BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	
	)	R 2024-017
PROPOSED CLEAN CAR AND	)	
TRUCK STANDARDS: PROPOSED 35 ILL.	)	(Rulemaking – Air)
ADM. CODE 242	)	

NOTICE OF FILING

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(VIA ELECTRONIC MAIL)

(SEE PERSONS ON ATTACHED SERVICE LIST)

PLEASE TAKE NOTICE that I have today filed with the Office of the Clerk of the Illinois Pollution Control Board, **EXHIBITS INTENDED FOR USED DURING QUESTIONING AT FIRST HEARING** on behalf of THE ALLIANCE FOR AUTOMOTIVE INNOVATION, copies of which are hereby served upon you.

Respectfully submitted,
Alliance for Automotive Innovation

By: /s/ *Melissa S. Brown*______
One of Its Attorneys

Dated: November 27, 2024

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Date: November 27, 2024

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BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
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PROPOSED CLEAN CAR AND	)	
TRUCK STANDARDS: PROPOSED 35 ILL.	)	(Rulemaking – Air)
ADM. CODE 242	)	

THE ALLIANCE FOR AUTOMOTIVE INNOVATION'S
EXHIBITS INTENDED FOR USE DURING QUESTIONING AT FIRST HEARING

The Alliance for Automotive Innovation ("Auto Innovators"), by and through its attorneys, pursuant to the Illinois Pollution Control Board's ("Board") Hearing Officer Order dated November 13, 2024, hereby files the exhibits intended to be used by the Auto Innovators at the First Hearing when posing follow-up questions to Proponents' witnesses. The exhibits are attached hereto and marked as Exhibits A, B, C, and D.

Table of Contents of Exhibits

Exhibit	Description	Pages
A	National Renewable Energy Laboratory report titled "The 2030 National Charging Network: Estimating U.S. Light Duty Demand for Electric Vehicle Charging Infrastructure"	1-81
B	Automotive News article titled "47 States fail to meet the ideal ratio of chargers to EVs, report says"	82-89
C	Argonne National Laboratory Final Report titled "Cost Analysis and Projections for U.S.-Manufactured Automotive Lithium-ion Batteries"	90-146
D	Alliance for Automotive Innovation Second Quarter 2024 report titled "Get Connected: Electric Vehicle Quarterly Report"	147-167

Respectfully submitted,

ALLIANCE FOR
AUTOMOTIVE INNOVATION

Dated: November 27, 2024

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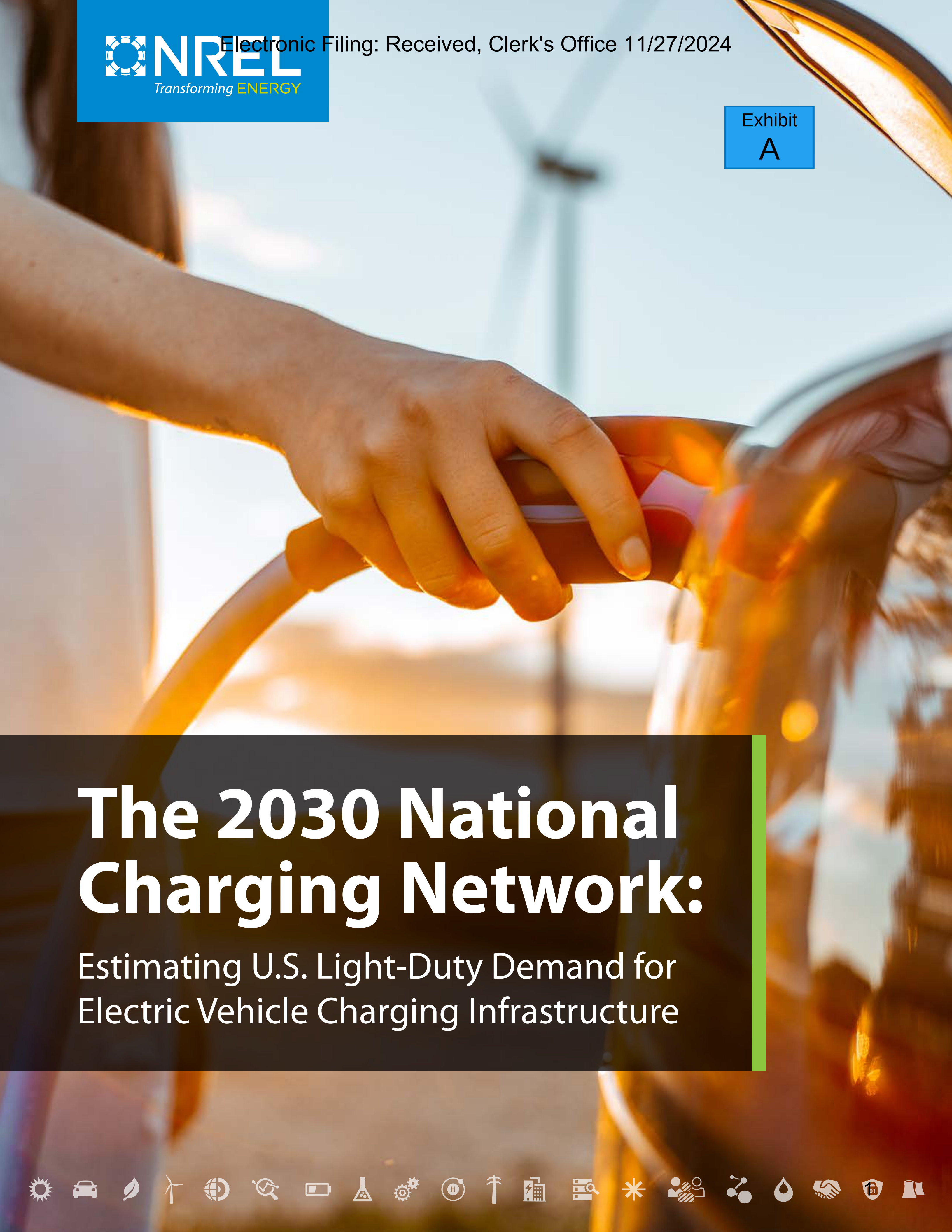
NREL Transforming ENERGY

Exhibit A



The 2030 National Charging Network:

Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure

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Special thanks to external reviewers who provided feedback during various phases of this work. While reviewers were critical to improving the quality of this analysis, the views expressed in this report are not necessarily a reflection of their (or their organization's) opinions. External reviewers included:

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List of Acronyms

BEV	battery-electric vehicle
CBSA	core-based statistical area
CCS	Combined Charging System
DC	direct current
DOE	U.S. Department of Energy
EV	electric vehicle
EVI-X	electric vehicle infrastructure analysis tools
EVSE	electric vehicle supply equipment
FHWA	Federal Highway Administration
ICCT	International Council on Clean Transportation
Joint Office	Joint Office of Energy and Transportation
L1	Level 1
L2	Level 2
LDV	light-duty vehicle
NACS	North American Charging Specification
NHTS	National Household Travel Survey
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
SFH	single-family home
SOC	state of charge
TAF	Traveler Analysis Framework
TNC	transportation network company
VMT	vehicle miles traveled
ZEV	zero-emission vehicle

Executive Summary

U.S. climate goals for economywide net-zero greenhouse gas emissions by 2050 will require rapid decarbonization of the light-duty vehicle[1] fleet, and plug-in electric vehicles (PEVs) are poised to become the preferred technology for achieving this end (U.S. Department of Energy 2023). The speed of this intended transition to PEVs is evident in actions taken by government and private industry, both in the United States and globally. New PEV sales have reached 7%–10% of the U.S. light-duty market as of early 2023 (Argonne National Laboratory 2023). Globally, PEV sales accounted for 14% of the light-duty market in 2022, with China and Europe at 29% and 21%, respectively (IEA 2023). A 2021 executive order (Executive Office of the President 2021) targets 50% of U.S. passenger car and light truck sales as zero-emission vehicles (ZEVs) by 2030, and California has established requirements for 100% light-duty ZEV sales by 2035 (California Air Resources Board 2022), with many states adopting or considering similar regulations (Khatib 2022). These goals were set prior to passage of the landmark U.S. Bipartisan Infrastructure Law and Inflation Reduction Act, which provide substantial policy support through tax credits and investment grants (Electrification Coalition 2023). Companies in the automotive industry have committed to this transition, with most companies rapidly expanding offerings (Bartlett and Preston 2023) and many pledging to become ZEV-only manufacturers. Tesla has been a ZEV-only company since its inception in 2003; Audi, Fiat, Volvo, and Mercedes-Benz are targeting ZEV-only sales by 2030; and General Motors and Honda are targeting ZEV-only sales by 2035 and 2040, respectively (Bloomberg New Energy Finance 2022). The combination of policy action and industry goal-setting has led analysts to project that by 2030, PEVs could account for 48%–61% of the U.S. light-duty market (Slowik et al. 2023). This transition is unprecedented in the history of the automotive industry and will require support across multiple domains, including adequate supply chains, favorable public policy, broad consumer education, proactive grid integration, and (germane to this report) a national charging network.

As established by the Infrastructure Investment and Jobs Act, also known as the Bipartisan Infrastructure Law, the Joint Office of Energy and Transportation (Joint Office) is setting the vision for a national charging network that is *convenient, affordable, reliable, and equitable to enable a future where everyone can ride and drive electric*. This report supports the vision of the Joint Office by presenting a quantitative needs assessment[2] for a national charging network capable of supporting 30–42 million PEVs on the road by 2030.[3]

[1] This study considers personally owned, light-duty vehicles with gross vehicle weight rating of 8,500 pounds or less. Importantly, this definition includes vehicles driven for transportation network companies (ride-hailing) but excludes motorcycles, light-duty commercial vehicles, and Class 2b and 3 work trucks, the implications of which are discussed in Section 4 of this report.

[2] This study is presented as a needs assessment where the national charging network is sized relative to simulated demand from a hypothetical PEV fleet. This is slightly different from an infrastructure forecast, which might make considerations for charging providers being incentivized (by private investors or public funding) to future-proof investments, install charging in quantities far exceeding demand, or deploy charging as part of a larger business model that considers utilization as a secondary metric of success.

[3] National PEV fleet size scenarios have been developed using the National Renewable Energy Laboratory's Transportation Energy & Mobility Pathway Options (TEMPO) model and are consistent with multiple 2030 scenarios developed by third parties. Please see Section 2.2.1 for additional details.

Estimating infrastructure needs at the national level is a challenging analytic problem that requires quantifying the needs of future PEV drivers in various use cases, under region-specific environmental conditions, and with consideration for the built environment. This analysis leverages the National Renewable Energy Laboratory's suite of electric vehicle infrastructure analysis tools (EVI-X) and the best available real-world data describing PEV adoption patterns, vehicle technology, residential access, travel profiles, and charging behavior to estimate future charging needs. Multiple PEV charging use cases are considered, including typical needs to accommodate daily driving for those with and without residential access, corridor-based charging[4] supporting long-distance road trips, and ride-hailing electrification. While the analysis is national in scope, the simulation framework enables inspection of results by state and city, with parametric sensitivity analysis used to test a range of assumptions. This modeling approach is used to draw the following conclusions:

- **Convenient and affordable charging at/near home is core to the ecosystem but must be complemented by reliable public fast charging.** Industry focus groups with prospective PEV buyers consistently reveal that consumers want charging that is as fast as possible. However, consumer preferences tend to shift after a PEV purchase is made and lived experience with charging is accumulated. Home charging has been shown to be the preference of many PEV owners due to its cost and convenience. This dichotomy suggests that reliable public fast charging is key to consumer confidence, but also that a successful charging ecosystem will provide the right balance of fast charging and convenient destination charging in the appropriate locations.[5] Using sophisticated planning tools, this analysis finds that a national network in 2030 could be composed of 26–35 million ports to support 30–42 million PEVs. For a mid-adoption scenario of 33 million PEVs, a national network of 28 million ports could consist of:
    - 26.8 million privately accessible Level 1 and Level 2 charging ports located at single-family homes, multifamily properties, and workplaces[6]
    - 182,000 publicly accessible fast charging ports along highway corridors and in local communities
    - 1 million publicly accessible Level 2 charging ports primarily located near homes and workplaces (including in high-density neighborhoods, at office buildings, and at retail outlets).

  In contrast to gas stations, which typically require dedicated stops to public locations, the PEV charging network has the potential to provide charging in locations that do not

[4] This study defines corridors as all roads within the National Highway System (Federal Highway Administration 2017), including the Interstate Highway System, as well as other roads important to national transportation.
[5] This study considers Level 1 and Level 2 alternating-current (AC) chargers rated between 1.4 and 19.2 kW as destination chargers for light-duty vehicles. Direct-current (DC) chargers with nominal power ratings between 150 and 350+ kW are considered fast chargers for light-duty vehicles in this work. It is the opinion of the authors that referring to all DC charging as "DC fast charging" (DCFC) (as is typically done) is inappropriate given that the use of "fast" as a descriptor ultimately depends on the capacity of the battery being charged. As larger capacity light-duty PEVs enter the market and medium- and heavy-duty model options emerge, it is likely the case that some DC chargers will actually be used to slowly charge PEVs. Thus, the common practice of referring to all DC charging as DCFC is noticeably absent from this report.
[6] This analysis employs a novel charging infrastructure taxonomy that considers workplace charging as a mix of publicly and privately accessible infrastructure at a variety of location types as discussed in Section 2.3.2.

require an additional trip or stop. Charging at locations with long dwell times (at/near home, work, or other destinations) has the potential to provide drivers with a more convenient experience. This network must include reliable fast charging solutions to support PEV use cases not easily enabled by destination charging, including long-distance travel and ride-hailing, and to make electric vehicle ownership attainable for those without reliable access charging while at home or at work.

- **Fast charging serves multiple use cases, and technology is evolving rapidly.** The majority of the 182,000 fast charging ports (65%) simulated in the mid-adoption scenario meet the needs of those without access to reliable overnight residential charging (estimated as 3 million vehicles by 2030 in the mid-adoption scenario). Support for ride-hailing drivers and travelers making long-distance trips accounts for the remainder of simulated fast charging demand (21% and 14%, respectively). While most near-term fast charging demand is simulated as being met by 150-kW DC chargers, advances in battery technology are expected to stimulate demand for higher-power charging. We estimate that by 2030, DC chargers rated for at least 350 kW will be the most prevalent technology across the national fast charging network.
- **The size and composition of the 2030 national public charging network will ultimately depend on evolving consumer behavior and will vary by community.** While growth in all types of charging is necessary, the eventual size and composition of the national public charging network will ultimately depend on the national rate of PEV adoption, PEV preferences across urban, suburban, and rural locations, access to residential/overnight charging, and individual charging preferences. Sensitivity analysis suggests that the size (as measured by number of ports) of the 2030 national public charging network could vary by up to 50% (excluding privately accessible infrastructure) by varying the share of plug-in hybrids, driver charging etiquette, and access to private workplace charging (see alternate scenarios presented in Section 3.3). Additionally, the national network is expected to vary dramatically by community. For example, densely populated areas will require significant investments to support those without residential access and ride-hailing electrification, while more rural areas are expected to require fast charging along highways to support long-distance travel for those passing through.
- **Continued investments in U.S. charging infrastructure are necessary.** A cumulative national capital investment of $53–$127 billion[7] in charging infrastructure is needed by 2030 (including private residential charging) to support 33 million PEVs. The large range of potential capital costs found in this study is a result of variable and evolving equipment and installation costs observed within the industry across charging networks, locations, and site designs. The estimated cumulative capital investment includes:
    - $22–$72 billion for privately accessible Level 1 and Level 2 charging ports
    - $27–$44 billion for publicly accessible fast charging ports
    - $5–$11 billion for publicly accessible Level 2 charging ports.

  The cost of grid upgrades and distributed energy resources have been excluded from these estimates. While these excluded costs can be significant in many cases and will

[7] The scope of cost estimates can be generally defined as capital expenses for equipment and installation necessary to support vehicle charging. Please refer to Section 2.3.4 for additional detail.

ultimately be critical in building out the national charging network, they tend to be site-specific and have been deemed out of scope for this analysis.

- **Existing announcements put the United States on a path to meet 2030 investment needs.** This report estimates that a $31–$55-billion cumulative capital investment in publicly accessible charging infrastructure is necessary to support a mid-adoption scenario of 33 million PEVs on the road by 2030. As of March 2023, we estimate $23.7 billion of capital has been announced for publicly accessible light-duty PEV charging infrastructure through the end of the decade,[8] including from private firms, the public sector (including federal, state, and local governments), and electric utilities. Public and private investments in publicly accessible charging infrastructure have accelerated in recent years. If sustained with long-term market certainty grounded in accelerating consumer demand, these public and private investments will put the United States on a path to meeting the infrastructure needs simulated in this report. Existing and future announcements may be able to leverage direct and indirect incentives to deploy charging infrastructure through a variety of programs, including from the Inflation Reduction Act and the Low Carbon Fuel Standard, ultimately extending the reach of announced investments.

While this analysis presents a needs-based assessment where charging infrastructure is brought online simultaneous to growth in the vehicle fleet, actual charging infrastructure will likely be necessary before demand for charging materializes. The position that infrastructure investment should "lead" vehicle deployment is based on the understanding that many drivers will need to see charging available at the locations they frequent and along the highways they travel before becoming confident in the purchase of an electric vehicle (Muratori et al. 2020). On the other hand, infrastructure investment should be careful not to lead vehicle deployment to the point of creating prolonged periods of poor utilization, thereby jeopardizing the financial viability of infrastructure operators.[9] These considerations suggest the balance of supply and demand for charging should be closely monitored at the local level and that steps should be taken to enable the efficient deployment of charging (defined as minimizing soft costs [Nelder and Rogers 2019]), including streamlined permitting and utility service connection processes (Hernandez 2022). While not the case today, an environment where infrastructure can be deployed efficiently enables the industry to responsively balance the supply of infrastructure subject to forecasts for unprecedented increases in demand.

This study leads us to reflect on how charging infrastructure planning has often been analogized to a pyramid, with charging at home as the foundation, public fast charging as the smallest part of the network at the tip of the pyramid, and destination charging away from home occupying the middle of the pyramid. While this concept has served a useful purpose over the years, we recommend a new conceptual model. The balance of public versus private charging and fast

[8] Based on investment tracking conducted by Atlas Public Policy.

[9] While utilization is a key metric to most station owners, it is not the only metric of success. Business models underlying charging networks are complex and evolving, with some stations collocated with more lucrative retail activities (as is the case with most gas stations today offering fuel at lower margins than items in the convenience store) and some stations deployed at a loss to help "complete" the network in areas critical for enabling infrequent, long-distance travel. Business relationships between charging networks, automakers, advertisers, and site hosts also make it difficult to measure the success of an individual station from utilization alone.

charging versus destination charging suggests a planning philosophy akin to a tree, as shown in Figure ES-1.

As with a tree, there are parts of the national charging network that are visible and those that are hidden. Public charging is the visible part of the network that can be seen along highways, at popular destinations, and through data accessible online. Private charging is the hidden part of the network tucked away in personal garages, at apartment complexes, and at certain types of workplaces. This private network is akin to the roots of a tree, as it is foundational to the rest of the system and an enabler for growth in more visible locations.

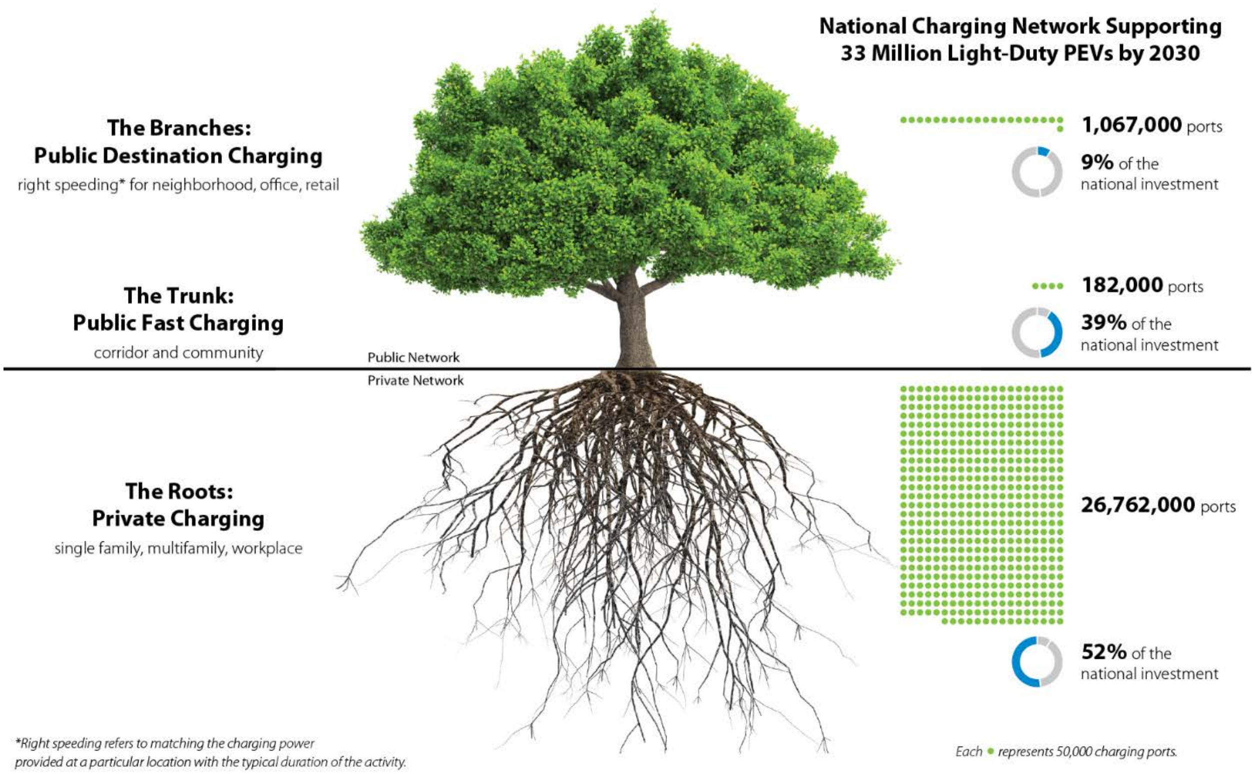

Figure ES-1. Conceptual illustration of national charging infrastructure needs

If access to private charging are the roots of the system, a reliable public fast charging network is the trunk, as it benefits from access to charging at home and other private locations (a key selling point of PEVs) and ultimately helps grow the system by making PEV ownership more convenient (enabling road trips and supporting those without residential access). While fast charging is estimated to be a relatively small part of the national network in terms of number of total ports, it requires significant investment and is vital to enabling future growth by assuring drivers they will be able to charge quickly whenever they need or want.

The last part of the system is a broad set of publicly accessible destination charging locations in dense neighborhoods, office buildings, and retail outlets where the speed of charging can be designed to match typical parking times ("right-speeding"). This network is similar to the branches of a tree in that its existence is contingent on a broad private network and a reliable fast charging network. As with the branches of a tree, the public destination charging network is ill-equipped to grow without the support of charging elsewhere.

This analysis envisions a future national charging network that is strategic in locating the right amount of charging, in the right locations, with appropriate charging power. Ensuring that this infrastructure is reliable will be essential to establishing driver confidence and accelerating widespread adoption of PEVs. A successful national charging network will position PEVs to provide a superior driving experience, lower total cost of ownership for drivers, become profitable for industry participants, and enable grid integration, all while meeting U.S. climate goals.

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1. Introduction

U.S. climate goals for economywide net-zero greenhouse gas emissions by 2050 will require rapid decarbonization of the light-duty vehicle (LDV) fleet, and plug-in electric vehicles (PEVs) are poised to become the preferred technology for achieving this end (U.S. Department of Energy 2023). The speed of this intended transition to PEVs is evident in actions taken by government and private industry, both in the United States and globally. New PEV sales have reached 7%–10% of the U.S. light-duty market as of early 2023 (Argonne National Laboratory 2023). Globally, PEV sales accounted for 14% of the light-duty market in 2022, with China and Europe at 29% and 21%, respectively (IEA 2023). A 2021 executive order (Executive Office of the President 2021) targets 50% of U.S. passenger car and light truck sales as zero-emission vehicles (ZEVs) by 2030, and California has established requirements for 100% light-duty ZEV sales by 2035 (California Air Resources Board 2022), with many states adopting or considering similar regulations (Khatib 2022). These goals were set prior to passage of the landmark U.S. Bipartisan Infrastructure Law and Inflation Reduction Act, which provide substantial policy support through tax credits and investment grants (Electrification Coalition 2023). Companies in the automotive industry have committed to this transition, with most companies rapidly expanding offerings (Bartlett and Preston 2023) and many pledging to become ZEV-only manufacturers. Tesla has been a ZEV-only company since its inception in 2003; Audi, Fiat, Volvo, and Mercedes-Benz are targeting ZEV-only sales by 2030; and General Motors and Honda are targeting ZEV-only sales by 2035 and 2040, respectively (Bloomberg New Energy Finance 2022). The combination of policy action and industry goal-setting has led analysts to project that by 2030, PEVs could account for 48%–61% of the U.S. light-duty market (Slowik et al. 2023). This transition is unprecedented in the history of the automotive industry and will require support across multiple domains, including adequate supply chains, favorable public policy, broad consumer education, proactive grid integration, and (germane to this report) a national charging network.

As established by the 2021 Bipartisan Infrastructure Law, the U.S. Joint Office of Energy and Transportation (Joint Office) is setting the vision for a national charging network that is *convenient, affordable, reliable, and equitable to enable a future where everyone can ride and drive electric*. This report supports the vision of the Joint Office by presenting a quantitative needs assessment for a national charging network capable of supporting 30–42 million PEVs on the road by 2030.

Estimating infrastructure needs at the national level is a challenging analytic problem that requires quantifying the needs of future PEV drivers in various use cases, under region-specific environmental conditions, and with consideration for the built environment. This analysis leverages the National Renewable Energy Laboratory's (NREL's) suite of electric vehicle infrastructure analysis tools (EVI-X) and the best available real-world data describing PEV adoption patterns, vehicle technology, residential access, travel profiles, and charging behavior to estimate future charging needs. Multiple PEV charging use cases are considered, including typical needs to accommodate daily driving for those with and without residential access, corridor-based charging supporting long-distance road trips, and ride-hailing electrification. While the analysis is national in scope, the simulation framework enables inspection of results by state and city, with parametric sensitivity analysis used to test a range of assumptions.

The remainder of Section 1 reviews the current state of the U.S. PEV and electric vehicle supply equipment (EVSE) markets, discusses recent EVSE initiatives and analysis studies, highlights equity considerations in the deployment of charging infrastructure, and outlines the structure used for the remainder of the report.

1.1. Current State of U.S. PEV and EVSE Markets

Mass-market PEV sales began in the United States at the end of 2010 with just a few models available to consumers. As new plug-in models have been introduced and production volumes have increased, sales have accelerated accordingly. It took nearly 8 years to reach 1 million cumulative sales, but just 2 1/2 more years to reach 2 million cumulative sales in June 2021. As of February 2023, U.S. cumulative PEV sales have surpassed 3.4 million, with PEV sales at 7%–10% of all LDVs in early 2023 (Argonne National Laboratory 2023). The growth in PEV sales has been accompanied by a similar growth in PEV capabilities, with electric driving range and maximum charging power improving dramatically in recent years.

The U.S. Department of Energy's (DOE's) Alternative Fueling Station Locator contains information on public and private nonresidential alternative fueling stations in the United States and Canada, including PEV charging infrastructure. PEV charging continues to experience rapidly changing technology and growing infrastructure. According to the Station Locator, as of March 2023, about 132,000 publicly accessible charging ports are currently installed in the United States. This includes about 29,000 direct-current (DC) charging ports and 103,000 Level 2 (L2) ports.

While strides have been made in recent years to improve interoperability[10] of PEV charging, the U.S. network remains fragmented. Today, nearly all U.S. PEV manufacturers equip their new battery-electric vehicles (BEVs) with DC charging inlets compatible with the SAE standard Type 1 Combined Charging System (CCS-1). Tesla, the largest PEV manufacturer in the U.S. and operator of the largest U.S. DC charging network,[11] does not follow this standard. Tesla BEVs sold in the U.S. have historically been equipped with a proprietary inlet type exclusive to Tesla with compatible DC chargers available through the Tesla Supercharger network.

However, Tesla has recently taken steps to open their charging network. In a November 2022 release, Tesla announced they are opening their connector design to other charging providers and vehicles manufacturers (Tesla 2022). Tesla's North American Charging Specification (NACS) is currently available at select third-party charging stations, including some locations on EVgo's network (EVgo 2023). Tesla has also recently taken steps to open their Supercharger network to other vehicles (Tesla 2023). A small number of Superchargers in New York and California have recently been retrofitted to support charging vehicles with CCS-1 inlets relying on activation through the Tesla mobile app. Tesla has announced plans to make 7,500 chargers publicly accessible to non-Tesla PEVs by the end of 2024 (including 3,500 Superchargers) (The White House 2023). Finally, Tesla has recently reached agreements that will soon give all Ford and

[10] While interoperability related to connector compatibility is discussed in the body of the report, interoperability of competing charging networks to allow for roaming is another important dimension. Absence of network-to-network interoperability forces drivers to maintain multiple sets of apps and credentials in order to access individual charging networks (a substandard experience relative to the convenience of legacy fueling infrastructure).

[11] As of March 2023.

General Motors customers access to the majority of Tesla's North American Supercharger network via adapters, with new Ford and General Motors BEVs being equipped with NACS inlets starting in 2025 (Ford Motor Company 2023; General Motors 2023).

The U.S. L2 network also remains fragmented, but to a lesser extent. There are two L2 connectors used in the United States: the SAE J1772 connector (used by all PEV manufacturers except Tesla) and the Tesla NACS connector. The NACS connector is natively only compatible with Tesla vehicles; however, an adapter is available that allows Tesla vehicles to charge using J1772 connectors. L2 NACS connectors are currently available as part of Tesla's network of Destination Chargers and account for 12% of all publicly accessible L2 charging ports.

Despite the fragmented nature of today's charging ecosystem, this analysis makes no attempt to develop charging infrastructure scenarios by connector. Such scenarios would require estimating future market shares and corporate strategies for different light-duty PEV manufacturers to project the future interoperability of charging networks, which is beyond the purview of this analysis. The remainder of this report will not address interoperability challenges or fragmentation between connector types. Additional information on PEV charging infrastructure trends can be found on DOE's Alternative Fuels Data Center (2023b).

1.2. Recent Charging Infrastructure Investment and Analysis Studies

Significant investments are being made in U.S. charging infrastructure for PEVs. At the forefront of these investments is the federal government's commitment to invest up to $7.5 billion into publicly accessible PEV charging infrastructure through the Bipartisan Infrastructure Law. This consists of the $5.0-billion National Electric Vehicle Infrastructure (NEVI) Formula Program administered by the U.S. Department of Transportation through the states, District of Columbia, and Puerto Rico and the $2.5-billion Charging and Fueling Infrastructure Discretionary Grant Program being administered through the U.S. Department of Transportation (the latter including eligibility for all alternative fuel infrastructure). An additional $3.0 billion in public investment has been made across all levels of government, led by programs from the state of California.

Atlas Public Policy's EV Hub tracks domestic investments in PEV charging infrastructure. As of April 1, 2023, EV Hub reports a cumulative total of $11.2 billion in charging infrastructure announcements from the private sector, led by companies including Tesla, Electrify America, BP, General Motors, Daimler, and Mercedes. This excludes an estimated $3.0 billion in capital raised by charging companies (including ChargePoint, EVgo, Blink, and Volta), some percentage of which is expected to be invested in EVSE hardware and installation. EV Hub reports an additional $2.0 billion in approved utility filings, led by utilities including Southern California Edison, Consolidated Edison, and Pacific Gas & Electric.

As of March 2023, we estimate $23.7 billion has been announced for publicly accessible light-duty PEV charging infrastructure through the end of the decade.[12] Importantly, this estimate excludes financial incentives to deploy charging infrastructure through a variety of programs,

[12] While based on data provided by Atlas Public Policy, NREL's estimate deviates from a recent Atlas Public Policy assessment (Nigro 2023), which reports cumulative U.S. public charging infrastructure funding at $19.9 billion. This discrepancy is primarily due to NREL's inclusion of funding assumed to primarily (though not exclusively) support deployment of public charging infrastructure (most notably the Charging and Fueling Infrastructure Discretionary Grant Program, which includes eligibility for all alternative fuel infrastructure).

including from the Inflation Reduction Act and the Low Carbon Fuel Standard in place in California, Oregon, and Washington. While these incentives are significant and will ultimately extend the reach of announced investments, their value is dependent on factors outside the purview of this analysis and are thus excluded from this report's estimate of announced charging infrastructure investments.

At least four existing studies have attempted to estimate the national charging infrastructure investment need for light-duty PEVs. The International Council on Clean Transportation's (ICCT's) 2021 white paper "Charging Up America: Assessing the Growing Need for U.S. Charging Infrastructure Through 2030" estimates that 26 million light-duty PEVs would require a total of 2.4 million workplace and public charging ports (Bauer et al. 2021). This results in an estimated $28-billion investment for nonresidential charging infrastructure (including installation labor costs but excluding utility upgrades). When accounting for private-access charging at single-family and multifamily residences (estimated at $20.5 billion), ICCT finds a total of $48.5 billion in cumulative investment will be needed by the end of the decade.

Atlas Public Policy's 2021 *U.S. Passenger Vehicle Electrification Infrastructure Assessment* examined the charging infrastructure investment necessary through 2030 to put the United States on a path to 100% light-duty PEV sales by 2035 (McKenzie and Nigro 2021). Atlas finds that $39 billion in public charging infrastructure will be necessary by 2030 (including installation labor costs but excluding utility upgrades). When accounting for private-access charging at single-family and multifamily residences and private depot charging, Atlas finds a total need of $87 billion in cumulative investment by 2030.

McKinsey & Company's 2022 article "Building the electric-vehicle charging infrastructure America needs" examines a scenario with 50% of LDV sales as PEVs by 2030 (Kampshoff et al. 2022). This analysis estimates 1.2 million public chargers and 28 million private chargers will be necessary by 2030 (a 20x increase over today's network).

S&P Global Mobility's 2023 report *EV Chargers: How many do we need?* finds that U.S. PEV charging infrastructure will need to quadruple by 2025 and grow by a factor of 8 by 2030 (S&P Global Mobility 2023). Assuming 28 million PEVs on the road by 2030, this report estimates 2.13 million Level 2 and 172,000 DC chargers in public locations will be necessary. These estimates are in addition to privately accessible residential chargers.

These findings are all consistent in showing that continued investment in U.S. charging infrastructure is necessary to support the electrification of the light-duty fleet. A comparison of these findings with this report is included in the discussion section.

1.3. Equity Considerations

Equitable deployment of charging infrastructure for all populations is of critical importance as investments accelerate. This analysis indirectly addresses equitable infrastructure deployment by considering the needs of individuals without reliable access to residential charging, drivers for ride-hailing platforms, and (in some cases) ride-hailing drivers without access to residential charging. These individuals are more likely to be from low-income households, renters, and those without access to off-street parking. As discussed later in this report, charging infrastructure supporting these populations is explicitly considered in this study.

A broader set of analytic tools that directly address equitable charging infrastructure deployment is being developed by the Joint Office United Support for Transportation (JUST) Lab Consortium with leadership from Argonne National Laboratory, Lawrence Berkeley National Laboratory, and NREL (Joint Office of Energy and Transportation 2023). The JUST Lab Consortium is conducting actionable research on integrating equity into federally funded PEV infrastructure deployment efforts. This consortium builds on prior efforts at each lab that have developed foundational capabilities, including launch of an Electric Vehicle Charging Justice40 Map (Argonne National Laboratory 2022), application of geospatial analysis to prioritize charging deployments for underserved communities (Zhou et al. 2022), and development of the Electric Vehicle Infrastructure for Equity (EVI-Equity) model for quantifying equity metrics of proposed charging network designs (Lee et al. 2022). Embedding these tools within the national framework presented in this report is a key objective for future research.

1.4. Report Motivation and Structure

This report is being published at a unique time in the evolution of the national charging network. In September 2022, the U.S. Department of Transportation, in consultation and coordination with the new Joint Office, approved Year 1 NEVI plans for all 50 states (plus Washington, D.C., and Puerto Rico) as part of a $5-billion investment funded by the Bipartisan Infrastructure Law (U.S. Department of Transportation 2022). In March 2023, the U.S. Department of Transportation opened applications for the first round of funding under the $2.5-billion Charging and Fueling Infrastructure Discretionary Grant Program, also funded by the Bipartisan Infrastructure Law (U.S. Department of Transportation 2023). In the private sector, Tesla continues its trajectory of expanding the country's largest DC network (including opening some Superchargers to non-Tesla vehicles), Electrify America is halfway through its 10-year, $2-billion mandatory investment period, and many other charging networks are entering the market and expanding their footprint.

Amidst these ongoing investments, this work aims to provide a shared point of reference for the near-term (through 2030) charging infrastructure needs of U.S. light-duty PEVs. Given the broad coalition of stakeholders dependent on and investing in charging infrastructure (including automotive manufacturers, charging network providers, electric utilities, and governments at every level), a public document of this nature can serve as a common reference for the industry.

The remainder of this report describes the integrated approach used for estimating needs of multiple LDV use cases (including typical driving needs, long-distance travel, and ride-hailing electrification), introduces and justifies modeling assumptions, describes potential alternate futures, and presents results over time at various levels of geographic resolution.

2. An Integrated Approach for Multiple LDV Use Cases

This report builds on the foundation of years of research and collaboration at NREL and beyond. Several recent analytic works serve as the basis for this study and will be referenced throughout the remainder of the report (see Table 1). The building blocks of this report include development and ongoing refinement of models used to estimate charging infrastructure needs for light-duty PEVs in multiple use cases.

The core tools used in this study are:

- EVI-Pro: For typical daily charging needs
- EVI-RoadTrip: For fast charging along highways supporting long-distance travel
- EVI-OnDemand: For electrification of transportation network companies (TNCs).

Each of these models is described in more detail in Section 2.1.

In addition to modeling tools, several assumptions must be made to define vehicle use scenarios and estimate the corresponding charging demands. These include scenario-specific assumptions on vehicle adoption (number of PEVs with regional variation), fleet composition (PEV chassis types and preference for BEVs/plug-in hybrid electric vehicles [PHEVs]), technology attributes (e.g., vehicle efficiency/range, charging efficiency/speed), and driving/charging behavior. A key determinant of charging behavior—particularly the demand for public charging—is the share of PEV owners able to access charging at their primary residence. Home charging is typically the most convenient and affordable charging location for those that have access, but many do not—as discussed at length by Ge et al. (2021). Assumptions for each of these “demand-side” considerations are discussed in Section 2.2.

This section concludes by establishing charging network terminology (with help from DOE’s Alternative Fuels Data Center) and proposes a new charging infrastructure taxonomy that explicitly decouples location type (e.g., home, work, retail) from access type (e.g., public, private). Finally, real-world observations of public charging utilization (Borlaug et al. 2023) and installed cost (Borlaug et al. 2020) are presented as “supply-side” considerations in Section 2.3.

Table 1. Foundational Studies Underlying National Analysis

Citation	Title	Venue	Technical Contribution
Wood et al. 2017	National Plug-In Electric Vehicle Infrastructure Analysis	DOE Office of Energy Efficiency and Renewable Energy technical report	Introduced coverage vs. capacity concept; first national instance of EVI-Pro
Wood et al. 2018	Charging Electric Vehicles in Smart Cities: An EVI-Pro Analysis of Columbus, Ohio	NREL technical report	Initial use of large-scale telematics data within EVI-Pro
Moniot, Rames, and Wood 2019	Meeting 2025 Zero Emission Vehicle Goals: An Assessment of Electric Vehicle Charging Infrastructure in Maryland	NREL technical report	Piloted use of EVI-Pro for scenarios with low levels of residential access
Borlaug et al. 2020	Levelized Cost of Charging Electric Vehicles in the United States	*Joule* article	Compiled public data on installed cost of charging (updated on rolling basis)
Alexander et al. 2021	Assembly Bill 2127: Electric Vehicle Charging Infrastructure Assessment: Analyzing Charging Needs to Support Zero-Emission Vehicles in 2030	California Energy Commission report	Revised EVI-Pro methodology to account for emerging charging behavior observations and implemented demand-based network sizing; introduced EVI-RoadTrip for corridor-based analysis
Ge et al. 2021	There's No Place Like Home: Residential Parking, Electrical Access, and Implications for the Future of Electric Vehicle Charging Infrastructure	NREL technical report	Collected novel survey data on residential parking and electrical access; proposed likely adopter model for estimating evolution of residential access as a function of PEV fleet size
Moniot, Ge, and Wood 2022	Estimating Fast Charging Infrastructure Requirements to Fully Electrify Ride-Hailing Fleets Across the United States	*IEEE Transactions on Transportation Electrification* article	Developed and applied EVI-OnDemand model for quantifying national infrastructure needs of ride-hailing electrification
Alexander and Lee 2023	California Electric Vehicle Infrastructure for Road Trips: Direct Current Fast Charging Needs to Enable Interregional Long-Distance Travel for Electric Vehicles	California Energy Commission staff report, forthcoming	Technical documentation for EVI-RoadTrip methodology
Borlaug et al. 2023	Public Electric Vehicle Charging Station Utilization in the United States	*Transportation Research Part D: Transport and Environment* article	Quantitative analysis of real-world infrastructure utilization; used as basis for network sizing approach

2.1. Modeling Philosophy and Simulation Pipeline

The core tools used in this study are EVI-Pro (for typical daily charging needs), EVI-RoadTrip (for fast charging along highways supporting long-distance travel), and EVI-OnDemand (for ride-hailing electrification). The development and application of individual models dedicated to specific use cases provides at least two benefits: (1) increased modularity maximizes the flexibility in our modeling; namely, models may be combined or run in isolation (where appropriate), as demonstrated in many of the studies listed in Table 1; and (2) each model can be tailored to the unique driving and charging behaviors of their associated use case. The models used in this study are a subset of the larger EVI-X modeling suite maintained by NREL for network planning, site design, and financial analysis across light-, medium-, and heavy-duty vehicles (National Renewable Energy Laboratory 2023).

LDV use cases vary widely and have unique infrastructure requirements that must be accommodated to facilitate a seamless transition to PEVs. Typical daily use of LDVs tends to be characterized by short trips with long dwell periods (e.g., 70% of daily driving under 40 miles and 95% under 100 miles with vehicles typically parked 95% of their lifetime). These periods present ample opportunities for destination charging (most notably at home and workplace locations) that is "right-speeded" to match typical dwell times. EVI-Pro assumes such an opportunistic approach to charging, attempting to make use of low-cost destination charging where convenient and rely on fast charging only when necessary.[13]

In contrast, the use of PEVs for long-distance travel and in ride-hailing applications requires that they can pull over in convenient locations and charge quickly to either resume a road trip or return to service. EVI-RoadTrip and EVI-OnDemand both employ this charging behavior philosophy but rely on distinct data sets to describe the geographic footprint of long-distance vs. ride-hailing travel patterns. Long-distance travel requires a network of fast charging stations along highways (including urban and rural areas that these highways pass through), while ride-hailing electrification necessitates access to fast charging within the urban areas where such services are most common (such as near urban centers and airport locations). Additional details of each model will be discussed in the following subsections of this report.

Each of these individual models is integrated into a shared simulation pipeline, as shown in Figure 1. Models are provided with a self-consistent set of exogenous inputs that prescribe the size, composition, and geographic distribution of the national PEV fleet; technology attributes of vehicles and charging infrastructure; assumed levels of residential/overnight charging access; and regional environmental conditions. Each model uses these inputs in bottom-up simulations of charging behavior by superimposing the use of a PEV over travel data from internal combustion engine vehicles. By relying on historical travel data from conventional vehicles, these models implicitly design infrastructure networks capable of making PEVs a one-to-one

[13] EVI-Pro assumes fast charging as being necessary only when long dwell time opportunities to charge slowly are not present in the detailed driving pattern data sets used as inputs. In reality, charging preferences will be dictated by myriad conditions that are challenging to anticipate in a model. For this reason, EVI-Pro has been configured in this analysis to simulate a minority of BEV drivers (10%) as preferring fast charging over slower alternatives, including opportunities to charge at home. The size of this behavior cohort is believed to be consistent with the limited set of real-world charging behavior observations available in the literature. BEV manufacturers are arguably in the best position to observe actual charging behavior in the field and are encouraged to consider publishing aggregated charging behavior statistics to inform the efficient deployment of charging infrastructure.

replacement for internal combustion engine vehicles, effectively minimizing impacts to existing driving behavior and identifying the most convenient network of charging infrastructure capable of meeting driver needs.

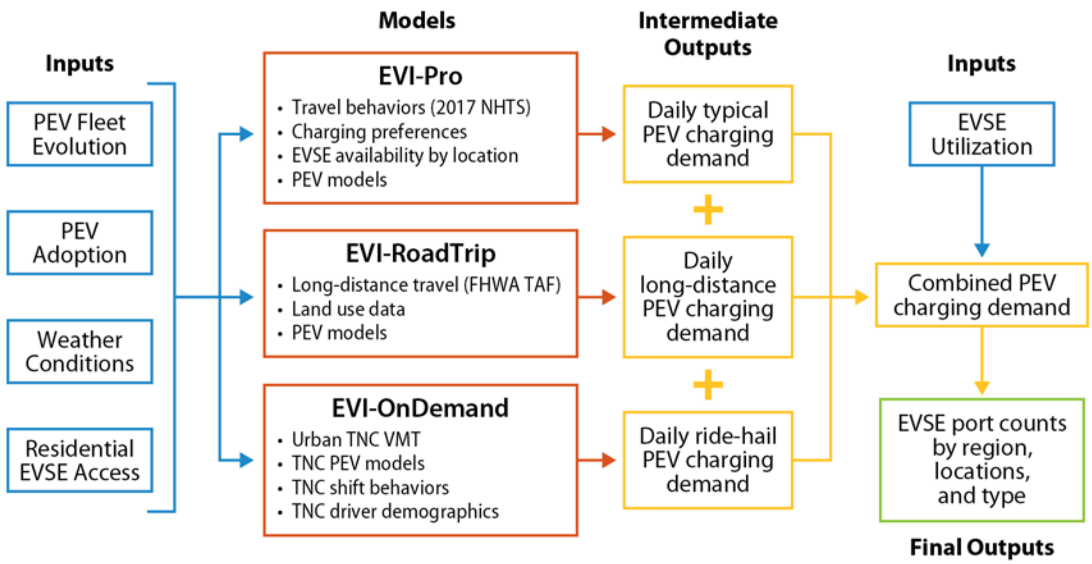

Figure 1. Shared simulation pipeline integrating EVI-Pro, EVI-RoadTrip, and EVI-OnDemand

The independent (but coordinated) simulations produce a set of intermediate outputs estimating daily charging demands for typical PEV use, long-distance travel, and ride-hailing electrification. These intermediate outputs are indexed in time (hourly over a representative 24-hour period) and space (core-based statistical area [CBSA] or county level) such that they can be aggregated into a composite set of charging demands across multiple use cases. Once combined, the peak hour for every combination of charging type (e.g., Level 1 [L1], L2, DC), location type (e.g., home, work, retail), and geography (e.g., CBSA) is identified for the purpose of network sizing. Rather than sizing the simulated charging network to precisely meet the peak hourly demand in all situations, the simulation pipeline uses an assumed networkwide utilization rate in the peak hour to "oversize" the network by some margin. This sizing margin accounts for the fact that charging demand tends to vary seasonally and around holidays. As the EVI-X modeling ensemble simulates demand on a typical day, the network sizing approach attempts to account for periods of peak demand, which could far exceed what is experienced on a typical day. This margin is calibrated based on analysis of real-world utilization data, as described later in this section.

The resulting final output of the pipeline is a set of charging infrastructure port counts by region, location type, and charging type that can be aggregated up to the national level or reported out for individual states or CBSAs. The remainder of Section 2.1 will be used to briefly describe the simulation models and data used as the justification for future utilization assumptions.

