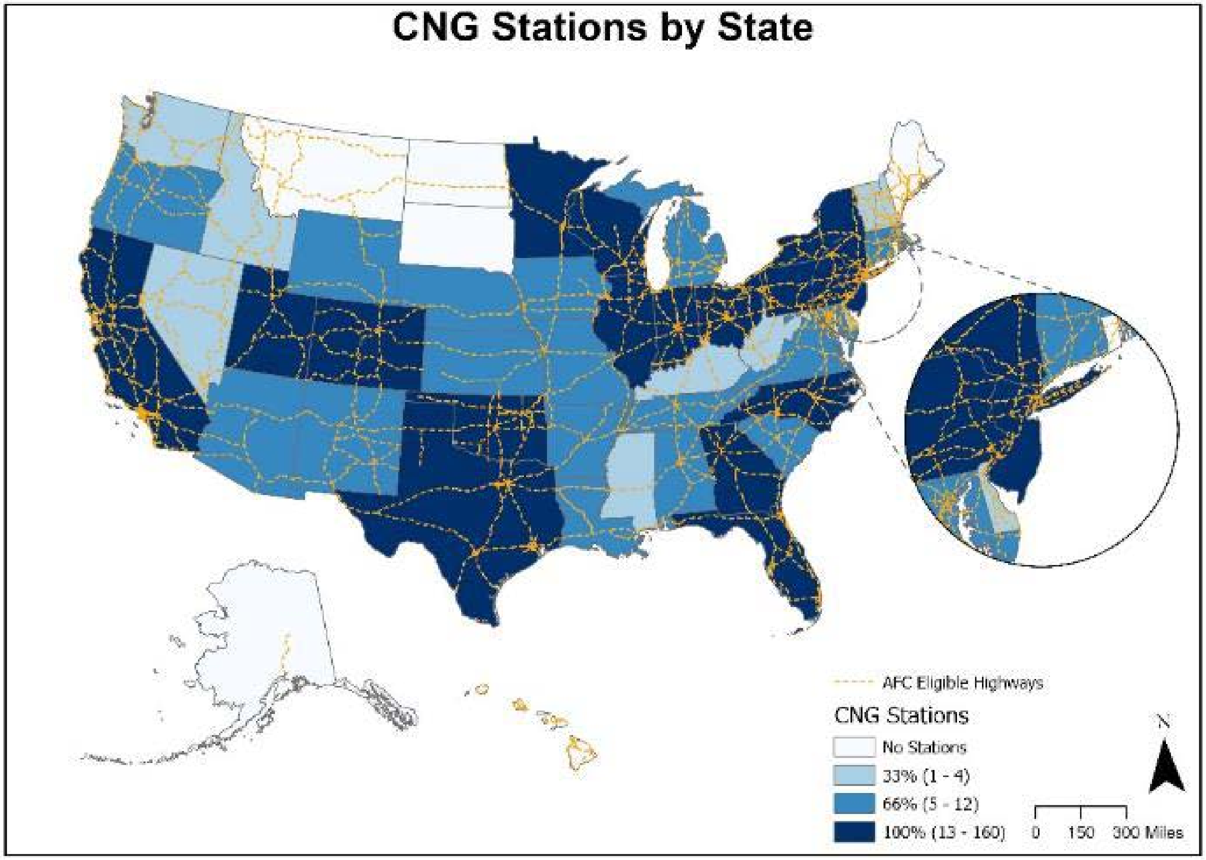

Figure 53. National stock of corridor-eligible CNG stations

Most states have relatively low coverage of CNG corridors, with many below 33% and only California and Oklahoma above that in the 33%–66% range. Figure 54 shows the statewide highway coverage of CNG corridors.

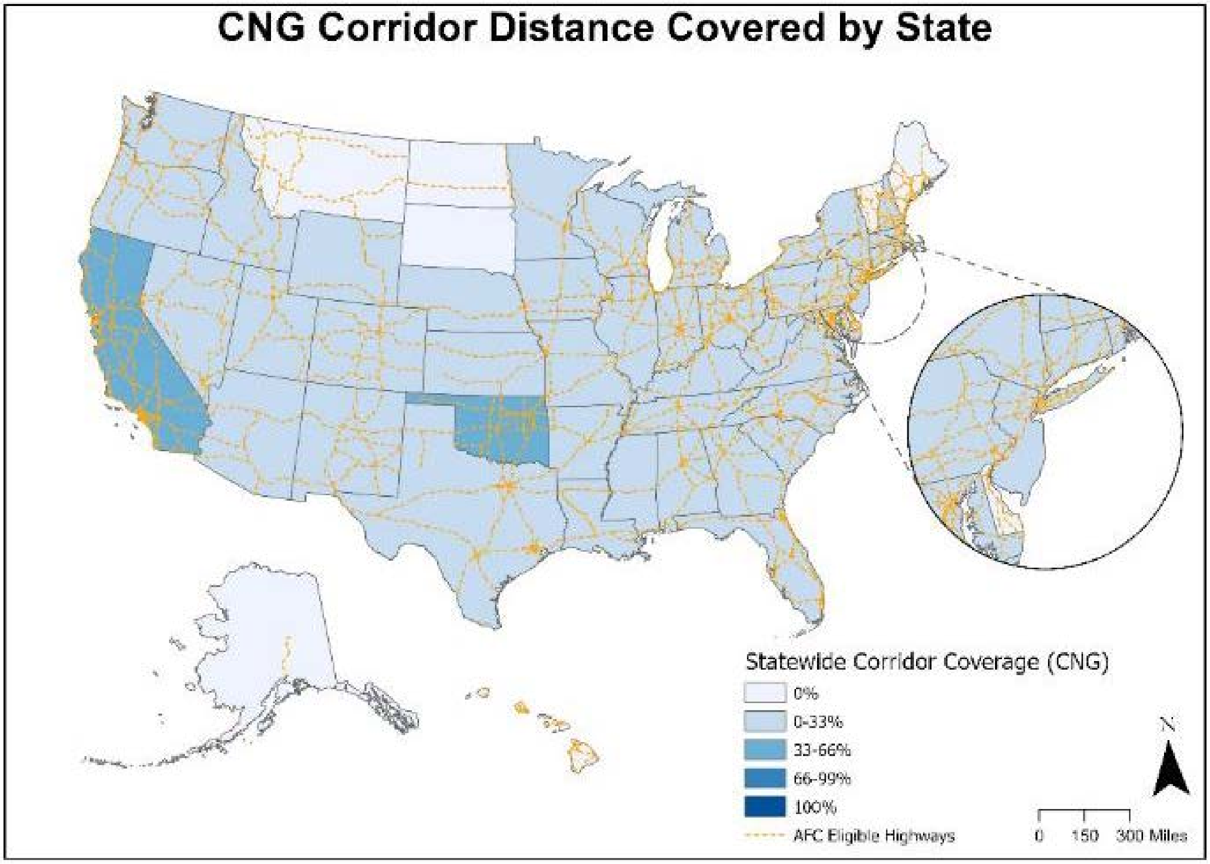

Figure 54. Statewide corridor coverage of valid CNG corridors

6.2.2 Electric Charging

All states except South Dakota and Alaska have at least some EV charging stations that are eligible for current or future corridor designation. South Dakota is an exception in the AFC programs because the state has not yet nominated any portion of the state's road system for AFCs. California has the most stations at 1,064. Note that a given station may have many more individual ports that allow for recharging of multiple vehicles at a time. Figure 55 shows the national stock of corridor-eligible EV stations.