2.1.1. EVI-Pro: Charging Demands for Daily Travel

EVI-Pro is a tool for projecting consumer demand for PEV charging infrastructure under typical daily conditions. EVI-Pro uses detailed data on personal vehicle travel patterns, vehicle attributes, and charging station characteristics in bottom-up simulations to estimate the quantity and type of charging infrastructure necessary to support regional adoption of PEVs. A block diagram of data flows within EVI-Pro is shown in Figure 2. EVI-Pro has been used in multiple detailed planning studies including Wood et al. (2017, 2018), Moniot et al. (2019), and Alexander et al. (2021).

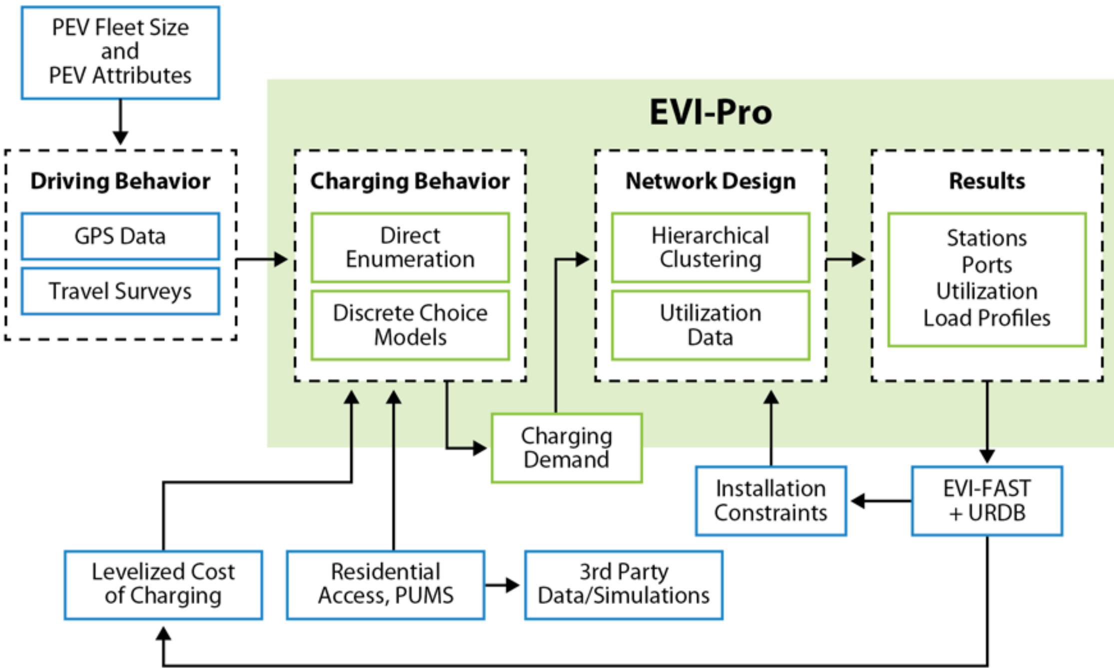

Figure 2. EVI-Pro block diagram for charging behavior simulations and network design

2.1.2. EVI-RoadTrip: Charging Demands for Long-Distance Travel

EVI-RoadTrip projects the amount and locations of DC charging infrastructure needed for BEVs' long-distance travel needs (i.e., >100 miles). This model addresses an under-researched but increasingly important use case for vehicle electrification: long-distance road trips. A fast charging network connecting regions across the nation is critical to accelerate the transition to electric vehicles (EVs) by enabling timely interregional travel and reducing range anxiety. The model follows three key steps within the context of this analysis (as shown in Figure 3): trip data generation, driving/charging simulation, and station siting/sizing. The model simulates interregional road trips by BEVs (including across state lines), estimates energy use and charging demand along the road trip routes, calculates geographic clusters of charging demand, and simulates the existence of charging stations to serve those clusters, typically locating them in locations zoned for retail activity. EVI-RoadTrip was introduced by Alexander et al. (2021) and is documented in Alexander et al. (2023).

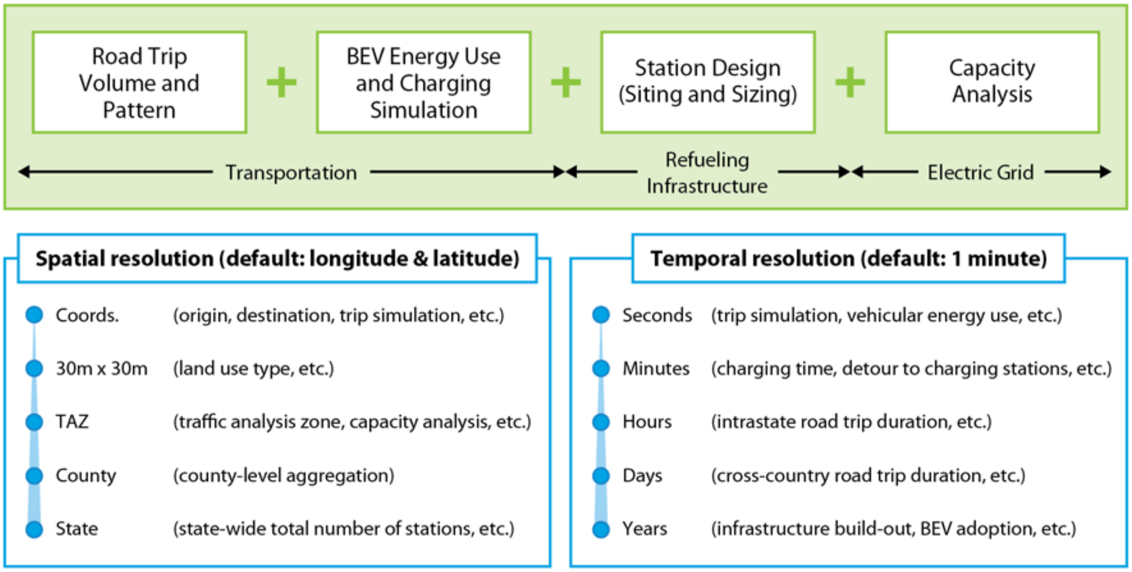

Figure 3. EVI-RoadTrip block diagram for traffic generation, charging behavior simulations, and network design

2.1.3. EVI-OnDemand: Charging Demands for Ride-Hailing PEVs

The charging demands from ride-hailing fleets are given unique attention within this study given the aggressive rate of fleet electrification pledged by major ride-hailing companies (Uber 2020; Lyft 2020) and the likely reliance on public infrastructure for many of these ride-hailing vehicles (Jenn 2020; Moniot et al. 2022). Further, ride-hailing vehicles operate distinctly from vehicles used for personal travel and are not comprehensively characterized in travel surveys. These factors motivated the use of EVI-OnDemand for estimating ride-hailing charging demand.

EVI-OnDemand simulates ride-hailing fleets operating in urban areas in a spatially implicit manner given the lack of data made available by prominent ride-hailing companies. The model estimates charging infrastructure necessary to support all-electric ride-hailing fleets with market shares consistent with present-day operations. Fleetwide charging demand for each geography is obtained through repeated simulations of heterogeneous drivers, until the total mileage across all drivers matches the projected total within the urban area being evaluated. As shown in Figure 4, drivers are uniquely modeled based on probabilistic sampling of driver shift length and the likelihood of overnight charging access. These factors influence the demand for fast charging mid-shift, modeled as time-sensitive en route charging. For instance, drivers with short shifts and access to overnight charging are unlikely to require access to fast charging infrastructure. In contrast, drivers with longer shifts and no access to overnight charging will depend more heavily on public-access DC charging. The model also considers local driving speeds and ambient conditions to produce plausible energy consumption rates while drivers are on shift.

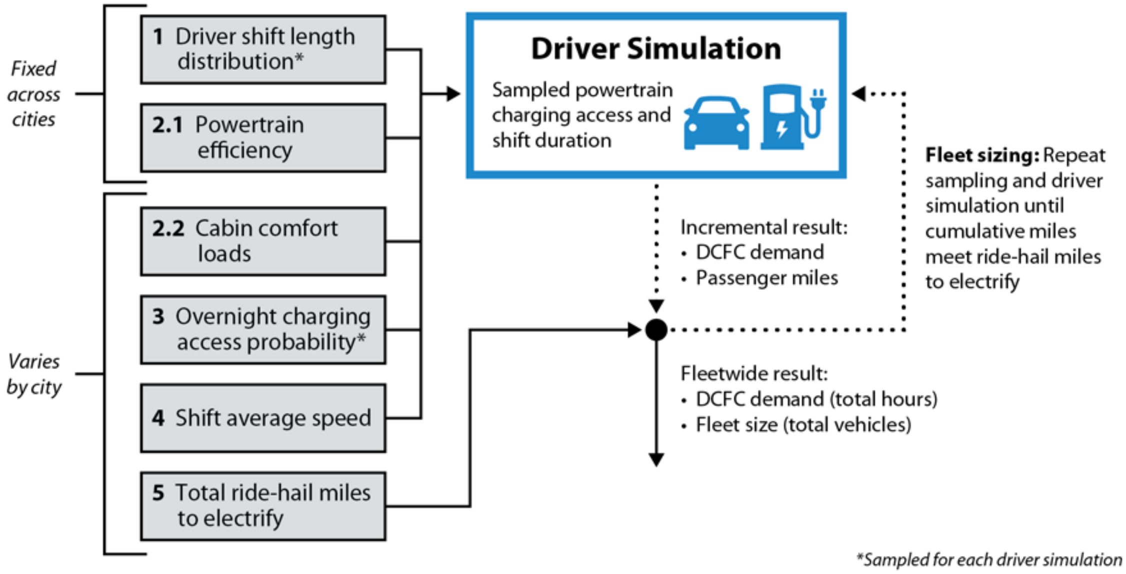

Figure 4. EVI-OnDemand block diagram for driver simulations and related assumptions

The key output from EVI-OnDemand for this study is the aggregate fleetwide demand for DC charging by city to support drivers mid-shift when needed. The aggregate demand for DC charging is disaggregated by time of day by leveraging emerging empirical data in the literature characterizing when ride-hailing vehicles frequent DC chargers (Jenn 2020). Additional documentation of the EVI-OnDemand simulation model can be found in Moniot, Ge, and Wood (2022) and the model source code (GitHub 2023).

2.1.4. Utilization-Based Network Sizing

Following independent use case simulations, charging demand from each model is aggregated in time and space to form a composite estimate of demand for each geography. The peak hourly demand from the composite profile is used to size each component of the network, represented as a combination of location type and charger type (e.g., public office L2, public retail 150-kW DC). This process is conceptually illustrated in Figure 5.

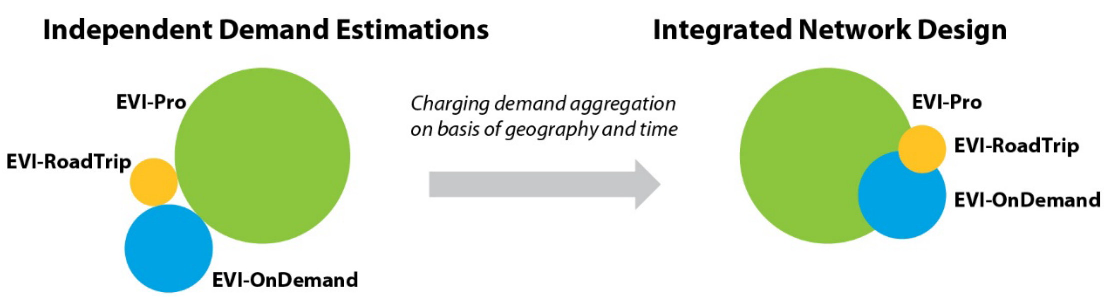

Figure 5. Conceptual diagram illustrating independent demand estimations, demand aggregation, and integrated network design

Demand aggregation allows for the resultant simulated charging network to incorporate resource sharing across different use cases, as is common in the real world (e.g., ride-hailing PEVs charging alongside road trippers or employees charging alongside shoppers). This effectively reduces the modeled network requirements when contrasted with a counterfactual where the network is synthesized for each use case independently and then summed, since the spatiotemporal charging demands for the different use cases may not necessarily align. An example of this occurrence is shown in Figure 6 for a simulated fast charging network in an illustrative region.

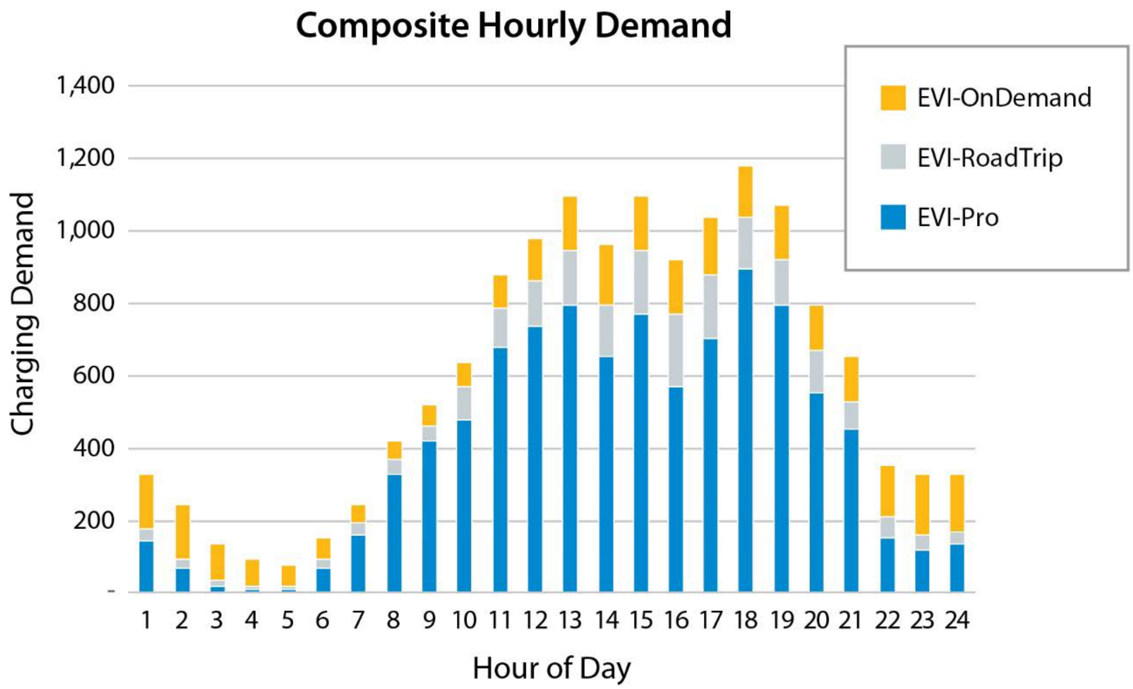

Figure 6. Composite hourly demand for DC charging by use case for an illustrative region

2.2. Demand-Side Considerations: Defining PEV Use Case Scenarios

Several input parameters must be specified and synchronized across the three EVI-X models used in this report to estimate comprehensive charging infrastructure needs for light-duty PEVs in the United States by 2030. This study considers multiple PEV use case scenarios relying on "demand-side" input assumptions, including fleet size, geographic distribution, vehicle and infrastructure technology attributes, residential charging access, and driving/charging behavior. To assess potential futures, a baseline scenario is first presented using demand-side assumptions shown in Table 2. Plausible alternatives to the baseline scenario are explored using parametric sensitivity analysis as defined by Table 3. These scenarios are not intended to be exhaustive in terms of the potential evolution pathways for the national charging network of 2030, but rather informative of the impacts of various considerations that will be important for charging infrastructure stakeholders to consider.

Table 2. Demand-Side Assumptions Used in the Mid-Adoption Scenario

Modeling Parameter	**2030 Nominal Assumption**
PEV fleet size (LDV only)	33 million (2.7 million registered as of 2022)
PEV powertrain shares	BEV = 90% (2022: 72%) PHEV = 10% (2022: 28%)
PEV body type distribution	Sedan = 24% (2022: 58%) C/SUV = 56% (2022: 40%) Pickup = 17% (2022: 0%) Van = 3% (2022: 2%)
Average PEV electric range (model year 2030)	BEV = 280 miles PHEV = 45 miles
BEV minimum DC charge time (model year 2030; 20%–80% state of charge [SOC])	20 minutes [a]
Maximum DC power rating (per port)	350+ kW
Geographical distribution	Scaled proportional to existing PEV and gasoline-hybrid registrations with a ceiling of 35% of LDVs on the road in 2030 as PEVs in high adoption areas and a floor of 3% in low adoption areas
PEVs with reliable access to residential charging	90%
Weather conditions	Typical ambient conditions are used for each simulated region, impacting electric range accordingly
Driving behavior	EVI-Pro: Consistent with Federal Highway Administration (FHWA) 2017 National Household Travel Survey (NHTS) EVI-RoadTrip: Directly applies FHWA Traveler Analysis Framework (TAF) EVI-On Demand: Consistent with Balding et al. (2019)
Charging behavior	All models attempt to maximize use of home charging (when available) and utilize charging away from home only as necessary. When fast charging is necessary, BEVs prefer the fastest option compatible with their vehicle, up to 350+ kW.

[a] Tesla recently reported an average charge duration of 27.5 minutes on their Supercharger network (Kane 2023), and a median duration of 36 minutes has been calculated from public 50-kW DC chargers as part of the EV WATTS program (Energetics 2023). These estimates are provided as context for the 2030 modeling assumption, despite the fact neither statistic necessarily aligns with 20%–80% SOC events in all cases.

Table 3. Description of Select Plausible Alternates to the Baseline Scenario

Scenario	Description
High Adoption	PEV fleet size growth to 42 million PEVs on the road by 2030 (baseline: 33 million PEVs by 2030)
Low Adoption	PEV fleet size growth to 30 million PEVs on the road by 2030 (baseline: 33 million PEVs by 2030)
Low Home Charging Access	Assumes 85% of PEV drivers with residential access based on the “existing electrical access” scenario from Ge et. al (2021) (baseline: 90% residential access)
High Home Charging Access	Assumes 98% of PEV drivers with residential access based on the “potential electrical access” scenario from Ge et. al (2021) (baseline: 90% residential access)
Reduced Daily Travel	PEVs are driven 60% of days, 25% less than the baseline (80% of days)
Bad Charging Etiquette	PEVs are not unplugged during public destination L2 charging until the driver’s activity at the destination is complete and the vehicle departs (baseline: PEVs are capable of being unplugged when they are finished charging and made available for another PEV)
PHEV Success	PHEVs retain 2022 PEV market share (28%) through 2030 (baseline: PHEVs have 10% PEV market share in 2030)
Alternate PEV Adoption	PEV adoption is geographically uniform in 2030 with no urban early adopter preference (baseline: geographic distribution of PEVs in 2030 reflects 2022 distribution of PEVs and hybrid electric vehicles)
Extreme Weather	EVSE network designed for extreme (95th percentile) weather conditions affecting PEV range and increasing charging demand (baseline: EVSE network designed for average weather conditions)
Slow TNC Electrification	TNC fleets are only 50% PEVs by 2030 (baseline: 100% TNC PEVs by 2030)
Private Workplace Charging	100% of workplace charging at private EVSE through 2030 (baseline: 100% in 2022, decreasing to 50% by 2030)

The remainder of this subsection reviews demand-side assumptions in greater detail, including assumptions for fleet size/composition, technology attributes, residential charging access, and driving/charging behavior.

2.2.1. PEV Adoption and Fleet Composition

National PEV adoption scenarios were developed using NREL’s Transportation Energy & Mobility Pathway Options (TEMPO) model, an all-inclusive transportation demand model that covers the entire United States (Muratori et al. 2021). This study examines three TEMPO PEV adoption scenarios (shown in Figure 7), each of which implicitly assumes the shape of the sales curve between 2022 and 2030. The low adoption scenario assumes 30 million light-duty PEVs on the road by 2030 (correlating with 43% of light-duty sales as PEVs by 2030); the mid-adoption scenario assumes 33 million (correlating with 50% of sales); and the high adoption scenario assumes 42 million (correlating with 68% of sales). This report’s baseline scenario uses the mid-adoption national fleet size scenario of 33 million light-duty PEVs on the road by 2030.

The TEMPO PEV adoption scenarios are largely consistent with scenarios developed as part of infrastructure analysis studies conducted by ICCT, Atlas Public Policy, McKinsey & Company, and S&P Global Mobility (as described in Section 1.2). These studies consider national 2030 PEV fleet sizes between 26 and 48 million.

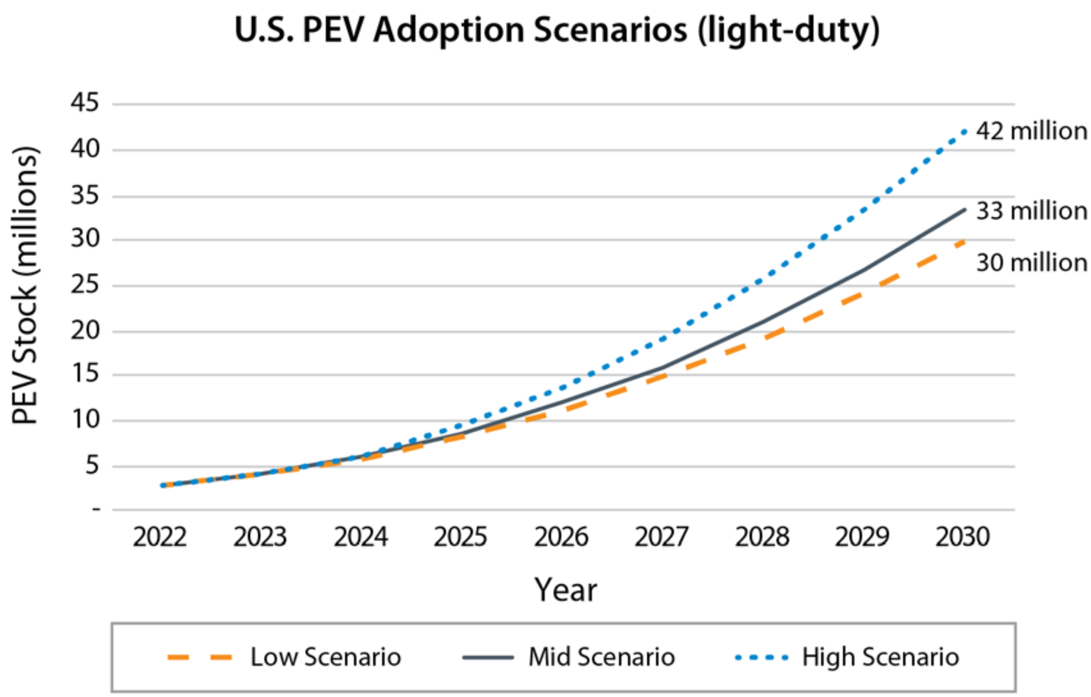

Figure 7. U.S. national light-duty PEV stock under three adoption scenarios

As of 2022, PHEVs accounted for 28% of total PEV stock. Recent sales trends and manufacturer announcements suggest the industry is trending toward increased shares of BEVs. The baseline scenario assumes 90% of 2030 PEVs are BEVs, with the remainder of the PEV fleet consisting of PHEVs. The "PHEV Success" scenario is provided to consider potential impacts to the national charging network resulting from PHEVs holding constant at 28% of the growing PEV fleet.

Regarding body type, PEV sales to date have been dominated by sedans, accounting for 58% of all PEV registrations in 2022. However, this trend is expected to shift in coming years as the supply of C/SUV and pickup PEVs increases. The baseline scenario assumes the 2030 PEV fleet mirrors the body type distribution of new (<2 years old) vehicle registrations in 2022 with 24% sedan, 56% C/SUV, 17% pickup, and 3% van.

The spatial distribution of the 2030 PEV fleet is assumed to be proportional to existing PEV and gasoline-hybrid registrations. As visualized in Figure 8, this approach results in the greatest PEV adoption occurring in urban areas with up to 35% of LDVs on the road as PEVs in 2030, and the lowest levels of PEV adoption in the rural areas with as low as 3% of LDVs on the road as PEVs in 2030. This assumption is tested using the "Alternate PEV Adoption" scenario, in which PEV adoption in 2030 is assumed uniform across all states and CBSAs. While this alternate adoption scenario is not intended as a projection, it is useful in illustrating the impact of more homogeneous PEV adoption across urban and rural areas.

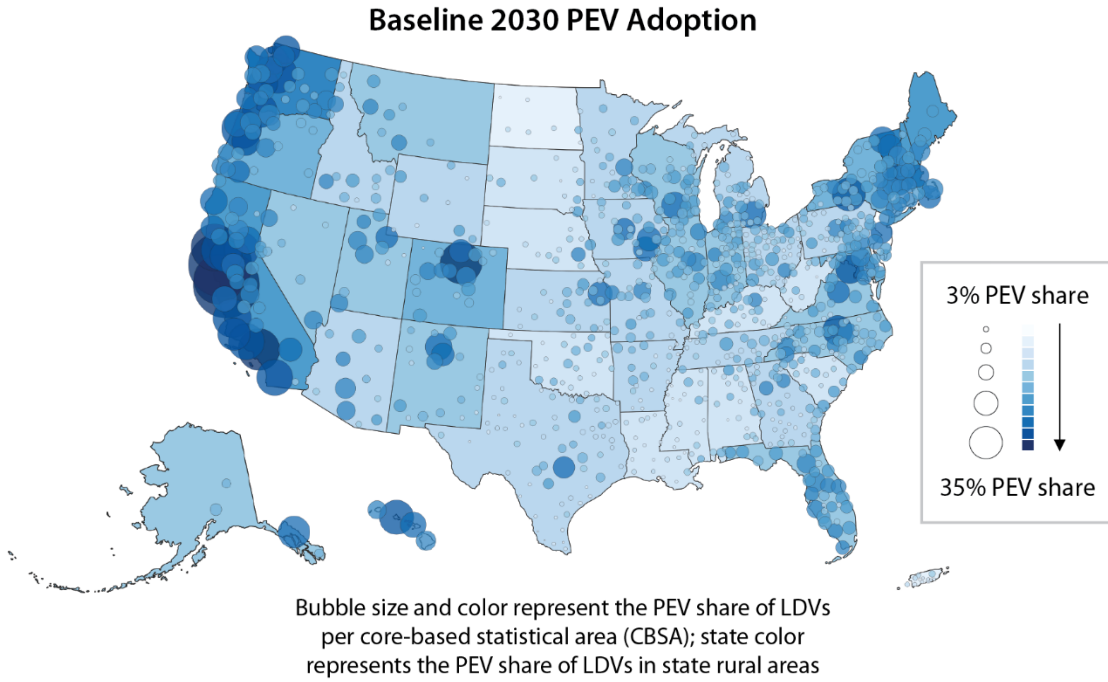

Figure 8. Assumed spatial distribution of 33 million PEVs in 2030 by CBSA and state

In addition to modeling regional preferences for PEVs, the baseline scenario also considers regional preferences for body types, as shown in Figure 9. Using 2022 LDV registration data, we find that:

- Sedans tend to be most popular in urban areas and rural parts of the Southeast.
- C/SUVs tend to be most popular in Colorado, Michigan, and the Northeast.
- Pickups tend to be most popular in rural areas west of the Mississippi River.
- Vans tend to be most popular in urban and rural areas around the Great Lakes.

These trends are reflected in the adoption scenarios, with the 2030 PEV fleet disaggregated independently by body type using regional preferences reflected in the 2022 LDV registration data for all fuel types.

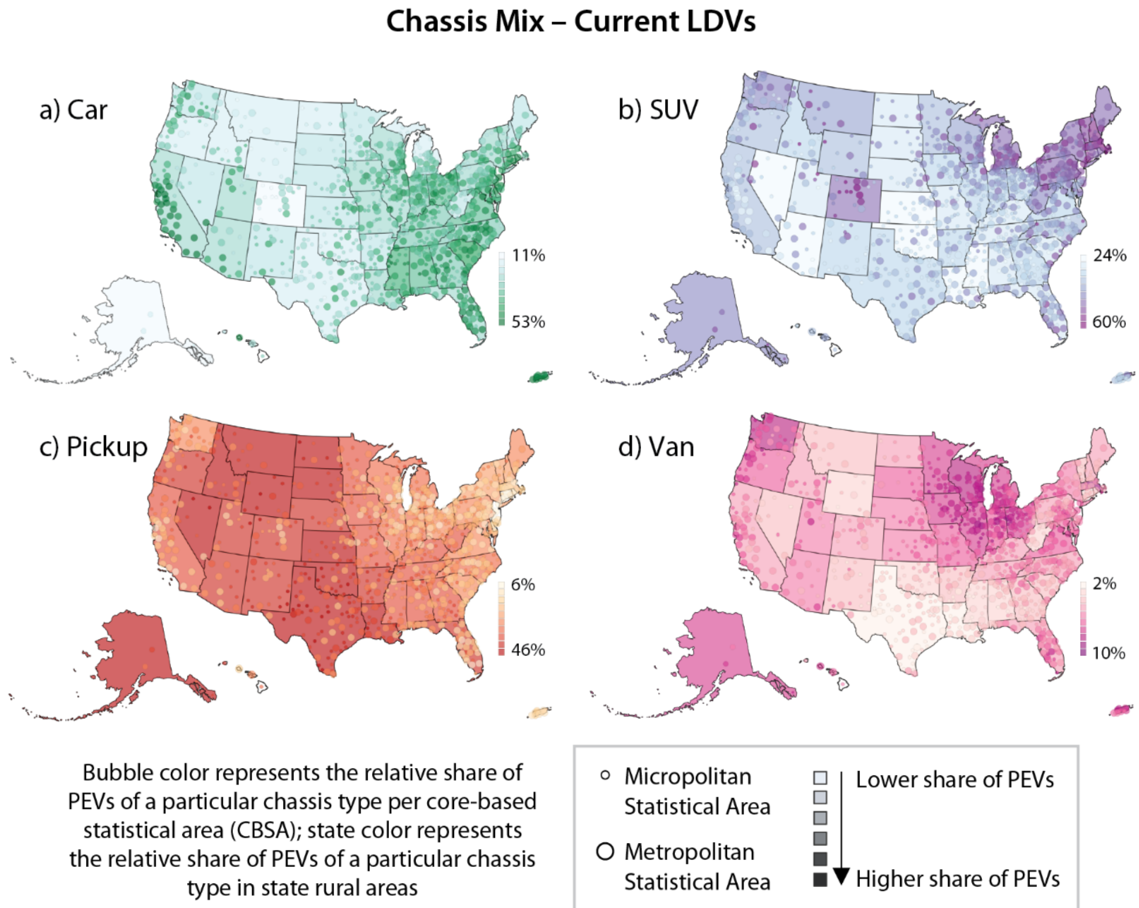

Figure 9. Spatial distribution of new (2019–2022) LDV registrations by body type.

Source: Experian LDV registrations

2.2.2. PEV Technology Attributes

Eight PEV types are represented in this study, resulting from the combination of two powertrain types (BEV and PHEV) and four body types (sedan, C/SUV, pickup, and van). Each PEV type includes up to three vintages, referred to as model year groups. The 2020 model year group is meant to capture PEVs sold up to 2020, the 2025 model year group captures PEVs sold between 2021–2025, and the 2030 model year group captures 2026–2030. While the actual PEV market is far more diverse than this simple representation, the vehicles used in this study are meant to serve as exemplars of the larger market and believed to provide a sufficient level of detail for analysis of 2030 charging infrastructure needs. Table 4 provides a summary of vehicle attributes used in the baseline scenario.

Table 4. Vehicle Model Attributes Used in the Baseline Scenario

Vehicle Model	Model Year Group	Energy Consumption Rate, Wh/mi [a]	Nominal Electric Driving Range, mi	Peak DC Charge Power, kW	Minimum DC Charge Time, minutes [b]
BEV sedan	2020 2025 2030	320 300 300	190 260 290	150 150 250	26 24 20
PHEV sedan	2020 2025 2030	290 290 290	45 50 55	N/A N/A N/A	N/A N/A N/A
BEV C/SUV	2020 2025 2030	390 430 420	190 240 280	150 150 350	30 30 20
PHEV C/SUV	2020 2025 2030	370 380 370	35 40 40	N/A N/A N/A	N/A N/A N/A
BEV pickup	2020 2025 2030	– 570 500	– 280 300	– 250 350+	– 24 20
PHEV pickup	2020 2025 2030	– 440 420	– 35 35	– N/A N/A	– N/A N/A
BEV van	2020 2025 2030	– 460 440	– 240 280	– 150 350	– 30 20
PHEV van	2020 2025 2030	– 390 380	– 35 40	– N/A N/A	– N/A N/A

[a] Excludes charging efficiency losses. Alternating-current (AC) charging assumed as 90% efficient in all cases.
[b] Assumes 20% to 80% SOC under ideal conditions (preconditioned pack, moderate ambient temperature, no power derating, etc.).

Given the adoption trajectory assumed in the baseline scenario, the 2030 PEV fleet in this analysis is dominated by the 2030 model year group. Stock turnover and a dramatic increase in projected PEV sales toward the end of the decade result in the 2020, 2025, and 2030 model year groups representing 5%, 20%, and 75% of the 2030 on-road fleet, respectively.

PEV technology is assumed to improve over the period of this analysis, most dramatically with respect to DC charge acceptance increasing from peak power ratings of 150 kW in the 2020 model year group to 250–350 kW in the 2030 model year group.[14] Most modern BEVs are capable of relatively high DC charging rates under low-SOC conditions, but as SOC increases during a charging event, a vehicle's battery management system begins to taper its charge rate to protect the pack from overvoltage and thermal abuse.

[14] PHEVs are assumed to be incapable of DC charging in this analysis.

This analysis assumes that advances in battery technology (potentially including prevalence of 800-V packs, multilayer cathodes, electrolyte improvements, and advanced charge protocols) will not only enable higher peak power levels at low SOC, but also decrease overall DC charge times. All BEVs sold after 2025 are assumed to be capable of 20-minute DC charge times assuming 20% to 80% state of charge under ideal conditions (preconditioned pack, moderate ambient temperature, no power derating, etc.). In the real world, actual DC charging times will vary based on arrival and departure SOC, pack thermal conditions (temperatures that are too high or too low will result in power derating), the vehicle's battery management system, and the capabilities of the charging station.

2.2.3. Residential Charging Access (There's No Place Like Home)

The key enabler for early adoption of PEVs has been home charging at residential locations, where vehicles tend to remain parked for long durations overnight. Going forward, there is uncertainty around how effectively home charging can scale as the primary charging location for PEV owners. As the PEV market expands beyond early adopters (typically high-income single-family homes [SFHs] that have access to off-street parking) to mainstream consumers, planners must consider developing charging infrastructure solutions for households without consistent access to overnight home charging. This includes, but may not be limited to, renters, residents of apartment buildings (and other multifamily dwellings), and individuals in SFHs without access to off-street parking. In situations where residential off-street charging access is unattainable, a portfolio of solutions may be possible, including providing access to public charging in residential neighborhoods (on street), at workplaces, at commonly visited public locations, and (when necessary) at centralized locations via high-power fast charging infrastructure (similar to existing gas stations).

The future of U.S. residential charging access was explored in depth by Ge et al.'s (2021) report *There's No Place Like Home*. This research reviewed public information on residential housing attributes with implicit relation to home charging access, including national data on vehicle ownership, residence type, housing density, and housing tenure (i.e., rent or own). These public data were complemented by a panel survey sample of 3,772 U.S. individuals to uncover previously unknown distributions of residential parking availability, parking behavior, existing electrical access, and perceived potential for new electrical access by parking location. These responses connected parking availability and existing or potential electrical access to residence type to inform charging access scenarios that were incorporated into the final projection framework. Charging access trends with respect to residence type were identified and coupled with a PEV likely adopter model to infer national residential charging access scenarios as a function of the national PEV fleet size.

This work serves as the basis of residential charging access assumptions in this report, which assumes 90% of PEVs have reliable access to overnight charging in a scenario with 33 million PEVs nationwide. Alternate 2030 scenarios for residential access explore home charging as low as 85% and as high as 98%. The distribution of residential access across CBSAs is shown in Figure 10. Note that residential access and fleet size are coupled within the national framework, such that locations with high PEV adoption tend to be estimated with lower levels of residential access, as can be seen for CBSAs in California and the Pacific Northwest where residential access decreases over time as the size of the PEV fleet increases.

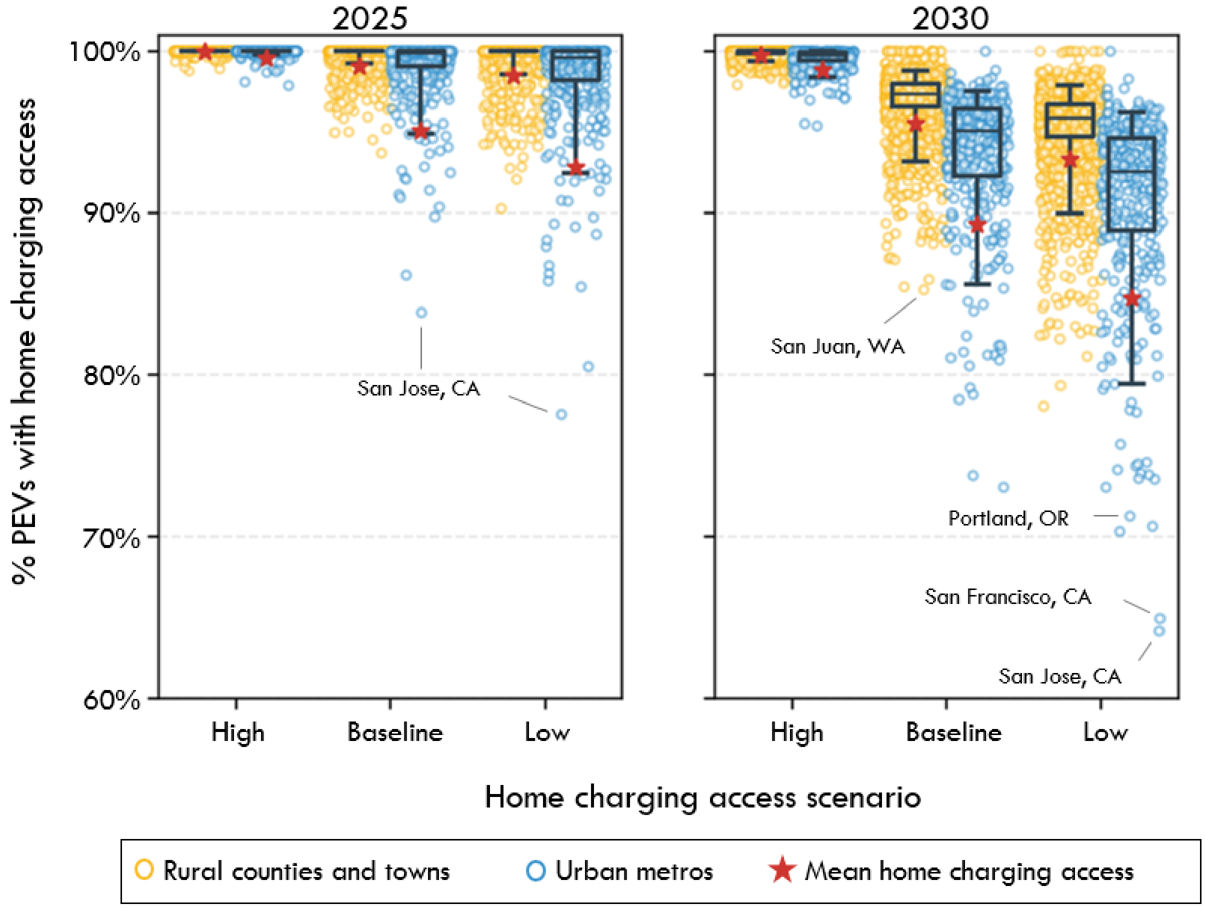

Figure 10. Residential charging accessibility scenarios as a function of PEV stock share. In the boxplot figure, the box reflects the inner quartile range (25%–75%), with the horizontal line reflecting the median value. Whiskers represent the 5th and 95th percentile values, respectively.

This analysis pays special attention to the demographics of ride-hailing drivers, who (consistent with industry goals) are assumed to achieve 100% adoption of PEVs by 2030. Drivers for ride-hailing services are disproportionately lower income, complicating opportunities to leverage data sources representative of the general population. This analysis introduces a means of characterizing the likelihood of access to overnight charging for ride-hailing drivers. Note that emerging business models, such as leased vehicles with overnight charging at a depot location or leases where public charging is included in the lease of the vehicle, are not explicitly considered. However, such models could be evaluated in the future by assuming greater rates of overnight charging access irrespective of driver housing status or through a driver preference for midday fast charging.

Consistent with the approach outlined by Moniot, Ge, and Wood (2022), Ge et al.'s (2021) report is once again leveraged for estimating residential access among ride-hailing drivers. Although this survey was intended to be representative of the broader population, the survey produced relationships between demographic descriptors—tenure, housing type, and income—and overnight charging access, which allows for the estimation of ride-hailing drivers' residential charging access if their income distribution is known. Ride-hailing driver income data[15] (Benenson Strategy Group 2020) were combined with demographic data from the U.S. Census and information from Ge et al. (2021) to estimate regional-specific residential access rates among ride-hailing drivers. This approach enables differentiation across geographies by accounting for variability in housing stock and household income, leading to consideration of lower overnight charging access in dense CBSAs (such as New York City) versus more sprawling CBSAs with a greater availability of more affordable housing options with more favorable rates of overnight charging (such as Houston).

The baseline scenario distribution of residential access across CBSAs is shown in Figure 11. This distribution results in a national average of 60% for residential charging access among ride-hailing drivers (significantly lower than the 90% assumed for the overall PEV fleet). These CBSA-specific residential access rates are used by EVI-OnDemand when simulating charging behavior among ride-hailing drivers.

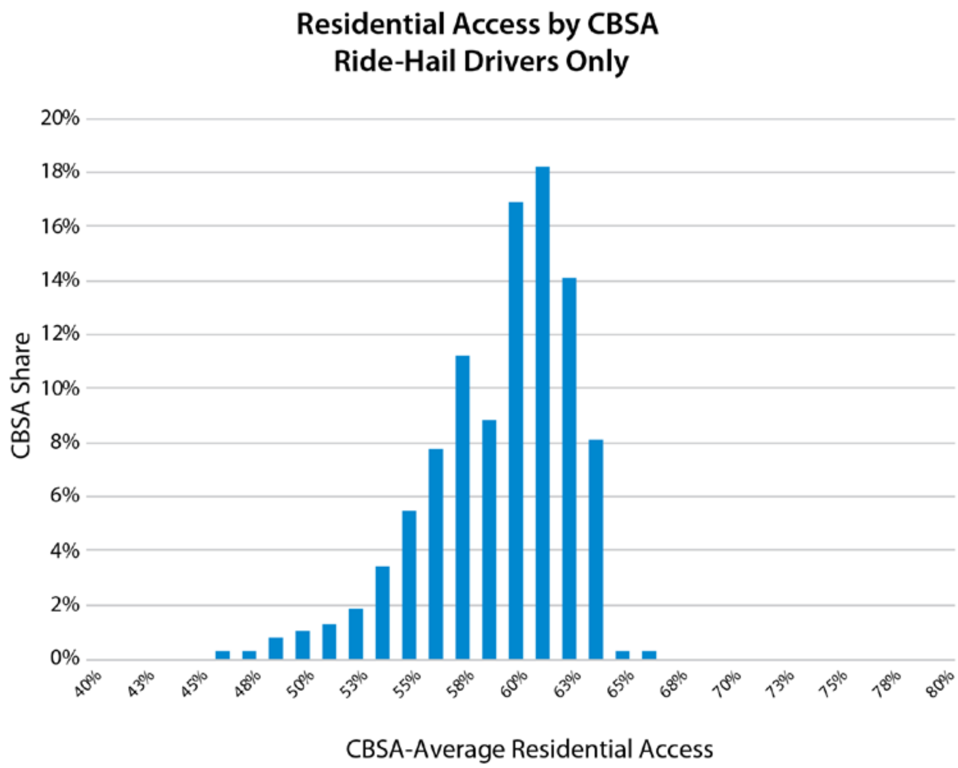

Figure 11. Likelihood of overnight charging access for ride-hailing drivers for the baseline scenario across all metropolitan CBSAs

[15] Driver household income data are used instead of the income obtained exclusively from ride-hailing services. Household income includes additional revenue from separate forms of employment and across all household members. This value is considered to be a more accurate indicator of the type of housing the driver lives in, and also enables direct comparison against household-level census data.

2.2.4. Driving Patterns

PEV driving patterns in this analysis are represented by an ensemble of data sets from conventional vehicles, which are simulated as PEVs to estimate the charging infrastructure necessary for supporting electrification of LDVs in multiple use cases. EVI-Pro simulations rely on FHWA's 2017 NHTS and a national data set licensed from INRIX. EVI-RoadTrip utilizes FHWA's TAF to describe long-distance driving trends, and EVI-OnDemand employs observations from a Fehr & Peers analysis of the ride-hailing industry in select U.S. markets (Balding et al. 2019). As each of these datasets were developed prior to the onset of the COVID-19 pandemic in March 2020, their use within this study imply an assumption that mobility patterns have fully returned to the pre-pandemic state by 2030. Estimating the near-term evolution of personal mobility in the United States was deemed out of scope for this analysis.

Driving pattern inputs to EVI-Pro are derived from the 2017 NHTS. The NHTS is a national travel survey conducted every 6–8 years to describe travel activity at the household level across all transportation modes (e.g., walk, bike, drive, ride-hail, transit, air). In addition to being publicly accessible, the NHTS enables "trip chaining," or the linking of automobile trips in a sequential manner. This is a key feature for PEV charging simulations in EVI-Pro, as it enables battery SOC to be estimated over a 24-hour period. A visualization of 2017 NHTS auto weekday trip distribution by hour of day and activity type is shown in Figure 12 for illustrative purposes.

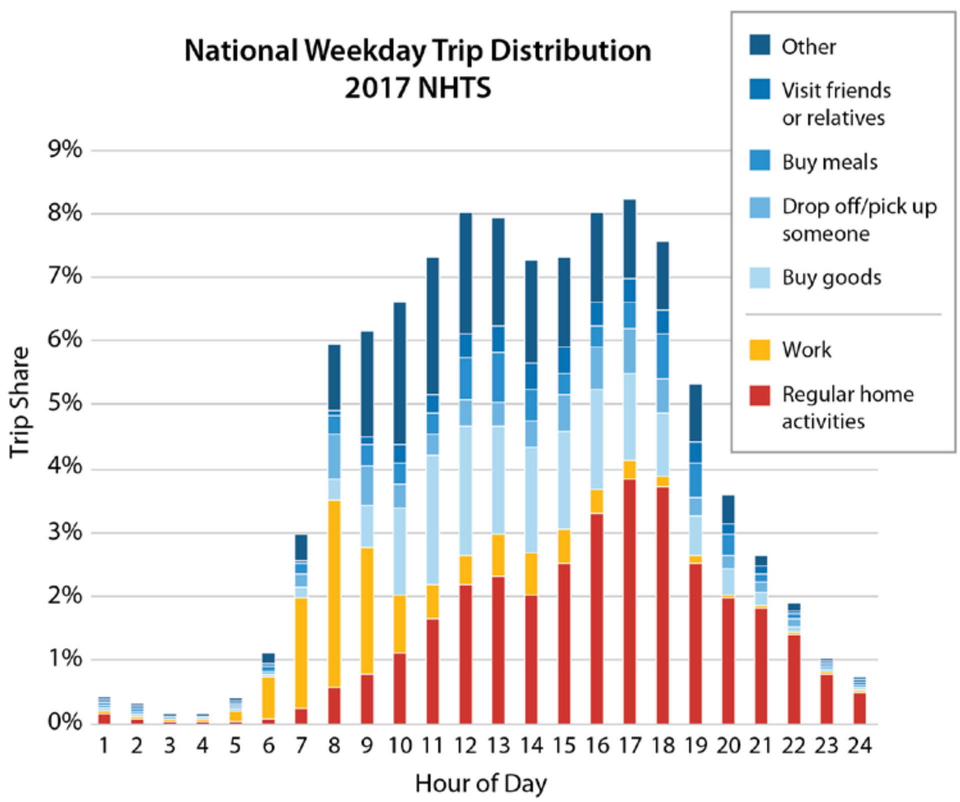

Figure 12. 2017 NHTS auto weekday trip distribution by hour of day and activity type ("other" activities include general errands, buy services, exercise, recreational activities, health care visits, religious or community activities, work-related meetings, volunteer activities, paid work from home, attending school as a student, changing type of transportation, attending childcare, and attending adult care)

While the NHTS data include data points for hundreds of thousands of household vehicles, select cities and states are intentionally oversampled, leaving many geographies with sparse samples. To derive trip chains from all CBSAs and rural counties, a procedure for drawing weighted samples from the NHTS that are representative of any target geography was developed. This method relies on broadly accessible demographic variables from the U.S. Census to sample household vehicles from the NHTS that are representative of a particular census tract in question. This approach was calibrated using standard in-sample linear regression techniques and independently validated using out-of-sample travel survey data from the 2012 California Household Travel Survey.