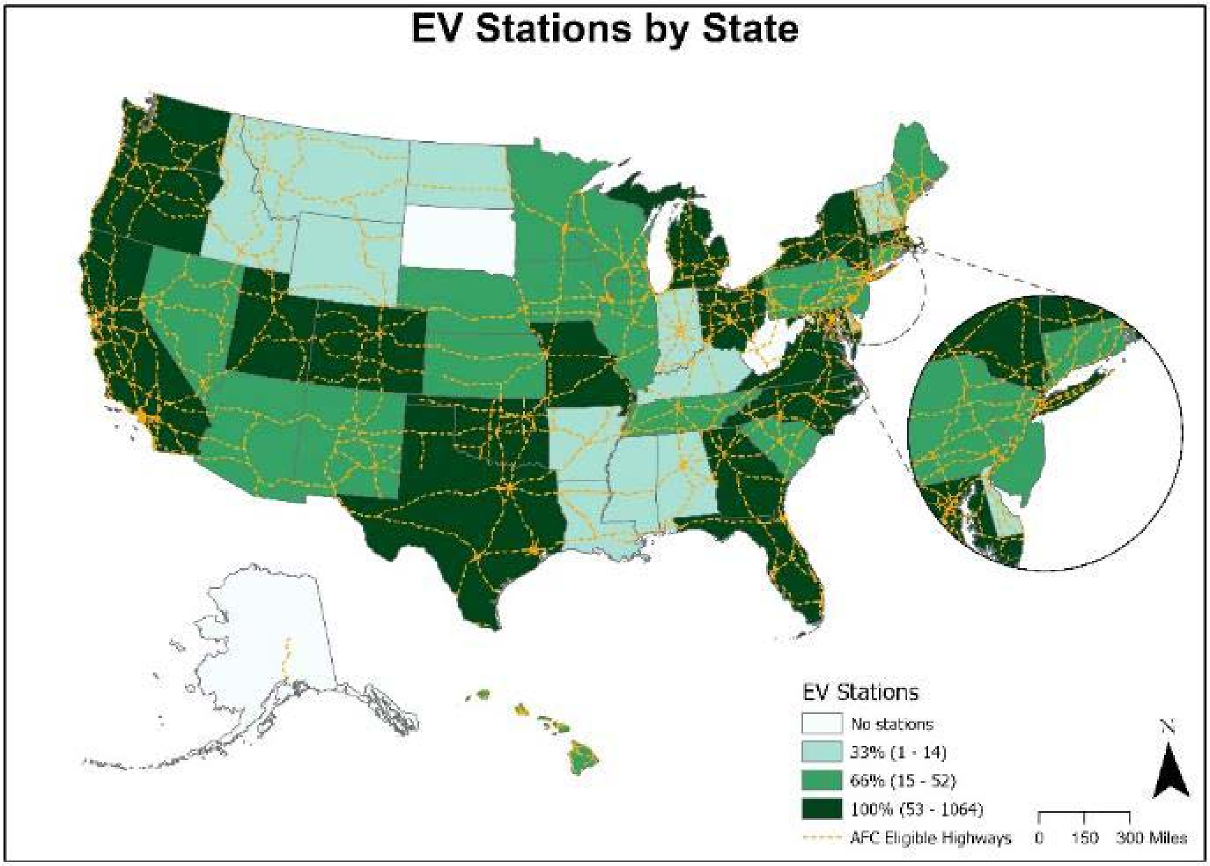

Figure 55. National stock of corridor-eligible EV stations

While most states have corridor-eligible stations, fewer have enough stations to designate any length of valid corridor. California and some eastern states have the best coverage in the 33%–66% range; however, California's larger size indicates an even larger AFC network, comparatively. Figure 56 shows the current coverage of each state's EV corridors.

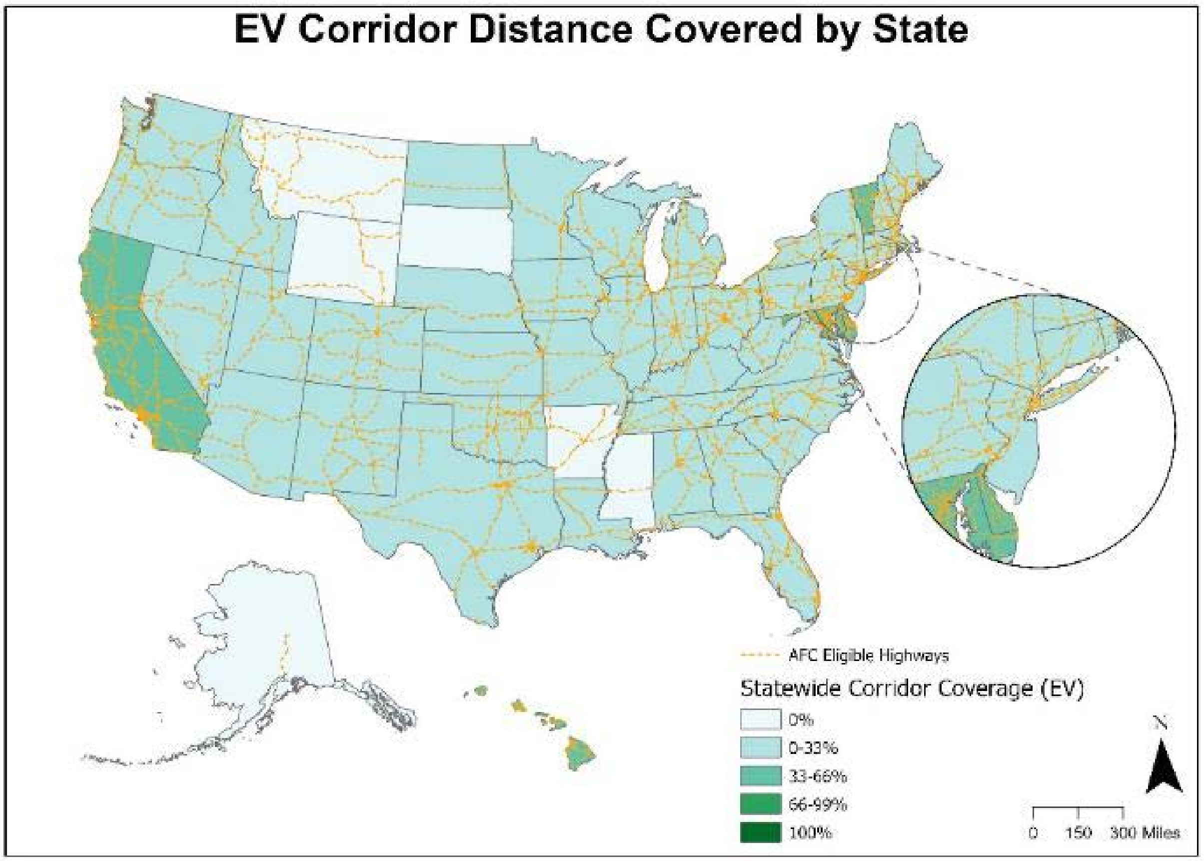

Figure 56. Statewide corridor coverage of valid EV corridors

At the time of this report, Tesla stations are not considered to be valid for AFCs. However, with their extensive charger network, the inclusion of Tesla in the AFC program would certainly bolster the national EV corridor connectivity. Figure 57 shows the impact including Tesla stations would have on each state's EV charger stock.