One limitation of the NHTS is a lack of spatial information regarding trip destinations. Use of NHTS driving data in EVI-Pro requires that attention be paid to appropriately defining geographies. While geographic precision is often desired, small geographies run the risk of vehicles crossing boundaries during normal operation and placing demand for charging outside the geography in which their "home" is located. To ensure appropriate spatial resolutions are considered when using NHTS data for EVI-Pro simulations, a spatially explicit analysis was required. For this analysis, we relied on a large, national data set of real-world travel patterns with geocoded trip origins and destinations. The data provider for this analysis was INRIX, and the data included millions of trips from Jan.–Feb. 2020 (data during the COVID-19 lockdown were intentionally excluded). This data set is visualized in Figure 13.

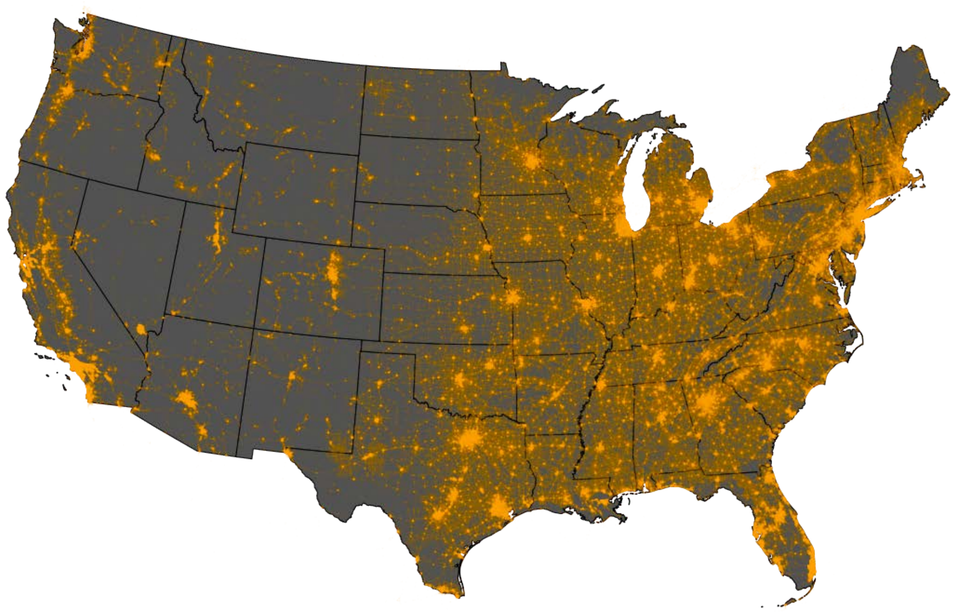

Figure 13. National origin-destination data set from Jan.–Feb. 2020 (licensed from INRIX)

Multiple geographies were evaluated using this data set, including counties, census urbanized areas, and CBSAs (including metropolitan and micropolitan statistical areas). For each geography, the frequency of interregional travel was tested and evaluated for suitability of a net-zero charging demand difference in EVI-Pro. This analysis revealed that CBSAs were the smallest geography with national coverage for which a modeling assumption of net-zero flow in charging demand could be considered valid. Consequently, CBSAs are the default geography for aggregating the individual EVI-Pro simulations that depend on the weighted sampling of NHTS driving days.

EVI-RoadTrip relies on long-distance travel data from the TAF. Since long-distance travel tends to be underrepresented in travel surveys and often crosses political boundaries, FHWA developed a synthetic data set with national coverage to estimate long-distance passenger travel. FHWA's TAF was modeled using a variety of predictors, such as population and economic activity, and calibrated to a large travel survey (Federal Highway Administration 2018). TAF consists of a set of county-to-county trip tables for long-distance passenger trips (defined as trips longer than 100 miles) by automobile, bus, air, and rail. The TAF projects person-trip flows for auto travel in 2008 and for 2040, the latter of which is shown in Figure 14.

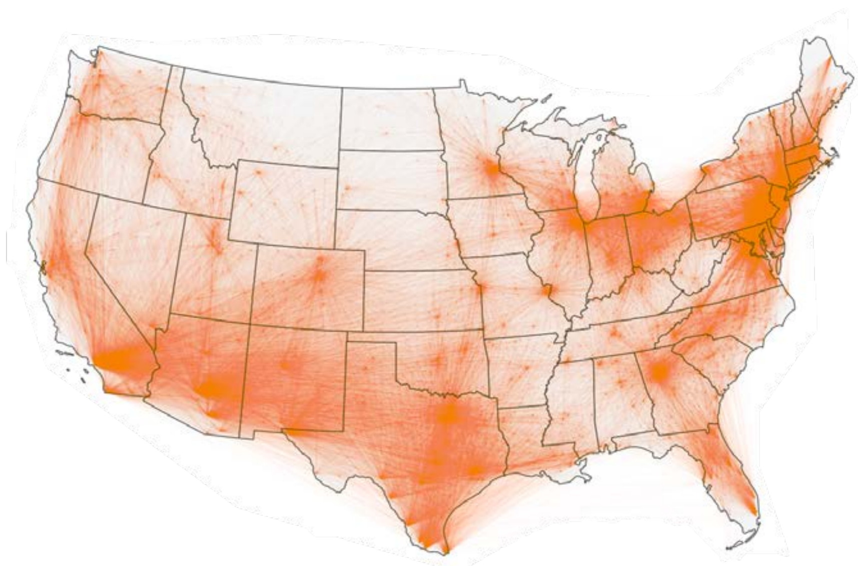

Figure 14. County-to-country origin-destination flows visualized from the FHWA TAF data set

EVI-OnDemand requires the total passenger miles served by PEVs in ride-hailing fleets in order to estimate charging demands. Few data are available in the literature regarding the share of miles affiliated with ride-hailing fleets outside of an analysis performed by Fehr & Peers. In the analysis, the authors aggregated real-world ride-hailing miles provided by Uber and Lyft from September 2018 across the six metropolitan areas of Seattle, San Francisco, Los Angeles, Chicago, Washington, D.C., and Boston. Moniot, Ge, and Wood (2022) compared the total miles across the ride-hailing fleets for each region against the overall number of vehicle miles traveled (VMT) for the month as reported by the local metropolitan planning organization. It found that ride-hailing fleets comprise between 2% and 3% of VMT within the six regions analyzed, with greater rates of penetration within the urban cores of each region.

The VMT shares found by Fehr & Peers are used for the six regions provided, and a VMT share of 1.5% is assumed for all other regions in lieu of more granular data. The VMT shares reported by Fehr & Peers are assumed to have above-average rates of VMT penetration given the high household incomes and prominence of technology and information workers in the regions analyzed. VMT penetrations for each CBSA were multiplied by the inferred number of vehicle miles traveled in each CBSA. Total VMT values were obtained at the CBSA level by disaggregating state-level VMT values reported in Table VM-2 of the 2019 Highway Statistics Report (U.S. Department of Transportation 2020) based on vehicle registrations, which were separately sourced from IHS Markit (2017) at the ZIP code level and aggregated to CBSA and state levels.

A key variable influencing the charging demands of ride-hailing vehicles is the time vehicles are assumed to be spent on shift. Full-time drivers operating vehicles for ride-hailing services accrue significantly more miles than part-time drivers and will thus induce greater demand for charging. However, a greater share of full-time drivers may also reduce the total population of vehicles given the fleet sizing procedure introduced previously. Accurately characterizing drivers based on hours driving per shift or shifts per week is difficult given the lack of publicly available data pertaining to ride-hailing drivers. One study from 2019 found 11% of drivers to be full time using data from RideAustin (Wenzel et al. 2019). More recently, a blog post published by an Uber economist (Mishkin 2020) suggested that the vast majority of drivers are part time through analysis of proprietary driver data sourced from all Uber drivers in California. The assumed national composition of ride-hailing drivers by shift type and residential charging access is shown in Figure 15.

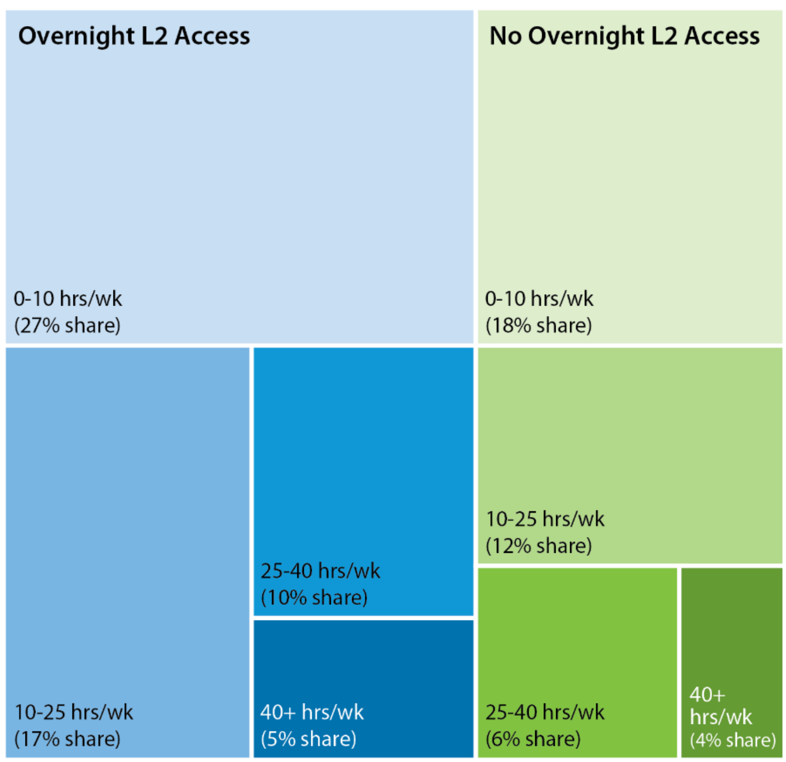

Figure 15. Assumed national composition of ride-hailing drivers by shift type and residential charging access

2.2.5. Charging Behavior

The final demand-side input into the national framework is assumed PEV charging behavior. Charging behavior assumptions embedded in EVI-RoadTrip and EVI-OnDemand are relatively straightforward. In these models, BEVs operate for as long as possible before crossing some range or SOC threshold, then seek out DC charging at the highest possible rate and return to their long-distance trip or ride-hail shift once sufficiently charged. The more complicated charging decisions are addressed by EVI-Pro during typical daily driving, particularly for those without residential access.

In support of this analysis, many informal conversations with industry stakeholders were conducted. Over these conversations, a consensus emerged on several key points, including:

- Home is likely the most convenient and cost-effective charging location (for those with access). The industry should take measured steps toward improving access to charging at or near home locations.
- For those with residential access, PEV technology is progressing in such a way (longer electric driving ranges) that home is likely the only place that *most* people will *need* to charge on a *regular* basis.
- For those without residential access, some drivers will find L2 charging away from home to be an effective solution, but only when appropriately collocated with activities with long dwell times (e.g., 8+ hours).

An interesting point of discussion in these interviews involved the design of fast charging installations, the primary question being “How fast is fast enough?” Historically, a significant share of the publicly accessible DC charging network has been rated at 50 kW. However, there is a recent trend toward “future proofing” DC stations, with a greater share of new installations at higher power ratings, including up to 350 kW. This trend is motivated by driver preferences for faster charging; however, battery technology tends to be the limiting factor on DC charging times. As previously discussed, modern BEVs have a maximum DC acceptance rating, which tends to decrease throughout the course of a fast charge event and can further be derated under adverse thermal conditions. Additionally, some destination charging locations may feature typical dwells of over an hour, providing ample opportunity for charging on units rated for 50–150 kW.

Ultimately, this study elected to employ a baseline charging behavior approach within EVI-Pro that attempts to maximize the use of residential charging as a first priority, then takes advantage of L2 charging away from home at locations with sufficiently long dwells (typically workplaces), and finally relies on fast charging to meet the needs of drivers that don’t have access to home charging and don’t exhibit dwell time away from home compatible with L2 charging speeds.[16]

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[16] EVI-Pro assumes fast charging as being necessary only when long dwell time opportunities to charge slowly are not present in the detailed driving pattern datasets used as inputs. In reality, charging preferences will be dictated by a myriad of conditions that are challenging to anticipate in a model. For this reason, EVI-Pro has been configured in this analysis to simulate a minority of BEV drivers (10%) as preferring fast charging over slower alternatives, including opportunities to charge at home. The size of this behavior cohort is believed to be consistent with the limited set of real-world charging behavior observations available in the literature. BEV manufacturers are arguably in the best position to observe actual charging behavior in the field and are encouraged to consider publishing aggregated charging behavior statistics to inform the efficient deployment of charging infrastructure.

When fast charging is employed within EVI-Pro, the highest rated power unit is selected among the set of 50-, 150-, 250-, and 350-kW charging so long as the selected charger does not exceed the maximum DC acceptance rate of the vehicle being simulated.

The decision to employ charging behavior that prioritizes the fastest possible DC charging (when other options have been exhausted) is based on several considerations. First, stakeholder feedback is consistent that when drivers seek fast charging, they prefer fast charging that is at least as fast as what their vehicle is rated for. Second, the industry (to this point) has largely stayed away from pricing models that incentivize fast charging that is only "as fast as necessary." While there is theoretically potential to optimize installation and operating costs by incentivizing drivers to charge only as fast as necessary, consensus is that such a sophisticated pricing model is inappropriate for this nascent industry. As of 2022, the general population has relatively minimal exposure to PEV charging. Overly complicated pricing models run the risk of introducing detrimental consumer experiences and slowing consumer acceptance of this new technology. The baseline scenario assumes drivers prefer DC charging that is "as fast as possible."

2.3. Supply-Side Considerations: Charging Network Terminology, Taxonomy, Utilization, and Cost

Multiple input parameters must be specified across the three EVI-X models used in this report to estimate the charging infrastructure needs for 33 million light-duty PEVs in the United States by 2030. This subsection reviews critical "supply-side" input assumptions, including EVSE terminology, EVSE taxonomy, network utilization, and infrastructure costs.

2.3.1. EVSE Terminology

Charging infrastructure terminology in this report is consistent with definitions used by the Federal Highway Administration (2023) and is aligned with Open Charge Point Interface (OCPI) terminology for the hierarchy of PEV charging stations, as shown in Figure 16 (adapted from DOE's Alternative Fuel Data Center):

- **Station location:** A site with one or more EVSE ports at the same address. Examples include a parking garage or a mall parking lot.
- **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, which can have one or more EVSE ports.
- **Connector:** What is plugged into a vehicle to charge it. Multiple connectors and connector types (e.g., Tesla, CCS, CHAdeMO) can be available on one EVSE port, but only one vehicle will charge at a time. Connectors are sometimes called plugs.

As discussed in Wood et al. (2017), charging infrastructure needs can be thought of in terms of coverage and capacity, wherein coverage needs tend to be defined in terms of number of stations and capacity needs tend to be defined in terms of number of ports. This analysis is primarily concerned with estimating future demand for charging, and thus presents results in terms of port counts (as opposed to stations).

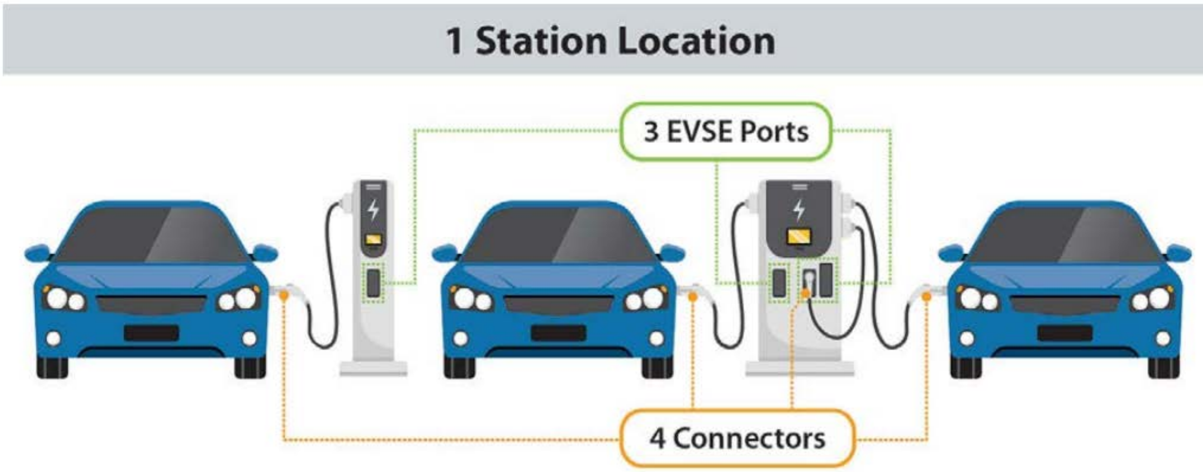

Figure 16. PEV charging infrastructure hierarchy.

Source: Alternative Fuels Data Center (2023a)

2.3.2. EVSE Taxonomy

Traditional EVSE taxonomy approaches adopt a pyramid concept that communicates charging needs in terms of home, workplace, and public charging. This legacy approach has the potential to confuse access type (e.g., public, private) and location type (e.g., home, office, retail). Further, the legacy pyramid concept is particularly ambiguous with respect to workplace charging. Work is commonly described as an activity type in travel surveys (used in analysis studies such as this report), but infrastructure investment is primarily concerned with the types of locations where people work. This ambiguity has the potential to mislead an audience into believing that most workplace charging should be located outside office buildings, when in reality the ability to charge at work is most valuable for those that cannot charge at home. While some office workers will have challenges accessing residential charging, employees working in the retail/service industry may have greater challenges and benefit more from access to charging at their workplace. This analysis proposes EVSE taxonomy along three dimensions, as shown in Figure 17.

The first dimension, access type, simply consists of public and private charging. Public charging is understood within this analysis as charging that is available to any driver regardless of their relation to the EVSE owner/operator. In contrast, access to private charging is determined by the EVSE owner/operator, who could be a homeowner, multifamily housing property manager, employer, or charging network company.

The second dimension, location type, describes types of properties where charging can be located (within the purview of this analysis). This dimension is defined as independent from the access type dimension. For example, charging located at an office building could be public or private access. Similarly, charging located at a retail outlet could be public (potentially designed for customers) or private (potentially designed for employees).

The inclusion of workplace and office as location types within this taxonomy may at first appear to be redundant. The use of workplace as a location type in this analysis is used exclusively alongside private-access charging as a catch-all for all occupation types (including people working in office buildings, retail outlets, recreation centers, health care facilities, schools/universities, community centers, places of worship, etc.). While most charging provided to employees at their workplace today is believed to be private access at office buildings, expected growth in PEV sales suggests that a broader set of occupations should be considered for charging while at work, potentially including charging that is publicly accessible. This analysis classifies 100% of simulated at-work charging as private access in 2022, which decreases to 50% by 2030. Public-access charging while at work is distributed between the aforementioned location types proportional to 2030 employment share forecasts from the Bureau of Labor Statistics (assuming no bias between likely 2030 PEV owners and occupation types). Expected occupations for PEV drivers in 2030 is a relatively under-researched area and a key topic for future study.

EVSE Taxonomy

Access Type	Public	Private
Location Type	Home: SFH Home: MFH Neighborhood Workplace Office Retail	Recreational Health Care School Community Center Transit Hub
EVSE Type	Level 1 Level 2 DC 50 kW	DC 150 kW DC 250 kW DC 350+ kW

Figure 17. EVSE taxonomy employed by this analysis

The third dimension is simply EVSE type using common definitions for L1, L2, and DC charging. Notably, multiple levels of DC charging are available to simulations within this analysis. DC charging rated at 50, 150, 250, and 350 kW are all considered with 350-kW charging labeled as DC350+ as a reflection that BEVs capable of charging above 350 kW are likely to enter the market over the next several years, and DC charging network operators are potentially considering the near-term deployment of charging infrastructure that exceeds 350 kW per port.

2.3.3. Network Utilization

Network sizing within the national simulation pipeline hinges on an assumed regional networkwide peak hour utilization rate (as previously described in this section). Peak hour utilization assumptions in this analysis are primarily informed by Borlaug et al. (2023), in which real-world utilization from tens of thousands of EVSE ports was analyzed. An excerpt of this analysis is shown in Figure 18, where average hourly utilization across a large network of chargers is plotted by location and EVSE type. Consistent with EVI-X modeling results, utilization of residential EVSE peaks in the evening hours and nonresidential use peaks between late morning and midday.

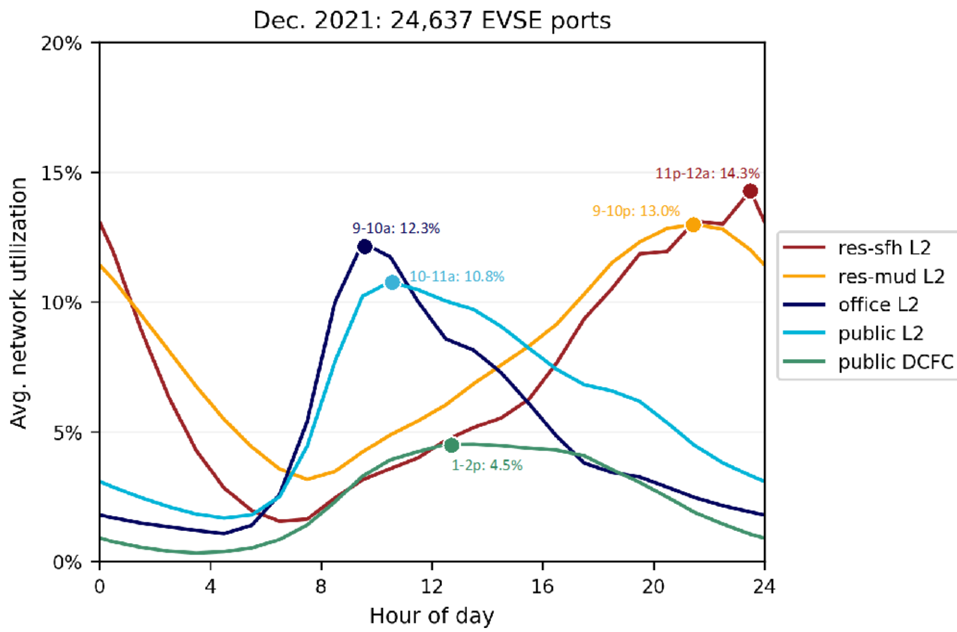

Figure 18. Average network utilization across 24,637 ports from December 2021 by location and EVSE type.

Source: Borlaug et al. (2023)

Analysis of historical EVSE data tends to find relatively low utilization rates (e.g., less than 10%). A common assumption is that EVSE utilization will improve as more PEVs hit the road and demand for charging increases. What is often overlooked is that the supply of charging infrastructure is also increasing in parallel to increases in demand. Thus, projections for increased EVSE utilization should consider the balance of infrastructure supply and demand.

This analysis leverages historical data to inform assumptions for networkwide peak hour utilization. Networkwide peak utilization is treated as a simplified metric for how a charging provider attempts to balance their supply of charging with observed demand from PEVs. Given that the industry is currently in a period of growth with charging supply and demand both increasing rapidly, it is assumed that charging providers are currently trying to stay ahead of increases in demand and proactively grow their networks to minimize congestion for charging to avoid queueing and negative driver perception of availability. In attempting to estimate the needs of the 2030 PEV fleet, this analysis primarily considers a scenario where supply of charging more closely matches the demand for charging. Historical EVSE data are used to quantify the 95th percentile of peak hourly networkwide utilization from existing EVSE for Office-L2 and Public-L2 and 90th percentile for Public-DC chargers (as defined by Borlaug et al. [2023]).

Figure 19 shows distributions of average daily and peak hourly utilization across thousands of real-world EVSE for the aforementioned charger types. This analysis finds peak hourly utilization of Office-L2, Public-L2, and Public-DC charging to be 60%, 55%, and 20%, respectively. These values are directly used within this analysis for network sizing based on simulated demand. The high peak hourly networkwide utilization of L2 EVSE (relative to DC EVSE) is believed to be a product of consistent and long-duration activity patterns aligned with use of the L2 units (such as arrival times at workplaces), whereas the timing of DC charging throughout the day is less predictable with short-duration events, and the network is consequently sized more conservatively to avoid queueing, resulting in relatively low utilization.

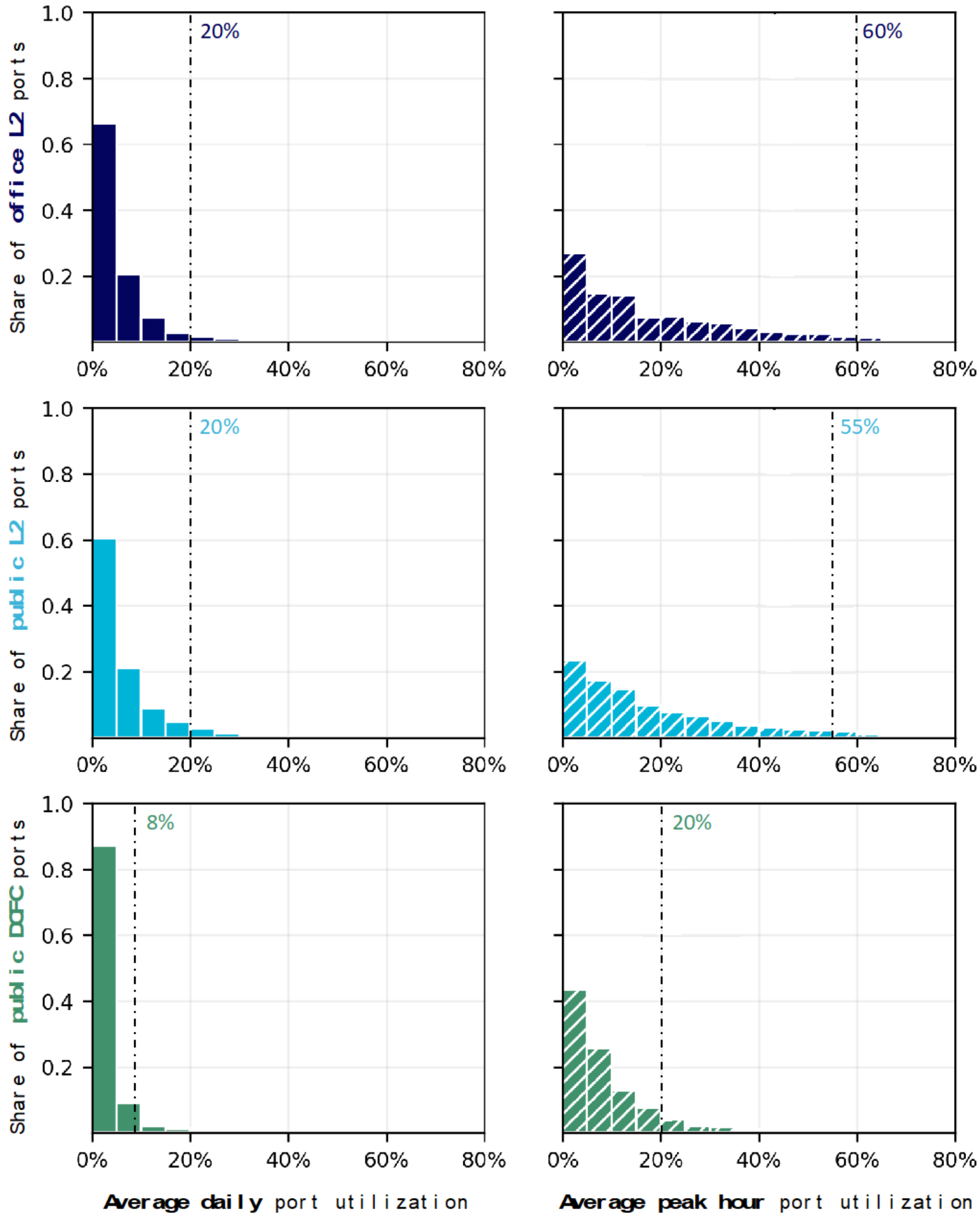

Figure 19. Distribution of average daily port utilization and average peak hour port utilization by location and EVSE type.

Source: Borlaug et al. (2023)

2.3.4. Cost

Charging infrastructure costs are used within the national pipeline as a postprocessing step to estimate the cumulative capital investment required to deploy the simulated network. These costs are based on historical observations from an ensemble of publicly accessible reports, as shown in Table 5. These costs include charging equipment and installation costs which are intended to reflect labor and materials for construction on the customer-side of the meter.

Cost estimates exclude cost of front-of-meter utility upgrades (such as new transformers and line extensions), distributed energy resources (such as on-site storage or generation), operating costs (such as utility energy and demand charges), maintenance costs (necessary for ensuring a high level of reliability), and certain construction soft costs (such as delays associated with local permitting utility service connection). While these additional cost elements are beyond the scope of this analysis (due primarily to a lack of publicly accessible data), they are far from trivial and could significantly contribute to overall costs for the national charging network. Additionally, lead times for these upgrades will dictate the pace of deployment. Previous studies have estimated that while charging infrastructure projects can often take 3-10 months to complete, situations requiring feeder upgrades can add one year to this timeline, and substation upgrades can potentially add up to 4 years (Borlaug et al. 2021).

Table 5. EVSE Capital Cost Assumptions

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.

Regarding the costs that are in scope (charging equipment and installation), no attempt is made to forecast how these costs may evolve in the future. In stakeholder interviews, it was revealed that future costs could plausibly trend in either direction. Economies of scale could put downward pressure on equipment prices, but economywide supply chain challenges could counteract these effects, particularly in a high-demand environment. Similarly, installation costs could decrease as installers continue to accumulate experience with charging projects and identify efficiencies, but installation costs are notorious for being site-specific (proximity to an existing transformer being a key consideration) and per-site costs could plausibly increase as "low-hanging fruit" continues to be picked. For these reasons, this analysis relies solely on historical observations for making cost estimates with no attempt to estimate future cost trajectories.

Estimates for out of scope costs, including how to measure soft costs (including permitting and site acquisition), how to account for fixed civil construction costs and their effect on station sizing and design, how to adequately account for the cost of maintaining a reliable network, how to optimize distributed energy resources (or mimic industry best practices), and approximate cost of and time associated with distribution system upgrades as a function of service connection power requirements are proposed as areas for future research.

3. The National Charging Network of 2030

Results of the national simulation pipeline (described in Section 2) are examined in detail throughout Section 3. First, a detailed breakdown of the 2030 network under the baseline scenario is presented by EVSE taxonomy, PEV use case, and geography. Next, the baseline national network growth trajectory necessary between 2022 and 2030 is presented. Finally, alternate scenario results are presented examining impacts of PEV adoption rate, residential access, TNC electrification rate, and others on the size and cost of the national charging network.

3.1. 2030 Results by EVSE Taxonomy, PEV Use Case, and Region

3.1.1. Results by EVSE Taxonomy

Tables 6 and 7 respectively summarize charging network size and investment need (with breakouts by EVSE taxonomy) based on analysis of the baseline scenario. Simulation results suggest that in this scenario, there is a need for 28 million charging ports by 2030 (85 ports/100 PEVs), with most of that infrastructure dedicated to private L2 charging located at SFHs. This finding is a result of several factors.

Home is assumed to be the most convenient and affordable charging location for those with access, and a large majority of PEV owners (approximately 90% nationally) in 2030 are assumed to have access to charging at home. While this high level of residential access is not representative of all drivers, the likely adopter model underlying this estimate assumes that in the near term, the majority of PEVs will be adopted by drivers with favorable residential access conditions. These conditions vary geographically across the country and will be explored later in this section. A scenario with lower levels of residential charging access is also presented in the sensitivity analysis later in this chapter. Low levels of residential charging access can be used to represent scenarios where infrastructure planning considers PEV adoption among a more diverse set of households than assumed by this report's baseline approach to identifying likely adopters.

After SFHs, over 1 million L2 ports (3 ports/100 PEVs) are simulated at privately accessible multifamily and workplace locations, and over 500,000 L2 ports (1.5 ports/100 PEVs) at publicly accessible neighborhood and office locations. This result reflects the need for destination charging located at or near long-duration activities (such as time spent at home and/or work). These long-duration activities provide ample time for L2 charging, which (like charging at SFHs) PEV drivers tend to find as convenient options for charging.

Approximately 500,000 L2 ports (1.5 ports/100 PEVs) are simulated at a variety of publicly accessible locations, including retail outlets, recreation centers, health care facilities, schools/universities, religious/community centers, and transportation hubs. These locations offer potential for occasional long-duration charging and (more often) short-duration convenience charging.

Finally, the national network includes 182,000 DC ports (0.6 ports/100 PEVs) with varying power capabilities. The simulated public DC network includes 63,000 DC150 ports, 55,000 DC250 ports, and 64,000 DC350+ ports. While the total count of public DC ports pales in comparison to the private and public L2 networks, they are core to the success of the overall network. Access to reliable, convenient, and affordable DC infrastructure supports the vehicle market by giving prospective drivers assurance they can get a fast charge when they need it and supports BEV drivers in a multitude of use cases (including road trips, those without residential access, and ride-hailing electrification).

Table 6. Simulated Cumulative National Network Size Through 2030 by Access, EVSE, and Location Types (includes a total of 28 million ports)

Port (thousands)

Access	Ports	EVSE / Location	Ports
Public	1,248		
		Level 2	**1,067**
		Neighborhood	305
		Office	206
		Retail	178
		Health Care	100
		Recreational	84
		Transport Hub	75
		School	62
		Com. Center	56
		DC Fast	**182**
		DC150	63
		DC250	55
		DC350+	64
Private	26,762		
		Level 1	**7,024**
		Single Family	7,024
		Level 2	**19,738**
		Single Family	18,686
		Multifamily	568
		Workplace	485

The simulated 2030 national network has an estimated capital cost of \$53–\$127 billion. 39% of this cost (\$27–\$44 billion) is dedicated to public DC infrastructure. The remainder of the public infrastructure investment need is dedicated to public L2 (\$5–\$11 billion, 9% of the total investment) and is distributed across a broad set of locations serving a variety of use cases. The majority of the national investment is dedicated to the private network (\$22–\$72 billion, 52% of the total investment), with charging at SFHs playing a prominent role for the reasons previously discussed.

Table 7. Simulated Cumulative National Infrastructure Investment Need Through 2030 by Access, EVSE, and Location Types (a total of $53–$127 billion). Excludes cost of utility upgrades, distributed energy resources, operating costs, and maintenance costs.

Cost (% of total)

Access				EVSE / Location	%
Public	48%				
		$31 Billion to $55 Billion	*$5 Billion to $11 Billion*	**Level 2**	**9%**
				Neighborhood	3%
				Office	2%
				Retail	1%
				Recreational	1%
				Health Care	1%
				School	1%
				Com. Center	1%
				Transport Hub	0%
			$27 Billion to $44 Billion	**DC Fast**	**39%**
				DC150	11%
				DC250	12%
				DC350+	16%
Private	52%				
		$22 Billion to $72 Billion	*$1 Billion to $7 Billion*	**Level 1**	**4%**
				Single Family	4%
			$21 Billion to $65 Billion	**Level 2**	**48%**
				Single Family	39%
				Multifamily	5%
				Workplace	4%

3.1.2. Results by PEV Use Case

This analysis considers three overarching PEV use cases: (1) typical daily driving, (2) long-distance travel, and (3) ride-hailing. Each of these use cases contributes to the demand for a robust national network of DC charging. Figure 20 shows the simulated size of the national 2030 DC network assuming only demand for individual use cases and the combined demand across three use cases. When considered independently, long-distance travel needs contribute 29,600 corridor ports to the national network, local needs contribute 134,400 community ports, and ride-hailing contributes about another 43,700 ports. If modeled in isolation, these three distinct networks would require about 208,000 ports, but when considering the opportunity for shared use (as is the case in the real world), the size of the national network decreases to 181,500 ports (an efficiency improvement of 13% enabled by shared use).

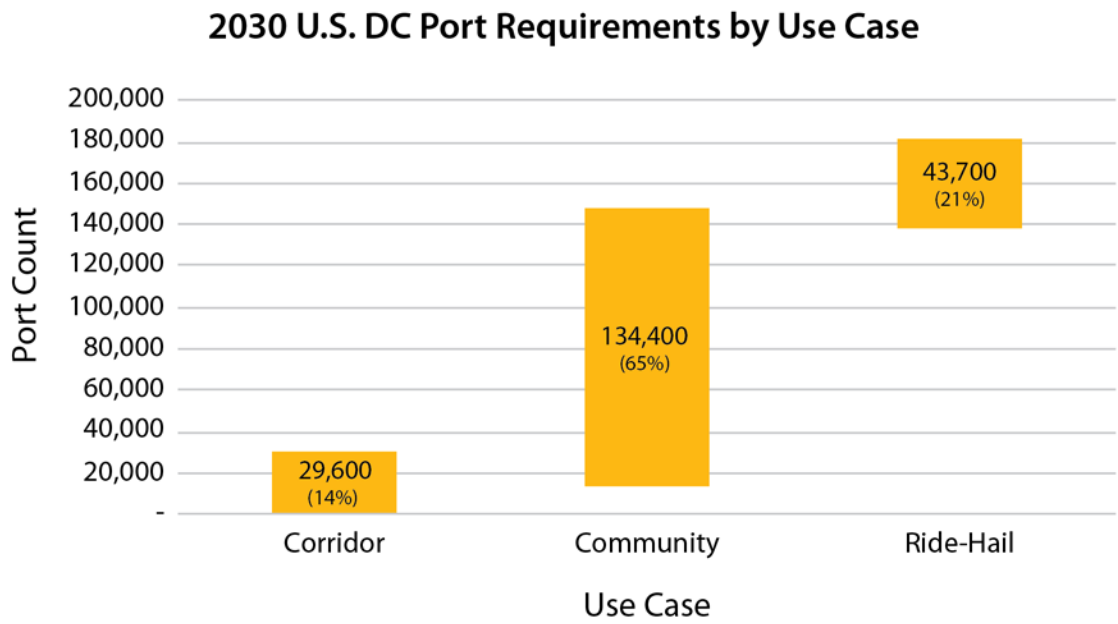

Figure 20. Simulated national DC charging network sized individually by use case and sized by consolidating demand

While 100% of the charging demand from EVI-RoadTrip is attributed to public DC, EVI-Pro and EVI-OnDemand simulate the balance of private and public charging based on vehicle technology, residential access, and travel patterns.

Figure 21 shows the daily charging demand from typical use of light-duty PEVs as simulated by EVI-Pro. Demand (expressed in daily kWh/vehicle) is broken out by powertrain type (BEV/PHEV), body style (sedan, C/SUV, pickup, van), and residential access. BEVs with access to residential charging can be seen to provide relatively low levels of demand for charging away from home, instead relying on home charging for most of their daily driving needs. Conversely, BEVs without residential access are exclusively reliant on charging while at work and other publicly accessible locations, particularly public DC. PHEVs exhibit similar charging patterns as BEVs, with lower overall charging demands and absence of public DC charging. As PHEVs are assumed not to be capable of DC charging, the only charging options within EVI-Pro for PHEVs without residential access are L2 charging at work and publicly accessible locations.

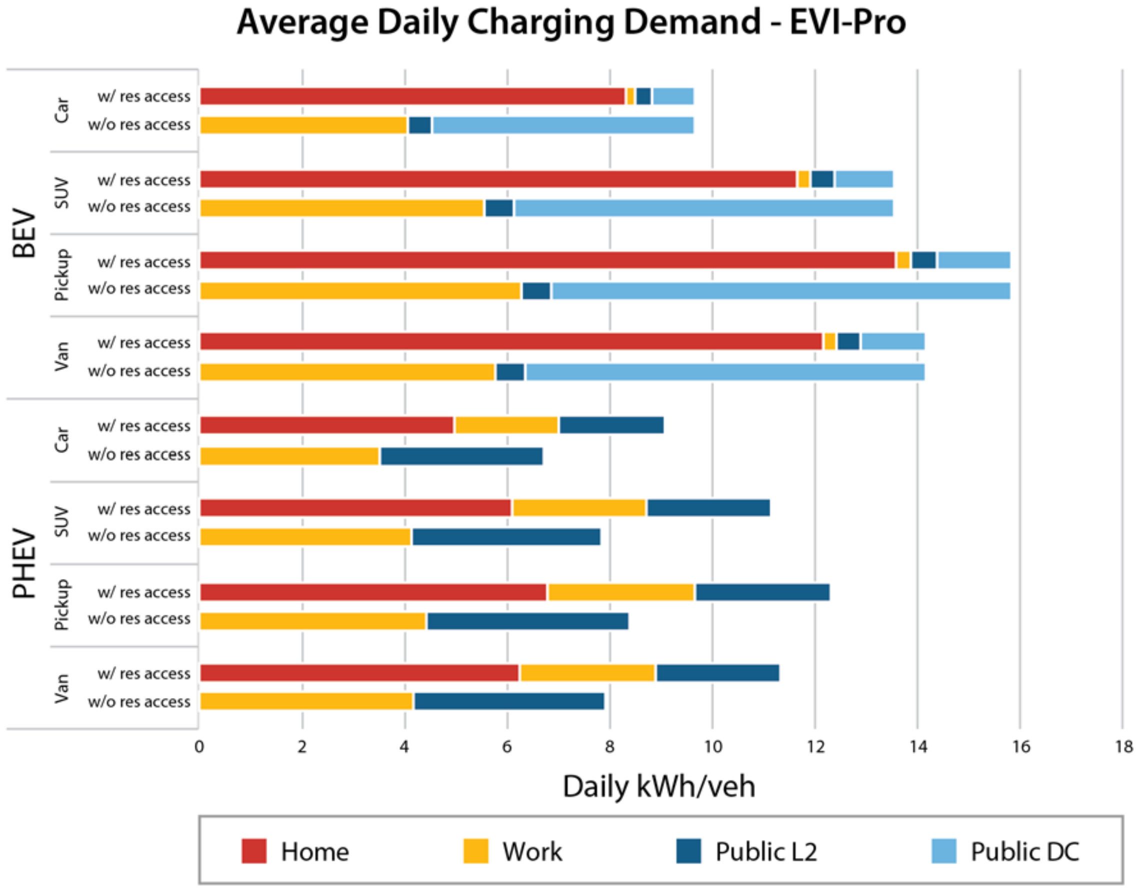

Figure 21. Average daily charging demand simulated by EVI-Pro for typical daily travel, broken out by powertrain type, body style, and residential access

Figure 22 shows the daily charging demand simulated by EVI-OnDemand for ride-hailing use cases, broken out by shift duration (expressed as hours worked per week) and residential access. Overall charging demands for the ride-hailing use case are significantly higher per vehicle than the typical daily use case. Ride-hailing charging demand is also a strong function of shift duration, with full-time drivers (40+ hours/week) demanding approximately 5 times more charging than those that only operate occasionally (0–10 hours/week). The composition of charging demand is a strong function of shift duration and residential access. Occasional drivers with residential access are typically simulated as providing no demand for public DC charging, while full-time drivers with residential access can require public DC to meet approximately 60% of their needs. Conversely, all drivers without residential access are simulated as needing 100% of their charging needs to be met by public DC charging.

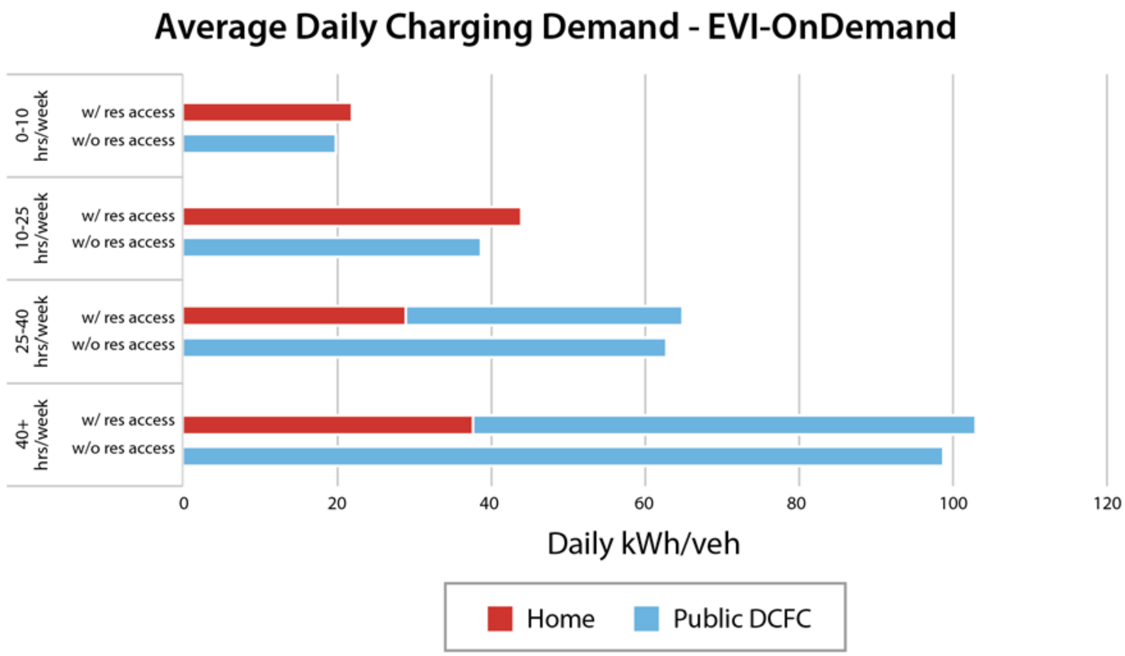

Figure 22. Average daily charging demand simulated by EVI-OnDemand for ride-hailing use cases, broken out by shift duration and residential access

3.1.3. Results by Region

Tables 8, 9, and 10 provide baseline 2030 results by state (including D.C. and Puerto Rico). Tables are provided for the private, public L2, and public DC networks in each state, respectively.

Table 8. State-Level Port Count Summary for the Simulated 2030 Private Network

State	PEVs	Single Family	Multifamily	Workplace	Total
AK	60,000	46,000	1,100	1,000	48,100
AL	310,000	266,000	900	3,800	270,700
AR	190,000	159,000	300	2,200	161,500
AZ	780,000	635,000	4,900	10,200	650,100
CA	7,330,000	5,073,000	157,800	154,000	5,384,800
CO	790,000	619,000	11,300	10,900	641,200
CT	340,000	264,000	9,900	5,000	278,900
DC	70,000	53,000	1,600	1,200	55,800
DE	100,000	79,000	800	1,300	81,100
FL	1,900,000	1,515,000	60,000	20,000	1,595,000
GA	810,000	670,000	6,800	10,600	687,400
HI	170,000	125,000	8,200	2,300	135,500
IA	270,000	230,000	1,100	3,500	234,600
ID	210,000	170,000	600	2,800	173,400
IL	1,100,000	893,000	34,600	14,600	942,200
IN	500,000	421,000	3,700	6,200	430,900
KS	230,000	192,000	700	3,100	195,800
KY	300,000	255,000	1,800	3,800	260,600
LA	230,000	193,000	1,400	2,600	197,000
MA	810,000	600,000	34,200	13,200	647,400
MD	680,000	517,000	10,900	10,500	538,400
ME	160,000	128,000	2,700	3,000	133,700
MI	720,000	614,000	4,000	9,800	627,800
MN	560,000	454,000	6,200	10,000	470,200
MO	450,000	377,000	2,700	5,700	385,400
MS	150,000	129,000	200	1,800	131,000
MT	100,000	84,000	400	1,600	86,000
NC	890,000	718,000	5,500	11,600	735,100
ND	50,000	46,000	200	900	47,100
NE	160,000	138,000	400	2,000	140,400
NH	170,000	128,000	6,100	2,800	136,900
NJ	820,000	616,000	35,700	12,000	663,700
NM	200,000	162,000	800	2,600	165,400
NV	320,000	252,000	3,600	4,300	259,900
NY	1,420,000	1,086,000	53,900	21,400	1,161,300
OH	860,000	722,000	6,100	10,700	738,800
OK	240,000	205,000	500	3,300	208,800
OR	720,000	519,000	6,200	13,000	538,200
PA	1,060,000	872,000	7,600	14,300	893,900
PR	90,000	70,000	4,200	1,400	75,600
RI	100,000	76,000	3,500	1,400	80,900
SC	380,000	314,000	2,400	4,500	320,900
SD	70,000	61,000	100	1,200	62,300
TN	530,000	442,000	3,300	6,700	452,000
TX	2,230,000	1,850,000	12,400	28,000	1,890,400
UT	380,000	303,000	3,600	5,100	311,700
VA	950,000	739,000	13,100	14,200	766,300
VT	100,000	80,000	1,700	1,600	83,300
WA	1,340,000	975,000	20,300	23,800	1,019,100
WI	530,000	437,000	7,500	7,500	452,000
WV	120,000	97,000	300	1,500	98,800
WY	50,000	43,000	100	700	43,800

Table 9. State-Level Port Count Summary for the Simulated 2030 Public L2 Network

State	PEVs	Neighborhood	Office	Retail	Other	Total
AK	60,000	500	500	400	1,200	2,600
AL	310,000	2,400	1,700	1,600	3,800	9,500
AR	190,000	1,400	1,300	1,000	2,500	6,200
AZ	780,000	6,900	3,500	4,300	7,600	22,300
CA	7,330,000	74,400	44,000	54,400	89,300	262,100
CO	790,000	7,300	4,100	4,500	9,200	25,100
CT	340,000	3,100	1,500	1,800	3,300	9,700
DC	70,000	800	400	500	800	2,500
DE	100,000	900	400	500	900	2,700
FL	1,900,000	19,400	7,100	8,100	16,100	50,700
GA	810,000	6,900	4,100	4,500	9,000	24,500
HI	170,000	1,900	800	900	1,700	5,300
IA	270,000	2,100	1,900	1,500	4,000	9,500
ID	210,000	1,600	1,300	1,200	3,200	7,300
IL	1,100,000	11,000	5,100	6,000	10,900	33,000
IN	500,000	4,100	2,600	2,600	5,600	14,900
KS	230,000	1,800	1,800	1,300	3,000	7,900
KY	300,000	2,400	1,900	1,600	4,200	10,100
LA	230,000	1,800	1,200	1,100	2,500	6,600
MA	810,000	7,900	4,200	5,300	9,100	26,500
MD	680,000	7,300	3,400	4,400	7,000	22,100
ME	160,000	1,400	1,100	1,200	2,300	6,000
MI	720,000	6,100	3,600	4,100	7,700	21,500
MN	560,000	4,900	3,700	4,300	7,700	20,600
MO	450,000	3,600	2,700	2,500	5,500	14,300
MS	150,000	1,100	1,100	800	2,200	5,200
MT	100,000	800	800	700	1,600	3,900
NC	890,000	7,300	4,400	4,900	9,500	26,100
ND	50,000	400	600	400	1,200	2,600
NE	160,000	1,300	1,300	900	2,000	5,500
NH	170,000	1,600	1,000	1,100	2,400	6,100
NJ	820,000	8,900	3,600	4,800	7,600	24,900
NM	200,000	1,600	1,100	1,100	2,400	6,200
NV	320,000	2,700	1,600	1,800	3,500	9,600
NY	1,420,000	14,100	7,200	8,000	15,400	44,700
OH	860,000	7,200	4,000	4,500	8,500	24,200
OK	240,000	1,900	1,600	1,400	3,300	8,200
OR	720,000	5,500	4,200	5,500	9,000	24,200
PA	1,060,000	10,100	4,900	6,000	10,900	31,900
PR	90,000	1,000	500	500	1,200	3,200
RI	100,000	900	500	600	1,000	3,000
SC	380,000	3,100	1,800	1,900	3,800	10,600
SD	70,000	500	700	500	1,500	3,200
TN	530,000	4,400	2,800	2,900	5,900	16,000
TX	2,230,000	18,600	10,600	11,900	22,300	63,400
UT	380,000	3,300	1,800	2,200	3,800	11,100
VA	950,000	9,200	5,000	6,000	10,700	30,900
VT	100,000	800	700	600	1,900	4,000
WA	1,340,000	11,100	7,200	10,000	15,700	44,000
WI	530,000	4,500	2,800	3,200	6,100	16,600
WV	120,000	900	800	700	1,700	4,100
WY	50,000	400	400	300	1,000	2,100

Table 10. State-Level Port Count Summary for the Simulated 2030 Public DC Network

State	PEVs	DC150	DC250	DC350+	Total
AK	60,000	200	200	300	700
AL	310,000	900	900	700	2,500
AR	190,000	800	900	700	2,400
AZ	780,000	1,200	1,100	1,500	3,800
CA	7,330,000	10,700	7,500	10,900	29,100
CO	790,000	1,500	1,200	1,500	4,200
CT	340,000	600	400	500	1,500
DC	70,000	100	100	100	300
DE	100,000	100	100	100	300
FL	1,900,000	2,800	2,600	2,400	7,800
GA	810,000	1,800	1,800	1,500	5,100
HI	170,000	300	200	200	700
IA	270,000	900	1,000	900	2,800
ID	210,000	600	500	700	1,800
IL	1,100,000	2,000	2,000	1,700	5,700
IN	500,000	1,100	1,100	1,000	3,200
KS	230,000	800	800	900	2,500
KY	300,000	800	900	900	2,600
LA	230,000	600	700	600	1,900
MA	810,000	1,300	1,100	1,100	3,500
MD	680,000	1,100	800	900	2,800
ME	160,000	400	300	400	1,100
MI	720,000	1,700	1,500	1,400	4,600
MN	560,000	1,500	1,200	1,500	4,200
MO	450,000	1,200	1,300	1,100	3,600
MS	150,000	600	700	600	1,900
MT	100,000	600	500	700	1,800
NC	890,000	1,700	1,600	1,600	4,900
ND	50,000	400	300	400	1,100
NE	160,000	600	600	700	1,900
NH	170,000	300	200	300	800
NJ	820,000	1,200	900	1,000	3,100
NM	200,000	500	600	1,200	2,300
NV	320,000	600	600	1,100	2,300
NY	1,420,000	2,500	1,800	2,000	6,300
OH	860,000	1,700	1,700	1,600	5,000
OK	240,000	600	800	800	2,200
OR	720,000	1,200	900	1,500	3,600
PA	1,060,000	1,900	1,600	1,900	5,400
PR	90,000	200	100	200	500
RI	100,000	200	100	100	400
SC	380,000	700	700	600	2,000
SD	70,000	400	300	400	1,100
TN	530,000	1,100	1,200	1,000	3,300
TX	2,230,000	3,900	4,400	5,000	13,300
UT	380,000	700	700	1,200	2,600
VA	950,000	1,800	1,500	1,700	5,000
VT	100,000	300	200	300	800
WA	1,340,000	2,100	1,400	2,100	5,600
WI	530,000	1,300	1,100	1,100	3,500
WV	120,000	400	400	500	1,300
WY	50,000	200	200	400	800

Table 11 provides a port count summary for the private charging network in the top 10 CBSAs by modeled PEV population. As was the case with the national summary, the private network in these markets is simulated as being dominated by EVSE installed at SFHs. Los Angeles is by far the largest CBSA simulated in this analysis, nearly double the size of the next largest CBSA (San Francisco) in terms of assumed PEV fleet size.

Table 11. Port Count Summary for the Simulated Private Network in the Top 10 CBSAs in Terms of Assumed PEV Adoption

		Private Ports		
CBSA	PEVs	Single Family	Multifamily	Workplace
Los Angeles-Long Beach-Anaheim, CA	2,468,000	1,701,000	67,000	43,000
New York-Newark-Jersey City, NY-NJ-PA	1,422,000	1,048,000	7,000	20, 000
San Francisco-Oakland-Berkeley, CA	1,216,000	759,000	40,000	29,000
Washington-Arlington-Alexandria, DC-VA-MD-WV	868,000	628,000	19,000	14,600
Chicago-Naperville-Elgin, IL-IN-WI	848,000	658,000	36,000	11,000
Seattle-Tacoma-Bellevue, WA	805,000	558,000	17,000	15,000
San Diego-Chula Vista-Carlsbad, CA	676,000	466,000	18,000	11,000
Dallas-Fort Worth-Arlington, TX	651,000	542,000	4,000	9,000
Riverside-San Bernardino-Ontario, CA	641,000	486,000	5,000	11,000
Boston-Cambridge-Newton, MA-NH	595,000	426,000	30,000	10,000

Tables 12 and 13 provide port count summaries for the public L2 and DC charging networks in the top 10 CBSAs, respectively. As was the case with the national summary, the public network in these markets is simulated as being dominated by L2 EVSE in terms of port count. On the basis of cost, the public DC network is expected to require the majority of financial resources in all of these markets.

Table 12. Port Count Summary for the Simulated Public L2 Network in the Top 10 CBSAs in Terms of Assumed PEV Adoption

		Public L2 Ports			
CBSA	PEVs	Neighborhood	Office	Retail	Other
Los Angeles-Long Beach-Anaheim, CA	2,468,000	27,000	18,000	14,000	27,000
New York-Newark-Jersey City, NY-NJ-PA	1,422,000	16,000	8,000	6,000	13,000
San Francisco-Oakland-Berkeley, CA	1,216,000	14,000	12,000	9,000	18,000
Washington-Arlington-Alexandria, DC-VA-MD-WV	868,000	9,000	6,000	4,000	9,000
Chicago-Naperville-Elgin, IL-IN-WI	848,000	9,000	4,000	3,000	7,000
Seattle-Tacoma-Bellevue, WA	805,000	7,000	7,000	4,000	9,000
San Diego-Chula Vista-Carlsbad, CA	676,000	7,000	5,000	4,000	7,000
Dallas-Fort Worth-Arlington, TX	651,000	6,000	4,000	3,000	6,000
Riverside-San Bernardino-Ontario, CA	641,000	6,000	5,000	4,000	7,000
Boston-Cambridge-Newton, MA-NH	595,000	6,000	4,000	3,000	6,000

Table 13. Port Count Summary for the Simulated Public DC Network in the Top 10 CBSAs in Terms of Assumed PEV Adoption

		Public DC Ports		
CBSA	PEVs	DC150	DC250	DC350+
Los Angeles-Long Beach-Anaheim, CA	2,468,000	3,000	2,200	3,200
New York-Newark-Jersey City, NY-NJ-PA	1,422,000	1,900	1,400	1,500
San Francisco-Oakland-Berkeley, CA	1,216,000	2,000	1,100	1,600
Washington-Arlington-Alexandria, DC-VA-MD-WV	868,000	1,300	900	1,000
Chicago-Naperville-Elgin, IL-IN-WI	848,000	1,300	1,100	900
Seattle-Tacoma-Bellevue, WA	805,000	1,000	700	1,100
San Diego-Chula Vista-Carlsbad, CA	676,000	800	600	900
Dallas-Fort Worth-Arlington, TX	651,000	900	900	700
Riverside-San Bernardino-Ontario, CA	641,000	900	700	800
Boston-Cambridge-Newton, MA-NH	595,000	900	800	800

Table 14 identifies the top 10 CBSAs in terms of simulated DC ports per 1,000 PEVs. This table highlights areas where demand for DC charging seemingly exceeds expectations based on the local fleet size. Within the context of this analysis, EVI-Pro and EVI-OnDemand assume that all charging demand from vehicles owned within a given CBSA is self-contained within that geography. However, EVI-RoadTrip simulated charging demand on long-distance trips in a spatially explicit way that considers the frequency of BEV travel between counties using an origin-destination matrix from FHWA's TAF (as shown in Figure 23). Charging demand from vehicles "passing through" is believed to be the cause of elevated demand in these locations. For example, the California CBSAs of Merced, Redding, and Bakersfield along the I-5 and CA-99 north-south corridors are relatively small PEV markets where demand from vehicles on long trips between larger surrounding CBSAs make an outsized impact.

Table 14. Top 10 CBSAs by Simulated DC Ports per 1,000 PEVs

CBSA	PEVs	DC Ports	DC Ports per 1,000 PEVs
Merced, CA	26,000	349	13.2
Redding, CA	24,000	236	9.7
Bakersfield, CA	83,000	639	7.7
El Paso, TX	50,000	365	7.3
Lafayette, LA	24,000	173	7.2
St. George, UT	27,000	191	7.1
Gainesville, FL	29,000	202	6.9
Duluth, MN	24,000	161	6.8
Green Bay, WI	27,000	177	6.6
Youngstown-Warren-Boardman, OH-PA	31,000	202	6.5
Top 200 CBSAs	**27,621,000**	**110,000**	**4.0**

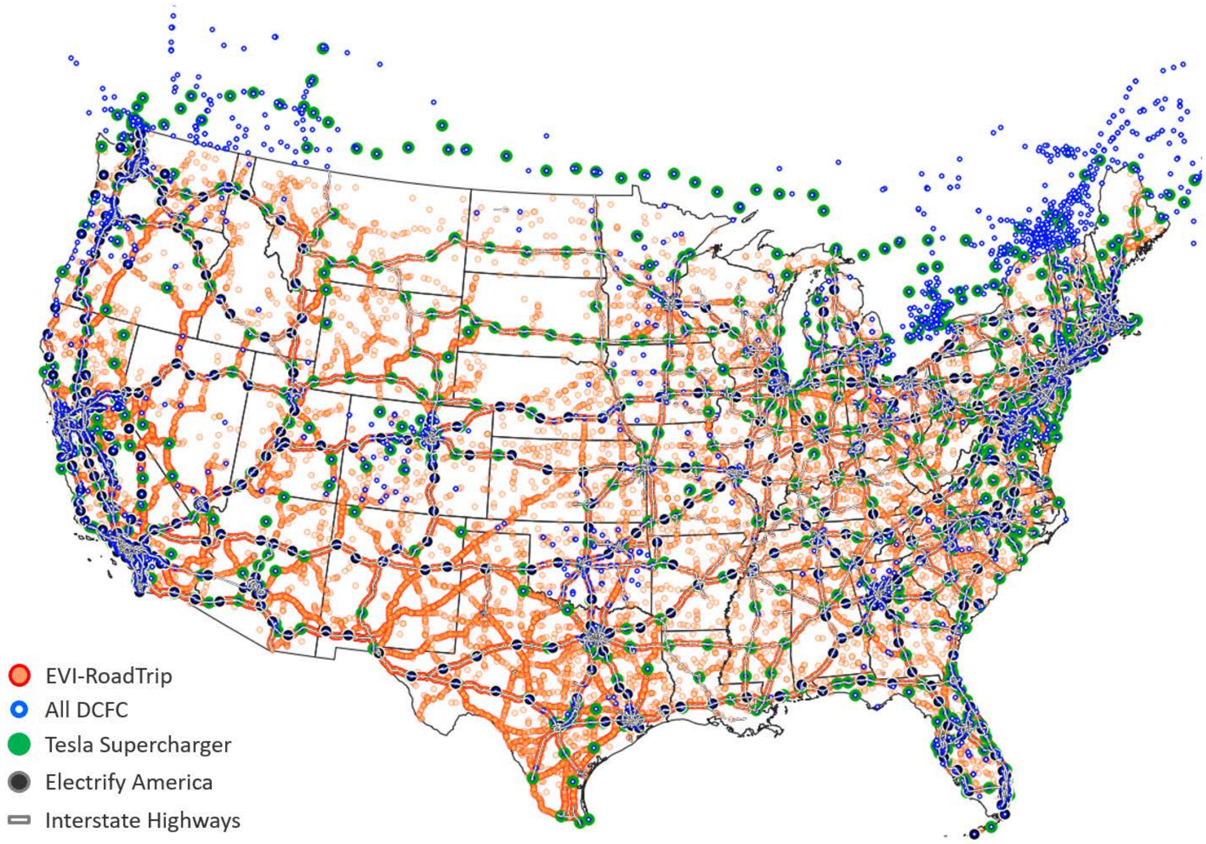

Figure 23. Example charging demand from EVI-RoadTrip overlaid with locations of existing DC stations, including those part of the Tesla Supercharger and Electrify America networks

A closer look at the EVI-RoadTrip simulation results reveals significant variability in simulated utilization across the national corridor network. As shown in Figure 24, among the 1,300 simulated corridor stations (nominally spaced every 50 miles), 60% are estimated to experience four or fewer charging events in the peak hour of a typical day. Of course, some station locations are simulated as having much higher demand; about 10% of stations are estimated to experience 10 or more events during the peak hour of a typical day. This variability of utilization speaks directly to the potential financial viability of operating a national network of corridor stations. In order to achieve national coverage, a significant number of sites are required where low utilization (and revenue) should be expected, even in a national environment with 33 million PEVs on the road.

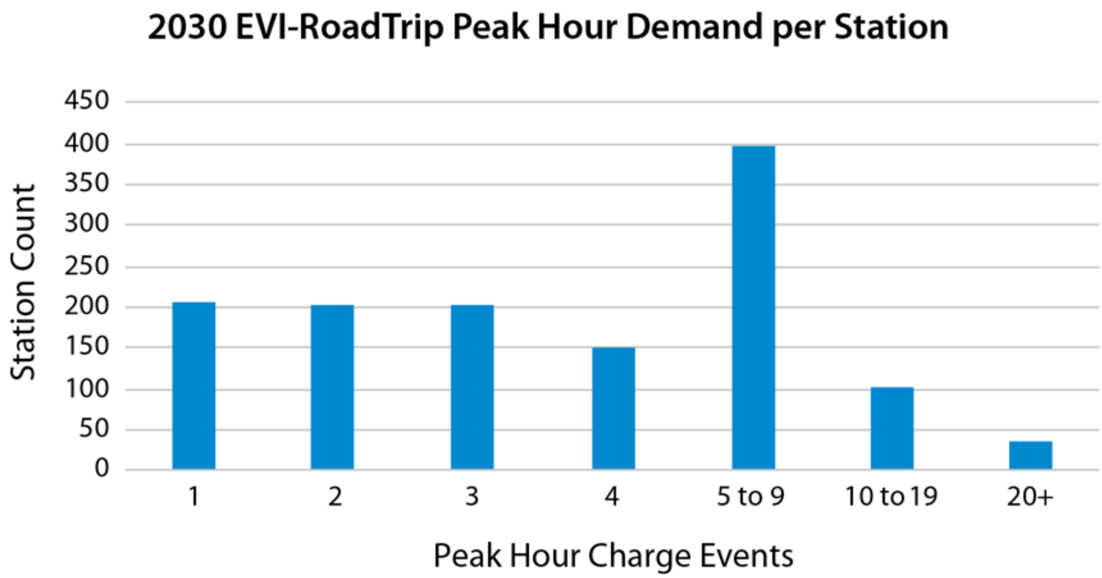

Figure 24. Distribution of peak hourly utilization across corridor stations as simulated by EVI-RoadTrip

For the last example of regionally specific results, we revisit the EVI-OnDemand simulations. Figure 25 shows a scatter plot of normalized DC charging demand across CBSAs as a function of worst-case ambient conditions (based on the Extreme Weather scenario). Ambient conditions are known to impact charging demand, as PEVs tend to consume more energy while being driven in hot and cold environments, typically due to increased electrical loads for operating cabin and powertrain thermal management systems. Charging speeds can also be impacted in extreme environmental conditions, resulting in decreased throughput that could be compensated for with additional infrastructure. In this analysis, BEV sedans are simulated in EVI-OnDemand as achieving energy consumption rates between 300 and 550 Wh/mi while in ride-hailing service. Increased energy consumption is shown to directly correlate to elevated infrastructure needs with EVI-OnDemand.

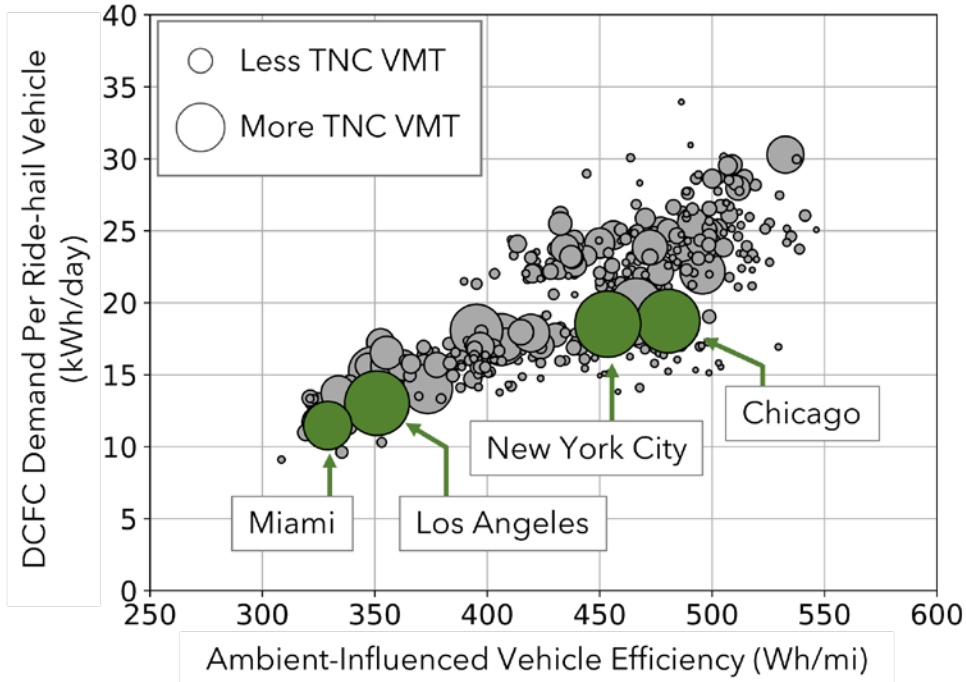

Figure 25. Normalized DC charging demand across CBSAs as a function of worst-case ambient conditions

3.2. Network Growth From 2022 to 2030

National results from the simulation pipeline between 2022 and 2030 are shown in Figure 26. Under the baseline scenario, the size of the national charging network is estimated to require growth from approximately 3.1 million ports in 2022 to 28 million ports by 2030, with the vast majority of this infrastructure simulated as privately accessible L2 units. Isolating for size of the public network, a total of 1.2 million publicly accessible ports (3.6 public ports/100 PEVs) are estimated as being necessary to support 33 million light-duty PEVs in 2030.

Given the large cost differences in L2 and DC infrastructure (reviewed in Section 2), port shares alone may mislead readers as to the significant levels of investment needed to build out the public DC charging network. A cumulative investment of $31–$55 billion in publicly accessible charging infrastructure is estimated through 2030, with a 20/80 share between L2 and DC charging ports (in terms of cost). When including the needs of the private network, the cumulative national infrastructure investment estimate increases to $53–$127 billion with a 52/39/9 share between private, public DC, and public L2 (in terms of cost).

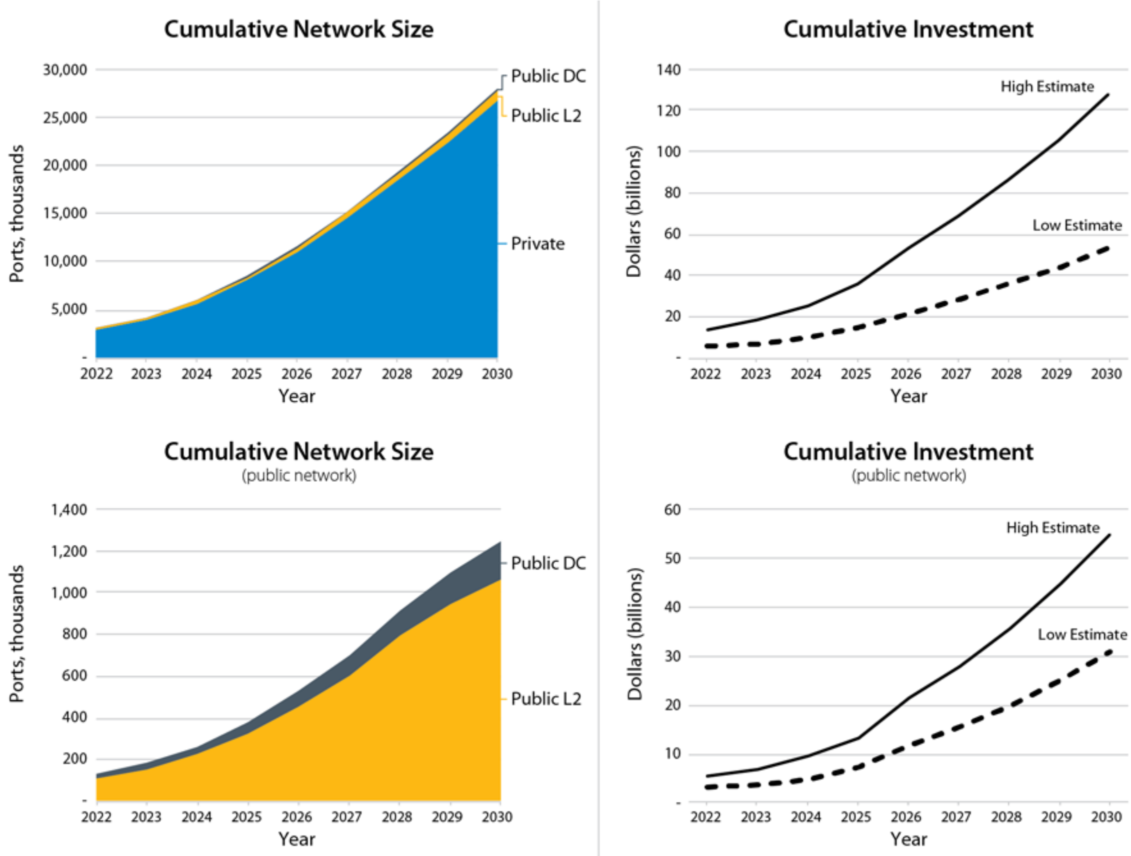

Figure 26. Simulated cumulative network size (left column) and cumulative investment (right column) between 2022 and 2030. Both private and public infrastructure estimates are shown in the top row, while the bottom row isolates the public network result.

The trajectory for network growth and investment needs is shown in Figure 27, with annual needs shown between 2023 and 2030. National simulations estimate annual growth in private and public ports increasing from 1 million in 2023 to 4.5 million in 2030, the vast majority being private EVSE. When isolating publicly accessible charging, simulations suggest annual growth of the public network increasing from 50,000 ports in 2023 to over 200,000 ports in 2028. Interestingly, annual growth in the public network slows after 2028 despite PEV sales continuing to accelerate. This trend is due to a reduced rate of public L2 deployment. While simulated demand for public L2 continues to grow in 2029 and 2030, a significant portion of the new demand is modeled as being met by public L2 infrastructure already installed (implying improved utilization of the simulated public L2 network over time).

Again, the composition of the public network undersells the significance of DC charging. Annual investment in the public network is simulated as increasing from \$0.7–\$1.4 billion in 2023 to \$6.2–\$10.4 billion in 2030, with most of this investment dedicated to DC charging (approximately 80%). As PEV charging technology matures and larger batteries are deployed in PEVs to support longer driving ranges and larger body styles, the mix of DC charging trends toward higher-power installations. While 80% of the 2023 investment in public DC is dedicated to DC150, this share decreases to 27% by 2030, with the majority of investment need shifting to DC350+ by 2026.

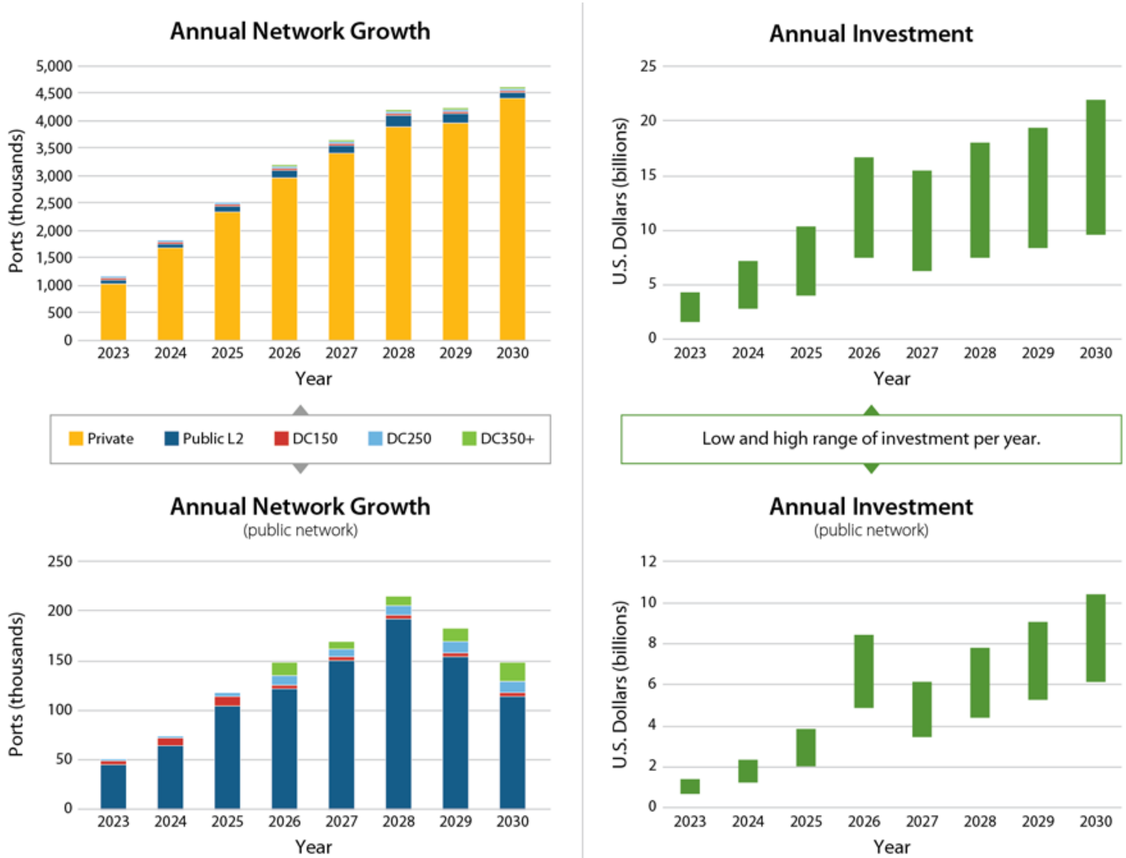

Figure 27. Simulated annual network growth (left column) and investment need (right column) between 2023 and 2030. Both private and public infrastructure estimates are shown in the top row, while the bottom row isolates the public network result.

3.3. Alternate Scenarios

In addition to baseline results presented thus far, a number of alternate scenarios have been simulated to examine impacts of PEV adoption rate, residential access, TNC electrification and more on the size and cost of the national charging network. These scenarios are once again shown in Table 15 (repeated from Section 2.2).

Table 15. Description of Select Plausible Alternates to the Baseline Scenario

Scenario	Description
High Adoption	PEV fleet size growth to 42 million PEVs on the road by 2030 (baseline: 33 million PEVs by 2030)
Low Adoption	PEV fleet size growth to 30 million PEVs on the road by 2030 (baseline: 33 million PEVs by 2030)
Low Home Charging Access	Assumes 85% of PEV drivers with residential access based on the "existing electrical access" scenario from Ge et. al (2021) (baseline: 90% residential access)
High Home Charging Access	Assumes 98% of PEV drivers with residential access based on the "potential electrical access" scenario from Ge et. al (2021) (baseline: 90% residential access)
Reduced Daily Travel	PEVs are driven 60% of days, 25% less than the baseline (80% of days)
Bad Charging Etiquette	PEVs are not unplugged during public destination L2 charging until the driver's activity at the destination is complete and the vehicle departs (baseline: PEVs are capable of being unplugged when they are finished charging and made available for another PEV)
PHEV Success	PHEVs retain 2022 PEV market share (28%) through 2030 (baseline: PHEVs have 10% PEV market share in 2030)
Alternate PEV Adoption	PEV adoption is geographically uniform in 2030 with no urban early adopter preference (baseline: geographic distribution of PEVs in 2030 reflects 2022 distribution of PEVs and hybrid electric vehicles)
Extreme Weather	EVSE network designed for extreme (95th percentile) weather conditions affecting PEV range and increasing charging demand (baseline: EVSE network designed for average weather conditions)
Slow TNC Electrification	TNC fleets are only 50% PEVs by 2030 (baseline: 100% TNC PEVs by 2030)
Private Workplace Charging	100% of workplace charging at private EVSE through 2030 (baseline: 100% in 2022, decreasing to 50% by 2030)

Alternate scenario results are presented in Tables 16 and 17 for changes in the composition and cost of the national charging network, respectively, relative to the baseline scenario. As a reminder, the baseline scenario considers 33 million PEVs requiring 28 million charging ports at a cumulative cost of $53–$127 billion. This hypothetical network consists of 26.8 million private L2 ports at a cost of $22–$72 billion, 1 million public L2 ports at a cost of $5–$11 billion, and 182,000 public DC ports at a cost of $31–$55 billion.

At first glance, significant variability in the size and composition of the simulated national charging network can be observed across alternate scenarios. Relative to the baseline scenario, national network size and capital cost vary by ±25% across the range of scenarios considered (±50% when isolating to the public network).

Table 16. Relative Port Counts Resulting from Parametric Sensitivity Analysis

Baseline	**26,762**	**1,067**	**182**	**28,010**
Relative Port Counts (thousands)				
Scenario	**Private**	**Public L2**	**Public DC**	**Total**
High Adoption	7,038	302	29	7,370
Low Adoption	(2,120)	(111)	(8)	(2,239)
Low Home Charging Access	(1,236)	70	13	(1,153)
High Home Charging Access	2,459	(167)	(33)	2,259
Reduced Daily Travel	(157)	(180)	(22)	(358)
Bad Charging Etiquette	360	473	(0)	833
PHEV Success	388	615	(17)	986
Alternate PEV Adoption	1,736	16	7	1,758
Extreme Weather	87	162	49	298
Slow TNC Electrification	(41)	(10)	(17)	(69)
Private Workplace Charging	436	(450)	(0)	(15)

Table 17. Relative Infrastructure Costs Resulting from Parametric Sensitivity Analysis

Baseline	$22B to $72B	$5B to $11B	$27B to $44B	$53B to $127B
	Relative Cost ($ billions)			
Scenario	Private	Public L2	Public DC	Total
High Adoption	$12.5	$2.3	$5.9	$20.7
Low Adoption	($3.9)	($0.8)	($1.7)	($6.5)
Low Home Charging Access	($1.5)	$0.5	$2.5	$1.5
High Home Charging Access	$2.8	($1.3)	($6.2)	($4.6)
Reduced Daily Travel	($1.0)	($1.3)	($4.3)	($6.7)
Bad Charging Etiquette	$2.9	$3.5	($0)	$6.4
PHEV Success	$1.6	$4.6	($3.4)	$2.7
Alternate PEV Adoption	$2.2	$0.1	$1.1	$3.4
Extreme Weather	$0.9	$1.2	$9.1	$11.2
Slow TNC Electrification	($0.1)	($0.1)	($3.0)	($3.2)
Private Workplace Charging	$3.5	($3.4)	($0)	$0.1

The "Low Adoption" and "High Adoption" scenarios result in different PEV fleet sizes, impacting the size of the simulated charging network. "Low Adoption" assumes a national PEV fleet size of 30 million. This results in decreased demand for charging of all types, with 2.2 million fewer ports and cost reduced by $6.5 billion. Conversely, the "High Adoption" scenario assumes an on-road fleet of 42 million by 2030. Naturally, this increases demand for charging such that 7.3 million more ports are necessary at an incremental cost of $20.7 billion. Of the scenarios explored, the "High Adoption" scenario increases the size and cost of the national charging network by the most significant margin.

The "High Home Charging Access" and "Low Home Charging Access" scenarios adjust the baseline assumption of 90% overnight residential charging access to 98% and 85%, respectively. The "Low Home Charging Access" scenario shifts demand toward nonresidential locations such that the national public charging network increases by 83,000 ports at an incremental cost of $3.0 billion. Conversely, high residential access is simulated as shifting charging demand away from nonresidential locations such that the national public charging network decreases by 200,000 ports at a cost savings of $7.5 billion.

The "Reduced Daily Travel" scenario decreases driving across the fleet by 25%. As expected, this leads directly to a decrease in size and cost of the national network with 358,000 few ports needed at a cost savings of $6.7 billion. Of the scenarios explored, the “Reduced Daily Travel” scenario decreases the cost of the national charging network by the most significant margin.

While PEVs are assumed to be unplugged when finished L2 charging at nonresidential locations in the baseline scenario, the “Bad Charging Etiquette” scenario assumes L2 chargers are not available until the driver departs that location. This behavior scenario results in a less efficient utilization of infrastructure and increases the network size requirement by 833,000 ports at a cost of $6.4 billion.

The baseline scenario assumes PHEVs comprise 10% of on-road PEVs by 2030. The implications of this assumption are tested in the “PHEV Success” scenario, where PHEV on-road share is increased to 28% (consistent with present-day adoption). In this scenario, the shift to more PHEVs impacts the composition of the simulated national charging network, with L2 EVSE (private and public) increasing by 1 million ports and public DC charging ports decreasing by 17,000 ports (a consequence of PHEVs being simulated as primarily relying on L2 charging away from home and BEVs primarily relying on DC charging away from home).

The baseline scenario assumes PEVs in 2030 are adopted proportional to existing PEV and gasoline-hybrid registrations, with up to 35% of vehicles on the road as PEVs in urban areas and as low as 3% of vehicles on the road as PEVs in rural areas. The implications of this assumption are tested in the “Alternate PEV Adoption” scenario in which PEV adoption is enforced as uniform across the country. This scenario shifts PEVs from urban areas into rural areas and ultimately has the effect of dispersing demand for charging across larger areas and depressing sharing potential (utilization). This increases the cost of the national network by $3.4 billion.

The baseline scenario considers infrastructure needs under typical ambient conditions for each region. The “Size Network for Extreme Weather” scenario instead simulates demand assuming vehicle efficiency in line with the hottest or coldest day of a typical year in each location (whichever is worse). This increases the energy consumption of PEVs (even for the same amount of driving) and requires additional infrastructure to meet said demand. This scenario increases the size of the national charging network by 298,000 ports at a cost of $11.2 billion.

While the two largest U.S. TNCs (Uber and Lyft) have announced targets for 100% electrification of their operations by 2030, the “Slow TNC Electrification” scenario is used to demonstrate the impacts to national infrastructure needs in the event these firms fall short of their electrification goals. This scenario assumes 50% of on-road ride-hailing vehicles are converted to PEVs by 2030. Given that EVI-OnDemand (as deployed within this analysis) simulates electric TNCs primarily relying on DC charging away from home, impacts to L2 port counts are relatively muted. On the other hand, slow TNC electrification significantly decreases national fast charging needs (primarily in urban areas), with 17,000 fewer DC ports required at a cost savings of $3.0 billion.

4. Discussion

This report spans several areas worthy of further discussion. The final section of this report is organized into discussion of philosophical contributions, modeling uncertainty, cost estimate considerations, critical topics for future research, and avenues for accessing EVI-X modeling capabilities.

4.1. Philosophical Contribution

This analysis proposes a novel EVSE taxonomy that independently decouples access type, location type, and charger type. While the legacy home/work/public charging pyramid so often used to conceptualize conversation around infrastructure has served a useful purpose, we argue it inadvertently confuses issues of access type (e.g., public, private) and location type (e.g., home, office, retail) and is particularly ambiguous with respect to workplace charging (as discussed in Section 2.3.2). The analytic results of this analysis have been used to conceptualize an infrastructure planning philosophy that is akin to a tree (as shown in Figure 28).

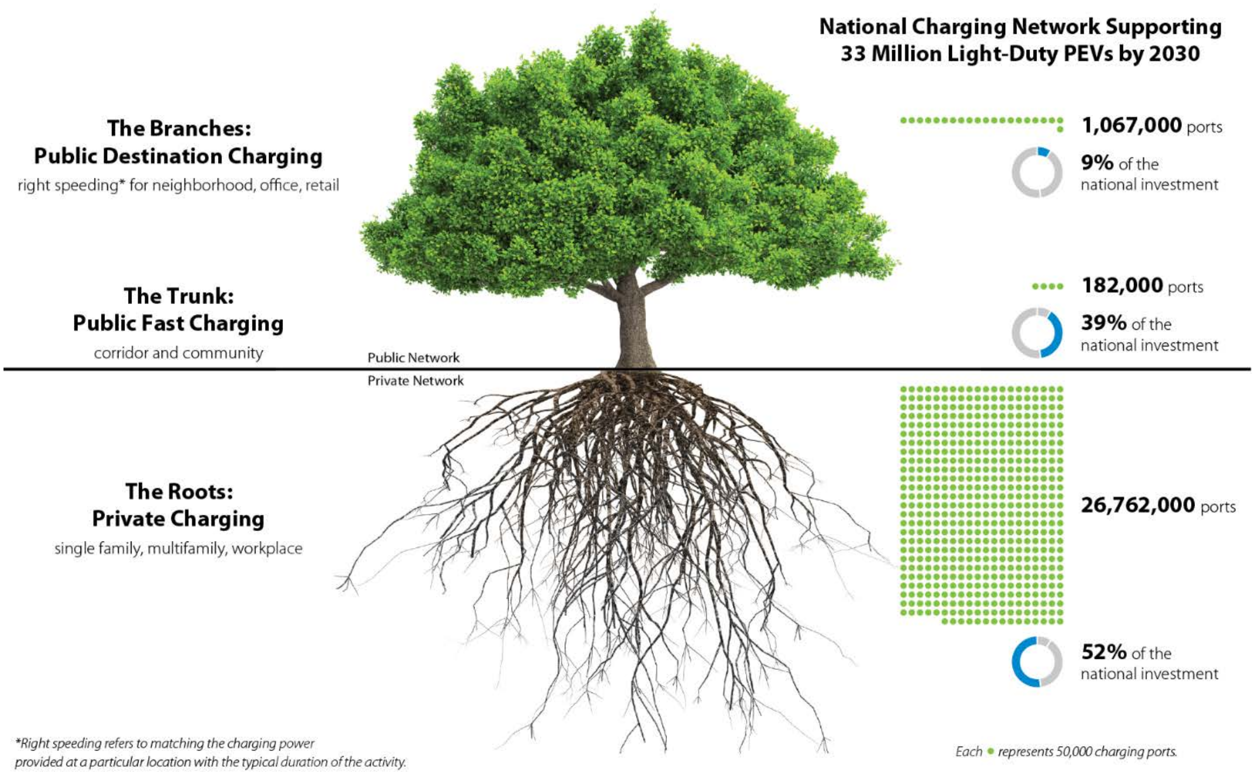

Figure 28. Conceptual illustration of national charging infrastructure needs

As with a tree, there are parts of the national charging network that are visible and those that are hidden. Public charging is the visible part of the network that can be seen along highways, at popular destinations, and through data accessible online. Private charging is the hidden part of the network tucked away in personal garages, at apartment complexes, and at certain types of workplaces. This private network is akin to the roots of a tree, as it is foundational to the rest of the system and an enabler for growth in more visible locations.

If access to private charging at home is the roots of the system, a reliable public fast charging network is the trunk, as it benefits from access to charging at home and other private locations (a key selling point of PEVs) and ultimately helps grow the system by making PEV ownership more convenient (enabling road trips and supporting those without residential access). While fast charging is estimated to be a relatively small part of the national network in terms of number of total ports, it requires significant investment and is vital to enabling future growth by assuring drivers they will be able to charge quickly whenever they need or want.

The last part of the system is a broad set of publicly accessible destination charging locations in dense neighborhoods, office buildings, and retail outlets where the speed of charging can be designed to match typical parking times ("right-speeding"). This network is similar to the branches of a tree in that its existence is contingent on a broad private network and a reliable fast charging network. As with the branches of a tree, the public destination charging network is ill-equipped to grow without the support of charging elsewhere.

4.2. Modeling Uncertainty

Throughout this study, the importance of residential charging shines through. Based on survey data, 90% of PEVs nationally are assumed to have access to reliable, overnight charging access in the baseline 2030 scenario. This assumption implies over 26 million private residential ports installed by 2030 (at single-family and multifamily locations) at a cost of \$20–\$67 billion. Sensitivity analysis on this assumption to adjust residential access up to 98% shows that capital costs can be decreased by \$4.6 billion in the "High Home Charging Access" scenario. While there is undeniable value to having access to midday charging away from home to better align with expectations for increased solar penetration on the electric grid (Powell 2022), efforts to improve U.S. residential charging access have the potential to not only reduce capital costs on the public network, but also provide drivers with a primary charging location that offers maximal affordability, convenience, and flexibility. This report reinforces recent findings on the value of residential charging (Pierce and Slowik 2023).

While not necessarily a large part of the 2030 fleet in terms of number of vehicles, PEVs used within ride-hailing services present an outsized demand on public infrastructure, particularly fast charging (Jenn 2020). This analysis adopts an aggressive electrification assumption for TNCs based on recent announcements from Uber and Lyft for 100% ZEVs by 2030. Under this assumption, the ride-hailing use case represents approximately 21% of simulated fast charging demand nationally. As shown in the "Slow TNC Electrification" scenario, reducing 2030 TNC electrification to 50% decreases capital costs by \$3.2 billion. The sensitivity between TNC electrification rates and charging infrastructure investment needs (particularly public fast charging) should motivate close coordination between charging network investors (public and private) and TNCs.

Geographically, this study finds that the majority of public infrastructure necessary in rural communities is likely to serve travelers from larger, urban areas passing through on long-distance travel. This finding is the product of relatively low levels of PEV adoption and high levels of residential charging access in rural areas (as compared to urban). This situation presents opportunities for economic activity in rural communities. Foot traffic from travelers visiting local retailers while charging presents an economic opportunity facilitated by new federal tax credits for refueling infrastructure passed in the Inflation Reduction Act of 2022.

As discussed in Section 1.2, several recent U.S. charging infrastructure assessments have been completed for 2030 scenarios, as shown in Table 18. While assumptions, methods, and results differ across these studies, there is consensus that the U.S. PEV fleet is poised for dramatic growth that will require significant investments in publicly accessible charging infrastructure. While evolving consumer preferences and charging business models will ultimately dictate the size and composition of the public network, the baseline scenario and associated sensitivity analysis are believed to provide a reasonable baseline that balances the cost and convenience advantages of destination charging at long-duration locations with the need for fast charging that supports those without residential access, long-distance travel, and ride-hailing electrification.

Table 18. Summary of Recent 2030 U.S. Charging Infrastructure Assessments

Organization (Reference)	Light-Duty PEV Stock	Est. 2030 Public Ports (including DC)	Est. 2030 DC Ports
ICCT (Bauer et al. 2021)	26,000,000	2,400,000	180,000
Atlas Public Policy (McKenzie and Nigro 2021)	48,000,000	600,000	300,000
McKinsey (Kampshoff et al. 2022)	44,000,000	1,200,000	600,000
S&P Global (S&P Global Mobility 2023)	28,000,000	2,300,000	172,000
NREL (current report)	33,000,000	1,250,000	182,000

4.3. Cost Estimate Considerations

This report estimates that a $53–$127-billion cumulative national charging infrastructure investment, including $31–$55 billion for publicly accessible charging infrastructure, is necessary to support charging infrastructure needs under the baseline scenario. Considering the estimate does not explicitly account for the cost of grid upgrades beyond charging hardware and installation costs, this estimate is likely a conservative one.