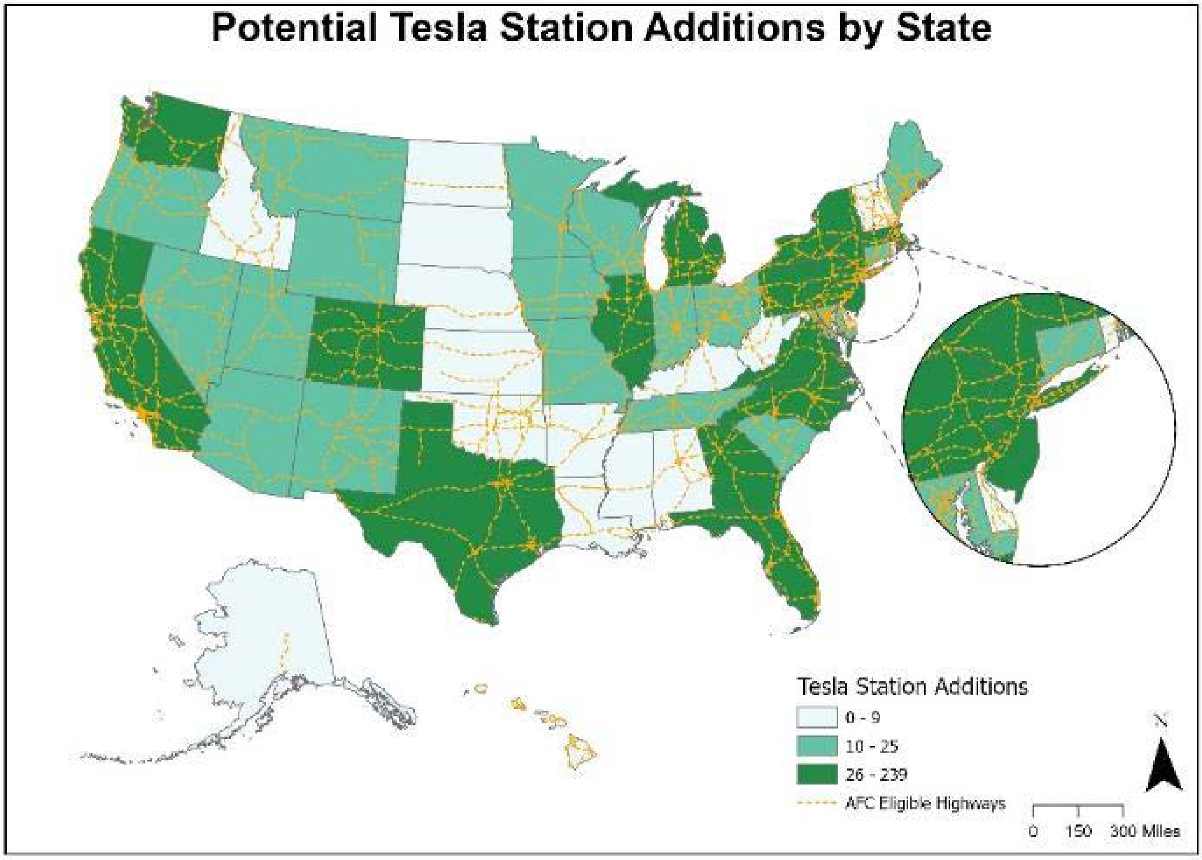

Figure 57. Overall AFC EV charging station additions if Tesla chargers were included

6.2.3 Hydrogen

Hydrogen is a unique alternative fuel in that only one state has made any significant steps toward adoption: California. Hawaii has a single station, but all others have none, as shown in Figure 58. For this reason, only California has any AFC coverage for hydrogen at 10.3% of the state's highway network. Figure 58 and Figure 59 show the contrast of hydrogen corridor coverage by state.

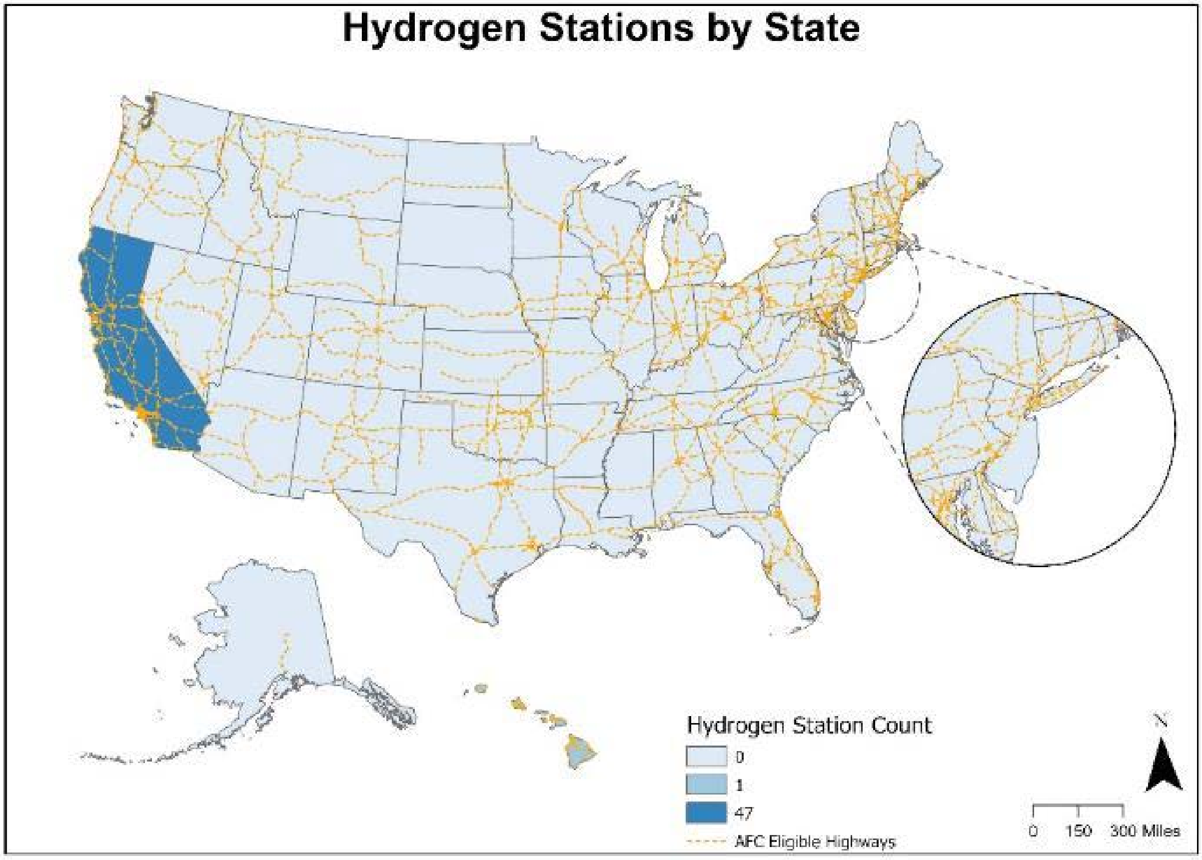

Figure 58. National stock of corridor-eligible hydrogen stations

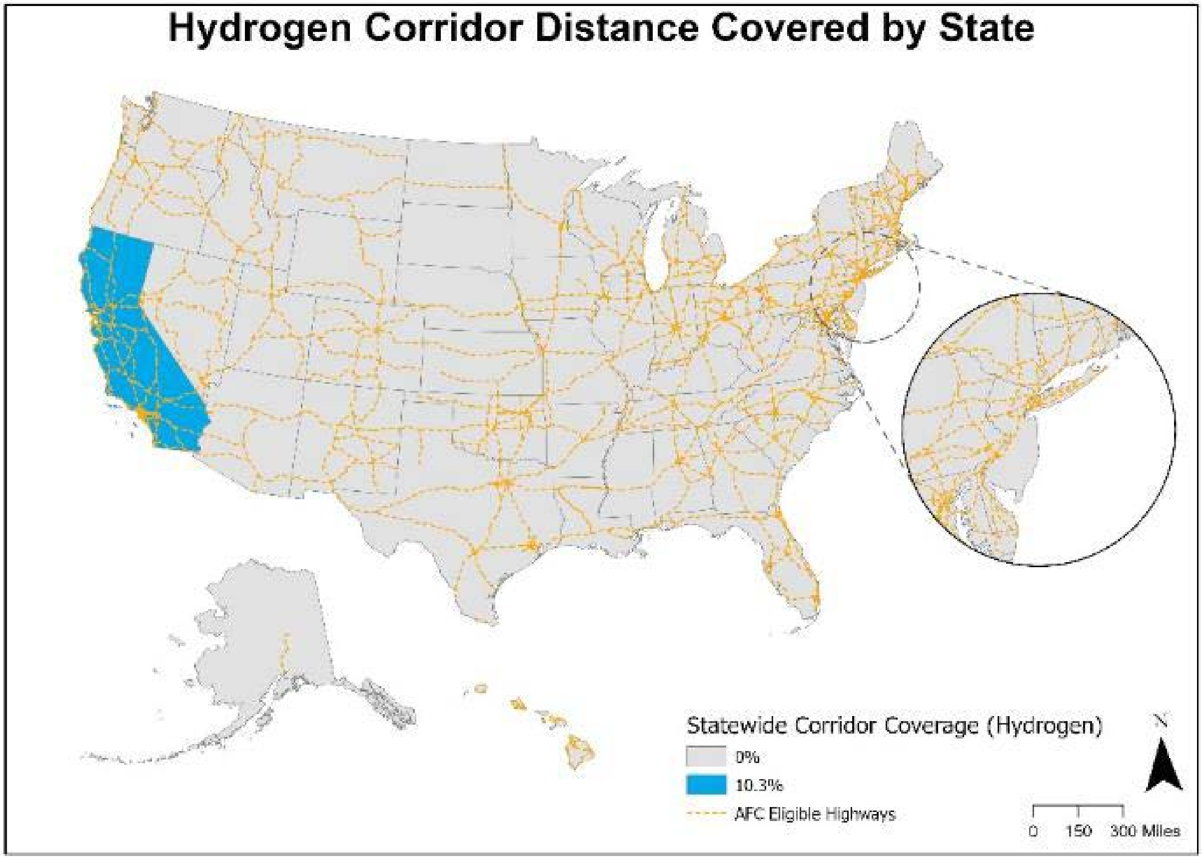

Figure 59. Statewide corridor coverage of valid hydrogen corridors

6.2.4 LNG

LNG station adoption shows similar spatial coverage to CNG but with fewer stations overall, as shown in Figure 60. However, due to a large corridor range of 200 miles, LNG has considerable corridor coverage despite a relatively low overall station count, as shown in Figure 61.