As of March 2023, we estimate $23.7 billion has been announced for publicly accessible light-duty PEV charging infrastructure through the end of the decade, including from the Bipartisan Infrastructure Law, private firms, state and local governments, and electric utilities. Public and private investments in publicly accessible charging infrastructure have accelerated in recent years. If sustained with long-term market certainty grounded in accelerating consumer demand, these public and private investments will put the United States on a path to meeting the infrastructure needs simulated in this report. Existing and future announcements may be able to leverage direct and indirect incentives to deploy charging infrastructure through a variety of programs, including from the Inflation Reduction Act and the Low Carbon Fuel Standard, ultimately extending the reach of announced investments.

Interpretation of the infrastructure cost estimates made by this report should also take into account that hardware and installation cost parameters have been developed purely based on historic observations in the literature. While these estimates reflect the best available public data and charging infrastructure costs to date, they are neither comprehensive of all charging installers nor predictive of how costs may evolve over time. For example, some observers have speculated that Tesla's Supercharger network is being developed at costs far below industry average by taking advantage of their unique scale and experience (Lambert 2022). While it has long been understood that charging infrastructure capital costs vary dramatically from site to site based on a variety of suitability measures, perhaps it should come as no surprise that costs also vary dramatically between charging developers. Regarding the evolution of charging infrastructure capital costs, valid arguments can be made in favor of costs decreasing or increasing over time (as previously discussed in Section 2.3.4).

Uncertainty aside, the magnitude of these costs underscores the need to take measures to improve the efficiency of charging infrastructure installations (both cost and time) for the benefit of all stakeholders. For example, many states today employ a just-in-time construct where infrastructure is only built as new service is requested by customers. Such a framework would likely need to be revised to allow for both a more cost-efficient, resource-efficient, and time-efficient advanced build of utility infrastructure to accommodate EVs ahead of need and, especially, ahead of a rapid onset of new high-power service requests; otherwise, the necessary number of chargers may not be in place during a period of accelerating demand for EVs. In a recent analysis, the Interstate Renewable Energy Council argues that "*to accommodate the required growth, utilities must have efficient processes in place to interconnect new chargers to the grid, especially in preparation for a surge of new service requests that could result from federal spending*" (Hernandez 2022). Such efficiencies could potentially be achieved by all stakeholders (utilities, charging networks, and government) having access to an objective estimate of connection needs with sufficient spatial and temporal resolution as to facilitate a robust planning process. It is our hope this analysis will serve as the foundation for such a planning tool and enable modernizing the regulatory framework to meet the new transportation sector needs.

4.4. Critical Topics for Future Research

While this study attempts to exhaustively consider key use cases for charging personally owned light-duty PEVs, it does not consider the charging infrastructure needs of light-, medium-, and heavy-duty PEVs used for commercial purposes (with the exception of ride-hailing services). Medium-duty commercial vehicles (work trucks) in the 2b–3 segment (gross vehicle weight rating of 8,500–14,000 pounds) are of particular interest because they represent a large number of vehicles on the road and traditionally take advantage of the same fueling infrastructure used by light-duty vehicles. Manufacturers are bringing 2b–3 electric work trucks to market that will likely take advantage of much of the same public charging infrastructure prescribed for personal use of light-duty vehicles in this report. While not explicitly considered here, this incremental demand would likely improve utilization of infrastructure ostensibly deployed to support light-duty vehicles and necessitate additional charging infrastructure beyond what has been estimated in this work. While the unique nature of commercial vehicles (in terms of travel patterns and overnight access to private/depot charging infrastructure) make them ill-suited to the methods/data underlying this analysis, quantifying synergies with charging infrastructure primarily deployed for supporting personally owned, light-duty vehicles is a topic ripe for future research.

While not the focus of this report, we would be remiss to not comment on the importance of reliable charging infrastructure. This analysis envisions a future national charging network that is strategic in locating the right amount of charging, in the right locations, with appropriate charging speeds. However, this vision is irrelevant if the public concludes that charging infrastructure is ultimately unreliable. Even if a relatively small amount of infrastructure fails drivers, this could negatively impact the public's perception of electric mobility. There is perhaps no charging infrastructure topic more urgent at this moment than ensuring that all new installations going forward are designed and supported over the long term with reliability front of mind.

4.5. Accessing EVI-X Capabilities

Great care was taken to structure this analysis in a way to provide users with maximum flexibility in defining customizable scenarios and viewing results at a state or local level. Unfortunately, the medium of a technical report does not lend itself well to exposing all of these results in a readily accessible format. To that end, this report is published alongside a set of downloadable data tables summarizing analysis results from the baseline and alternate scenarios at the state and CBSA level (https://data.nrel.gov/submissions/214). Updates to the online version of EVI-Pro (EVI-Pro Lite) are also being made and should be accessible online late in 2023 to enable customized scenario development at the local level. These updates are expected to include capabilities derived from EVI-RoadTrip and EVI-OnDemand.

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Appendix: 2022 Modeling Comparison

A basic test of the simulation pipeline is applied by comparing the national network size from the 2022 simulation to the actual size of the public network as of 2022. As shown in Figure A-1, the 2022 simulation result produces 115,000 publicly accessible L2 ports and 22,000 DC charging ports. This results in a network that is 7% larger than the 100,000 publicly accessible L2 ports and 27,000 DC charging ports reported by the Station Locator on DOE's Alternative Fuels Data Center (as of Dec. 16, 2022). The large disparity in DC ports is due to the simulation dispatching exclusively high-power DC ports (i.e., 80% 150 kW and 20% 250 kW) when charging "as fast as possible" (default for the baseline scenario), whereas the actual DC network has been developed over time and primarily consists of <150-kW ports, with higher-powered options only becoming more common as of late.

While significant effort has been invested in designing realistic models and populating them with the best available data, no specific effort to calibrate the model against observed size of the national network has been made.

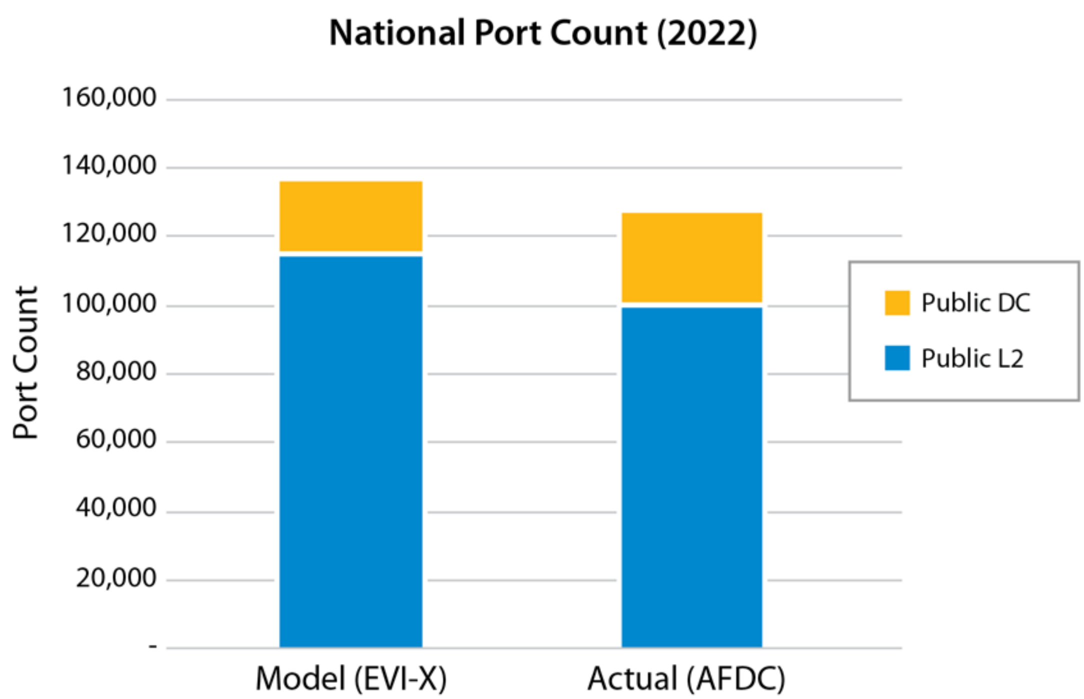

Figure A-1. Size of the 2022 national charging network as simulated in the national pipeline compared to the actual network as measured by the Alternative Fuels Data Center

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MOBILITY

47 states fail to meet the ideal ratio of chargers to EVs, report says

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EVs charging at a public station in Ann Arbor, Mich. (PAIGE HODDER)

By: **Hannah Lutz**

September 09, 2024 08:00 AM

Nearly every state fails to meet the optimal ratio of chargers to electric vehicles, according to a new report.

While the optimal number of public electric vehicle chargers varies from one state to the next because of uneven EV adoption nationwide, 47 states fall short of their target ratios.

Only the District of Columbia and three states — Vermont, Massachusetts and Rhode Island — have the prime ratio of EVs to public chargers, according to the report published Sept. 9 by Here Technologies, a location data and technology platform, and SBD Automotive, a global automotive research firm.

The ideal ratio of registered EVs to public Level 2 and fast chargers across the U.S. is nine to 10 EVs per charging plug on average. But each state has its own target ratio based on road networks, population density, rate of EV adoption and the current fleet of EVs.

Many believe that the number of EVs per public charger should decline as EV volume grows, the groups said. But the number of EVs per public charge point should actually increase as the market matures and chargers improve, they said.

Most states fall short on EV chargers

Just 3 states and the District of Columbia meet an optimal electric vehicle-to-public charger ratio, according to an analysis by Here Technologies and SBD Automotive.

Optimal ratio   Actual ratio

	Optimal ratio	Actual ratio	Difference
Washington, D.C.	6.4	11.1	+4.7
Vermont	6.8	8.1	+1.3
Massachusetts	8.4	8.7	+0.3
Rhode Island	6.5	6.6	+0.1
Connecticut	8.2	8	-0.2
Maine	6	5.7	-0.3
Wyoming	4	3.3	-0.7
New York	9.2	7.3	-1.9

	Optimal ratio	Actual ratio	Difference
Kansas	8.1	6.1	**-2**
Missouri	8.1	6	**-2.1**
North Dakota	4.1	1.8	**-2.3**
South Dakota	5.6	3	**-2.6**
West Virginia	5.8	2.6	**-3.2**
Maryland	12.3	9	**-3.3**
Delaware	11.4	8	**-3.4**
Arkansas	7.6	3.8	**-3.8**
Colorado	13.8	9.9	**-3.9**
Iowa	8.8	4.7	**-4.1**
Utah	13.1	8.5	**-4.6**
Nebraska	9.5	4.9	**-4.6**
Mississippi	7.3	2.4	**-4.9**
Montana	10.1	4.8	**-5.3**
North Carolina	13.1	7.6	**-5.5**
Tennessee	12.2	6.5	**-5.7**
Ohio	11.1	5.4	**-5.7**
New Mexico	11.9	6.2	**-5.7**
Alabama	10	4.1	**-5.9**
Minnesota	13	7.1	**-5.9**

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	Optimal ratio	Actual ratio	Difference
Georgia	13.8	7.8	**-6**
South Carolina	11.4	5.4	**-6**
Louisiana	9.6	3.3	**-6.3**
Pennsylvania	12.9	6.5	**-6.4**
Michigan	11.9	5.4	**-6.5**
Oregon	16.9	10.3	**-6.6**
Indiana	12.5	5.7	**-6.8**
New Hampshire	13	5.8	**-7.2**
Kentucky	12.4	4.9	**-7.5**
Virginia	16.4	8.9	**-7.5**
Nevada	17.7	10	**-7.7**
Wisconsin	13.6	5.6	**-8**
Idaho	15.5	5.9	**-9.6**
California	22.7	12.7	**-10**
Washington	21.6	11.3	**-10.3**
Texas	19.5	7.4	**-12.1**
Arizona	21.5	9	**-12.5**
Florida	20.6	7.8	**-12.8**
Illinois	23.1	7.9	**-15.2**

	Optimal ratio	Actual ratio	Difference
Alaska	21.2	5.7	**-15.5**
Oklahoma	19.7	3.7	**-16**
Hawaii	26.6	9.3	**-17.3**
New Jersey	28.6	9.8	**-18.8**

Source: Here Technologies and SBD Automotive

The groups' EV Index is based on the evolution of the market and public charging in Europe, said Robert Fisher, electrification and sustainability principal at SBD Automotive.

"The U.S. is, of course, behind Europe when it comes to maturity of the EV market. So it could be that things evolve a little bit differently in the U.S.," Fisher said.

The U.S. public charging map could differ from Europe in the long run because the states have a wide range of population densities, said Ronak Amin, global product marketing manager at Here Technologies.

"Europe has these rural areas, but not maybe quite like the Wyomings and the South Dakotas of the world. So that ratio could be potentially higher in the U.S.," he said.

The U.S. also will likely have more private chargers than Europe, which would reduce pressure on public charging infrastructure, Fisher said.

The private charging variable and fluctuating EV demand leads to the industry's chicken-and-egg conundrum: build chargers and wait for drivers to come, or sell lots of EVs and then build the charging network?

"When more EVs are being sold, if the charging infrastructure doesn't keep up, then more states will miss their ratio," Fisher said. Inversely, "if more chargers are being installed, but not enough EVs are being sold, then you can overshoot your ratio, and that's a problem as well."

Overshooting the ratio hurts charger operators' bottom lines in an already challenging business.

"We are a little bit concerned in some European countries that they've already overshot, and it's becoming too difficult as a business to be a charge point operator," Fisher said. "In the U.S., we don't have that problem yet, but it could become a problem in the future."

The ranking

The EV-to-charger ratios are part of a broad look at charging across the country. The firms ranked all 50 states and the District of Columbia based on the ratios, along with the distance drivers must travel to find a charger, the speed of charging and the number of EVs on the road compared with gasoline-powered vehicles.

Delaware soared to the top of the overall ranking, up from 15th place a year earlier. Growth in high-power charging and an increase in EV sales drove Delaware's progress, according to the study. Washington, D.C., which was the top scorer last year, moved to second place. Massachusetts and Nevada tied for third.

Idaho, Arkansas and Alaska made up the bottom three.

The EV Index shows both the progress of charging infrastructure and the challenges the EV market continues to face.

The number of public chargers grew by a third since last year's study amid private and public charging infrastructure investments.

Delaware, Tennessee, Louisiana, Texas and Indiana increased their charger count the most on a percentage basis. California added the highest number of chargers, installing more than 6,000 over the last year, Amin said.

The National Electric Vehicle Infrastructure program, which launched more than two years ago, was designed to increase chargers along highways.

The government set aside $5 billion in federal funds to build out a nationwide charging network over five years. The chargers should be installed at least every 50 miles along major interstates and within one mile of highway exits. The stations must be able to charge four EVs at once, and some states require the sites to have certain features, such as 24-hour amenities and pull-through lanes.

The Joint Office of Energy and Transportation said in May that 33 chargers backed by the program were open in six states.

State-by-state coordination and a series of requirements and approvals have contributed to the slow rollout of federally funded chargers. Some charger operators have delayed deployments until they get the funding, Fisher said.

"We could be seeing a sort of unnatural slowdown in charge point deployment currently because of that NEVI program," he said. "But overall, I do think that when we look back on this in, say 2028, we'll say it was foundational to getting the network up to where it needs to be."

Reliability setbacks, charging power lags

The federal program includes strict reliability requirements, but for now, charger reliability remains an issue.

More than 10 percent of the public chargers in Hawaii, Alaska, West Virginia and Washington, D.C. were out of order when Here and SBD Automotive compiled the index. Hawaii's performance was the worst, with more than a fifth of chargers out of service.

Kansas, Massachusetts, Maine and Nebraska had at least 98 percent of chargers online.

States with the most chargers offline typically started installing them several years ago, and some have aged out, Amin said. Weather and limited access to charger technicians also play a role in poor charger performance in states such as Alaska and Hawaii, he said.

Charging speed was an issue in some areas. Michigan, for example, fell in the overall rankings largely because of a decrease in the average charger power there.

The National Electric Vehicle Infrastructure program and other initiatives focus on fast chargers, which can take 20 minutes to restore power to 80 percent and are typically used when a driver is traveling long distances, and the battery is depleted or won't get the car to the destination. It's often a planned charging stop.

But nearly three-quarters of public charging plugs are Level 2, slower chargers, according to the Department of Energy's Alternative Fuels Data Center. Level 2 chargers, which take several hours to power a battery, are typically used at home or work or to top off during daily activities, such as shopping or dining at a restaurant. Level 2 chargers are significantly less expensive for the charger operator and for drivers, Amin said.

"There's this delicate balance of what needs to be deployed out there," he said. Charger operators are "safeguarding their business. They don't want to put out these really expensive chargers and utilization is low. They're trying to understand the calculus behind that."

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Final Report

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Cost Analysis and Projections for U.S.-Manufactured Automotive Lithium-ion Batteries

Final Report

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Prepared for
U.S. Department of Energy

January 2024

Abstract

This document reports on a study conducted to estimate the cost of U.S-produced automotive battery packs for model years (MY) 2023 to 2035, using Argonne National Laboratory's BatPaC tool. The costs were estimated by designing batteries for several classes of vehicles for four discrete model years (2023, 2026, 2030, and 2035), where a representative battery technology and material prices are selected based on information available today. Correlations were developed from the four discrete years to enable annual pack cost estimates as a function of pack size (kWh) and model year. A consolidated cost curve was then developed that includes battery size, technology by model year, and the anticipated sales volumes of each class of vehicles over the years. This cost curve estimates the volume-averaged, U.S.-manufactured battery pack cost of PHEVs and BEVs in the United States to be $140/kWh for the model year 2023, which will reduce to $86/kWh in MY2035. Applying tax credits from section 45X of the Inflation Reduction Act can further reduce the average pack cost to as low as $56/kWh in MY2029. The report also includes several sensitivity studies that investigate the effect of pack production volume, material prices, fast charge requirements, and labor rates.

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Introduction

Electric vehicles are expected to represent increasing percentages of the vehicles sold in the US in the next 10-15 years. The cost of these vehicles will depend largely on the cost of the energy storage component, the lithium-ion battery pack. With fierce competition for the large automotive market, domestic and international battery and automobile manufacturers have been preparing to produce a competitive product that balances performance and cost. With such new products on the horizon, scientists, engineers, and entrepreneurs are pushing novel chemistries and manufacturing technologies as they compete for the market. The U.S. Department of Energy (DOE) has funded the R&D of lithium-ion batteries for nearly 40 years, which has progressively supported the scientific community. Asia and Europe have aggressively developed the manufacturing and marketing of EVs in the past two decades. The US government has legislated various incentives to promote the domestic production and adoption of EVs.

Some electric vehicles today can compete with internal combustion engine vehicles (ICEV) based on total cost of ownership, principally due to the lower cost of electric energy per mile (Liu, et al., 2021). DOE has set a target of $80/kWh (Office of Energy Efficiency and Renewable Energy, 2023), which is also the price at which popular media expects EVs to achieve purchase price (without any government incentives) parity with internal combustion engine (ICE) vehicles (Voelcker, 2023). Various organizations offer values of the current battery prices and projections for the future. Organizations such as the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) and the U.S. Environmental Protection Agency (EPA) have their own estimates, often composites of multiple forecasts, that have been used for prior rule making. This analysis intends to develop a cost curve for automotive batteries that can support proposed fuel economy (National Highway Traffic Safety Administration, 2023) and greenhouse gas (United States Environmental Protection Agency, 2023) standards.

The study simulates the cost of EV batteries for HEV, PHEV, BEV, and MHD vehicles. The PHEV, BEV, and MHD results are used to calculate a volume-averaged, composite cost curve for EV packs in the U.S. Since HEV batteries are designed for regenerative braking and supplementing power, and require very small batteries, these were excluded from deriving the composite cost curve. This allowed the curve to estimate the cost of batteries for plug-in vehicles that require significant energy storage for sustained propulsion.

Objective and Approach

The objective of this record is to document the development of a cost curve for automotive batteries:

- For the period 2023-2035,
- Using Argonne National Laboratory's Battery Performance and Cost (BatPaC) model (Chemical Sciences and Engineering, 2023) (Knehr K. W., Kubal, Nelson, & Ahmed, 2022),
- With assumptions and parameter values proposed by the model developers, under the guidance of DOE, NHTSA, and EPA staff.

All costs are reported in 2023 $\$/kWh_{rated}$.

Methodology

Vehicles – The electric vehicles considered included light duty vehicles, which comprised of hybrid electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs), electric vehicles (EVs), and medium-heavy duty vehicles (MHDs). Two batteries were designed to represent the HEV batteries for this study: 48 kW – 1.2 kWh and 70 kW – 1.8 kWh, where the pack kWh is rated energy. Each of the PHEV and EV batteries were subsequently designed to represent four classes of vehicles: Compact, Midsize, Midsize SUV, and Pickup. Each PHEV and EV battery was then assigned a combination of power (kW) and energy (rated kWh) (National Highway Traffic Safety Administration, 2023).

Electrode Chemistries and Model Years – A combination of electrode chemistries and associated properties was selected to represent each of the Model Years (MY) where the BatPaC simulations were run (BloombergNEF, 2023; Benchmark Minerals Intelligence, 2023; Firth, Implications of Economy-Wide Decarbonization on the Battery Industry, 2021; Gokhale, 2023; Mell, 2021; Berry, 2023; Miller, 2023; Sekine, 2023; Moganty, 2023). The distinct changes in the dominant electrode chemistry were made for four MYs, namely 2023, 2026, 2030 and 2035. Separate specifications were selected for the two main cathode materials, the nickel-manganese containing layered oxides (Ni/Mn) and the lithium iron phosphates (LFP). The costs of the materials were estimated from market research reports (Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Intercalation, Ltd., 2023; Ballif, Haug, Boccard, Verlinden, & Hahn, 2022; Sanders, 2023).

With the representative electrode chemistries selected for each of the four model years, their associated properties, the cell and pack design parameters, and manufacturing plant parameters were selected. For example, the cell capacities (Ah), the cell plant capacity (GWh), and the number of packs produced were all increased in future years to lower the pack costs by leveraging economies of scale. Decisions on pack designs and plant capacities were based on observed trends in the market and manufacturing announcements (EV/Hybrid Analyses, 2023; EV Sales Forecast, 2023; Ricardo, 2023; National Highway Traffic Safety Administration, 2023; Irle, 2023; Fox-Penner, Gorman, & Hatch, 2018).

Simulation Inputs – Tables 1-12 show the specifications for the different vehicles for the four model years for which the BatPaC simulations were run. This was done separately for the Ni/Mn and the LFP vehicles.

Table 1. Production volumes assumed for vehicle types in BatPaC simulations (numbers in thousands of vehicles produced per year per plant).

Vehicle Type	2023	2026	2030	2035
Hybrid Electric Vehicle (HEV)	200	200	200	200
Plug-in Hybrid Electric Vehicle (PHEV)	20	60	100	100
Battery Electric Vehicle, Light Duty (BEV LD)	60	140	250	400
Battery Electric Vehicle, Medium/Heavy Duty (BEV MHD)	2	4	7	10

Table 2. Cells per pack and rated energy/power combinations for HEV and PHEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
1.2 / 48	HEV	60	60	60	48
1.8 / 70	HEV	60	60	60	48
12 / 100	PHEV Compact (Ni/Mn)	84	84	84	72
12 / 100	PHEV Compact (LFP)	90	90	90	90
18 / 150	PHEV Midsize (Ni/Mn)	84	84	84	72
18 / 150	PHEV Midsize (LFP)	90	90	90	90
24 / 200	PHEV Midsize SUV (Ni/Mn)	90	84	84	72
24 / 200	PHEV Midsize SUV (LFP)	90	90	90	90
40 / 250	PHEV Pickup (Ni/Mn)	156	120	102	84
40 / 250	PHEV Pickup (LFP)	156	90	90	90

Table 3. Modules per pack and rated energy/power ratings for HEV and PHEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
1.2 / 48	HEV	1	1	1	1
1.8 / 70	HEV	1	1	1	1
12 / 100	PHEV Compact (Ni/Mn)	6	6	6	6
12 / 100	PHEV Compact (LFP)	6	6	6	6
18 / 150	PHEV Midsize (Ni/Mn)	6	6	6	6
18 / 150	PHEV Midsize (LFP)	6	6	6	6
24 / 200	PHEV Midsize SUV (Ni/Mn)	6	6	6	6
24 / 200	PHEV Midsize SUV (LFP)	6	6	6	6
40 / 250	PHEV Pickup (Ni/Mn)	6	6	6	6
40 / 250	PHEV Pickup (LFP)	6	6	6	6

Table 4. Total cells per pack and rated energy/power rating for high performance (Ni/Mn cathode), BEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
65 / 125	BEV250 Compact	260	192	168	132
75 / 165	BEV250 Midsize	300	224	192	152
80 / 130	BEV300 Compact	320	240	192	160
90 / 200	BEV250 Midsize SUV, BEV300 Midsize	360	272	228	184
105 / 260	BEV250 Pickup	420	312	264	216
110 / 210	BEV300 Midsize SUV	440	330	264	220
130 / 270	BEV300 Pickup	520	390	312	260
190 / 380	BEV MHD	800	576	480	384
220 / 440	BEV MHD	880	672	576	440
250 / 500	BEV MHD	960	768	624	520

Table 5. Total modules per pack and rated energy/power rating for high performance (Ni/Mn cathode), BEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
65 / 125	BEV250 Compact	20	8	6	4
75 / 165	BEV250 Midsize	20	8	6	4
80 / 130	BEV300 Compact	20	10	8	5
90 / 200	BEV250 Midsize SUV, BEV300 Midsize	20	8	6	4
105 / 260	BEV250 Pickup	20	8	6	4
110 / 210	BEV300 Midsize SUV	20	10	8	5
130 / 270	BEV300 Pickup	20	10	8	5
190 / 380	BEV MHD	20	12	10	8
220 / 440	BEV MHD	20	14	12	10
250 / 500	BEV MHD	20	16	12	10

Table 6. Total cells per pack and rated energy/power rating for low cost (LFP cathode), BEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
65 / 125	BEV250 Compact	260	168	104	78
75 / 165	BEV250 Midsize	300	192	120	90
90 / 200	BEV250 Midsize SUV	360	224	144	108
105 / 260	BEV250 Pickup	420	264	168	126
190 / 380	BEV MHD	768	462	304	228
220 / 440	BEV MHD	896	528	360	264
250 / 500	BEV MHD	1024	594	408	300

Table 7. Total modules per pack and rated energy/power rating for low cost (LFP cathode), BEV packs in BatPaC simulations.

kWh / kW	Vehicle	2023	2026	2030	2035
65 / 125	BEV250 Compact	20	8	4	1
75 / 165	BEV250 Midsize	20	8	4	1
90 / 200	BEV250 Midsize SUV	20	8	4	1
105 / 260	BEV250 Pickup	20	8	4	1
190 / 380	BEV MHD	24	14	8	1
220 / 440	BEV MHD	28	16	10	1
250 / 500	BEV MHD	32	18	12	1

Table 8. Material, cell design, and manufacturing inputs for HEV packs in BatPaC simulations.

Active Material Composition	**2023**	**2026**	**2030**	**2035**
Cathode Active Material (CAM)	NMC622	NMC811	NMC95	LMNO
Anode Graphite wt.%	100%	100%	100%	100%
Anode Silicon wt.%	0%	0%	0%	0%
CAM specific capacity, mAh/g	191	210	226	150
AAM combined capacity, mAh/g	350	350	350	350
Cell voltage (50% OCV)	3.705	3.713	3.734	4.550
Cell Design	**2023**	**2026**	**2030**	**2035**
Electrode Thickness, µm	75	85	95	120
Positive Active wt.%	94%	94%	94%	94%
Negative Active wt.%	96%	96%	96%	96%
Negative-to-Positive Capacity, N2P	1.10	1.05	1.05	1.05
Target Cell Capacity, Ah	5.0-7.5	5.0-7.5	5.0-7.5	5.0-7.5
Cell thickness, mm	12	12	12	12
Cell Length to Width (L/W) ratio	3	3	3	3
Cell Manufacturing	**2023**	**2026**	**2030**	**2035**
Cell Plant Capacity, GWh/yr	35	50	70	70
Cell Yield, %	89%	91%	93%	95%

Table 9. Material, cell design, and manufacturing inputs for high performance (Ni/Mn cathodes) PHEV and BEV vehicles.

Active Material Composition	**2023**	**2026**	**2030**	**2035**
Cathode Active Material (CAM)	NMC622	NMC811	NMC95	LMNO
Anode Graphite wt.%	100%	95%	85%	65%
Anode Silicon wt.%	0%	5%	15%	35%
CAM specific capacity, mAh/g	191	210	226	150
AAM combined capacity, mAh/g	350	458	673	1103
Cell voltage (50% OCV), V	3.705	3.704	3.631	4.400
Cell Design	**2023**	**2026**	**2030**	**2035**
Electrode Thickness, µm	75	85	95	120
Positive Active wt.%	96%	96%	96%	96%
Negative Active wt.%	98%	98%	98%	98%
Neg.-to-Pos. Capacity ratio	1.10	1.05	1.05	1.05
Cell Capacity (BEV), Ah	70	90	110	110
Cell Capacity (PHEV), Ah	40-70	40-90	40-110	40-110
Cell thickness (BEV), mm	20	20	20	12
Cell thickness (PHEV), mm	16	16	16	16
Cell L/W ratio (BEV)	3	5	5	8
Cell L/W ratio (PHEV)	3	3	3	3
Cell Manufacturing	**2023**	**2026**	**2030**	**2035**
Cell Plant Capacity, GWh/yr	35	50	70	70
Cell Yield, %	89%	91%	93%	95%

Table 10. Material, cell design, and manufacturing inputs for low cost (LFP cathodes) PHEV and BEV vehicles.

Active Material Composition	**2023**	**2026**	**2030**	**2035**
Cathode Active Material (CAM)	LFP	LFP	LFP	LFP
Anode Graphite wt.%	100%	95%	95%	95%
Anode Silicon wt.%	0%	5%	5%	5%
CAM specific capacity, mAh/g	157	157	157	157
AAM combined capacity, mAh/g	350	458	458	458
Cell voltage (50% OCV), V	3.325	3.316	3.316	3.316
Cell Design	**2023**	**2026**	**2030**	**2035**
Electrode Thickness, µm	75	90	110	130
Positive Active wt.%	96%	96%	96%	96%
Negative Active wt.%	98%	98%	98%	98%
Neg.-to-Pos. Capacity ratio	1.10	1.05	1.05	1.05
Cell Capacity (BEV), Ah	75	125	190	255
Cell Capacity (PHEV), Ah	40-80	40-135	40-135	40-135
Cell thickness (BEV), mm	20	20	20	20
Cell thickness (PHEV), mm	16	16	16	16
Cell L/W ratio (BEV)	3	5	5	8
Cell L/W ratio (PHEV)	3	3	3	3
Cell Manufacturing	**2023**	**2026**	**2030**	**2035**
Cell Plant Capacity, GWh/yr	35	50	70	70
Cell Yield, %	89%	92%	95%	95%

Table 11. Assumed price of active materials used in BatPaC.

Cathode	**2023**	**2026**	**2030**	**2035**
NMC622, $/kg	31.9	-	-	-
NMC811, $/kg	-	34	-	-
NMC95, $/kg	-	-	31.3	-
LMNO, $/kg	-	-	-	17.3
LFP, $/kg	13	11.5	10	9.5
Anode	**2023**	**2026**	**2030**	**2035**
Graphite, $/kg	10	9	8	8
Silicon, $/kg	30	30	30	30
95% G, 5% Si, $/kg	-	10.1	-	-
85% G, 15% Si, $/kg	-	-	11.3	-
65% G, 35% Si, $/kg	-	-	-	15.7

Table 12. Assumed price of other cell components in BatPaC simulations.

Other Components	2023	2026	2030	2035
Electrolyte, $/L	10	10	10	10
Separator, $/m²	0.5	0.5	0.5	0.5
Carbon additive, $/kg	7	7	7	7
Positive binder, $/kg	15	15	15	15
Positive solvent, $/kg	2.7	2.7	2.7	2.7
Positive current collector, $/m²	0.2	0.2	0.2	0.2
Negative binder, $/kg	10	10	10	10
Negative current collector, $/m²	1.2	1.2	1.2	1.2

Correlation Development – Cost results ($/kWh$_{rated}$) were generated for each vehicle for each MY by conducting BatPaC simulations with the input values in Tables 1-12. These results were correlated with a simpler equation form, with two independent variables: pack energy (kWh$_{rated}$) and model year (MY). This correlation facilitated the calculation of the cost on a smoothed curve. Three sets of correlation coefficients were determined for *i)* HEV packs (Ni/Mn only), *ii)* Ni/Mn–PHEV+BEV+MHD packs, and *iii)* LFP–PHEV+BEV+MHD packs.

Composite Cost Curve – The cost correlations were used to generate an estimate of the volume-averaged cost of PHEV and BEV (LD+MHD) battery packs in the United States between MY2023 to MY2035. The curve was generated using data on the number of each type of new vehicle sold each year, an average pack energy for each vehicle type, and the split between LFP and Ni/Mn cathodes in the market, The Ni/Mn and LFP costs were included in the final cost curve by weighing them with the percentage of vehicles that are estimated to use Ni/Mn and LFP batteries in the U.S. Further details on the cost curve methodology can be found in Appendix A5.

An analysis was also conducted to understand how the cost curve is impacted by the Internal Revenue Code 45X advanced manufacturing production tax credits (45X credits) established through the Inflation Reduction Act (IRA) for the domestic production of qualified battery components and critical minerals. Pack costs were reduced by applying tax credits based on guidance from the Internal Revenue Service (IRS) (Internal Revenue Service, 2023) and expectations for pack eligibility (U.S. Department of Energy, 2023). Details on the methodology and input values for the 45X study can be found in Appendix A6.

Sensitivity Studies – Some parameters were investigated further to determine their cost sensitivity and make decisions on whether these should be included in the consolidated cost curve. These included the effects of:

1. NMC811 vs. NMC622 in MY2023 – NMC811 is slightly more expensive but NMC622 is the dominant cathode material used in MY2023.
2. Pack production volume – was specified for each MY and not for each type of vehicle.
3. Material prices, i.e., vary each year or remain the same as in MY23.
4. Charge time constraints – with lack of clarity on fast charge times and the number of such packs available in vehicles, the fast charge constraint was not imposed on the results for the cost curve.
5. Labor wage rates of $25 vs. $50/hr.

Results

Trends in Battery Pack Cost

Simulations of the different batteries for the different vehicles and their production volumes described in Tables 1-12 generated the pack costs as shown in the following graphs (see tables in Appendix A1 and A2 for values and breakdowns). All costs are reported in 2023 $/kWh_{rated}$. The decreases in cost in the future model years are attributable to the following parameters:

1. Better active materials and improved cell design (*e.g.*, higher electrode loading)
2. Cheaper materials per Wh
3. Better economies of scale resulting from larger cells and production volumes

Figure 1 shows the results for the HEV battery packs modeled in this work. Figure 1a indicates the 1.2 kWh packs are expected to decrease in cost from \$570/kWh in MY2023 to \$450/kWh in MY2035. The 1.8 kWh pack cost is predicted to decrease from \$430/kWh to \$340/kWh. Both cases correspond to a ~20% decrease in cost from MY2023 to MY2035.

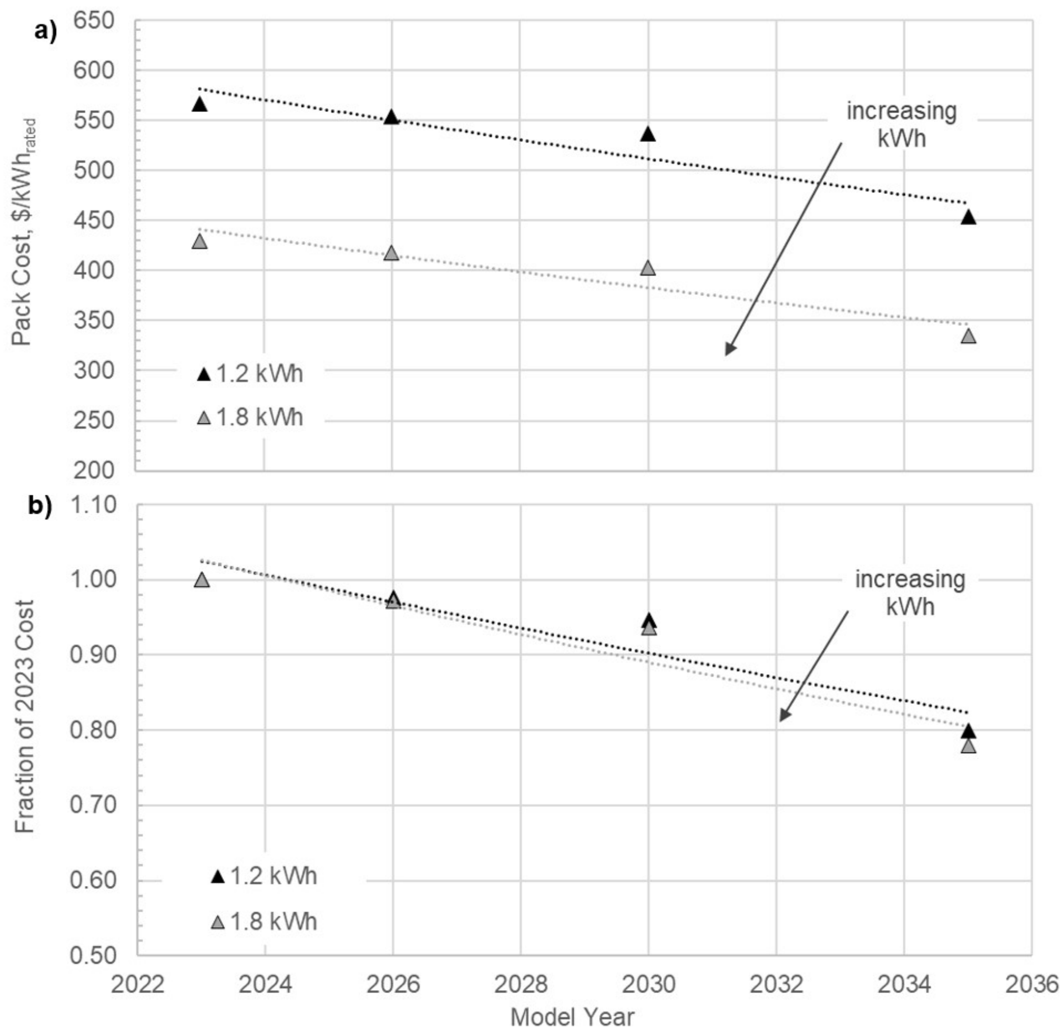

Figure 1. a) Estimated pack cost ($/kWh_{rated,2023}$) and b) fraction of MY2023 pack cost for HEV packs.

Figure 2 provides the results for the PHEV packs. In the figure, circles and dotted trend lines correspond to high performance packs with Ni/Mn containing cathodes. Triangles and dashed trend lines correspond to low-cost packs with LFP containing cathodes. The reductions in cost from MY2023 to MY2035 are similar for a given chemistry type across all pack sizes – *i.e.*, \$30 to \$38/kWh for low-cost LFP and ~\$50/kWh for Ni/Mn packs. The relative decreases in pack cost vary between the different pack sizes due to changes in the absolute cost (denominator value) of the packs. LFP packs are estimated to have a 17-27% decrease in cost from MY2023 to MY2035, and Ni/Mn packs are estimated to have a 25-35% decrease in cost. The larger decrease in the Ni/Mn packs is caused by advancement of the cathode past current nickel-manganese-cobalt (NMC) materials.

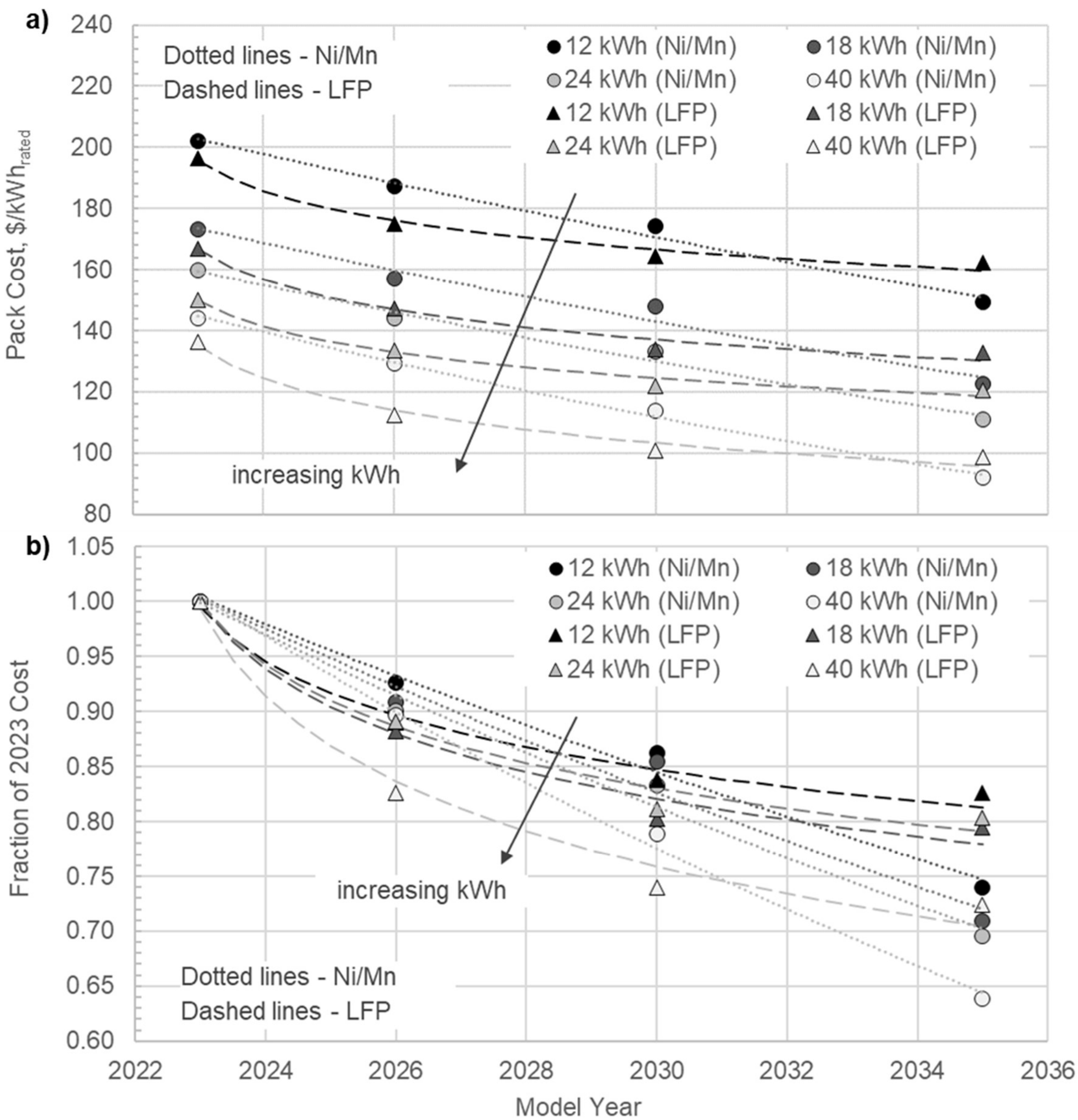

Figure 2. a) Estimated pack cost (\$/kWh$_{rated,2023}$) and b) fraction of MY2023 pack cost for PHEV packs.

Figure 3 shows the results for the light duty BEV packs. The reductions in cost from MY2023 to MY2035 are similar for a given chemistry type across all pack sizes – *i.e.*, ~$45/kWh (~40% reduction) for LFP and ~$55/kWh (~40% reduction) for Ni/Mn packs. Both packs are estimated to have similar costs by MY2035. Ni/Mn packs have a more linear trend because of the adoption of advanced cathode materials in the Ni/Mn case, e.g., LMNO for MY2035, compared to an exponential decaying trend of the LFP packs.

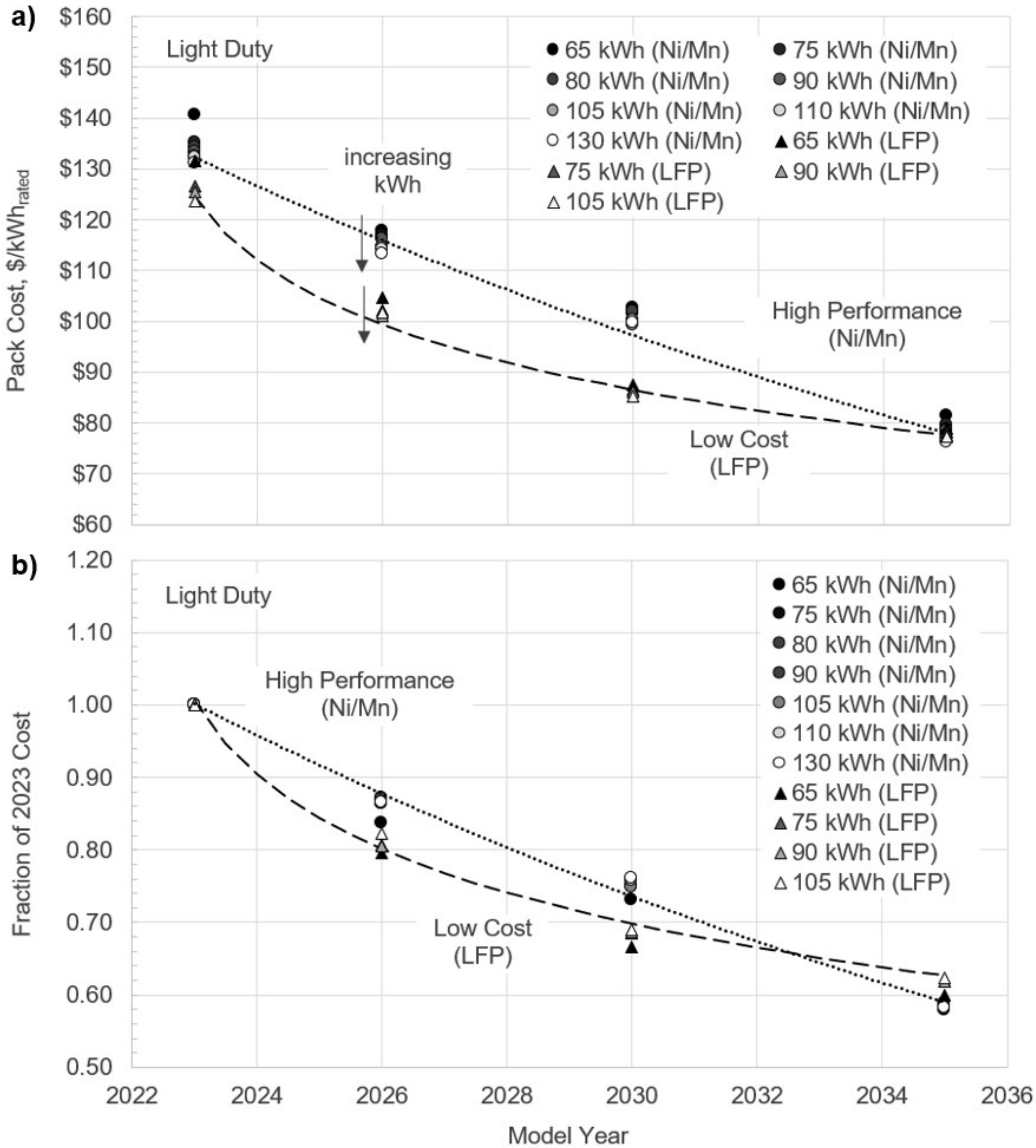

Figure 3. a) Estimated pack cost ($/kWh$_{rated,2023}$) and b) fraction of MY2023 pack cost for light duty BEVs.