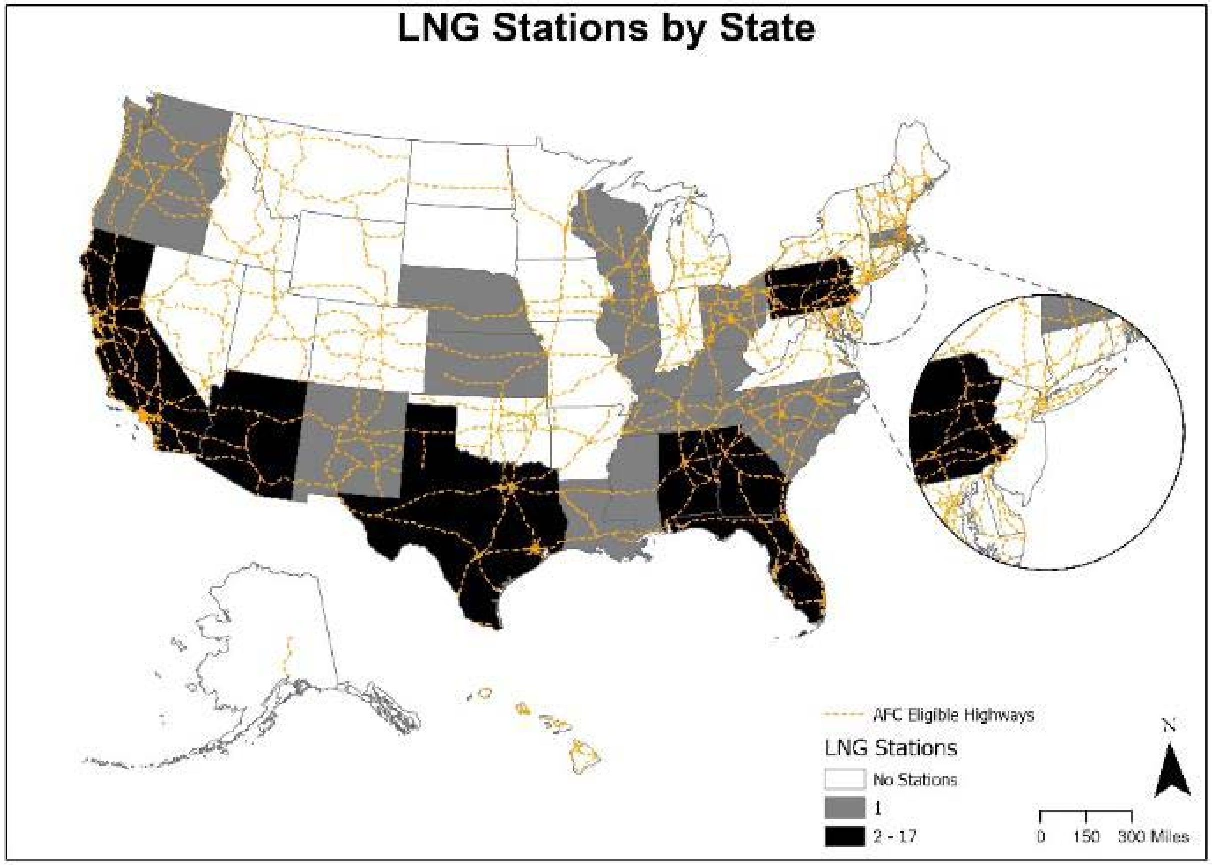

Figure 60. National stock of corridor-eligible LNG stations

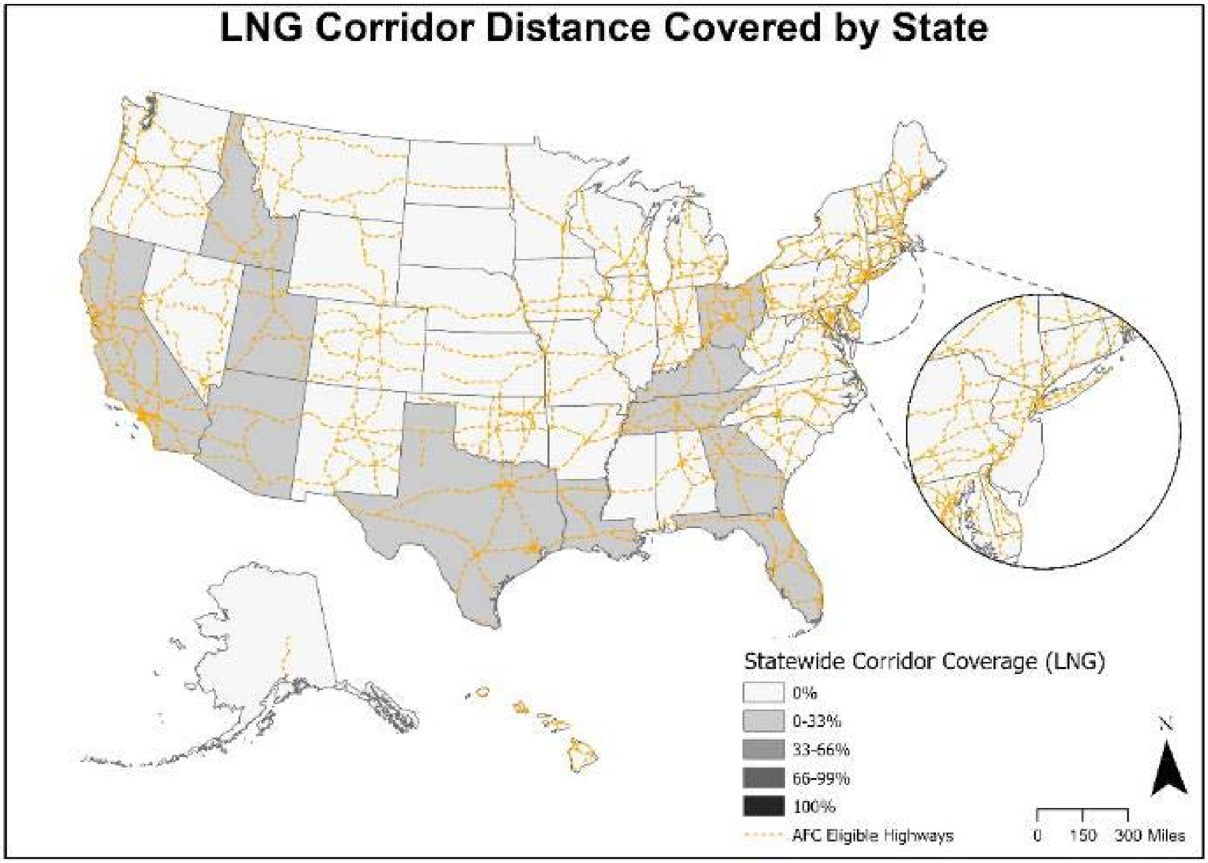

Figure 61. Statewide corridor coverage of valid LNG corridors

6.2.5 Propane

Finally, propane has significant station coverage across states, with only two states (Alaska and Vermont) having no valid stations, as shown in Figure 62. Similar to LNG, propane's long corridor range allows for considerable nationwide coverage of corridors despite a low overall station count.