Figure 4 provides the results for the medium/heavy (MHD) duty BEV packs. LFP packs are estimated to have a cost reduction of ~$40/kWh (40%) from MY2023 to MY2035, and Ni/Mn packs are estimated to have reductions of ~$50/kWh (40%). The MHD results are close to the LD results because the input parameters assumed MHD packs will benefit from the same technological advances and economies of scale on the cell level as the LD vehicles. The pack production levels were decreased to account for a lower market adoption (see Table 1); however, these changes had a minimal impact on the results (see sensitivity study in Figure 13). Larger packs were also not modeled because it was assumed vehicles with larger kWh requirements will incorporate multiple, smaller packs. These smaller packs will benefit from economies of scale since they will be used in several vehicle sizes.

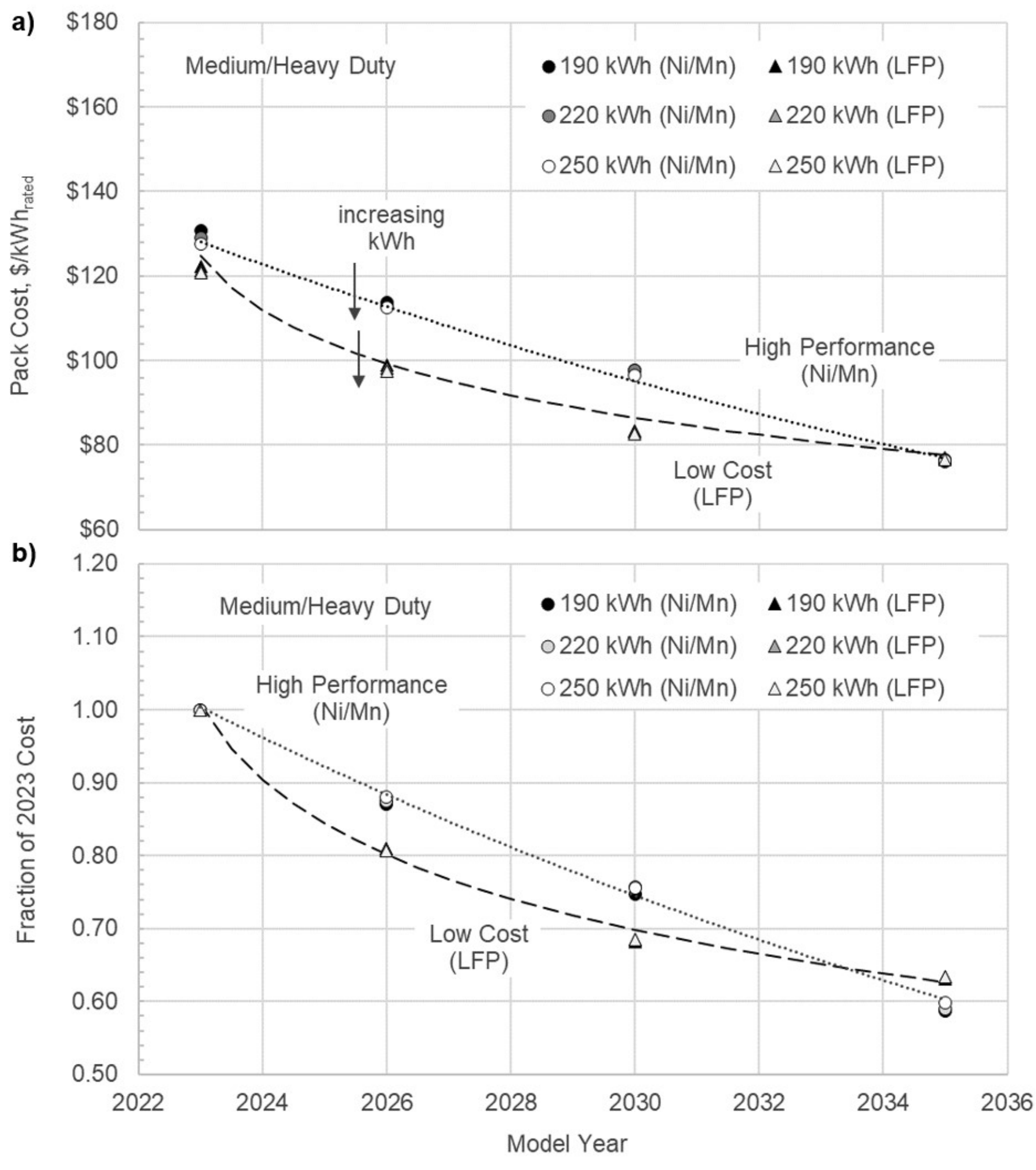

Figure 4. a) Estimated pack cost ($/kWh$_{rated,2023}$) and b) fraction of MY2023 pack cost for medium and heavy duty BEVs.

The results in the previous figures are summarized in Figure 5, which shows the pack costs for the Ni/Mn and LFP packs as a function of pack energy for each model year. The figure shows that the pack cost decreases rapidly as the pack energy increases above ~10 kWh, which is due to the decreased power-to-energy ratio requirements in the PHEV and BEV packs. The pack cost is also shown to level off as the energy increases past ~50 kWh, where power requirements are the same and the energy is increased by adding more, similar cells and modules.

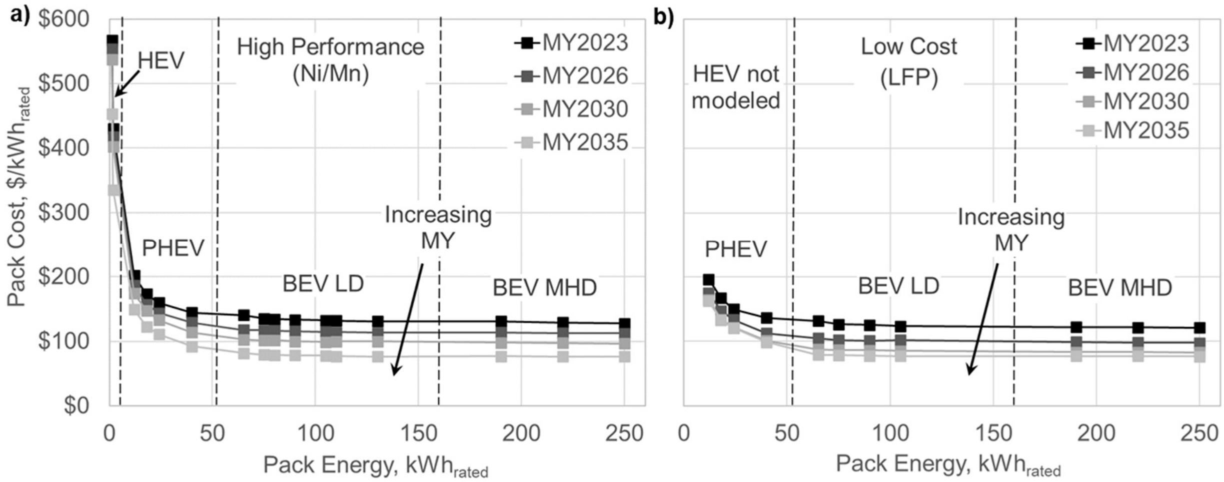

Figure 5. Estimated packs cost ($/kWh$_{rated,2023}$) for all vehicle types and model years for a) Ni/Mn and b) LFP containing cathodes.

HEV, PHEV, and BEV Cost Correlations

Correlations were developed from the simulated data to calculate the pack cost as a function of model year and pack size (kWh). The correlations had the following functional form:

$$C_{pack} = A + \frac{B}{x^C} - D(y - 2023)e^{E(y-2023)} \quad (1)$$

where C_{pack} is the cost of the pack in \$/kWh$_{rated,2023}$, x is the pack energy in kWh, and y is the model year. A, B, C, D, and E are constants given in Table 13. Three sets of constants were generated from the fits: one set for HEV packs, one for high performance (Ni/Mn) PHEV and BEV packs, and one for low cost (LFP) PHEV and BEV packs. The agreement between the equation and the simulated data is shown in Figure 6. Similar correlations generated for the pack specific energy (Wh/kg) and energy density (Wh/L) can be found in sections A3 and A4 in the Appendix, respectively.

Table 13. Constants for pack cost ($/kWh$_{rated,2023}$) correlations given in Equation 1.

Constant in Eq. 1	High Performance (Ni/Mn) (HEV, ≤5 kWh)	High Performance (Ni/Mn) (PHEV, EV)	Low Cost (LFP) (PHEV, EV)
A	119.3	124.5	115.7
B	492.4	1071	1141
C	0.7667	1.068	1.138
D	4.131	4.617	9.489
E	0.01352	-0.005038	-0.08312

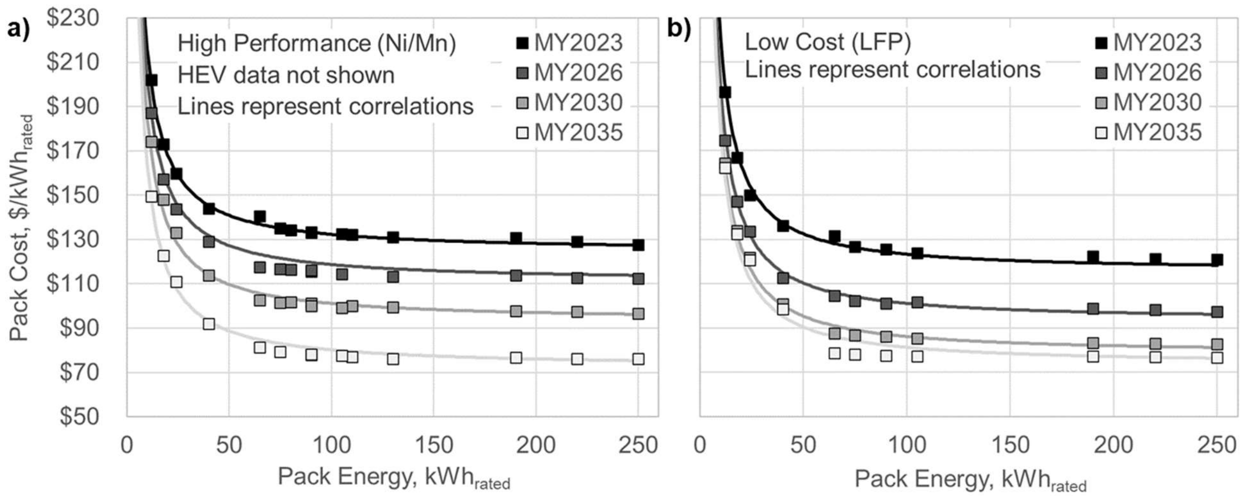

Figure 6. Comparison of pack cost ($/kWh$_{rated,2023}$) between full BatPaC simulations (symbols) and correlations in equation 1 (lines) for a) high performance (Ni/Mn) and b) low cost (LFP) packs.

Estimated Volume Averaged PHEV and BEV Costs

The correlation in Equation (1) was used to generate an estimate of the volume-averaged cost of PHEV and BEV battery packs in the United States between MY2023 to MY2035. Details of the calculations are provided in Appendix A5. In short, the costs were determined by first segmenting the entire vehicle fleet into twenty-four vehicles (*v*) based on vehicle type (BEV or PHEV), class (Compact, Midsize, Small SUV, Midsize SUV, Pickup, and MHD), and cathode chemistry (Ni/Mn or LFP). Ni/Mn was assumed to include NCA cathodes due to similarities in cost. The number of vehicles sold each year (N_v) was then estimated for each vehicle type based on available models and market research reports – *i.e.,* NREL TEMPO model, EPA OMEGA model, Rho Motion data, and Benchmark Minerals Intelligence data (United States Environmental Protection Agency, 2023; Benchmark Minerals Intelligence, 2023; Muratori, et al., Forthcoming; Rho Motion, 2023). The cost of each vehicle pack for each model year (C_v) was also estimated based on the projected pack energy, in kWh, for each class using the Argonne Autonomie model (Islam, et al., 2023) and the correlations shown in Equation (1). These two pieces of information (N_v and C_v) were used to estimate the volumed averaged pack cost at each model year using the following equation:

$$C_{fleet} = \frac{\sum_{v=1}^{v=24} C_v N_v}{\sum_{v=1}^{v=24} N_v} \quad (2)$$

where C_{fleet} is the estimated cost in $/kWh$_{rated,2023}$ and the summations are evaluated from 1 to 24 to account for all twenty-four vehicle segments. The results of the calculation are shown in Figure 7. The volume averaged pack cost is estimated to decrease from ~$140/kWh in MY2023 to ~$85/kWh in MY2035. This is a 40% reduction in cost. Most of the reduction is attributed to advances in pack chemistry, manufacturing, and design captured in Tables 1-12.

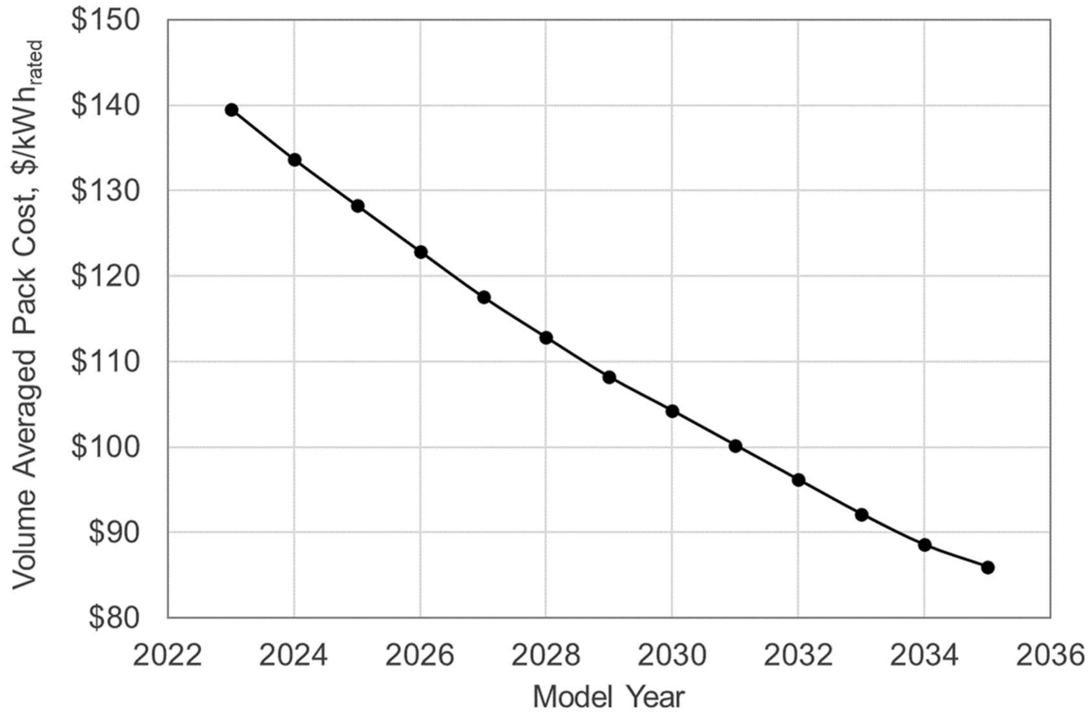

Figure 7. Estimated volume averaged pack cost ($\$/kWh_{rated,2023}$) for PHEV and BEV packs in U.S. fleet.

Impact of 45X Tax Credit on Pack Costs

The Internal Revenue Code 45X advanced manufacturing production tax credits (45X credits) established through the Inflation Reduction Act (IRA) for the domestic production of qualified battery components and critical minerals have the potential to significantly reduce the projected costs of packs in this work. An analysis was conducted to quantify the effect of the 45X credits. Details on the methodology and input values can be found in Appendix A6. Figure 8 to Figure 10 provide the estimated tax credits for each of the three vehicle categories reflected in the correlation development in equation 1. Tabulated results are included in the Appendix. Figure 8 provides the credits for Ni/Mn HEV packs. Figure 9 provides the credits for Ni/Mn PHEV and BEV packs. Figure 10 provides the credits for LFP PHEV and BEV packs. The credits were determined using the component mass and cost breakdowns for a representative pack within each category.

The figures provide values for eight different tax credits. There are four datasets that reflect the four different 45X credits [*i.e.,* modules, cells, electrode active materials (EAM), and critical minerals (CM)]. Each of these sets have two credits in the figure that reflect two scenarios corresponding to different levels of eligibility based on the U.S. supply chain: “full” refers to full market response where 100% of packs are eligible for the credit eligible for domestic producers and “low-end” refers to low-end market response where the percentage of packs eligible for the credit is based on the availability of domestic production of eligible minerals and components, as projected by Argonne analysis of market announcements as of November 2023 (U.S. Department of Energy, 2023). The results reflect the ramp downs of the tax credits prescribed in the IRA for cells, modules, and EAM after MY2029.

According to Figure 8, HEVs have the potential to achieve a total 45X tax credit of ~$56/kWh through MY2029 based on the summation of the "full" results (see Table 40 in the Appendix for tabulated results). The maximum credit drops nearly linearly to ~$1.7/kWh by MY2033 due to the ramp down of the cell, module, and EAM credits. The totals for the "low-end" market response for these same two cases are ~$52/kWh up to 2029 and ~$0.6/kWh after MY2033.

Figure 9 indicates that Ni/Mn PHEVs and BEVS have the potential to achieve a total, "full" credit of ~$54/kWh through MY2029 (see Table 41 in the Appendix). The maximum credit drops to ~$1.8/kWh by MY2033 due to the 45X ramp down. The "low-end" totals for these same two cases are ~$49/kWh up to MY2029 and ~$0.7/kWh after MY2033.

Figure 10 shows that LFP PHEVs and BEVs have the potential to achieve a total, "full" credit of ~$50/kWh through MY2029 (see Table 42 in the Appendix). The maximum credit drops to ~$0.5/kWh by MY2033 due to the 45X ramp down. The "low-end" totals for these same two cases are ~$48/kWh up to MY2029 and ~$0.3/kWh after MY2033.

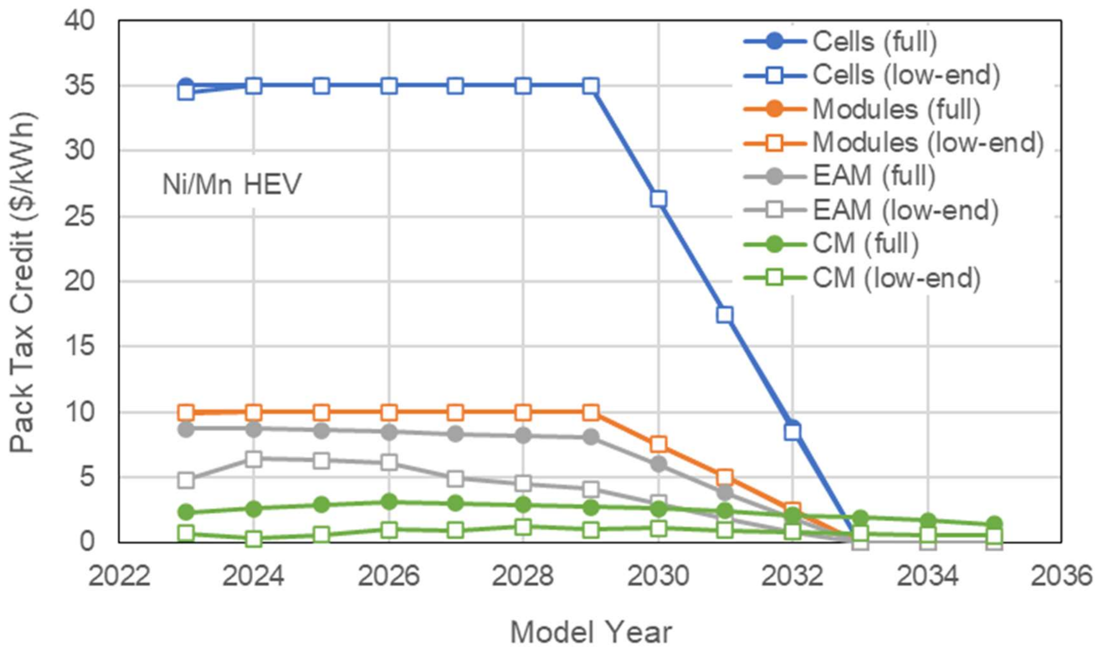

Figure 8. Estimated tax credits ($/kWh_{rated,2023}$) for Ni/Mn HEV packs under 45X. "Full" refers to full market response, i.e., availability, of domestic U.S. supply (i.e., packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market that can be supplied domestically based on announcements available as of the time of analysis (see Appendix A6 for details). EAM and CM refer to electrode active materials and critical minerals tax credits, respectively.

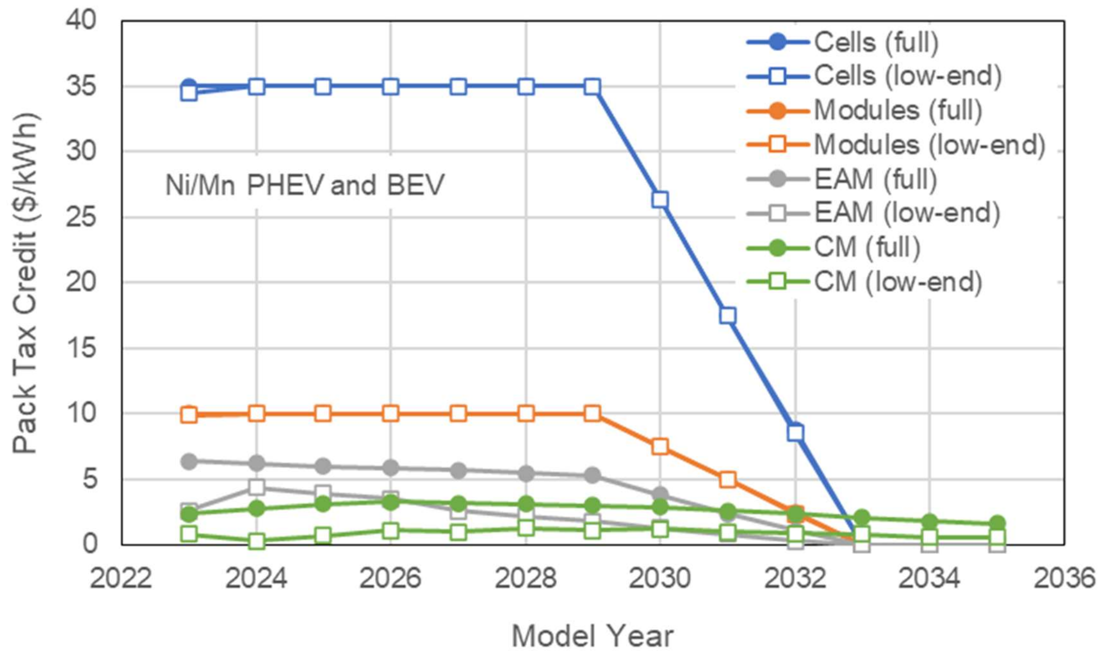

Figure 9. Estimated tax credits ($\$/kWh_{rated,2023}$) for Ni/Mn PHEV and BEV packs under 45X. "Full" refers to full market response, i.e., availability, of domestic U.S. supply (i.e., packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market that can be supplied domestically based on announcements available as of the time of analysis (see Appendix A6 for details). EAM and CM refer to electrode active materials and critical minerals tax credits, respectively.

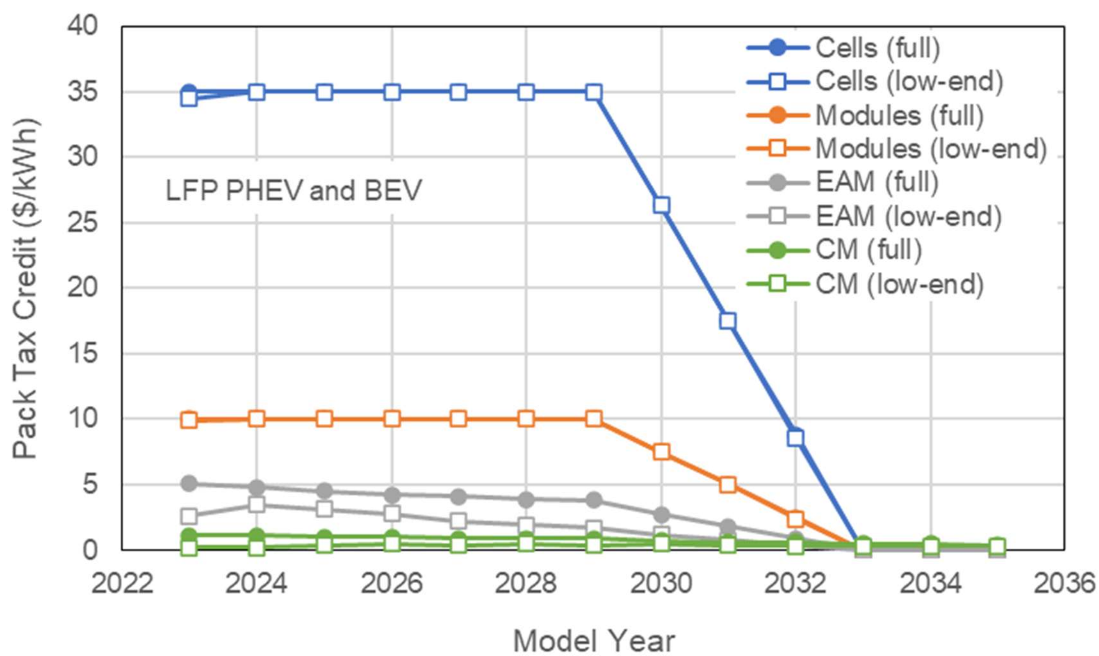

Figure 10. Estimated tax credits ($\$/kWh_{rated,2023}$) for LFP PHEV and BEV packs under 45X. "Full" refers to full market response, i.e., availability, of domestic U.S. supply (i.e., packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market that can be supplied domestically based on announcements available as of the time of analysis (see Appendix A6 for details). EAM and CM refer to electrode active materials and critical minerals tax credits, respectively.

The 45X tax credits were also incorporated into the volume-averaged pack cost calculations for PHEVs and BEVs (see previous section for details). The influence of three groupings of 45X credits is shown in Figure 11. The first grouping incorporates only the cell and module credits for the low-end case (open triangles in the figure). Note that the full and low-end responses for this grouping are nearly identical because the smallest low-end response is 97% (see Table 39 in Appendix A6). Therefore, this grouping reflects both cases (full and low-end) with negligible difference. The next grouping incorporates all credits, including electrode active materials and critical minerals at the low-end market response (solid triangles). The final grouping includes all credits at full market response (solid squares). Overall, the volume averaged pack cost has the potential to reach a minimum value of $55.6/kWh in MY2029 for a full market response and $60.5/kWh for the low-end response. The ramp down of the cell, module, and EAM credits beginning in 2030 will have a significant impact on the cost, raising it to ~91/kWh by MY2033 for both cases.

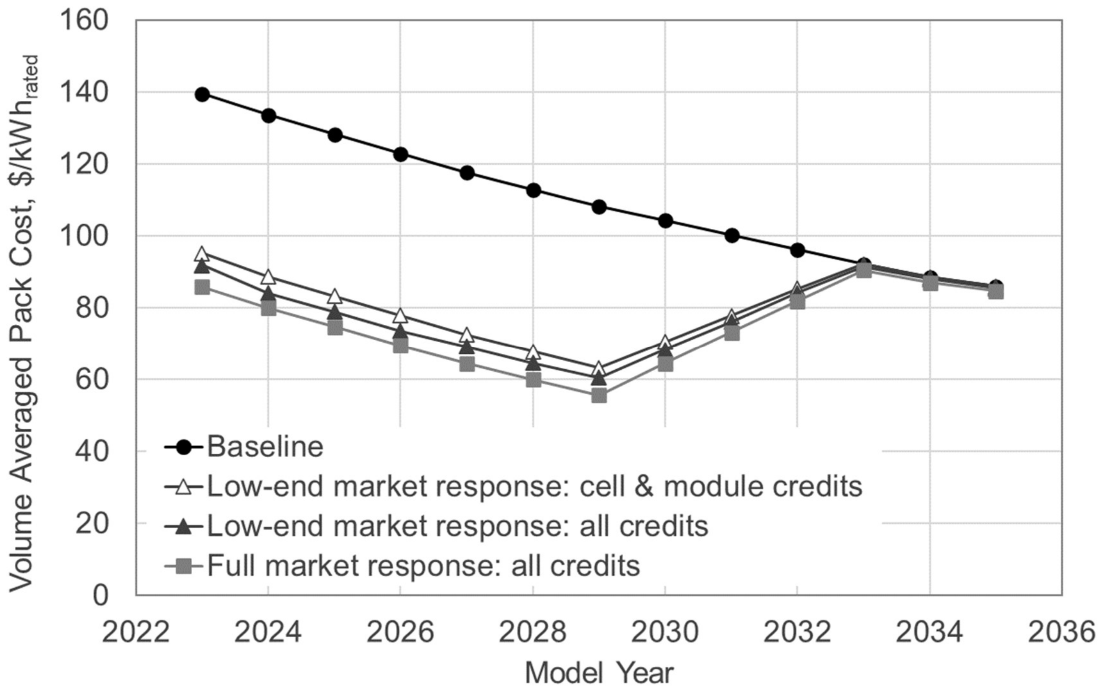

Figure 11. Impact of 45X tax credits on volume averaged pack cost ($/kWh$_{rated,2023}$).

Calculation Sensitivities

Sensitivity – MY2023 Cost with NMC811 vs. NMC622 as the Cathode Active Material

Some of the EV batteries available in the market in MY2023 use NMC811 as the cathode active material (BloombergNEF, 2023; Sanders, 2023), while the CAM selected as the dominant material in this analysis is NMC622. To address the question of the effect of NMC811 on a pack cost, a series of simulations were run by using NMC811 (and its associated properties and price), while keeping all other MY2023 specifications unchanged. Figure 12 compares the pack costs with NMC622 and NMC811, for all the batteries for BEV light duty (LD) vehicle, i.e., EVs only. The trends for both chemistries show a cost reduction trend for bigger batteries (higher kWh), where the slope gets increasingly shallow at higher kWh. The difference is less than $0.5/kWh for all kWhs, with the exception at 90 kWh where it was highest at $1/kWh. While the NMC811 offers higher specific capacity and higher voltage (compared to NMC622), it has a higher material price, and results in the net higher pack cost.

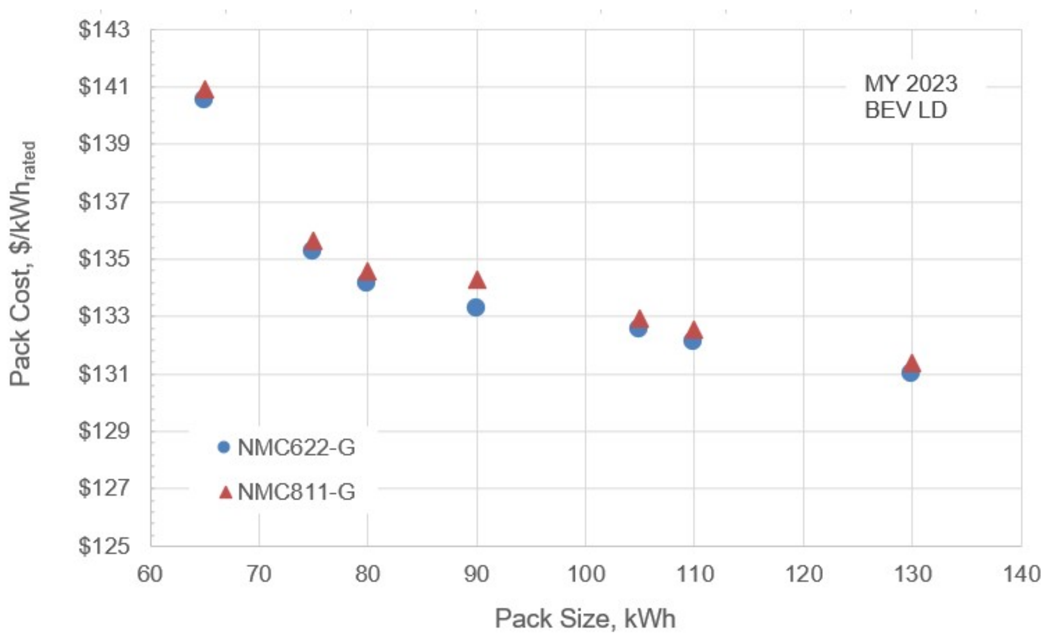

Figure 12. Comparison of pack costs for MY2023 with NMC622 and NMC811 as the cathode active material.

Sensitivity – Production Volume

Cost reduction from economies of scale is calculated according to Equation (3),

$$Cost = Cost_{reference}\left(\frac{Vol}{Vol_{reference}}\right)^{p} \tag{3}$$

Where, the desired cost is determined from the ratio of the actual to the reference production volume, raised to the power p. This cost equation is applied separately for all the processing steps in the plant, for the cell plant size which determines the amount of materials that are purchased, and the number of packs that are produced per year in the plant. As described in an earlier section, the cell plant size (GWh) and pack volumes were specified for each model year in the development of the consolidated cost curve.

Current cell plants around the world appear to have been optimized at above 35 GWh and the learning curve is relatively flat. Large cell plants are feasible because similar cells can be produced in large volume and then used to configure packs of different energy storage capacities (kWh). This was investigated by plotting the pack cost as a function of the annual pack production volume. Figure 13 plots the results for MY2023 vehicles with both NiMn and LFP chemistries and different pack energies. BEV pack costs change less than a $1/kWh above 200 thousand packs per year, while the smaller packs in PHEVs and HEVs show greater sensitivity.

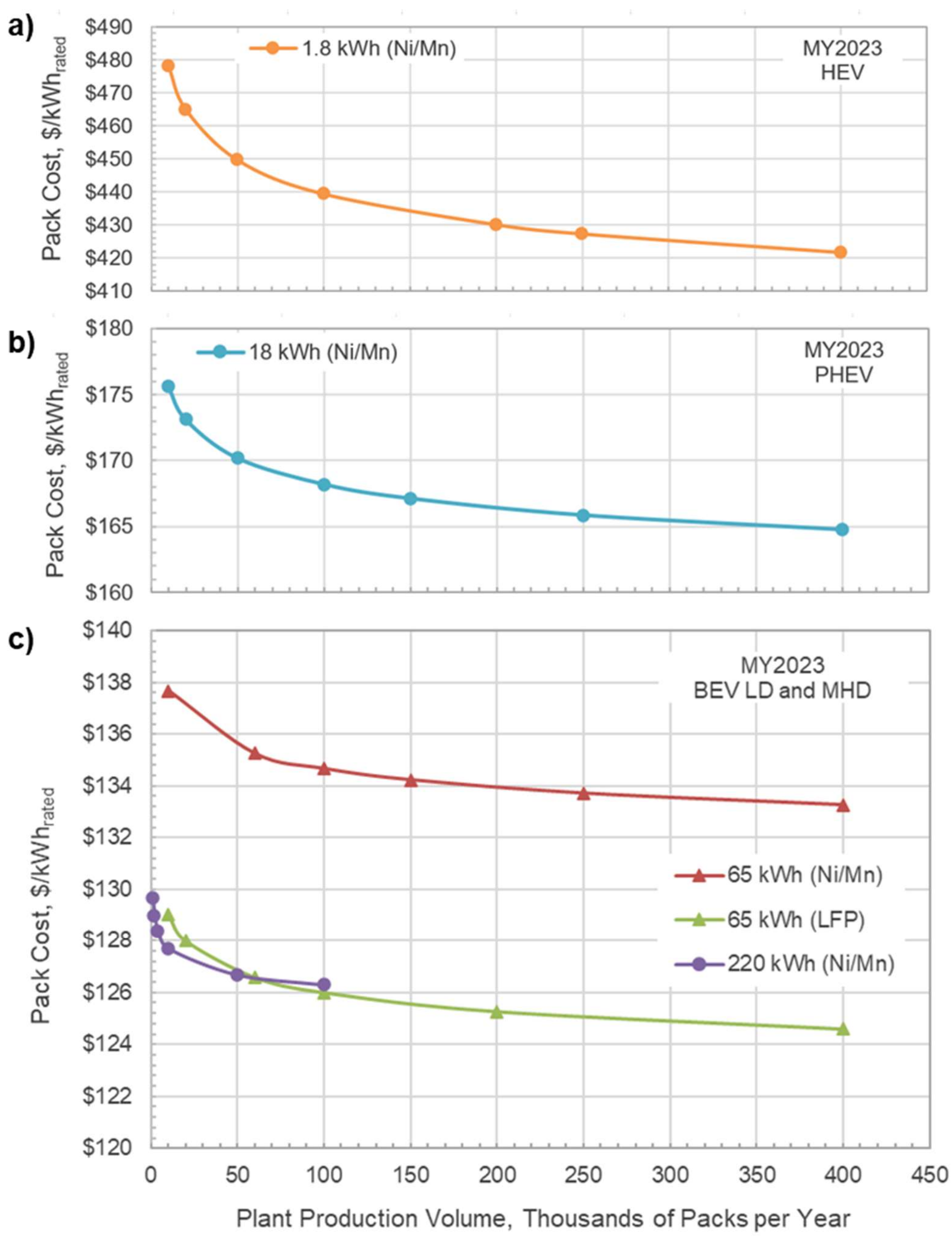

Figure 13. Effect of pack production volume in a plant on the pack cost ($/kWh_{rated,2023}$) for a) HEVs, b) PHEV, and c) BEVs. MY2023 with Cell plant capacity of 35 GWh.

Sensitivity – Raw Materials Prices

The price of the active materials has a large impact on the cost of the packs. For instance, the cathode active materials can contribute over 40% of the total pack cost (see Appendix A2). The price of the active materials through MY2035 were estimated from market research reports (Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Sanders, 2023); however, these projections may be impacted by future, unforeseen changes in the supply and demand of the raw materials. Figure 14a shows what might happen if the raw materials' prices remain at MY2023 values and all pack costs were based on the MY2023 price of the active materials. Solid symbols and dotted trendlines refer to calculations assuming 2023 prices. Open symbols and dashed trendlines refer to calculations with forecasted prices. The spread in costs for a given MY for a pack chemistry (LFP or Ni/Mn) is related to the plotting of four different pack sizes for each MY. Details on the inputs can be found in Appendix A7. Figure 14b quantifies the change in cost between forecasted and MY2023 active material prices. Overall, Figure 14b shows that maintaining MY2023 values will increase the LFP cost by \$4-\$10/kWh and the Ni/Mn cost by \$3-8/kWh. The maximum increase in LFP cost will be ~\$10/kWh by MY2035. This is due to the cathode and anode active material prices increasing from \$9.5 to \$13/kg and \$9.1 to \$11/kg, respectively. The maximum increase in Ni/Mn cost will be \$7.7/kWh in MY2030. This is due to the cathode NMC95 and graphite/silicon (G/Si) prices increasing from \$31.3 to \$36.1/kg and \$11.3 to \$13/kg, respectively.

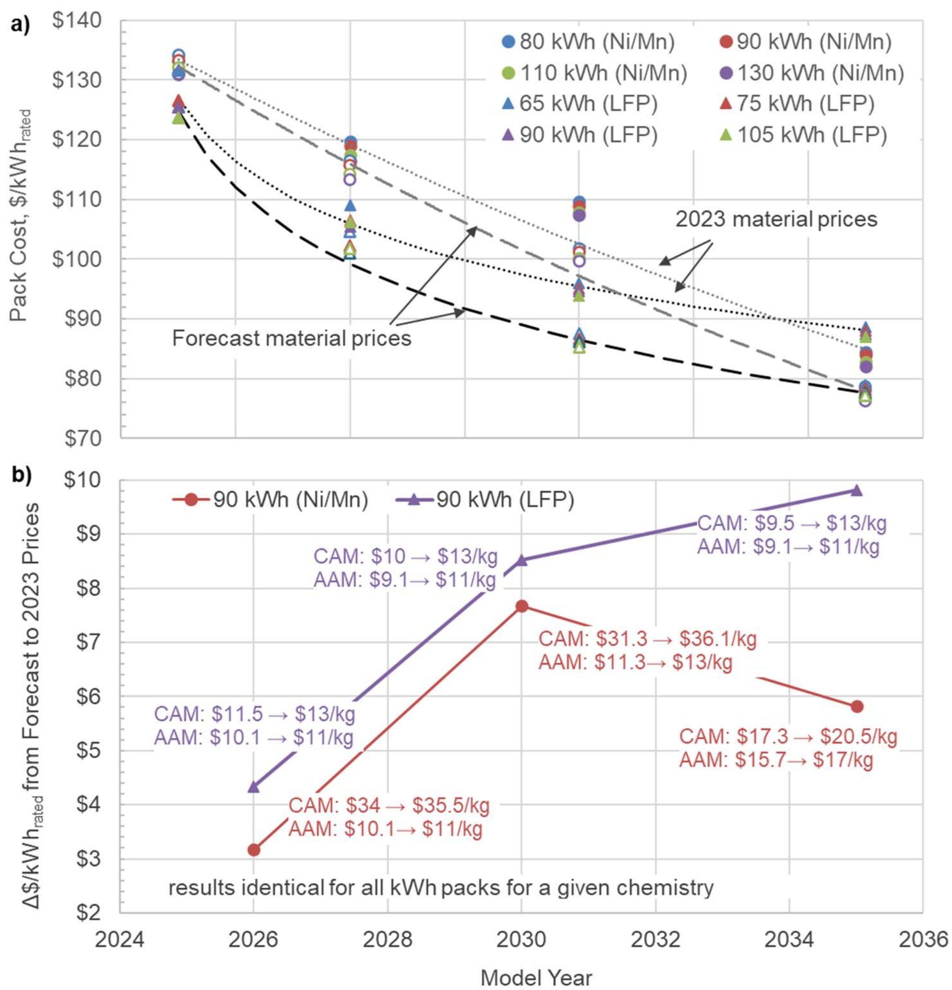

Figure 14. a) Pack costs (\$/kWh$_{rated,2023}$) assuming 2023 (solid symbols, dotted trendlines) and forecasted (open symbols, dashed trend lines) active material prices for Ni/Mn (circles, grey trend lines) and LFP (triangles, black trendlines) packs. b) Change in pack cost from forecasted to 2023 active material prices for 90 kWh packs. Results in b) apply to all kWh packs in a). CAM: cathode active material, AAM: anode active material.

Sensitivity – Fast Charge
Fast charging a pack requires the ability of the cell (particularly the anode layer) to process a large current during the charging period. For short durations the incoming current can be as high as 5-8 times average discharge rate (full discharge in 3 hours, referred to as a C/3 rate) (Ahmed S. , et al., 2017). This high current can initiate several degradation mechanisms (Raj, Rodrigues, & Abraham, 2020; Rodrigues, Shkrob, Colclasure, & Abraham, 2020) and is addressed through electrode design and charging protocols (Song J. , et al., 2021; Usseglio-Viretta, et al., 2020).

The effect of charge times on the design of the electrodes, assuming a well-developed charging protocol, translates to a lower loading of the active material, which in turn increases the ratio of inactive (current collectors, separators, and others) to electrode active materials (EAM) and, therefore, the cost of the cell and pack. Figure 15 plots the effect of charge times on the pack cost and shows that packs with charge times of 25 minutes or more cost ~$135/kWh for a 90 kWh pack and ~$143/kWh for a 65 kWh pack. Below 25 minutes, the cost begins to increase. For a 15-minute chart time, the cost rises to ~$144/kWh and ~$151/kWh, for the 90 and 65 kWh packs, respectively.

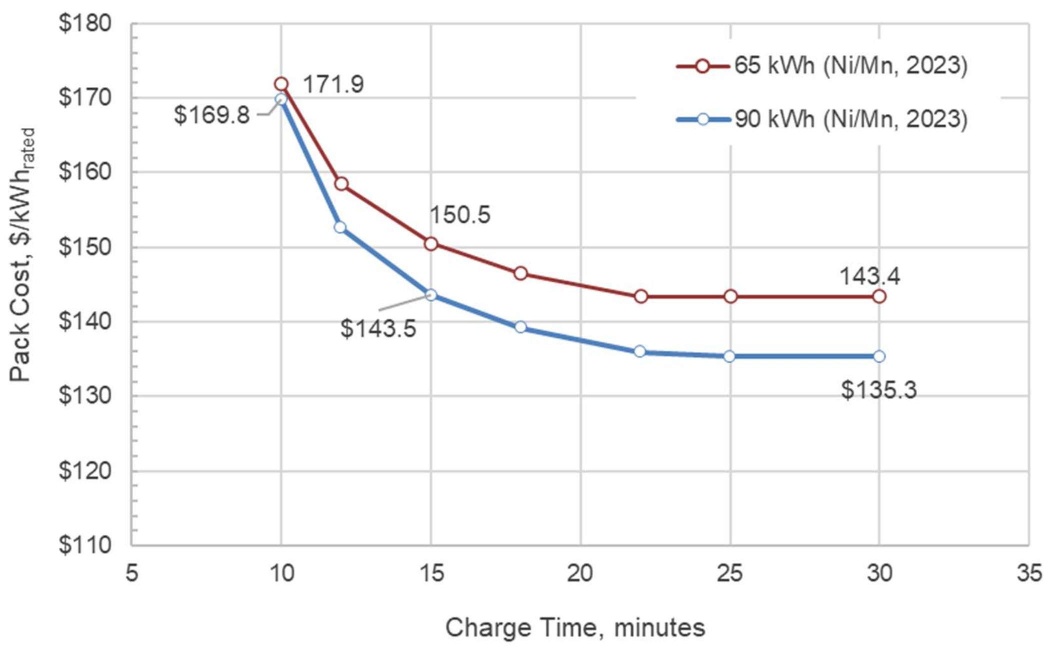

Figure 15. Pack cost ($/kWh$_{rated,2023}$) as a function of charging time, for a 65 kWh and 90 kWh NMC622-Graphite pack for MY2023.

Table 14. Pack costs as a function of charging times.

Charge Time, min	**30**	**15**	**10**
Cost (65 kWh), $/kWh	143	151	172
∆% w.r.t. 30 min	-	+4.95%	+19.9%
Cost (90 kWh), $/kWh	135	144	170
∆% w.r.t. 30 min	-	+6.67%	+25.5%

Sensitivity – Labor Rate

The labor rate assumed for the hourly workers in the manufacturing plant can have an impact on the total pack cost. The sensitivity of the pack cost to the labor rate was studied by re-running the BatPaC simulations with the labor rate doubled (from \$25/hr[1]) to \$50/hr[2]. The resulting data was used to generate correlation constants in Equation (1) for the new dataset. Table 15 provides a comparison of the correlation constants for the two cases (\$25 and \$50/hr.). Figure 16 shows how the data and correlation outputs change with labor rate.

Table 15. Constants for pack cost (\$/kWh$_{rated,2023}$) correlations given in equation 1 for \$25/hr. and \$50/hr. labor rates.

	Ni/Mn (HEV, ≤5 kWh)		**Ni/Mn (PHEV, EV)**		**LFP (PHEV, EV)**	
	\$25/hr.	**\$50/hr.**	**\$25/hr.**	**\$50/hr.**	**\$25/hr.**	**\$50/hr.**
A	119.3	122.9	124.5	128.9	115.7	120.6
B	492.4	509.6	1071	1480	1141	1535
C	0.7667	0.7649	1.068	1.164	1.138	1.148
D	4.131	4.443	4.617	5.278	9.489	10.04
E	0.01352	0.01018	-0.005038	-0.01290	-0.08312	-0.08346

In Figure 16, squares and solid lines represent the base case of \$25/hr., while circles and dashed lines represent the \$50/hr case. The results indicate that doubling the labor rate can increase the pack cost by up to ~\$10/kWh depending on the model year, pack size, and pack chemistry. For larger packs (>25 kWh), the figure shows that larger increases are observed for LFP packs, which tend to have higher labor due to the need to process more materials per kWh. The lower energy content (Wh/g) of LFP requires bigger cells and production costs to achieve the same pack energy (kWh) as nickel/manganese containing cathodes.