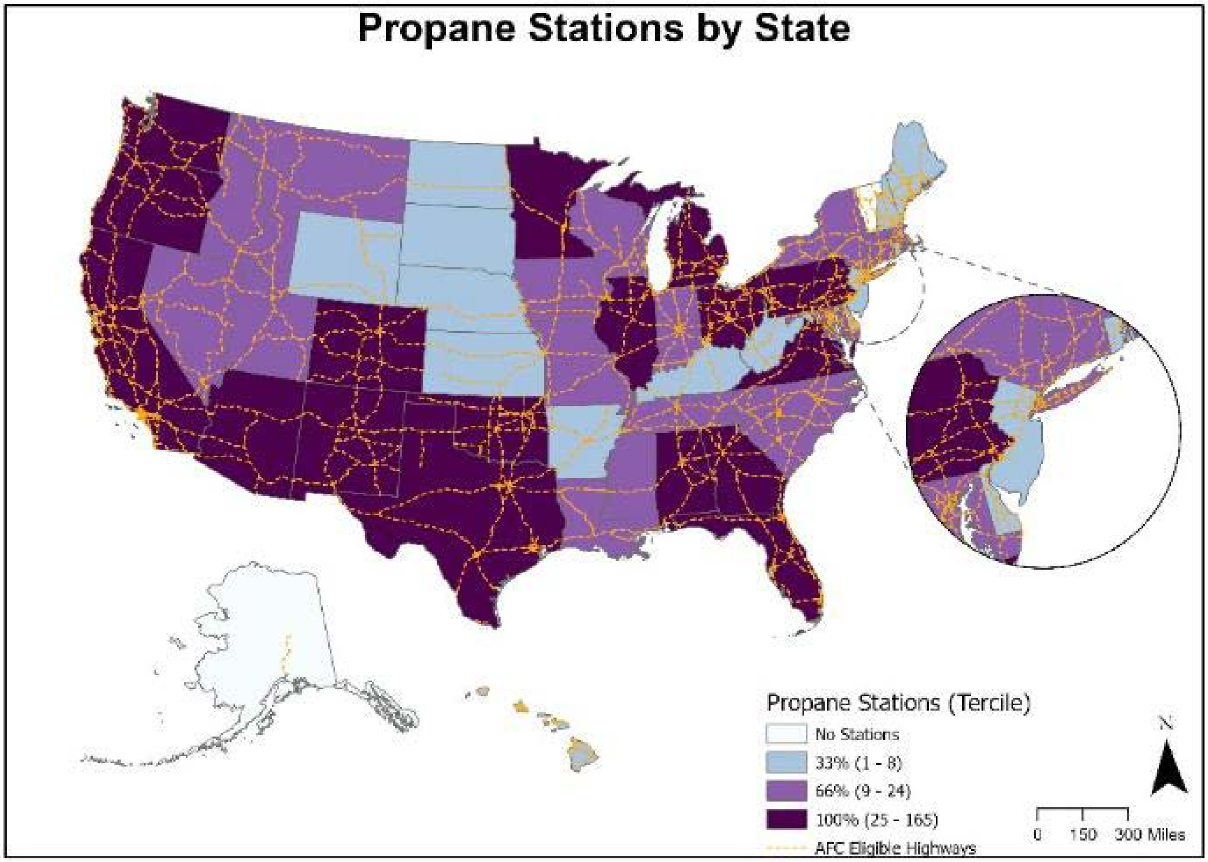

Figure 62. National stock of corridor-eligible propane stations

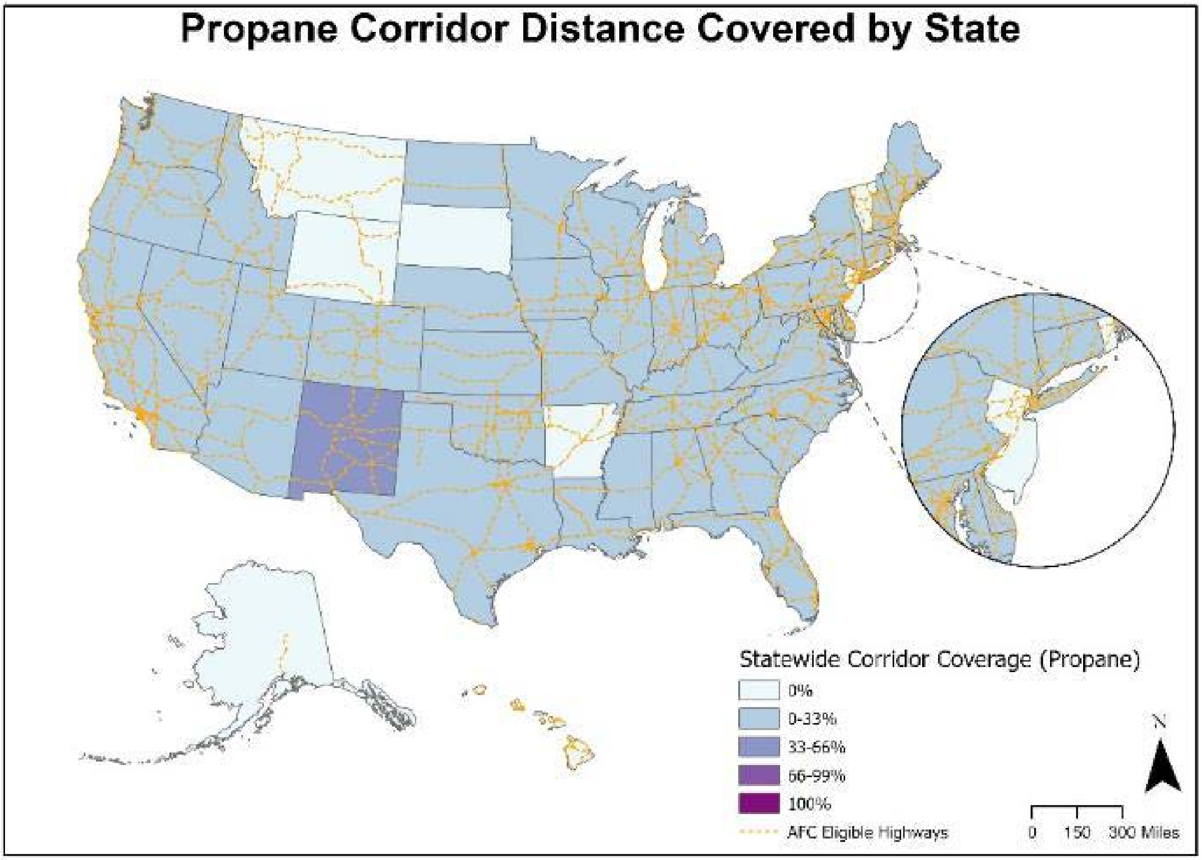

Figure 63. Statewide corridor coverage of valid propane corridors

6.2.6 Medium- and Heavy-Duty Considerations

The AFDC also stores data for CNG and LNG stations that support medium- and heavy-duty vehicles. From the subset of CNG and LNG stations that are eligible for corridors, all LNG stations are also heavy-duty capable, and 17.9% of CNG stations were medium duty and 80.5% were heavy duty. Figure 64 and Figure 65 show the LNG and CNG stations by vehicle class, respectively.

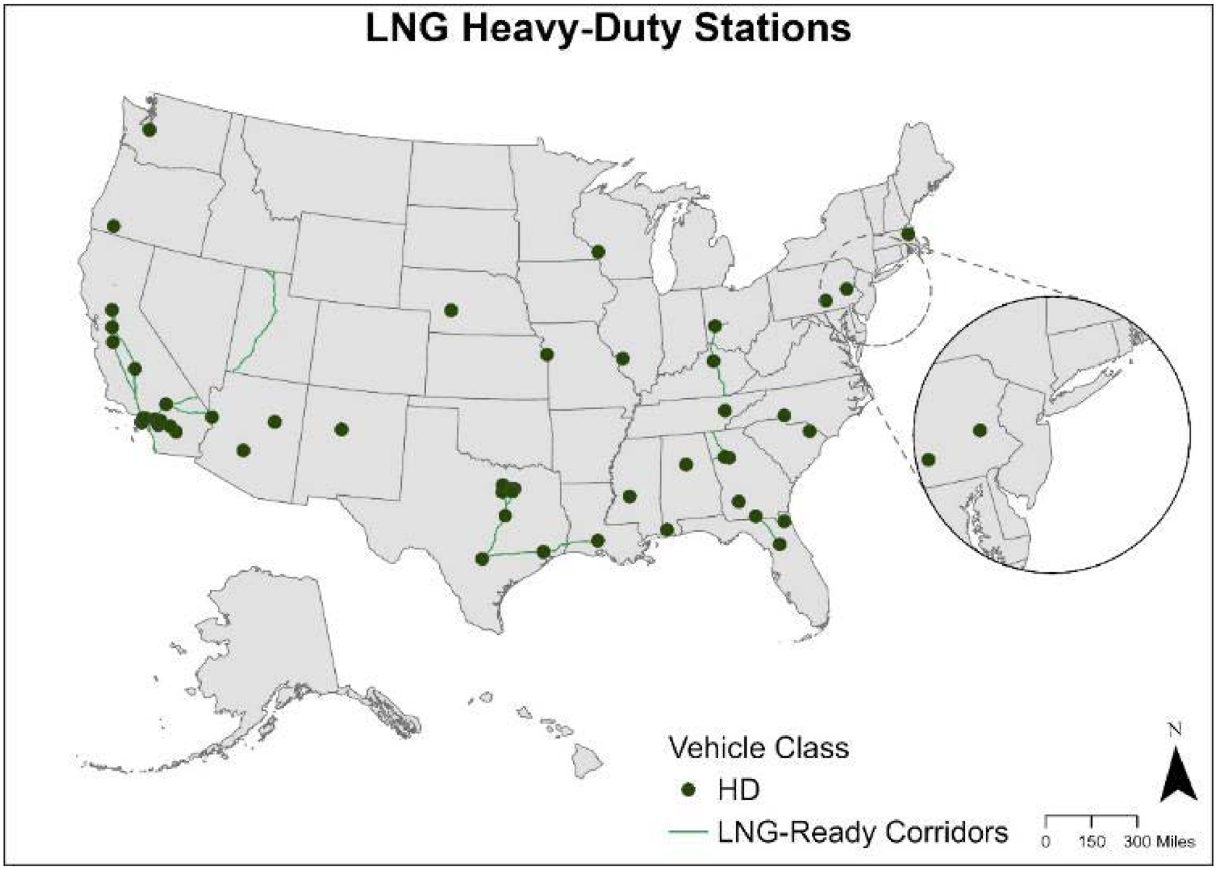

Figure 64. LNG heavy-duty corridor-valid stations

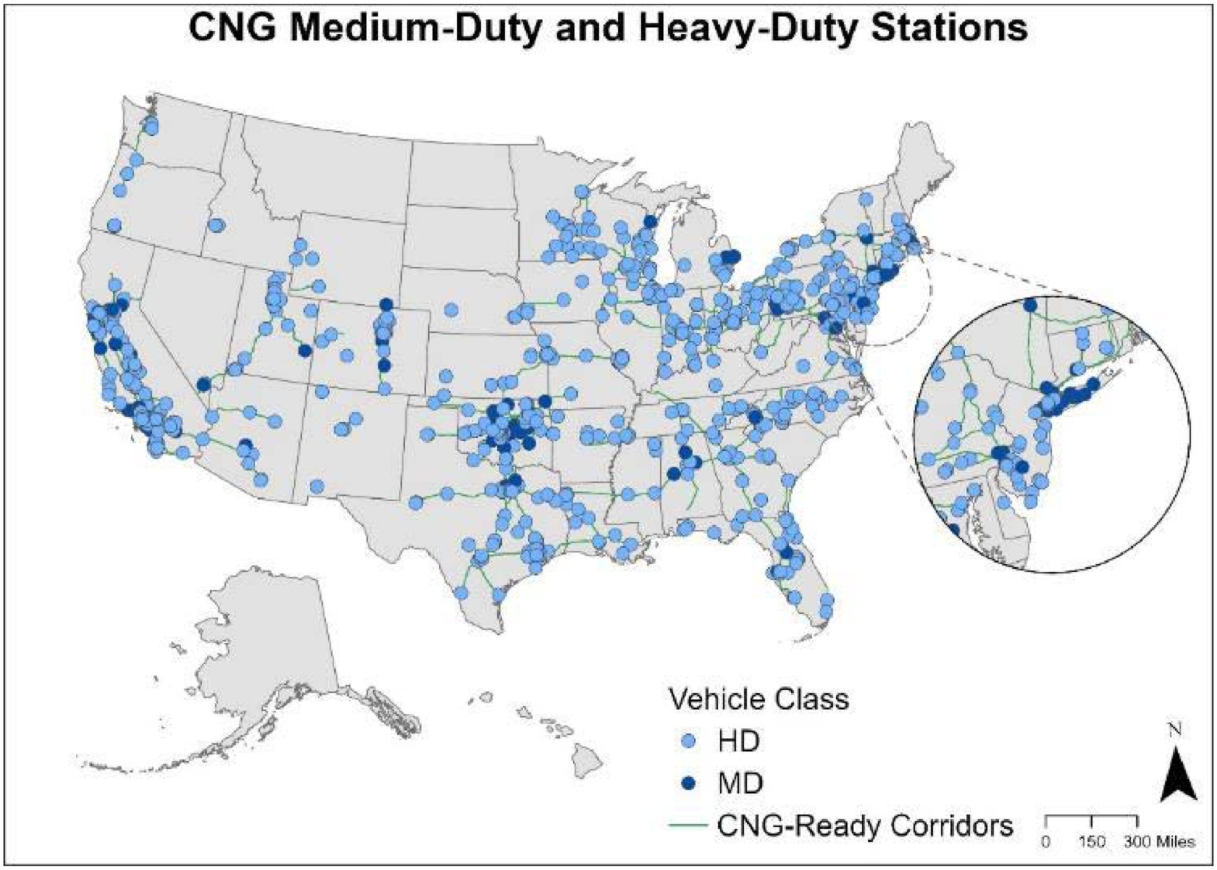

Figure 65. CNG medium- and heavy-duty corridor-valid stations

6.3 Future Directions of AFCs

Work is in progress for the AFC program that will shift future designations from needing prior nomination from states to automatically identifying when corridors change based on station additions or closures. The first five rounds of the AFC program focused on bolstering the country’s alternative fueling infrastructure toward completion across the National Highway System. While there is still more needed for 100% coverage of AFCs, future work for the next designation rounds may shift focus to corridor security. Future station implementation in terms of AFCs could be prioritized based on whether the new station opens new corridors, lengthens current corridors, or bolsters current corridors. Figure 66 shows an example of how corridors can be viewed from a robustness perspective by looking at average stations per corridor mile.