[1] Authors' estimate of average U.S. labor rate for battery manufacturing as of August 2023.
[2] \$50/hr case was analyzed to capture ongoing labor negotiations during Fall 2023.

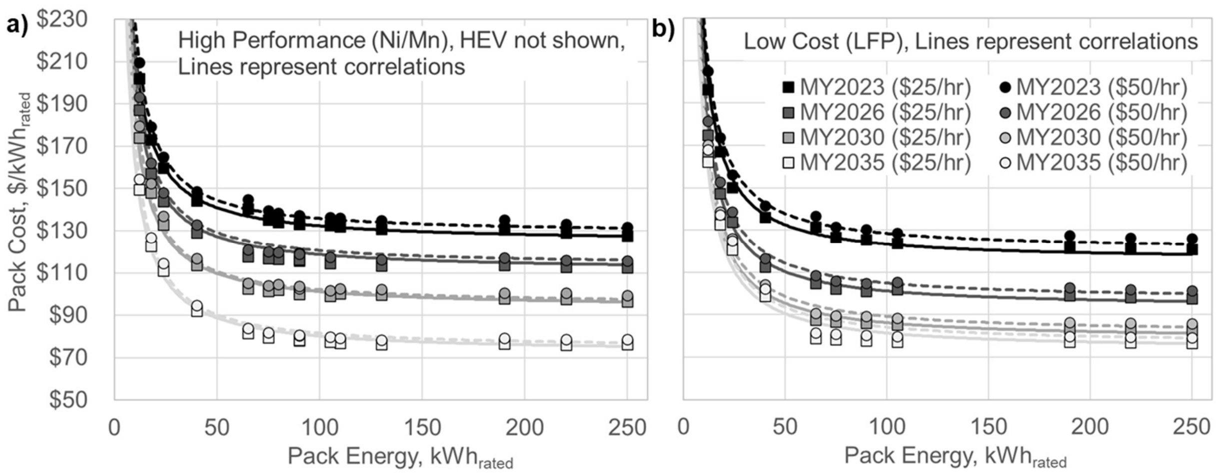

Figure 16. Comparison of pack cost ($/kWh_{rated,2023}$) between full BatPaC simulations (symbols) and correlations in equation 1 (lines) for a) high performance (Ni/Mn) and b) low cost (LFP) packs. Squares and solid lines are the baseline simulations which assume labor rate of $25/hr, while circles and dashed lines assume a labor rate of $50/hr.

The impact of labor rate on the results is further exemplified in Table 16 and Table 17, which provide outputs from the correlations for selected pack sizes. Table 16 shows that doubling the labor rate may increase the cost of high performance (Ni/Mn) packs by 1-7%, depending on the model year and pack size. The absolute cost of HEVs is impacted the most (~$20/kWh) because they have more, smaller cells for a given kWh, which results in higher labor costs. The percent change in cost is not the highest for HEVs (~3%) due to the higher total base cost. 10 kWh packs, which reflect PHEVs, have the highest percent change (~6.5%) and the second highest absolute change (~$13/kWh). Larger, 100 kWh packs, which reflect BEVs, have the lowest percent (~2%) and absolute cost (~$2/kWh) changes. These trends are related to increasing cell size and reducing cell quantity per kWh as the pack kWh increases.

Table 17 shows that doubling the labor rate may increase the cost of LFP packs by 3-4%, depending on the model year and pack size. 10 kWh packs have absolute changes of ~$8/kWh, while larger, 100 kWh packs have changes of ~$3/kWh.

Table 16. Outputs from correlations for three pack sizes for high performance (Ni/Mn) packs. The first two columns under each pack size provide the $/kWh_{rated,2023}$ output from correlations developed assuming $25/hr. and $50/hr. labor rates. The third column is the percent increase in pack cost from $25/hr. to $50/hr.

	1 kWh (HEV)			**10 kWh (PHEV)**			**100 kWh (BEV)**		
Model Year	**$25/hr.**	**$50/hr.**	**%**	**$25/hr.**	**$50/hr.**	**%**	**$25/hr.**	**$50/hr.**	**%**
2023	611.7	632.4	3.4%	216.1	230.2	6.6%	132.3	135.8	2.6%
2026	598.8	618.7	3.3%	202.4	215.0	6.2%	118.7	120.6	1.6%
2030	579.9	599.1	3.3%	184.9	196.5	6.3%	101.2	102.1	0.9%
2035	553.4	572.2	3.4%	163.9	176.0	7.4%	80.2	81.6	1.7%

Table 17. Outputs from correlations for two pack sizes for low cost (LFP) packs. The first two columns under each pack size provide the $/kWh$_{rated,2023}$ output from correlations developed assuming $25/hr. and $50/hr. labor rates. The third column is the percent increase in pack cost from $25/hr. to $50/hr.

	10 kWh (PHEV)			100 kWh (BEV)		
Model Year	**$25/hr.**	**$50/hr.**	**%**	**$25/hr.**	**$50/hr.**	**%**
2023	220.6	229.8	4.2%	123.3	128.4	4.1%
2026	198.4	206.3	4.0%	101.1	104.9	3.7%
2030	183.5	190.6	3.9%	86.2	89.2	3.5%
2035	178.6	185.5	3.9%	81.3	84.1	3.4%

Summary and Conclusions

Under guidance of the Department of Energy, EPA, and NHTSA managers, a study was conducted to estimate the current and future cost of battery packs for electric vehicles. The pack costs were calculated with Argonne's BatPaC tool for twenty categories of vehicles representing hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and full battery electric vehicles (BEV) for both light duty (LD) and medium/heavy duty vehicles (MHD). The cost of battery packs was calculated for four discrete model years (MY2023, MY2026, MY2030, and MY2035) by applying bottom-up assumptions into the BatPaC tool for cell chemistry, cell design, cell size, pack design, production volumes, and material prices. The Appendix provides many details of the methodology, supporting data, and other analyses, including the cost breakdown and the pack mass and volume projections for the different model years.

HEVs were estimated to have a model year 2023 (MY2023) cost of $430 to $570/kWh, which will reduce by ~20% by MY2035. High performance PHEVs made from nickel and manganese containing cathodes (Ni/Mn) were estimated to have MY2023 costs between $145 to $175/kWh with a 25% to 35% reduction in cost by MY2035. PHEVs made from lithium iron phosphate (LFP) cathodes were estimated to have MY2023 costs between $145 to $200/kWh, which will reduce by 17% to 27% by MY2035. Ni/Mn BEVs for LD and MHD vehicles had a MY2023 pack cost of $130 to $140/kWh and are estimated to decrease by ~40% by MY2035. LFP BEV packs had a MY2023 cost of $120 to $130/kWh and were also estimated to have a ~40% cost reduction by MY2035. The ranges in the cost and reduction numbers above reflect variations in the pack size (kWh) within a broad vehicle category.

The resulting costs were then used to produce a correlation for estimating the pack cost as a function of pack size (kWh) and model year. This correlation was used to produce a consolidated battery cost curve for light-, medium- and heavy-duty PHEVs and BEVs within the United States. The cost curve was derived by weighting the pack costs with projections for the number of new vehicles to be sold between MY2023 to MY2035. The cost curve showed that the volume averaged pack cost of PHEVs and BEVs in the United States was ~$140/kWh for MY2023, which is estimated to drop by ~39% to $86/kWh in MY2035 through a combination of technology advances and economies of scale. Modifications were also made to the estimated costs to reflect possible production incentives for a projection of U.S. manufacturers as of November 2023 per Internal Revenue Code Section 45X (Internal Revenue Service, 2023). Application of these credits was shown to enable a further reduction of the cost to a low of ~$56/kWh in 2029.

In addition, several sensitivity studies were conducted to explore the influence of further parameter modification on pack cost. First, the use of NMC811 (instead of NMC622) as the cathode active material for MY2023 was shown to have a negligible impact on pack cost. Second, changes in the pack production volume were shown to mainly have any significant impact on cost if the production volume is less than 100,000 packs per year. For instance, decreasing the production rate from 400,000 to 100,000 packs only increases the cost of HEVs, PHEVs, and BEVs by ~$20/kWh (4.5%), $3/kWh (1.8%), and $2/kWh (1.6%), respectively. Third, stagnant prices of raw materials could increase future pack costs by $3 to $10/kWh depending on the model year and pack chemistry. Fourth, charging times down to 25 minutes were shown to have a minimal impact on pack cost. Further decreasing the charging time to 15 minutes could result in a 5% to 7% increase in pack cost. Finally, doubling the production worker wage rate from $25/hr to $50/hr was shown to increase pack cost by 1% to 7%. These sensitivities suggest that the pack costs reported herein may be impacted by temporal uncertainties in technology successes and market directions. Therefore, it is recommended that these projected costs be compared with actual market data on an annual basis, and the underlying assumptions be updated to reflect the technology and market.

Definitions of Terms

AAM – Anode active material

BatPaC – Battery Performance and Cost

BEV – Battery electric vehicle

BEV250 – Battery electric vehicle w/ a target 250-mile range

BEV300 – Battery electric vehicle w/ a target 300-mile range

BMS – Battery management system

CAM – Cathode active material

CM – Critical mineral 45X tax credit

EAM – Electrode active material 45X tax credit

EPA – Environmental Protection Agency

GSA – General, sales, and administration

HEV – Hybrid electric vehicle

IRA – Inflation Reduction Act

IRS – Internal Revenue Service

LD – Light duty

LFP – Lithium iron phosphate ($LiFePO_4$)

LMNO – Lithium manganese nickel oxide ($LiMn_{1.5}Ni_{0.5}O_2$)

MHD – Medium/heavy duty

MY – Model year

NHTSA – National Highway Traffic Safety Administration

Ni/Mn – Nickel and manganese containing cathodes

NMC622 – Lithium nickel manganese cobalt oxide ($LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$)

NMC811 – Lithium nickel manganese cobalt oxide ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$)

NMC95 – Lithium nickel manganese cobalt oxide ($LiNi_{0.95}Mn_{0.025}Co_{0.025}O_2$)

NREL – National Renewable Energy Laboratory

PHEV – Plug-in hybrid electric vehicle

VO – Variable overhead

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Appendix

A1. Tabulated Results

The table below provides the tabulated results for the BatPaC simulations run using the input parameters given in Tables 1-12. These results are shown in graphical form in Figures 1 to 5.

Table 18. Pack Cost ($/kWh) from BatPaC simulations

kWh / kW	Vehicle	Chem.	2023	2026	2030	2035
1.2 / 48	HEV	Ni/Mn	567.08	553.61	537.05	453.50
1.8 / 70	HEV	Ni/Mn	430.11	417.92	402.74	335.48
12 / 100	PHEV Compact (Ni/Mn)	Ni/Mn	202.01	187.11	174.15	149.41
12 / 100	PHEV Compact (LFP)	LFP	196.44	174.80	164.49	162.30
18 / 150	PHEV Midsize (Ni/Mn)	Ni/Mn	173.12	157.19	147.99	122.74
18 / 150	PHEV Midsize (LFP)	LFP	166.99	147.22	134.01	132.61
24 / 200	PHEV Midsize SUV (Ni/Mn)	Ni/Mn	159.76	143.88	133.05	111.08
24 / 200	PHEV Midsize SUV (LFP)	LFP	150.03	133.65	121.72	120.56
40 / 250	PHEV Pickup (Ni/Mn)	Ni/Mn	144.19	129.22	113.76	92.03
40 / 250	PHEV Pickup (LFP)	LFP	136.20	112.51	100.79	98.62
65 / 125	BEV250 Compact	Ni/Mn	140.55	117.69	102.63	81.44
65 / 125	BEV250 Compact	LFP	131.59	104.68	87.58	78.84
75 / 165	BEV250 Midsize	Ni/Mn	135.25	116.89	101.49	79.49
75 / 165	BEV250 Midsize	LFP	126.59	102.18	86.64	78.27
80 / 130	BEV300 Compact	Ni/Mn	134.17	116.50	101.86	78.62
90 / 200	BEV250 Midsize SUV, BEV300 Midsize	Ni/Mn	133.28	116.28	100.04	78.36
90 / 200	BEV250 Midsize SUV	LFP	125.46	101.09	86.17	77.63
105 / 260	BEV250 Pickup	Ni/Mn	132.54	114.51	99.13	77.63
105 / 260	BEV250 Pickup	LFP	123.73	101.81	85.33	77.21
110 / 210	BEV300 Midsize SUV	Ni/Mn	132.13	114.21	100.10	76.95
130 / 270	BEV300 Pickup	Ni/Mn	130.99	113.27	99.64	76.25
190 / 380	BEV MHD	Ni/Mn	130.76	113.78	97.79	76.69
190 / 380	BEV MHD	LFP	122.29	98.92	83.40	77.19
220 / 440	BEV MHD	Ni/Mn	128.99	112.82	97.63	76.16
220 / 440	BEV MHD	LFP	121.35	98.15	83.07	76.90
250 / 500	BEV MHD	Ni/Mn	127.61	112.42	96.52	76.35
250 / 500	BEV MHD	LFP	120.91	97.56	82.73	76.62

A2. Selected Cost Breakdowns

This section contains cost breakdowns for several selected packs. The assumptions that go into the baseline cost calculations are given in Table 19. Further details can be found in the BatPaC manual and the latest version of BatPaC (Knehr K. W., Kubal, Nelson, & Ahmed, 2022).

Table 19. Description of baseline cost calculations.

Cost Component	Assumptions
Materials	Actives, separators, electrolyte, etc.
Purchased Items	Terminals, connectors, packaging, etc.
BMS	Battery management system (BMS)
Energy	$0.05/kWh
Depreciation	10-year lifetime for process equipment, 15 years for building equipment, 20 for building and land
Labor-related	$25/hr. × (1.4 for VO) × (1.25 for GSA)
Other Variable Overhead (VO)	2% of fixed capital investment
Other General, Sales, and Administration (GSA)	0.75% of fixed capital investment
Research & Development (R&D)	35% of depreciation
Financing	0.75% of total capital investment
Profits	5% of total capital investment
Warranty	5.6% of total pack cost

A2.1. Selected HEV Cost Breakdown

Table 20. Cost breakdown for the 1.8 kWh HEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	107.6	100.9	90.6	63.7	25.0%	24.1%	22.5%	19.0%
Purchased Items	147.6	146.6	145.8	125.9	34.3%	35.1%	36.2%	37.5%
BMS	60.7	60.7	60.7	55.2	14.1%	14.5%	15.1%	16.5%
Energy	4.3	4.1	3.9	3.4	1.0%	1.0%	1.0%	1.0%
Depreciation	26.1	25.0	24.1	20.7	6.1%	6.0%	6.0%	6.2%
Labor-related	14.6	13.8	13.2	11.7	3.4%	3.3%	3.3%	3.5%
Other Variable Overhead	7.4	7.1	6.9	5.9	1.7%	1.7%	1.7%	1.8%
Other GSA	4.6	4.4	4.3	3.7	1.1%	1.1%	1.1%	1.1%
R&D	9.1	8.8	8.4	7.2	2.1%	2.1%	2.1%	2.2%
Financing	3.3	3.2	3.1	2.6	0.8%	0.8%	0.8%	0.8%
Profits	22.0	21.2	20.4	17.5	5.1%	5.1%	5.1%	5.2%
Warranty	22.8	22.2	21.4	17.8	5.3%	5.3%	5.3%	5.3%
Total	430.1	417.9	402.7	335.5	100.0%	100.0%	100.0%	100.0%

A2.2. Selected PHEV Cost Breakdowns

Table 21. Cost breakdown for the high performance (Ni/Mn) 24 kWh PHEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	80.7	72.1	64.0	47.5	50.5%	50.1%	48.1%	42.8%
Purchased Items	23.8	21.7	21.2	19.4	14.9%	15.1%	16.0%	17.5%
BMS	17.9	17.0	16.5	15.9	11.2%	11.8%	12.4%	14.3%
Energy	1.8	1.6	1.6	1.5	1.1%	1.1%	1.2%	1.4%
Depreciation	7.8	7.0	6.8	6.3	4.9%	4.9%	5.1%	5.7%
Labor-related	5.3	4.2	3.9	3.6	3.3%	2.9%	2.9%	3.2%
Other Variable Overhead	2.2	1.9	1.9	1.7	1.3%	1.3%	1.4%	1.6%
Other GSA	1.3	1.2	1.2	1.1	0.8%	0.8%	0.9%	1.0%
R&D	2.7	2.5	2.4	2.2	1.7%	1.7%	1.8%	2.0%
Financing	1.0	0.9	0.9	0.8	0.6%	0.6%	0.7%	0.7%
Profits	6.7	6.0	5.8	5.2	4.2%	4.2%	4.3%	4.7%
Warranty	8.5	7.6	7.1	5.9	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*159.8*	*143.9*	*133.0*	*111.1*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 22. Breakdown of materials costs in high performance (Ni/Mn) 24 kWh PHEV pack.

	$/kWh				% of total material cost			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Cathode Active Materials	54.39	51.54	44.33	29.96	67.4%	71.5%	69.3%	63.1%
Anode Active Materials	10.54	7.63	5.82	3.97	13.1%	10.6%	9.1%	8.4%
Positive Current Collector	0.83	0.67	0.80	0.76	1.0%	0.9%	1.3%	1.6%
Negative Current Collector	5.23	4.24	5.05	4.81	6.5%	5.9%	7.9%	10.1%
Separators	3.56	2.88	3.43	3.29	4.4%	4.0%	5.4%	6.9%
Electrolyte	3.64	2.91	2.52	2.33	4.5%	4.0%	3.9%	4.9%
Carbon and Binder	2.52	2.21	2.02	2.38	3.1%	3.1%	3.2%	5.0%
Total of Materials Only Costs	*80.7*	*72.1*	*64.0*	*47.5*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 23. Cost breakdown for the low cost (LFP) 24 kWh PHEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	67.2	55.6	47.6	46.6	44.8%	41.6%	39.1%	38.6%
Purchased Items	23.0	24.0	23.6	23.6	15.3%	18.0%	19.4%	19.6%
BMS	19.0	17.7	17.2	17.2	12.6%	13.3%	14.1%	14.3%
Energy	2.1	1.9	1.8	1.8	1.4%	1.4%	1.4%	1.5%
Depreciation	9.1	8.2	7.6	7.6	6.0%	6.1%	6.3%	6.3%
Labor-related	6.0	4.9	4.2	4.2	4.0%	3.7%	3.5%	3.5%
Other Variable Overhead	2.5	2.3	2.1	2.1	1.7%	1.7%	1.7%	1.7%
Other GSA	1.6	1.4	1.3	1.3	1.0%	1.1%	1.1%	1.1%
R&D	3.2	2.9	2.7	2.7	2.1%	2.1%	2.2%	2.2%
Financing	1.1	1.0	0.9	0.9	0.7%	0.8%	0.8%	0.8%
Profits	7.4	6.7	6.2	6.2	5.0%	5.0%	5.1%	5.1%
Warranty	8.0	7.1	6.5	6.4	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*150.0*	*133.6*	*121.7*	*120.6*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 24. Breakdown of materials costs in low cost (LFP) 24 kWh PHEV pack.

	$/kWh				% of total material cost			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Cathode Active Materials	29.95	25.74	21.70	20.62	44.6%	46.3%	45.5%	44.3%
Anode Active Materials	11.65	8.35	7.30	7.30	17.3%	15.0%	15.3%	15.7%
Positive Current Collector	1.45	1.18	0.97	0.97	2.2%	2.1%	2.0%	2.1%
Negative Current Collector	9.11	7.43	6.10	6.10	13.6%	13.4%	12.8%	13.1%
Separators	6.30	5.11	4.18	4.18	9.4%	9.2%	8.8%	9.0%
Electrolyte	5.35	4.55	4.29	4.29	8.0%	8.2%	9.0%	9.2%
Carbon and Binder	3.37	3.21	3.11	3.11	5.0%	5.8%	6.5%	6.7%
Total of Materials Only Costs	*67.2*	*55.6*	*47.6*	*46.6*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

A2.3. Selected Light Duty (LD) BEV Cost Breakdowns

Table 25. Cost breakdown for the high performance (Ni/Mn) 75 kWh BEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	81.0	72.0	61.2	44.7	59.9%	61.6%	60.3%	56.2%
Purchased Items	15.2	11.6	10.6	8.8	11.2%	9.9%	10.4%	11.1%
BMS	5.3	5.1	4.9	4.5	4.0%	4.3%	4.8%	5.7%
Energy	1.7	1.5	1.4	1.3	1.3%	1.3%	1.4%	1.7%
Depreciation	7.5	6.3	5.6	5.0	5.6%	5.4%	5.5%	6.3%
Labor-related	4.2	3.2	2.7	2.3	3.1%	2.7%	2.6%	2.9%
Other Variable Overhead	2.1	1.7	1.5	1.4	1.5%	1.5%	1.5%	1.7%
Other GSA	1.3	1.1	1.0	0.9	0.9%	0.9%	0.9%	1.1%
R&D	2.6	2.2	2.0	1.7	1.9%	1.9%	1.9%	2.2%
Financing	0.9	0.8	0.7	0.6	0.7%	0.7%	0.7%	0.8%
Profits	6.2	5.2	4.6	4.0	4.6%	4.5%	4.6%	5.1%
Warranty	7.2	6.2	5.4	4.2	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*135.3*	*116.9*	*101.5*	*79.5*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 26. Breakdown of materials costs in high performance (Ni/Mn) 75 kWh BEV pack.

	$/kWh				% of total material cost			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Cathode Active Materials	54.38	51.58	44.57	30.15	67.2%	71.6%	72.8%	67.5%
Anode Active Materials	10.59	7.69	5.88	4.00	13.1%	10.7%	9.6%	9.0%
Positive Current Collector	0.85	0.66	0.55	0.50	1.1%	0.9%	0.9%	1.1%
Negative Current Collector	5.39	4.17	3.48	3.20	6.7%	5.8%	5.7%	7.2%
Separators	3.58	2.83	2.36	2.25	4.4%	3.9%	3.9%	5.0%
Electrolyte	3.65	2.91	2.37	2.18	4.5%	4.0%	3.9%	4.9%
Carbon and Binder	2.52	2.22	2.03	2.39	3.1%	3.1%	3.3%	5.4%
Total of Materials Only Costs	*81.0*	*72.0*	*61.2*	*44.7*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 27. Cost breakdown for the low cost (LFP) 75 kWh BEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	67.6	55.5	47.2	44.5	53.4%	54.4%	54.4%	56.9%
Purchased Items	16.5	11.6	9.7	8.9	13.0%	11.4%	11.2%	11.4%
BMS	5.5	5.2	4.9	2.0	4.3%	5.1%	5.6%	2.6%
Energy	2.0	1.7	1.6	1.5	1.6%	1.7%	1.8%	1.9%
Depreciation	8.6	7.0	5.8	5.3	6.8%	6.8%	6.7%	6.8%
Labor-related	5.0	3.7	3.0	2.7	4.0%	3.7%	3.4%	3.4%
Other Variable Overhead	2.3	1.9	1.6	1.5	1.9%	1.9%	1.8%	1.9%
Other GSA	1.5	1.2	1.0	0.9	1.2%	1.2%	1.1%	1.2%
R&D	3.0	2.4	2.0	1.9	2.4%	2.4%	2.3%	2.4%
Financing	1.0	0.8	0.7	0.6	0.8%	0.8%	0.8%	0.8%
Profits	6.9	5.6	4.6	4.2	5.4%	5.4%	5.4%	5.4%
Warranty	6.7	5.4	4.6	4.2	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*126.6*	*102.2*	*86.6*	*78.3*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 28. Breakdown of materials costs in low cost (LFP) 75 kWh BEV pack.

	$/kWh				% of total material cost			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Cathode Active Materials	29.95	25.76	21.75	20.78	44.3%	46.4%	46.1%	46.7%
Anode Active Materials	11.70	8.38	7.29	7.33	17.3%	15.1%	15.5%	16.5%
Positive Current Collector	1.49	1.18	0.92	0.77	2.2%	2.1%	2.0%	1.7%
Negative Current Collector	9.36	7.38	5.78	4.87	13.9%	13.3%	12.3%	10.9%
Separators	6.33	5.12	4.04	3.43	9.4%	9.2%	8.6%	7.7%
Electrolyte	5.36	4.55	4.27	4.19	7.9%	8.2%	9.0%	9.4%
Carbon and Binder	3.37	3.21	3.12	3.14	5.0%	5.8%	6.6%	7.0%
Total of Materials Only Costs	*67.6*	*55.5*	*47.2*	*44.5*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

A2.4. Selected Medium-Heavy Duty (MHD) BEV Cost Breakdowns

Table 29. Cost breakdown for the high performance (Ni/Mn) 220 kWh BEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	81.0	72.0	61.2	44.7	62.8%	63.8%	62.7%	58.7%
Purchased Items	12.9	10.5	9.0	7.7	10.0%	9.3%	9.2%	10.1%
BMS	2.6	2.5	2.9	2.7	2.0%	2.2%	3.0%	3.5%
Energy	1.7	1.5	1.4	1.3	1.3%	1.3%	1.4%	1.8%
Depreciation	7.2	6.2	5.5	4.9	5.6%	5.5%	5.7%	6.5%
Labor-related	4.2	3.3	2.8	2.4	3.2%	2.9%	2.8%	3.2%
Other Variable Overhead	2.0	1.7	1.5	1.3	1.5%	1.5%	1.5%	1.8%
Other GSA	1.2	1.1	0.9	0.8	1.0%	0.9%	1.0%	1.1%
R&D	2.5	2.2	1.9	1.7	2.0%	1.9%	2.0%	2.3%
Financing	0.9	0.8	0.7	0.6	0.7%	0.7%	0.7%	0.8%
Profits	6.0	5.1	4.5	4.0	4.6%	4.6%	4.7%	5.2%
Warranty	6.8	6.0	5.2	4.0	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*129.0*	*112.8*	*97.6*	*76.2*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

Table 30. Cost breakdown for the low cost (LFP) 220 kWh BEV pack.

	$/kWh				% of pack total			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
Materials	67.6	55.5	47.2	44.5	55.7%	56.6%	56.8%	57.9%
Purchased Items	14.7	10.4	8.4	7.9	12.2%	10.6%	10.1%	10.3%
BMS	2.7	3.1	2.9	2.0	2.2%	3.1%	3.5%	2.6%
Energy	2.0	1.7	1.6	1.5	1.7%	1.8%	1.9%	1.9%
Depreciation	8.4	6.8	5.8	5.3	6.9%	6.9%	6.9%	6.9%
Labor-related	5.1	3.9	3.1	2.7	4.2%	3.9%	3.7%	3.5%
Other Variable Overhead (VO)	2.3	1.8	1.6	1.4	1.9%	1.9%	1.9%	1.9%
Other GSA	1.4	1.2	1.0	0.9	1.2%	1.2%	1.2%	1.2%
R&D	2.9	2.4	2.0	1.8	2.4%	2.4%	2.4%	2.4%
Financing	1.0	0.8	0.7	0.6	0.8%	0.8%	0.8%	0.8%
Profits	6.7	5.4	4.6	4.2	5.5%	5.5%	5.5%	5.4%
Warranty	6.4	5.2	4.4	4.1	5.3%	5.3%	5.3%	5.3%
Total Pack Cost	*121.3*	*98.2*	*83.1*	*76.9*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

A3. Specific Energy (Wh/kg) Results and Correlations

Correlations were also developed for the specific energy (Wh/kg) of the packs simulated in this work. The correlations had the following functional form:

$$\dot{E}_{pack} = 1000\left[A + \frac{B}{x^C} - D(y-2023)e^{E(y-2023)}\right]^{-1} \quad \text{(A1)}$$

where *x* is the pack energy in kWh and *y* is the model year. A, B, C, D, and E are constants given in Table 31. The agreement between the equation and the data is shown in Figure 17.

Table 31. Constants for Wh/kg correlation given in Equation A1.

Constant in Eq. A1	High Performance (Ni/Mn) (HEV, ≤5 kWh)	High Performance (Ni/Mn) (PHEV, EV)	Low Cost (LFP) (PHEV, EV)
A	5.220	5.266	6.602
B	13.398	20.60	25.62
C	0.941	1.129	1.016
D	0.359	0.3537	0.3597
E	-0.081	-0.08158	-0.09757

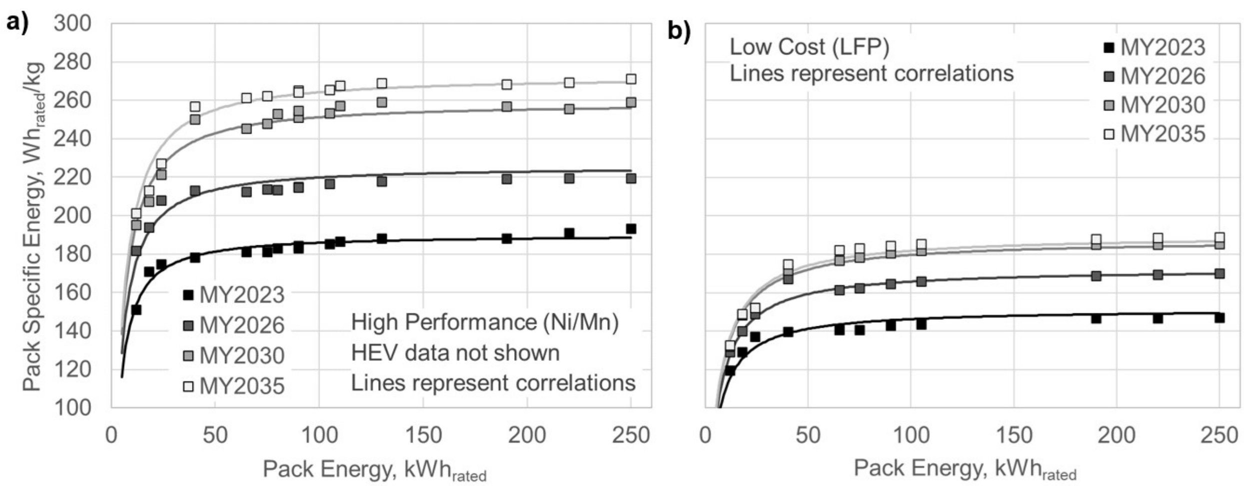

Figure 17. Comparison of specific energy (Wh/kg) between full BatPaC simulations (symbols) and correlations in equation A1 (lines) for a) high performance (Ni/Mn) and b) low cost (LFP) packs.

A4. Energy Density (Wh/L) Results and Correlations

Correlations were also developed for the energy density (Wh/L) of the packs simulated in this work. The correlations had the following functional form:

$$\hat{E}_{pack} = 1000\left[A + \frac{B}{x^C} - D(y-2023)e^{E(y-2023)}\right]^{-1} \quad \text{(A2)}$$

where *x* is the pack energy in kWh and *y* is the model year. A, B, C, D, and E are constants given in Table 32. The agreement between the equation and the data is shown in Figure 18. The slight underpredictions for larger packs in MY2035 result in a maximum error of 7% at 220 kWh for the Ni/Mn packs.

Table 32. Constants for Wh/L correlation given in Equation A2.

Constant in Eq. A2	High Performance (Ni/Mn) (HEV, ≤5 kWh)	High Performance (Ni/Mn) (PHEV, EV)	Low Cost (LFP) (PHEV, EV)
A	2.930	3.057	3.844
B	12.616	130.4	54.03
C	0.967	1.888	1.402
D	0.179	0.1902	0.2608
E	-0.04298	-0.05076	-0.09607

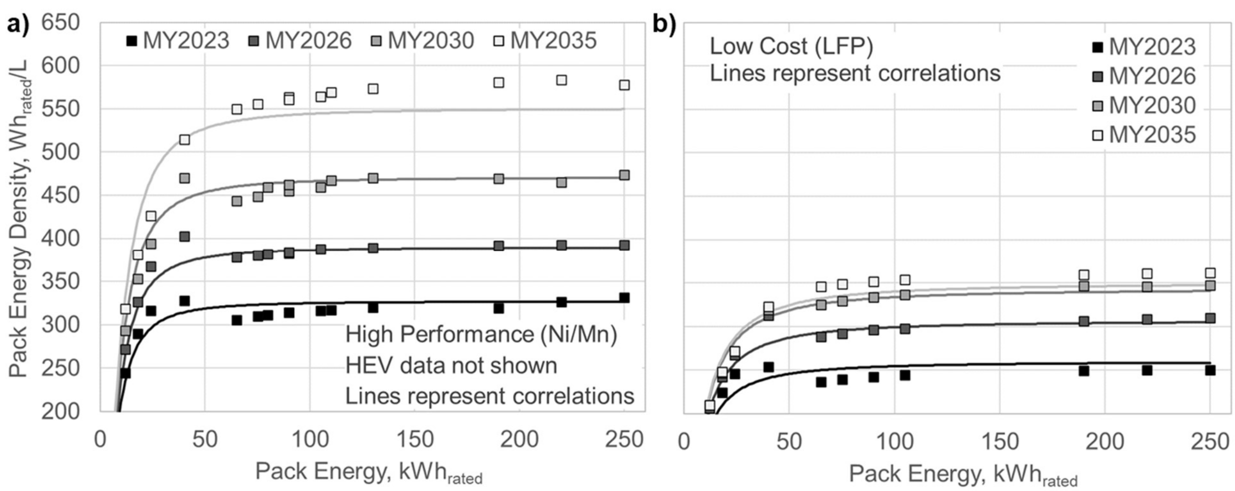

Figure 18. Comparison of energy density (Wh/L) between full BatPaC simulations (symbols) and correlations in equation A2 (lines) for a) high performance (Ni/Mn) and b) low cost (LFP) packs.

A5. Details for Estimating the Volume Averaged Cost of PHEV and BEV Packs in the U.S.

The volume averaged pack cost of PHEVs and BEVs was determined by first segmenting the U.S. vehicle fleet into the twenty-four vehicles shown in Table 33. The volume averaged cost of packs in the U.S. fleet was estimated each year using Equation (2) in the main text, which is repeated here as follows:

$$C_{fleet} = \frac{\sum_{v=1}^{v=24} C_v N_v}{\sum_{v=1}^{v=24} N_v} \quad (2)$$

where C_{fleet} is the volume averaged cost in $/kWh, C_v is the cost of each vehicle, *v*, in $/kWh, and N_v is the number of vehicles, *v*, sold each year. The summations are evaluated for vehicles, *v*, from 1 to 24 to represent the twenty-four vehicles listed in Table 33. The determination of N_v and C_v is explained in detail in the remainder of this section.

Table 33. Vehicles used to segment U.S. fleet in volume average pack cost calculation.

Vehicle, *v*	Type	Class	Chemistry
1	LD BEV	Compact	Ni/Mn
2	LD BEV	Midsize	Ni/Mn
3	LD BEV	Small SUV	Ni/Mn
4	LD BEV	Midsize SUV	Ni/Mn
5	LD BEV	Pickup	Ni/Mn
6	MHD BEV	MHD	Ni/Mn
7	LD BEV	Compact	LFP
8	LD BEV	Midsize	LFP
9	LD BEV	Small SUV	LFP
10	LD BEV	Midsize SUV	LFP
11	LD BEV	Pickup	LFP
12	MHD BEV	MHD	LFP
13	LD PHEV	Compact	Ni/Mn
14	LD PHEV	Midsize	Ni/Mn
15	LD PHEV	Small SUV	Ni/Mn
16	LD PHEV	Midsize SUV	Ni/Mn
17	LD PHEV	Pickup	Ni/Mn
18	MHD PHEV	MHD	Ni/Mn
19	LD PHEV	Compact	LFP
20	LD PHEV	Midsize	LFP
21	LD PHEV	Small SUV	LFP
22	LD PHEV	Midsize SUV	LFP
23	LD PHEV	Pickup	LFP
24	MHD PHEV	MHD	LFP

A5.1. Pack Sales for Each Year (N_v)

The number of vehicles sold each year (N_v) was estimated for each vehicle type based on the workflow shown in Figure 19.

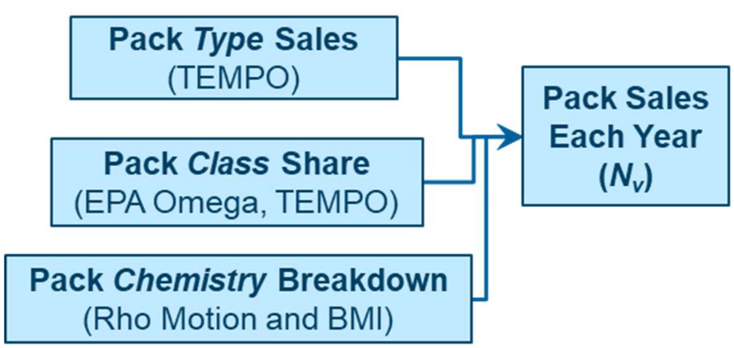

Figure 19. Workflow used to determine pack sales per year for each vehicle (N_v).

First, the total sales of PHEVs and BEVs was estimated for each year using the NREL TEMPO model (Muratori, et al., Forthcoming). Then, the EPA OMEGA model was used to estimate the percent breakdown of each class for each year for light duty vehicles (United States Environmental Protection Agency, 2023). This breakdown is shown in Figure 20a. The same breakdown was assumed for both LD PHEVs and LD BEVs. The number of MHD vehicles was estimated using the TEMPO model. Next, the fraction of packs using LFP or Ni/Mn chemistries was estimated using forecasts from Rho Motion and Benchmark Minerals Intelligence data (Benchmark Minerals Intelligence, 2023; Rho Motion, 2023). The Ni/Mn chemistry was assumed to include NCA cells due to similarities in cost. The estimated fraction is given in Figure 20b. The same fraction of LFP and Ni/Mn packs was assumed for all vehicle types (PHEV or BEV) and classes (Compact, Midsize, Small SUV, Midsize SUV, Pickup, and MHD). These three sets of information (type, class share, and chemistry breakdown) were used to determine N_v for each vehicle and each model year. Figure 21 shows the results for all twenty-four vehicles listed in Table 33.

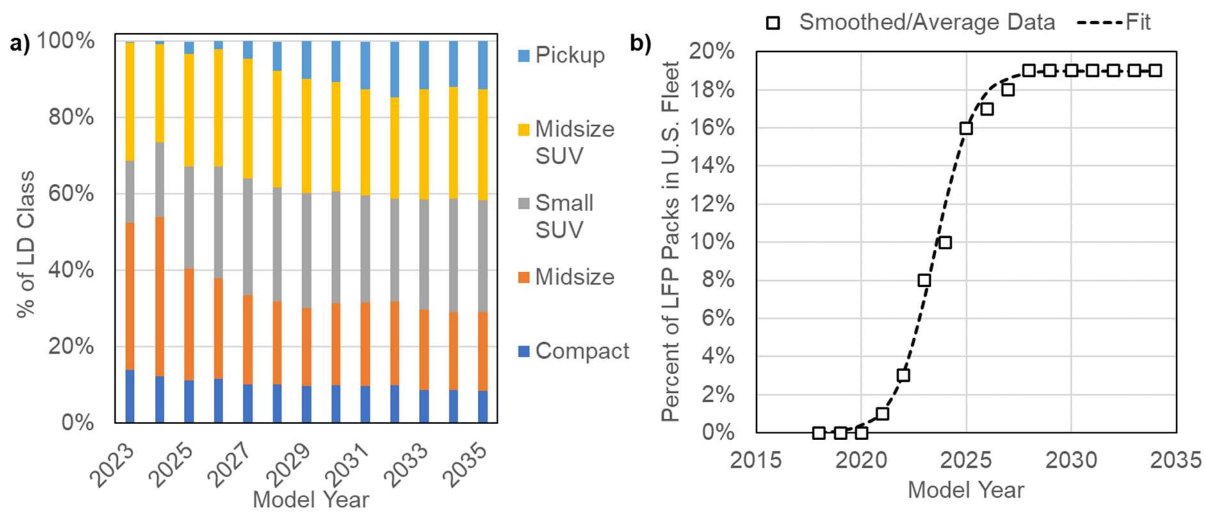

Figure 20. a) Estimated percent breakdown of vehicles based on class [data courtesy of Charbel Mansour, Paul Phillips, Ehsan Islam, and Aymeric Rousseau (Argonne)]. b) Estimated percentage of LFP packs in U.S. fleet [data courtesy of Jessica Suda (NHTSA) and Mike Safoutin (EPA)].

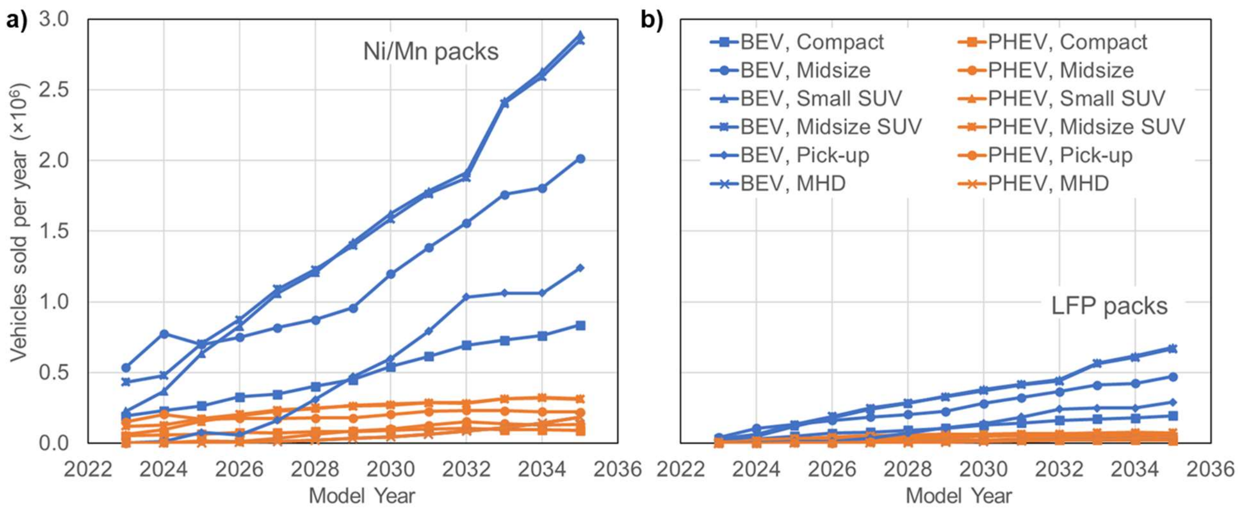

Figure 21. Number of packs sold per year (N_v) for each of the 24 vehicles in Table 33 organized into a) Ni/Mn and b) LFP packs [total packs per year courtesy of Catherine Ledna (NREL)].

A5.2. Pack Cost for Each Year (C_v)

The cost of each vehicle pack for each model year (C_v) was determined using the workflow shown in Figure 22.

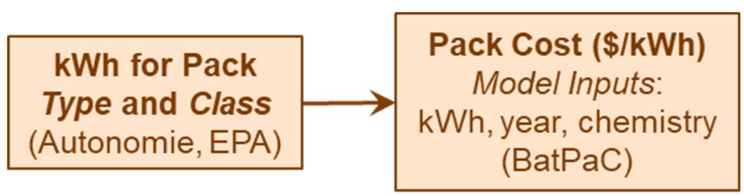

Figure 22. Workflow used to determine pack cost (C_v).

First, a representative pack energy, in kWh, was estimated for each vehicle and each year using the Argonne Autonomie model for LD vehicles and the EPA OMEGA model for MHD vehicles (see Figure 23) (Islam, et al., 2023; United States Environmental Protection Agency, 2023). The same values were used for both Ni/Mn and LFP packs. The pack energy and model year were then used as inputs into the correlations in Equation (1) in the main text to calculate the pack cost. The results of the calculations are shown in Figure 24. The cost values (C_v) in Figure 24 were combined with the sales values (N_v) in Figure 21 to determine the volume weighted average using Equation (2). The results are shown in Figure 7 in the main text.

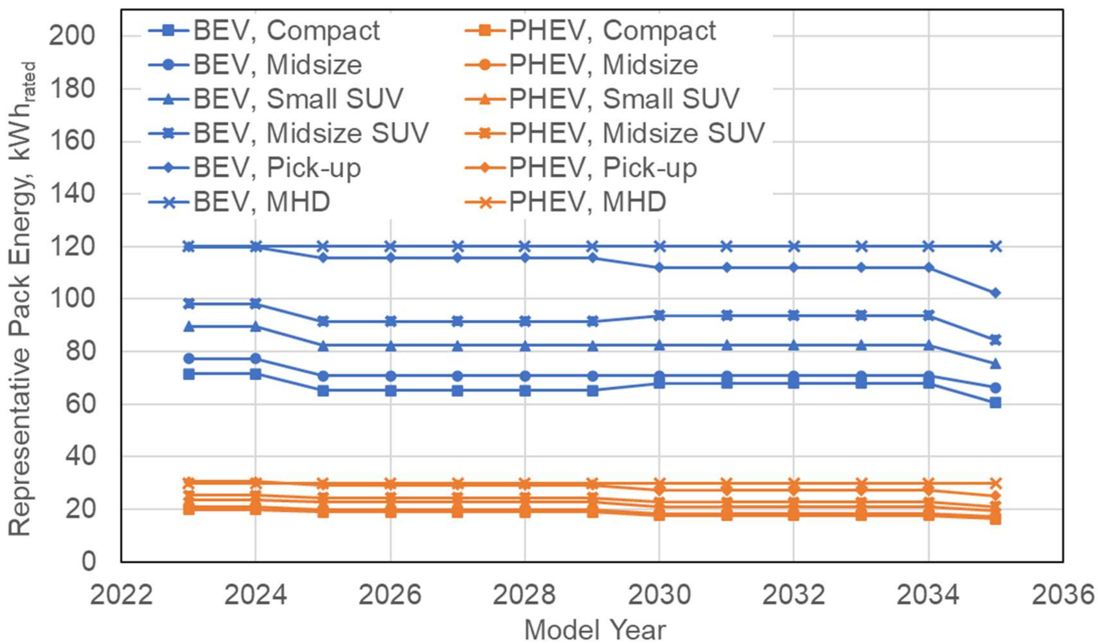

Figure 23. Representative pack energy used to estimate pack costs for all vehicles [data courtesy of Charbel Mansour, Paul Phillips, Ehsan Islam, and Aymeric Rousseau (Argonne National Laboratory)].

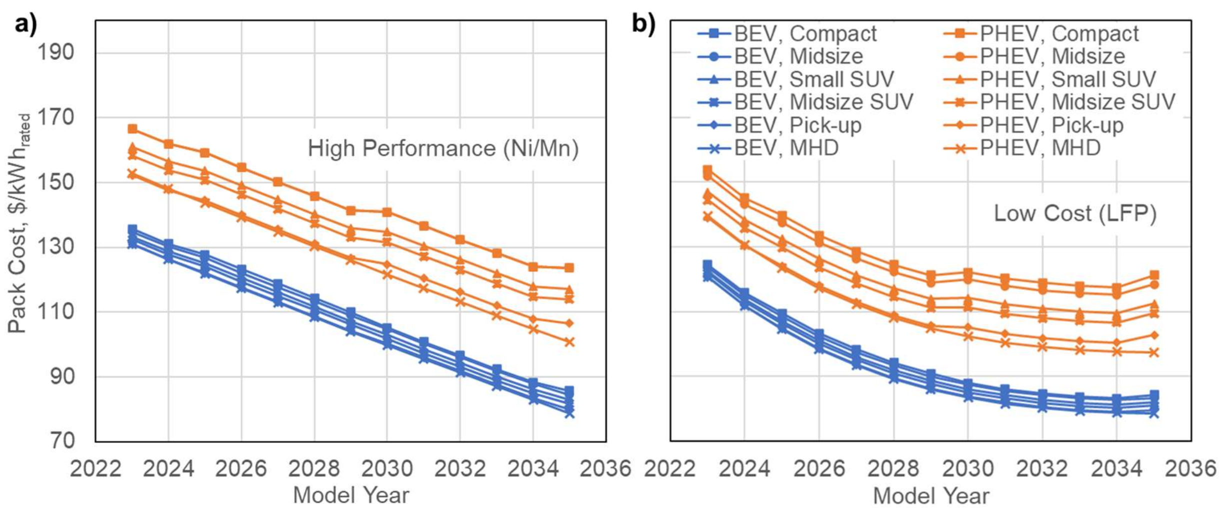

Figure 24. Pack costs (C_v) for a) Ni/Mn and b) LFP packs used in calculation of volume average cost curve.