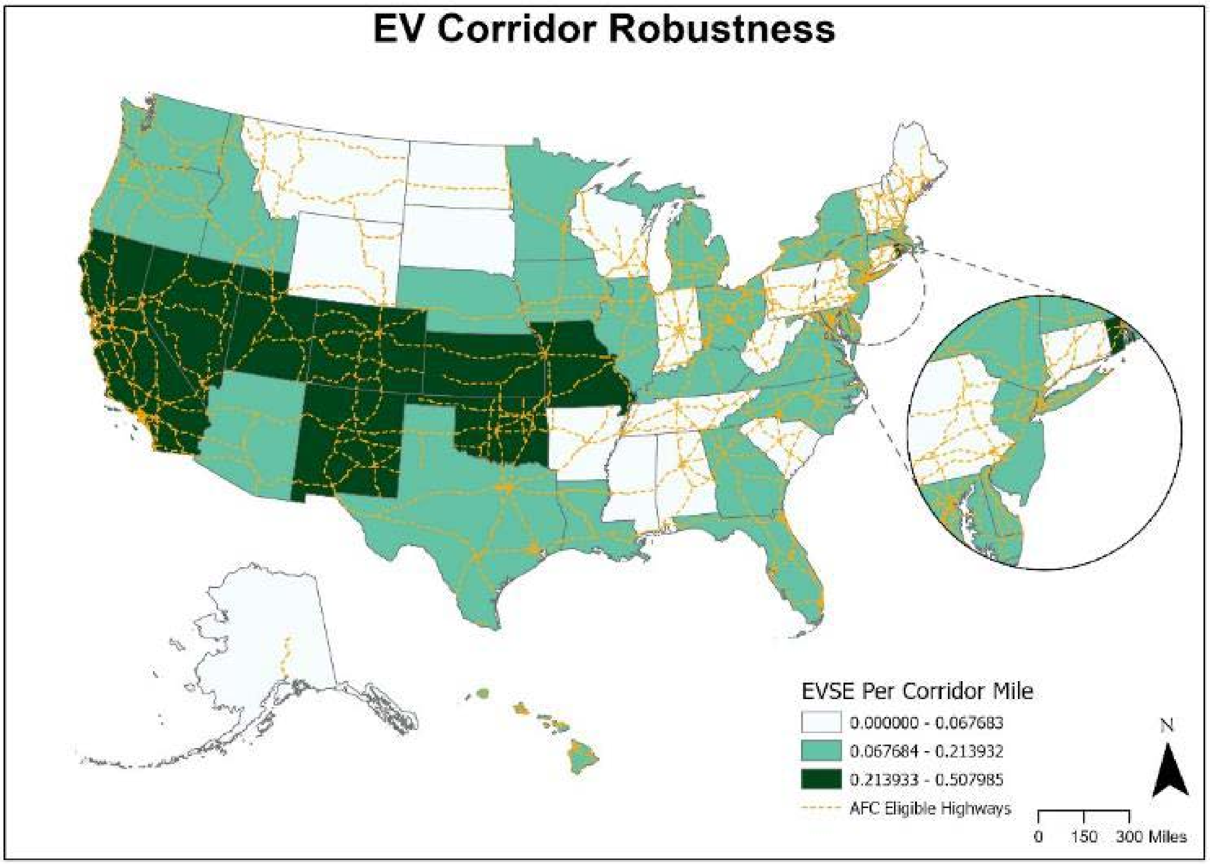

Figure 66. EV corridor robustness symbolized by average number of stations per corridor mile

7 Conclusions

Alternative fueling infrastructure has been broadly increasing since 2005, when growth in E85 stations accelerated and growth in public EV charging stations skyrocketed. This strong growth in public charging stations is understated because EVs are the only AFVs that primarily charge at home. There is a trend toward more powerful charging stations, as DCFC with 250–349 kW power became the most numerous power segment built out in Q1 2022 and now comprises nearly half of all DCFC ports. Although 13 other states have plans to build hydrogen stations, currently Hydrogen fueling infrastructure is largely confined to California (and one in Hawaii).

Most AFVs registered in the United States are FFVs capable of using up to 83% ethanol, although they usually just use gasoline. BEV registrations are growing rapidly and outpacing PHEV registrations. The largest number of PEVs are registered in California, followed by Texas, Florida, Washington, New York, and Georgia. CNG and propane vehicles are difficult to track because many are medium and heavy duty (and therefore outside of the light-duty registration database), and many of the light-duty vehicles are conversions that are registered as conventional vehicles. Therefore, the number of AFV models available for a given fuel is a helpful sign of interest in that fuel. Light-duty FFVs and CNG models have been decreasing since 2015 and were overtaken by PEV models in 2016. Heavy-duty vehicle fuel type is largely determined by the vehicle type, application, and duty cycle. CNG dominates transit buses, shuttle buses, and refuse trucks, while biodiesel leads semi-trucks, delivery trucks, and school buses. Most of these fleets have centralized operations and can operate on one refueling station, except for semi-trucks, which need corridors. Hydrogen FCEVs are in a unique position because they are almost all registered in California.

Fuel prices vary widely between fuels, with electricity always being the least expensive when accounting for the inherent efficiency advantage of EVs. CNG is almost always the second-least expensive, and propane tends to be the most expensive per GGE. Total station costs (regardless of how many vehicles refuel at a given station) tend to be highest for hydrogen stations, then CNG stations, and then a toss-up between propane and EV charging stations. EV charging stations have the highest variance, with the most significant drivers of equipment costs being the power rating of the charger, the existing grid power capacity at the site, and the location of the chargers within the site.

Alternative fueling infrastructure is heavily impacted by related laws and incentives. The number of new federal, state, and utility incentives related to alternative fuels, advanced vehicles, and other strategies in 2022 exceeded all previous years in the AFDC 21-year record. Most of this growth was in PEV and charging infrastructure incentives, with the two most substantial being the federal BIL and IRA.

EV charging stations are becoming more effective and less expensive due to some notable technology trends. They are becoming more powerful and therefore faster at charging. There is a new focus on ensuring that they are reliable, which has been identified as a significant problem and will be the focus of an upcoming NREL/NHTSA report. Advances are being made in next-generation technologies such as wireless charging, overhead pantograph chargers, and battery swap stations. Battery technologies are also impacting the formation of EV charging infrastructure as they are increasing in range and charging speed while decreasing in price. Two

NREL scenario models—ADOPT and TEMPO—simulate the complex relationship between PEV charging infrastructure, numerous other factors, and PEV adoption. ADOPT also addresses CNG and hydrogen vehicle markets.

Hydrogen and fuel cells offer significant near-term opportunities for applications requiring long driving ranges, fast fueling, and large or heavy payloads. Hydrogen prices continue to drop, and California and other states view hydrogen as a complement to achieving zero carbon emissions in sectors where batteries would be too large and expensive to replace conventional vehicles with PEVs. AFCs have been developed by FHWA and are being expanded for all five of the alternative fuels to enable vehicles to travel long ranges. The corridors for PEVs have been greatly accelerated by substantial funding and processes set forth in the BIL.

By defining and assessing the alternative fueling infrastructure in the U.S., this report has set the stage for upcoming work analyzing the trends and correlations between PEV adoptions and the development of public charging infrastructure. The myriad variables that impact these correlations will also be explored, with the end goal of better understanding the impact that PEV charging infrastructure has on PEV adoption.

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Appendix A: Validation of the ADOPT Model

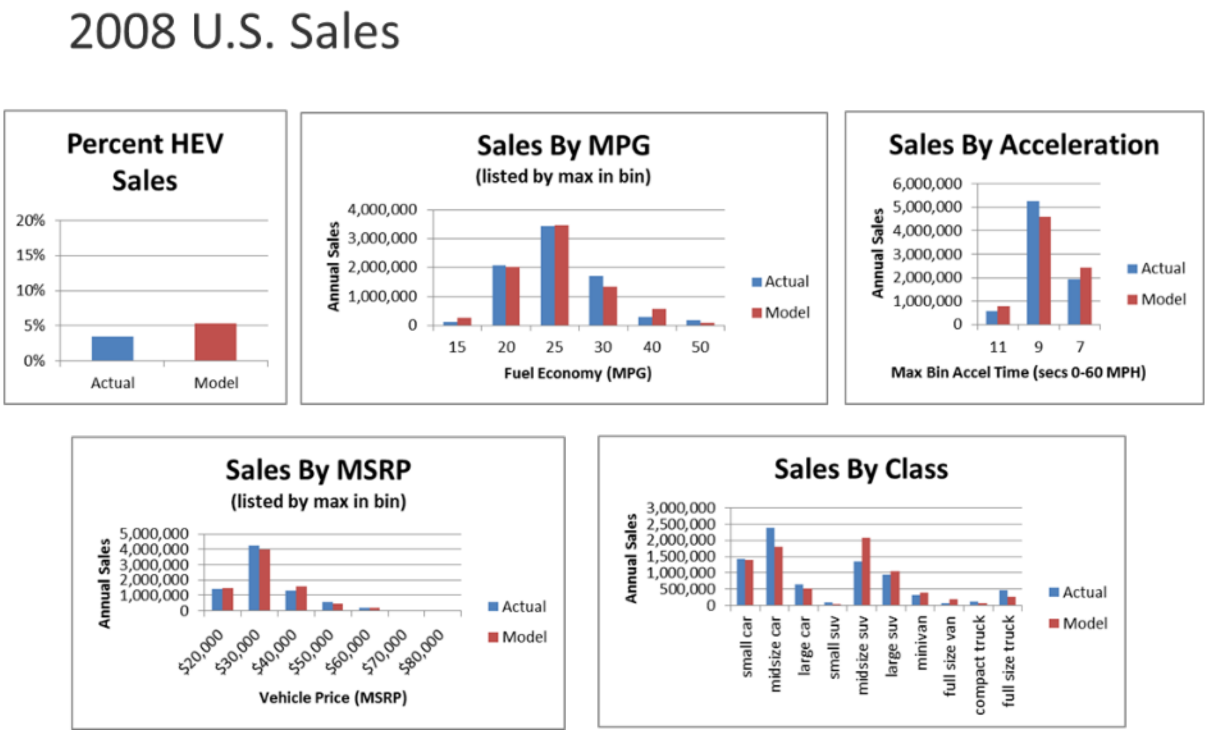

Figure A-1. ADOPT sales validation 2008.

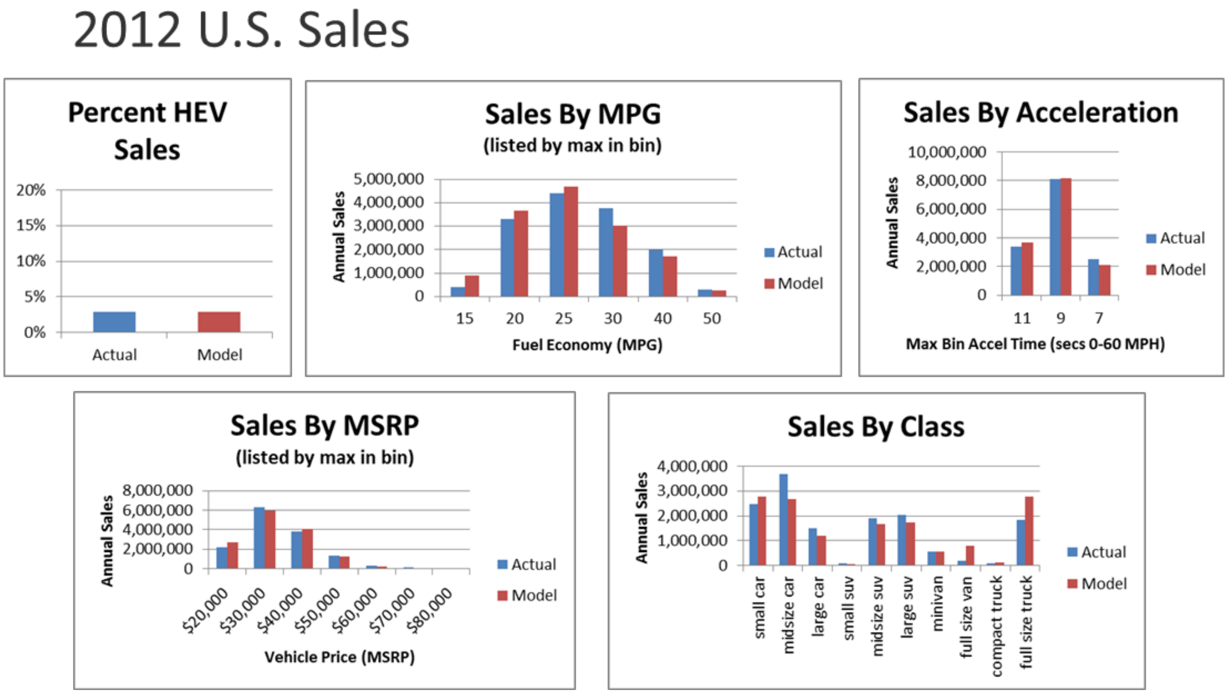

Figure A-2. ADOPT sales validation 2012.

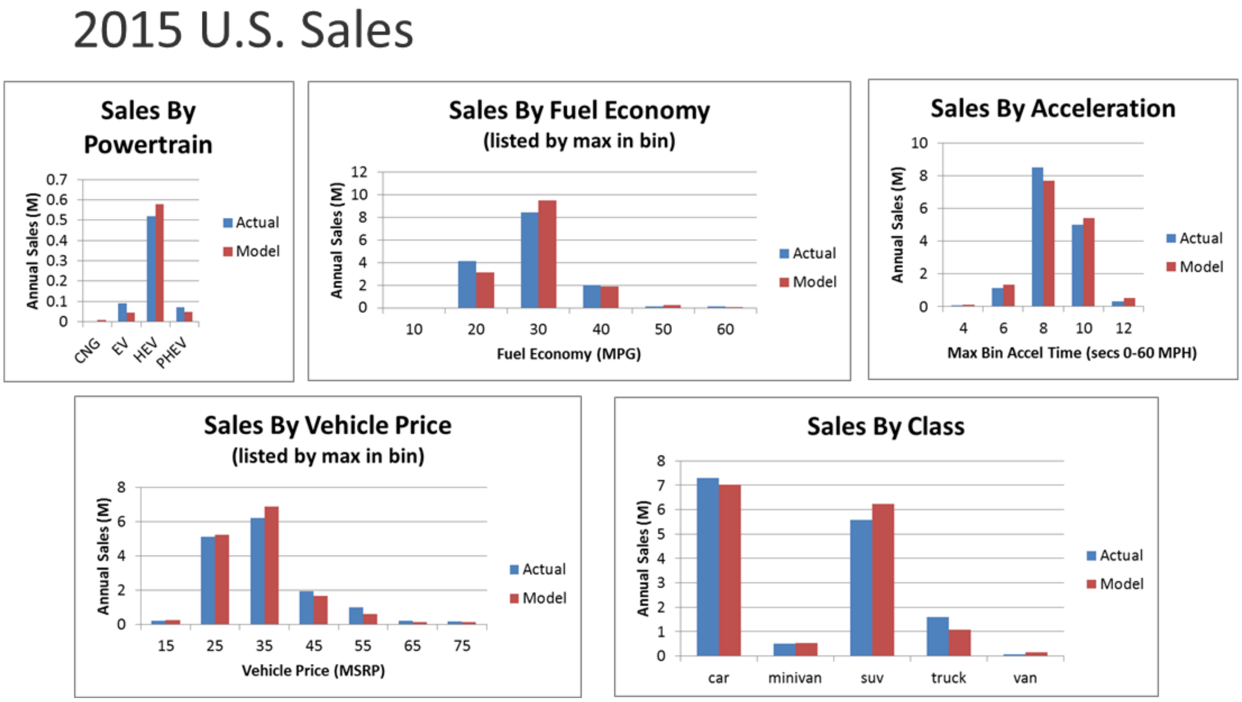

Figure A-3. ADOPT sales validation 2015.

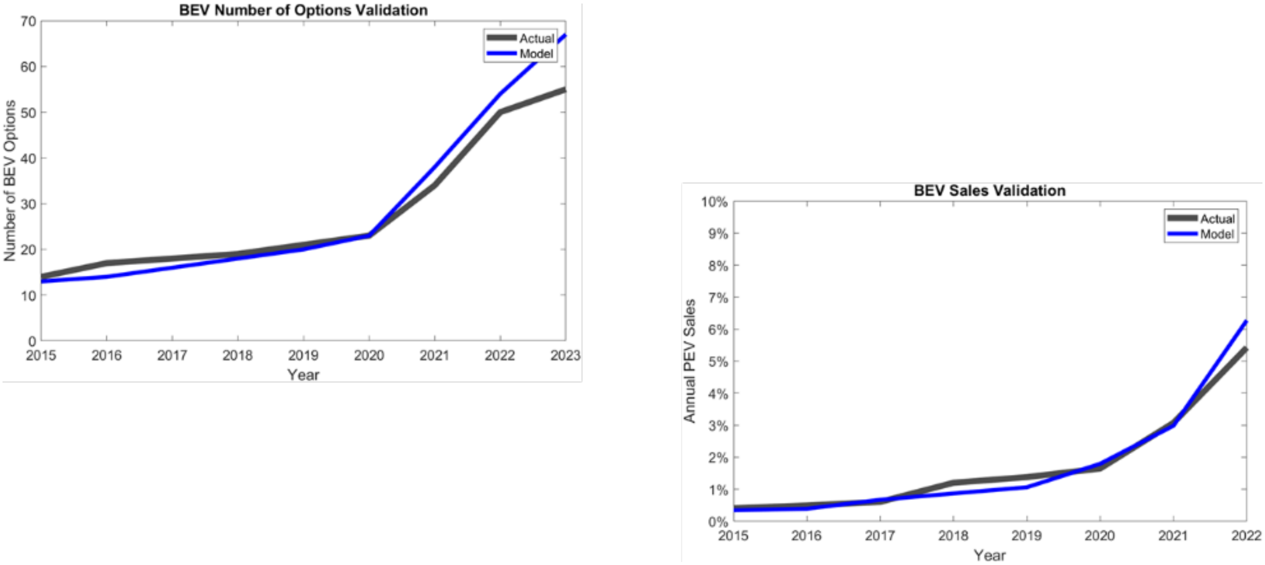

Figure A-4. ADOPT validation for the number of BEVs endogenously created through time and their sales through time.