A6. Details of 45X Analysis

The following tables were used for estimating the impact of the 45X tax credit on pack cost. The tax credits were determined by first estimating the $/kWh contribution of each component to the pack (Table 34 to Table 36). Next, tax credits were applied at each component based on the 45X credit (Table 37 and Table 38) and estimates for the eligibility of components based on announced production capacities (Table 39). The results of the analysis can be found in (Table 40 to Table 42). Tax credits were calculated for the same three vehicle categories used to generate the correlations in Equation 1 in the main text – *i.e.,* Ni/Mn HEV, Ni/Mn PHEV/BEV, and LFP PHEV/BEV. A comparison of tax credit calculations for multiple vehicles within these categories resulted in very small differences within a given category (data now shown). The HEV breakdowns (Table 34) are based on the 1.8-kWh pack. The Ni/Mn (Table 35) and LFP (Table 36) PHEV and BEV breakdowns are based on a 75-kWh pack.

Table 34. Mass (kg/kWh) and cost ($/kg) breakdowns for components in Ni/Mn HEV packs. Data is generated from BatPaC and used in 45X calculations. Values are interpolated for model years between these cases.

	Mass Breakdown (kg/kWh)				**Cost Breakdowns ($/kg)**			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
CAM[a]	1.31	1.18	1.09	1.37	31.90	34.00	31.30	17.30
AAM[a]	0.84	0.80	0.79	0.66	10.00	9.00	8.00	8.00
Separator	0.17	0.17	0.17	0.11	70.60	70.60	70.60	70.60
Electrolyte	0.74	0.70	0.68	0.60	8.33	8.33	8.33	8.33
Copper Foil	1.81	1.81	1.80	1.18	8.90	8.90	8.90	8.90
Aluminum Foil	0.68	0.68	0.67	0.44	3.70	3.70	3.70	3.70
Lithium[b]	0.10	0.09	0.08	0.06	90.78	186.00	144.00	136.50
Nickel[c]	0.48	0.57	0.62	0.22	20.09	19.19	20.53	21.42
Cobalt[c]	0.16	0.07	0.02	0.00	23.78	44.71	64.69	75.15
Manganese[c]	0.15	0.07	0.02	0.62	3.07	3.07	3.07	3.07

[a]CAM: cathode active material, AAM: anode active material, [b]metal contained in hydroxide, carbonate, or electrolyte salt (electrolyte ~2% of total lithium), [c]metal contained in sulphate.

Table 35. Mass (kg/kWh) and cost ($/kg) breakdowns for components in Ni/Mn PHEV & BEV packs. Data is generated from BatPaC and used in 45X calculations. Values are interpolated for model years between these cases.

	Mass Breakdown (kg/kWh)				**Cost Breakdowns ($/kg)**			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
CAM[a]	1.42	1.30	1.24	1.54	31.90	34.00	31.30	17.30
AAM[a]	0.89	0.65	0.45	0.23	10.00	10.05	11.30	15.70
Separator	0.04	0.04	0.03	0.03	70.60	70.60	70.60	70.60
Electrolyte	0.39	0.31	0.26	0.20	8.33	8.33	8.33	8.33
Copper Foil	0.32	0.25	0.21	0.08	8.90	8.90	8.90	8.90
Aluminum Foil	0.14	0.11	0.09	0.09	3.70	3.70	3.70	3.70
Lithium[b]	0.10	0.09	0.09	0.06	90.78	186.00	144.00	136.50
Nickel[c]	0.52	0.63	0.71	0.25	20.09	19.19	20.53	21.42
Cobalt[c]	0.17	0.08	0.02	0.00	23.78	44.71	64.69	75.15
Manganese[c]	0.16	0.07	0.02	0.69	3.07	3.07	3.07	3.07

[a]CAM: cathode active material, AAM: anode active material, [b]metal contained in hydroxide, carbonate, or electrolyte salt (electrolyte ~2% of total lithium), [c]metal contained in sulphate.

Table 36. Mass (kg/kWh) and cost ($/kg) breakdowns for components in LFP PHEV & BEV packs. Data is generated from BatPaC and used in 45X calculations. Values are interpolated for model years between these cases.

	Mass Breakdown (kg/kWh)				**Cost Breakdowns ($/kg)**			
	2023	**2026**	**2030**	**2035**	**2023**	**2026**	**2030**	**2035**
CAM[a]	1.93	1.94	1.94	1.96	13.00	11.50	10.00	9.50
AAM[a]	0.98	0.72	0.72	0.72	10.00	9.00	8.00	8.00
Separator	0.08	0.07	0.05	0.05	70.60	70.60	70.60	70.60
Electrolyte	0.57	0.50	0.48	0.47	8.33	8.33	8.33	8.33
Copper Foil	0.55	0.45	0.36	0.30	8.90	8.90	8.90	8.90
Aluminum Foil	0.24	0.19	0.16	0.13	3.70	3.70	3.70	3.70
Lithium[b]	0.09	0.09	0.09	0.09	85.76	72.36	53.60	50.25
Iron[c]	0.68	0.69	0.69	0.69	5.02	5.02	5.02	5.02

[a]CAM: cathode active material, AAM: anode active material, [b]metal contained in hydroxide, carbonate, or electrolyte salt (electrolyte ~2% of total lithium), [c]metal contained in phosphate.

Table 37. 45X tax credits for modules, cells, and electrode active materials (EAM) [data estimated per definition proposed by IRS (Internal Revenue Service, 2023)].

	Modules ($/kWh)	Cells ($/kWh)	CAM[a] (%)	AAM[a] (%)	Separator (%)	Electrolyte (%)	Cu Foil (%)	Al Foil (%)	Li[b] (%)	Ni[b] (%)	Co[b] (%)	Mn[b] (%)	Fe[b] (%)
2023	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2024	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2025	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2026	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2027	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2028	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2029	10	35	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
2030	7.5	26.25	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%
2031	5	17.5	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
2032	2.5	8.75	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
2033	0	0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2034	0	0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2035	0	0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

[a]CAM: cathode active material, AAM: anode active material, [b]metal salt/oxide used in battery

Table 38. 45X tax credits for critical minerals (CM) [data estimated per definitions proposed by IRS (Internal Revenue Service, 2023)]. Elements refer to lithium carbonate/hydroxide and nickel/cobalt/manganese sulfates.

	Lithium	Nickel	Cobalt	Manganese
2023	10%	10%	10%	10%
2024	10%	10%	10%	10%
2025	10%	10%	10%	10%
2026	10%	10%	10%	10%
2027	10%	10%	10%	10%
2028	10%	10%	10%	10%
2029	10%	10%	10%	10%
2030	10%	10%	10%	10%
2031	10%	10%	10%	10%
2032	10%	10%	10%	10%
2033	10%	10%	10%	10%
2034	10%	10%	10%	10%
2035	10%	10%	10%	10%

Table 39. Low-end market response of U.S. domestic supply chain. Calculated as share of U.S. demand met from November 2023 market announcements [data courtesy of David Gohlke, Tisi Barlock, and Jarod Kelly (Argonne)].

	Modules	Cells	CAM[a]	AAM[a]	Separator	Electrolyte	Cu Foil	Al Foil	Li[b]	Ni[c]	Co[c]	Mn[c]	Fe[c]
2023	99%	99%	31%	45%	52%	100%	100%	100%	6%	56%	36%	36%	31%
2024	100%	100%	67%	75%	47%	100%	100%	100%	3%	16%	27%	27%	67%
2025	100%	100%	60%	55%	79%	100%	100%	100%	28%	14%	19%	19%	60%
2026	100%	100%	55%	51%	83%	100%	100%	100%	51%	10%	16%	16%	55%
2027	100%	100%	38%	43%	55%	100%	100%	100%	49%	8%	29%	29%	38%
2028	100%	100%	32%	40%	44%	100%	100%	100%	70%	7%	39%	39%	32%
2029	100%	100%	27%	34%	35%	100%	100%	100%	66%	6%	36%	36%	27%
2030	100%	100%	26%	32%	32%	100%	100%	100%	81%	6%	34%	34%	26%
2031	100%	100%	24%	30%	30%	100%	100%	100%	74%	6%	31%	31%	24%
2032	97%	97%	22%	28%	28%	94%	100%	100%	67%	10%	28%	28%	22%
2033	100%	100%	24%	30%	29%	99%	100%	100%	61%	11%	28%	28%	24%
2034	98%	98%	23%	28%	28%	94%	100%	100%	55%	10%	26%	26%	23%
2035	98%	98%	23%	28%	28%	94%	100%	100%	56%	11%	27%	27%	23%

[a]CAM: cathode active material, AAM: anode active material, [b]metal contained in hydroxide or carbonate, [c]metal contained in sulphate or phosphate.

Table 40. Estimated tax credits ($/kWh) for Ni/Mn HEV packs. "Full" refers to full market response of domestic U.S. supply (packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market for packs that can be supplied domestically based on announcements as of November 2023.

	Modules		Cells		EAM[a]		CM[b]		Total	
	Full	**Low-end**	**Full**	**Low-end**	**Full**	**Low-end**	**Full**	**Low-end**	**Full**	**Low-end**
2023	10.0	9.9	35.0	34.5	8.7	4.8	2.3	0.7	56.0	49.9
2024	10.0	10.0	35.0	35.0	8.7	6.4	2.6	0.3	56.3	51.7
2025	10.0	10.0	35.0	35.0	8.6	6.3	2.9	0.6	56.5	51.9
2026	10.0	10.0	35.0	35.0	8.5	6.1	3.1	1.0	56.6	52.1
2027	10.0	10.0	35.0	35.0	8.3	4.9	3.0	0.9	56.3	50.9
2028	10.0	10.0	35.0	35.0	8.2	4.5	2.9	1.2	56.1	50.7
2029	10.0	10.0	35.0	35.0	8.1	4.1	2.7	1.0	55.8	50.1
2030	7.5	7.5	26.3	26.3	6.0	3.0	2.6	1.1	42.3	37.8
2031	5.0	5.0	17.5	17.5	3.8	1.8	2.4	0.9	28.7	25.3
2032	2.5	2.4	8.8	8.5	1.8	0.8	2.1	0.8	15.2	12.6
2033	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.7	1.9	0.7
2034	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.6	1.7	0.6
2035	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.5	1.4	0.5

[a]EAM: electrode active materials, [b]CM: critical materials.

Table 41. Estimated tax credits ($/kWh) for Ni/Mn PHEV and BEV packs. "Full" refers to full market response of domestic U.S. supply (packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market for packs that can be supplied domestically based on announcements as of November 2023.

	Modules		Cells		EAM[a]		CM[b]		Total	
	Full	Low-end	Full	Low-end	Full	Low-end	Full	Low-end	Full	Low-end
2023	10.0	9.9	35.0	34.5	6.4	2.6	2.4	0.8	53.8	47.8
2024	10.0	10.0	35.0	35.0	6.2	4.4	2.8	0.3	54.1	49.7
2025	10.0	10.0	35.0	35.0	6.0	3.9	3.1	0.7	54.2	49.5
2026	10.0	10.0	35.0	35.0	5.9	3.5	3.3	1.1	54.2	49.6
2027	10.0	10.0	35.0	35.0	5.7	2.6	3.2	1.0	53.9	48.6
2028	10.0	10.0	35.0	35.0	5.5	2.2	3.1	1.3	53.6	48.4
2029	10.0	10.0	35.0	35.0	5.3	1.8	3.0	1.1	53.3	47.9
2030	7.5	7.5	26.3	26.3	3.8	1.3	2.9	1.2	40.4	36.2
2031	5.0	5.0	17.5	17.5	2.4	0.8	2.6	1.0	27.5	24.3
2032	2.5	2.4	8.8	8.5	1.1	0.3	2.4	0.9	14.7	12.1
2033	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.8	2.1	0.8
2034	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.6	1.8	0.6
2035	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.6	1.6	0.6

[a]EAM: electrode active materials, [b]CM: critical materials.

Table 42. Estimated tax credits ($/kWh) for LFP PHEV and BEV packs. "Full" refers to full market response of domestic U.S. supply (packs are eligible for 100% of credits) and "low-end" refers to the share of the U.S. market for packs that can be supplied domestically based on announcements as of November 2023.

	Modules		Cells		EAM[a]		CM[b]		Total	
	Full	Low-end	Full	Low-end	Full	Low-end	Full	Low-end	Full	Low-end
2023	10.0	9.9	35.0	34.5	5.1	2.6	1.1	0.2	51.2	47.1
2024	10.0	10.0	35.0	35.0	4.8	3.5	1.1	0.2	50.9	48.8
2025	10.0	10.0	35.0	35.0	4.5	3.1	1.0	0.4	50.5	48.5
2026	10.0	10.0	35.0	35.0	4.2	2.8	1.0	0.5	50.2	48.3
2027	10.0	10.0	35.0	35.0	4.1	2.2	0.9	0.4	50.0	47.6
2028	10.0	10.0	35.0	35.0	3.9	1.9	0.9	0.5	49.8	47.4
2029	10.0	10.0	35.0	35.0	3.8	1.7	0.9	0.4	49.7	47.1
2030	7.5	7.5	26.3	26.3	2.7	1.2	0.7	0.5	37.2	35.4
2031	5.0	5.0	17.5	17.5	1.8	0.8	0.6	0.4	25.0	23.6
2032	2.5	2.4	8.8	8.5	0.9	0.4	0.6	0.3	12.7	11.6
2033	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.5	0.3
2034	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.5	0.3
2035	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.3	0.4	0.3

[a]EAM: electrode active materials, [b]CM: critical materials.

A7. Raw Materials Prices

Table 43 provides the raw material price estimates used in the calculations (Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Benchmark Minerals Intelligence, 2023; Intercalation, Ltd., 2023; Ballif, Haug, Boccard, Verlinden, & Hahn, 2022; Sanders, 2023). Table 44 provides the cathode active material (CAM) prices calculated from the raw materials. The prices include manufacturing costs and margin. The bold CAM prices refer to forecasted values used in the main study. The italicized values refer to the 2023 prices used in the sensitivity study. Table 45 provides the values for the anode active materials (AAM). Several of the 5% Si cases are bold because they are used in all LFP packs after 2026.

Table 43. Raw materials prices for each model year

		Price ($/kg)			
Precursor	**Purity**	**2023**	**2026**	**2030**	**2035**
$NiSO_4 \cdot 6H_2O$	battery grade, 22.4 wt.% Ni	4.5	4.3	4.6	4.8
$CoSO_4 \cdot 7H_2O$	battery grade, 20.5 wt.% Co	5	9.4	13.6	15.8
$MnSO_4 \cdot H_2O$	battery grade, 32.5 wt.% Mn	1	1	1	1
Li_2CO_3	battery grade, 99.5% Li_2CO_3	34	29	22	20.75
Li_2CO_3	Industrial grade, 99% Li_2CO_3	32	27	20	18.75
$LiOH \cdot H_2O$	battery grade, 57.0% LiOH	36	31	24	22.75
Graphite	natural/synthetic blend	10	9	8	8
Silicon	engineered material	30	30	30	30

*Table 44. Cathode active material (CAM) prices used in simulations. ****bold***** indicates forecasted prices used in simulations. *italicized* indicates 2023 values used in sensitivity study.*

CAM	2023	2026	2030	2035
NMC622	***31.9***	32.2	32.3	33.4
NMC811	*35.5*	**34.0**	32.7	33.2
NMC95	*36.1*	33.5	**31.3**	31.4
LMNO	*20.5*	19.0	17.5	**17.3**
LFP	***13***	**11.5**	**10.0**	**9.5**

*Table 45. Anode active material (AAM) prices used in simulations. ****bold***** indicates forecasted prices used in simulations. *italicized* indicates 2023 values used in sensitivity study. The low cost (LFP) cells used 5% Si in 2026, 2030 and 2035.*

AAM	2023	2026	2030	2035
G	***10***	9.0	8.0	8.0
95% G, 5% Si	*11*	**10.1**	**9.1**	**9.1**
85% G, 15% Si	*13*	12.2	**11.3**	11.3
65% G, 35% Si	*17*	16.4	15.7	**15.7**

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ELECTRIC VEHICLE QUARTERLY REPORT

SECOND QUARTER, 2024

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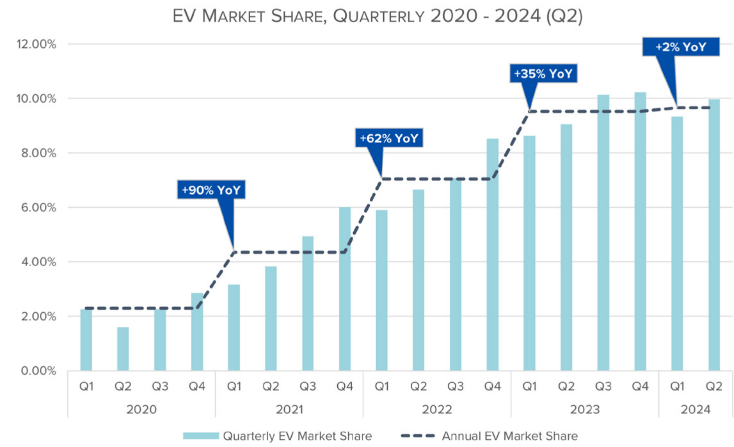
ELECTRIC VEHICLE SALES OVERVIEW (Q2 2024)

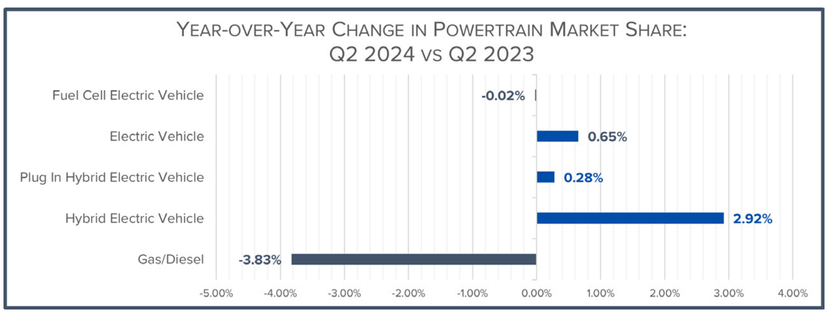
In the second quarter of 2024, automakers sold about 386,000 electric vehicles (EVs, including battery, plug-in hybrid, and fuel cell electric vehicles) in the United States, representing nearly 10 percent of overall light-duty vehicle sales. This represents a 0.6 percentage point (pp) market share increase over the first quarter of 2024 amounting to an increase of about 42,000 vehicle sales. EV sales volume in the second quarter is the highest on record, about 8,300 vehicles more than the next highest quarter (Q3 in 2023).

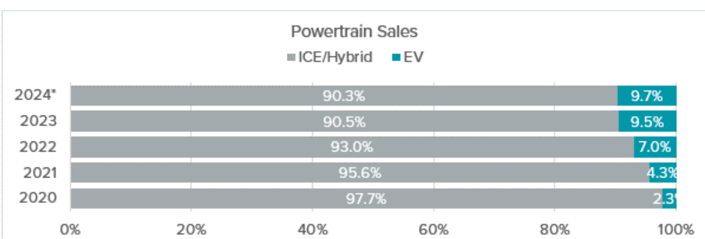


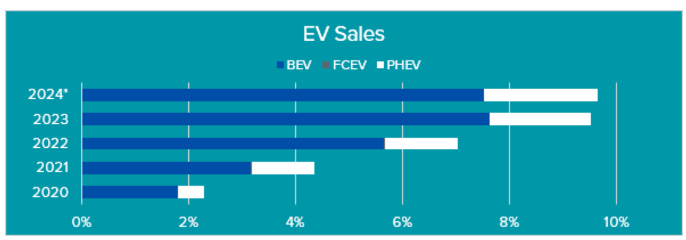
* See appendix - A for month-by-month EV market share

Year-over-year (YoY), market share increased 0.9 pp from the second quarter of 2023. The total volume of all light-duty sales in Q2 2024 was down 1.1 percent from Q2 2023, while the volume for EVs increased 9 percent (an increase of about 31,000 vehicles). For comparison, internal combustion engine (ICE) vehicle market share decreased by 3.8 pp during Q2 2024 compared to the same period last year. Nearly all of ICE market share was displaced by gains of traditional hybrids and electric vehicles, offset slightly by market share losses from FCEVs.

More than 730,000 EVs were sold in the first half of 2024, 9.7 percent of all light vehicle sales and an increased market share of 0.81 pp over the first half of 2023. The total volume of all light-duty sales for the first half of the year is up 1.4 percent from the same period a year ago, while the volume for EVs increased 10.6 percent (an increase of about 70,000 vehicles).



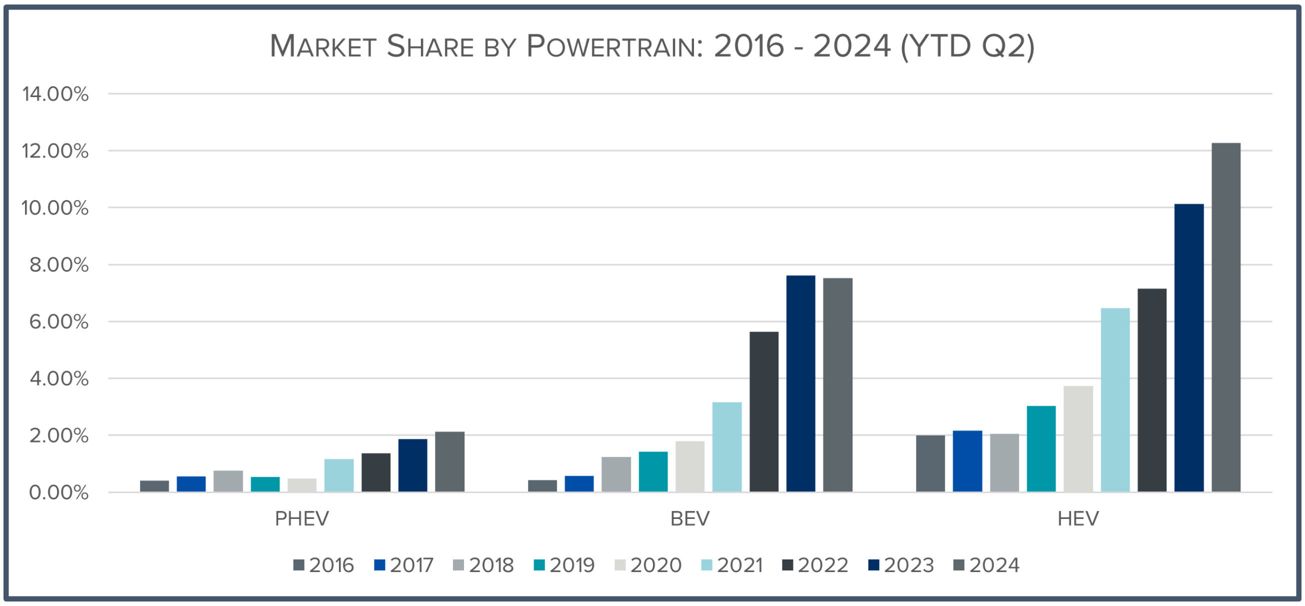


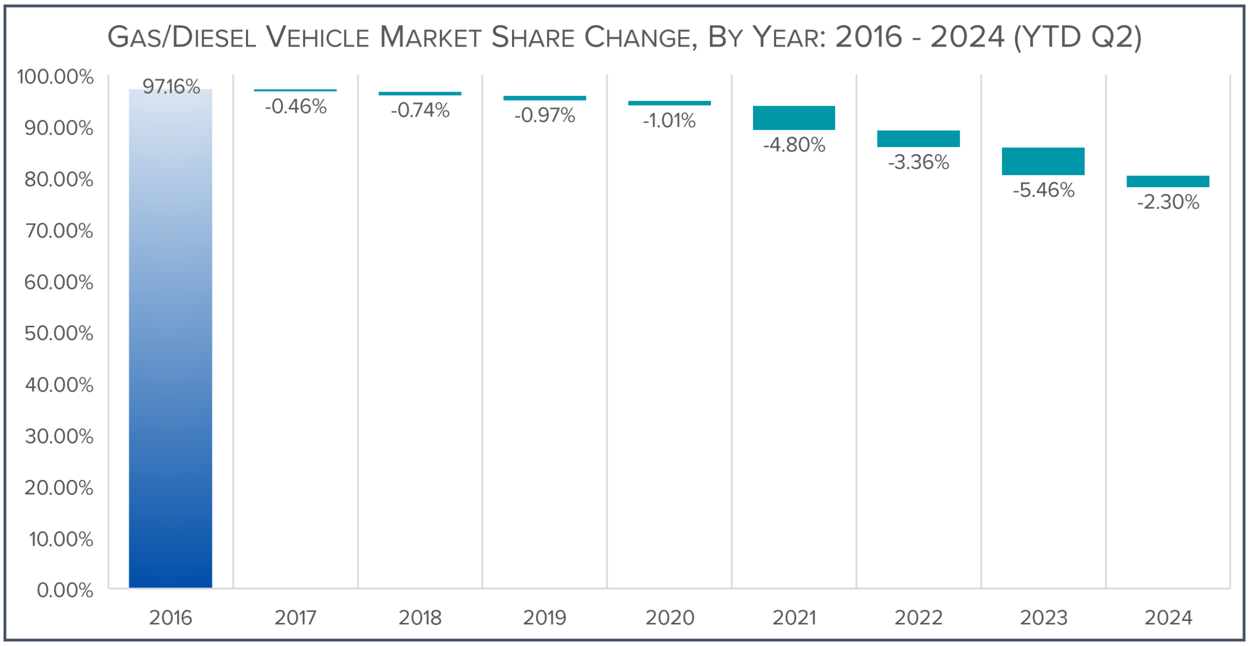


*Through Q2 2024

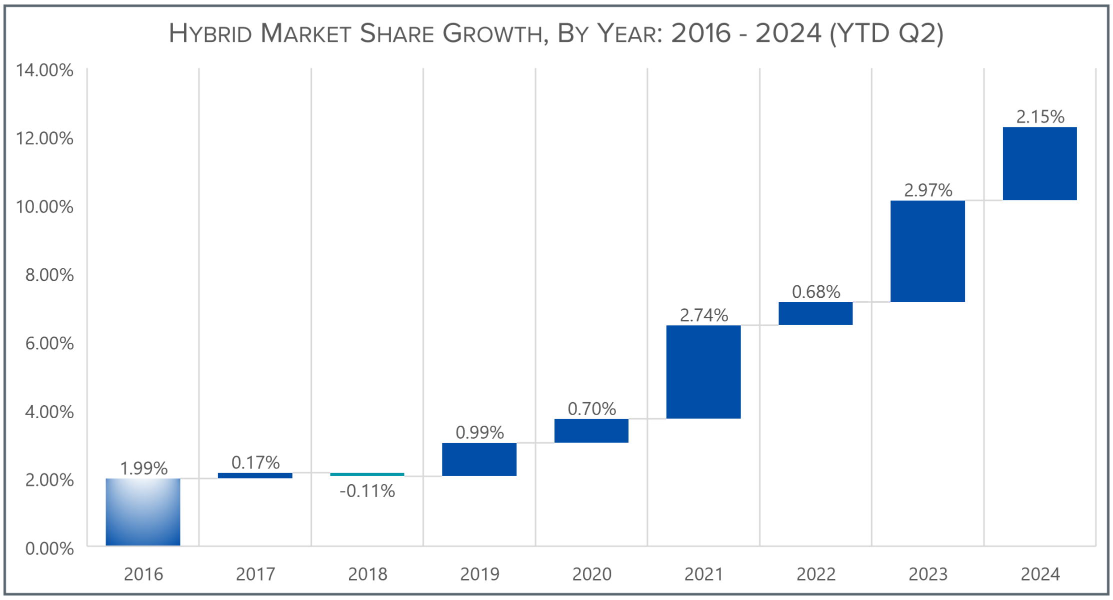
EVOLVING MARKET SHARE OF POWERTRAINS: 2016 - 2024

From 2016 through the second quarter of 2024, traditional internal combustion engine (ICE) market share has steadily declined. In 2016, ICE vehicles comprised more than 97 percent of all vehicle sales. Through the second quarter of 2024, the year-to-date ICE share dropped to 78 percent for an overall loss of 19.1 pp. That said, the ICE market share loss was replaced by increases in share of traditional hybrids, BEVs, and PHEVs. Traditional hybrids made up most of the alternative vehicle gains (+10.3 pp) followed by BEVs (+7.1 pp) and PHEVs (+1.7 pp) over the last eight and a half years.

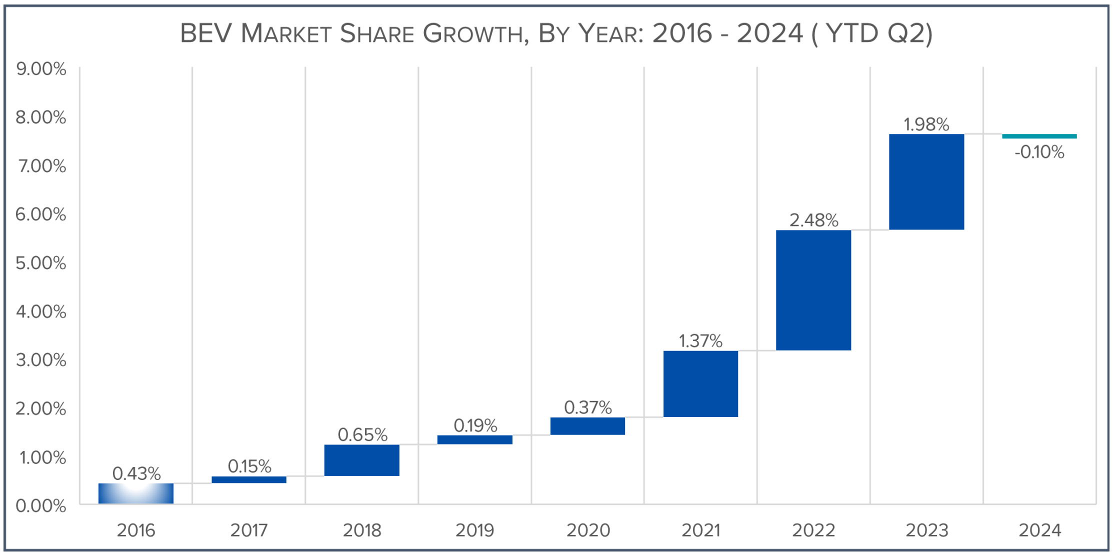




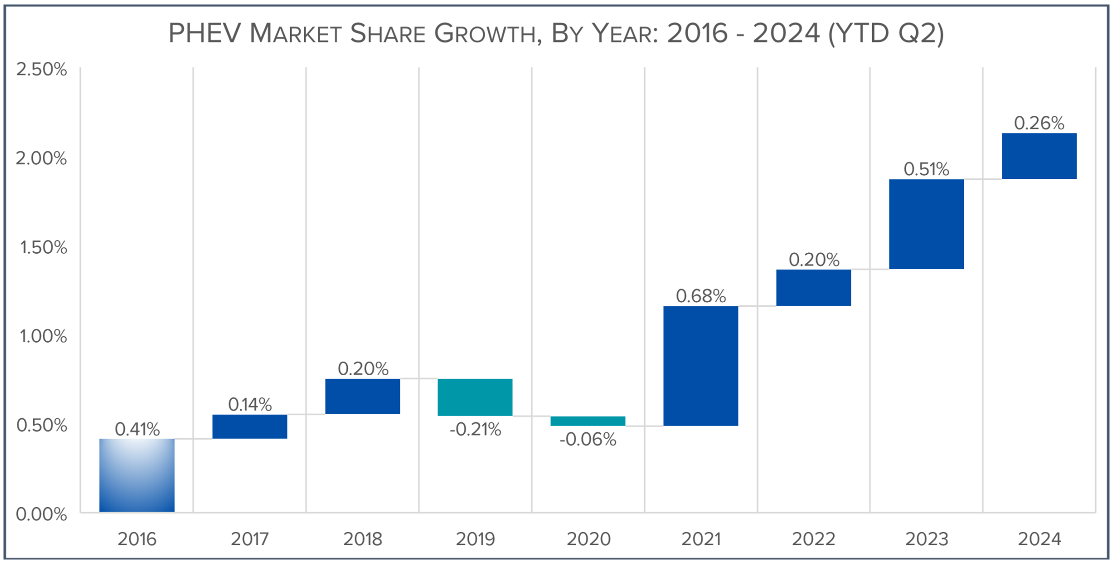
Hybrid market share grew from 2 percent in 2016 to 12.3 percent through Q2 2024 (+10.3 pp):



BEV market share grew from .43 percent in 2016 to 7.5 percent through Q2 2024 (+7.1 pp):



PHEV market share grew from .41 percent in 2016 to 2.1 percent through Q2 2024 (+1.7 pp):



[See Additional Historic Data on EV Sales]

ELECTRIC VEHICLE SALES BY SEGMENT

EV Model Availability

117 Vehicle Models Sold in Q2 2024:

68 Battery Electric Vehicles
- 20 Cars
- 38 Utility Vehicles
- 5 Pickups
- 5 Vans

47 Plug-in Hybrid Vehicles
- 17 Cars
- 29 Utility Vehicles
- 1 Van

2 Fuel Cell Electric Vehicles
- 1 Car
- 1 Utility Vehicle

See more information about ***EV CHOICE HERE***

For a list of EVs that qualify for the federal government's new clean vehicle tax credit of up to $7,500 ***CLICK HERE***.

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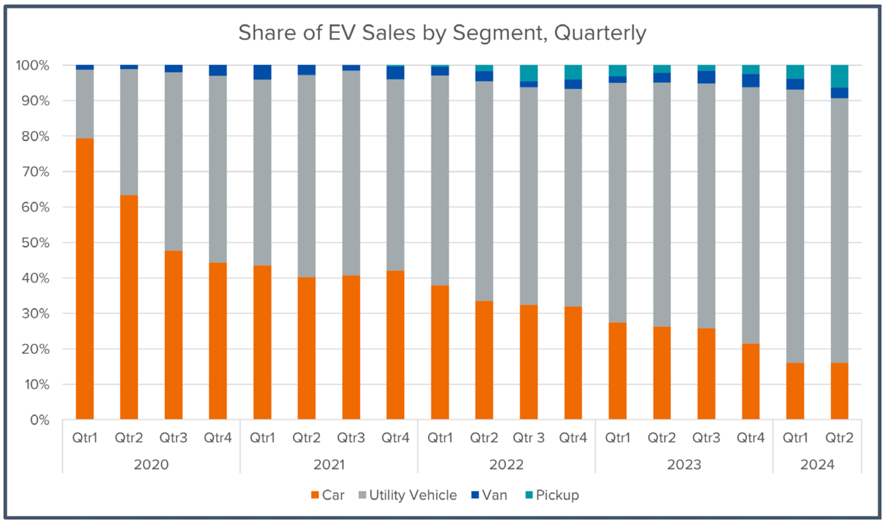
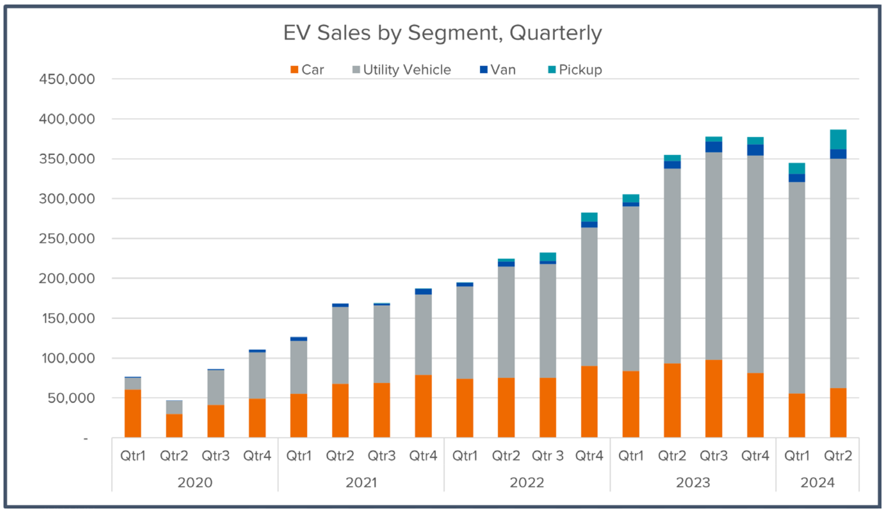
While passenger cars once dominated the EV market, manufacturers continue to introduce new models to satisfy a variety of consumer needs. Utility vehicle (UV) offerings continue to grow, and while electric pickup trucks are a relatively new entry to the market (making their commercial debut in September 2021), there are 5 models available now, with more expected soon. As a result, non-car segments are continuing to make gains, and in the second quarter of 2024, light truck (UVs, minivans, and pickups) sales comprised 84 percent of the EV market – a 10 pp increase over the second quarter of 2023.

Quarterly sales of BEV and PHEV UVs have grown from about 19 percent of EVs at the start of 2020 to 75 percent in the second quarter of 2024. Nearly 44,000 more UVs were sold in the second quarter of 2024 than the second quarter of 2023.

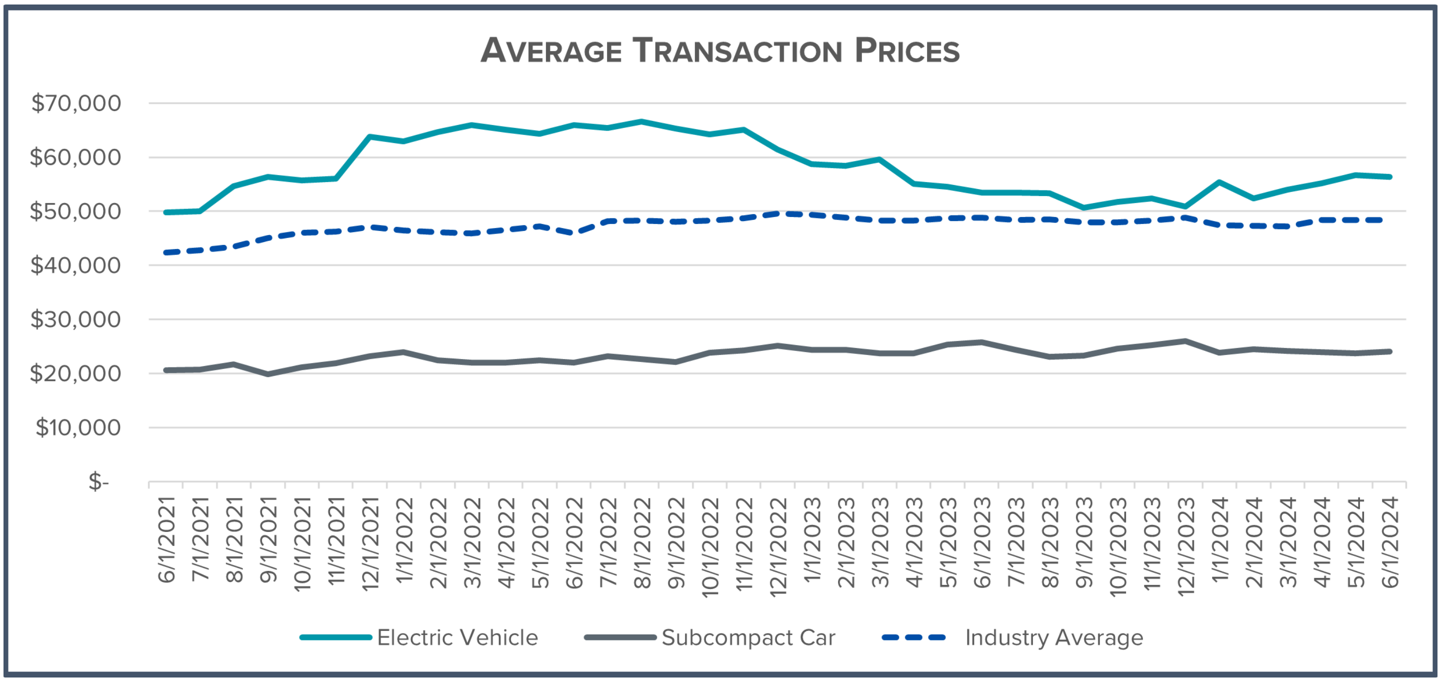




Source: Figures compiled by Alliance for Automotive Innovation with new registrations for retail and fleet data provided by S&P Global Mobility covering January 1, 2020 –June 30, 2024

ELECTRIC VEHICLE TRANSACTION PRICES

"The average transaction price of [EVs] in the United States, not including any government incentives, decreased from $57,405 in January 2024 to $56,371 in June 2024, according to data from Cox Automotive. [EV] transaction prices were 21.1 percent higher than the overall average light-duty vehicle transaction price in January 2024 and 15.9 percent higher in June 2024."[1]



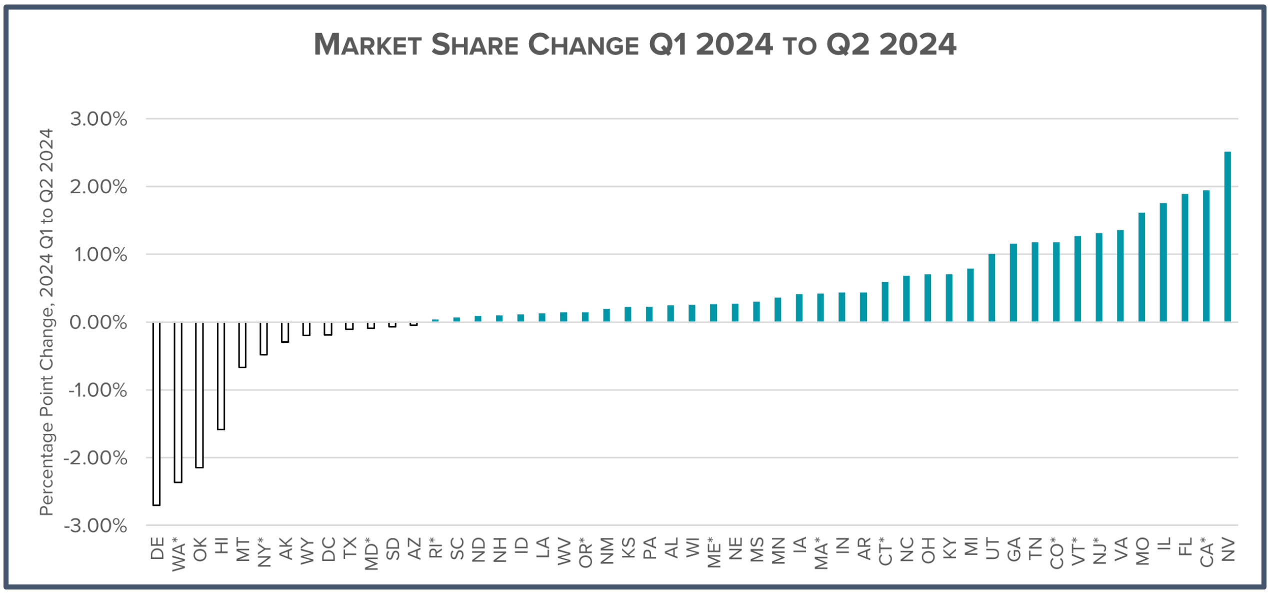
(Compiled from Kelley Blue Book Press Releases, 6/2021 – 6/2024)

[1] EIA, In-Brief Analysis, "U.S. share of electric and hybrid vehicle sales increased in the second quarter of 2024," 8/26/2024

ELECTRIC VEHICLE SALES BY STATE

For the Second Quarter of 2024:

California continued to lead the nation in EV sales, with BEVs, PHEVs and FCEVs making up nearly 27 percent of new light-duty vehicle registrations in the second quarter of 2024. There are currently ten additional states[2] and the District of Columbia with new EV registrations above 10 percent. Three-quarters of the states saw market share growth in Q2 vs. Q1 – twelve states saw a market share improvement of one percentage point or more. Nevada led all states, quarter over quarter, with an increase of 2.51 pp; Delaware decreased the most (-2.7 pp).



[3]

Year-over-year, for the second quarter of 2024, the market share of new EVs registered increased in all but seven states[4]. Nine states witnessed an increased market share of EVs by 2 pp or more. Making the largest increases were Colorado[5] (7.7 pp), Hawaii (4.9 pp), Nevada (4.7 pp), and Vermont (3.4 pp).

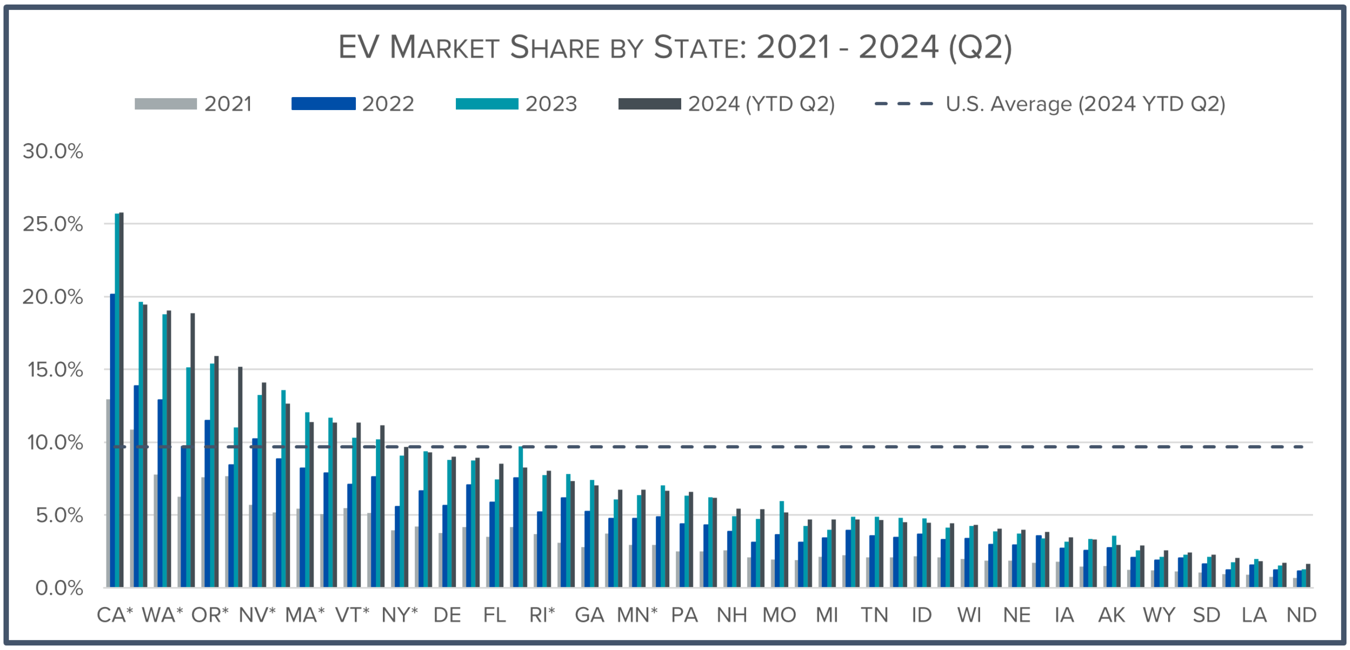
For the First Half of 2024:

Through the first half of the year, EV sales represented 9.7 percent of the market – a 0.8 pp increase over the same period of 2023. Nearly 26 percent of sales in California were EVs, but Colorado realized the greatest increase in market share, year-over-year with a 6.9 pp increase. Following Colorado, the states with the largest market share gains were Hawaii (4.5 pp), Oklahoma[6] (3.6 pp), Vermont (2.9 pp) and New York (2.1). Fourteen states increased their year-over-year EV market share by 1 pp or more. Nine states decreased.

While some states continue to have strong EV sales, nine states had new EV registrations of less than 3 percent; three of those states were under 2 percent. All states had a market share above 1 percent for new EV sales.

Year to date (through Q2), eleven states and the District of Columbia had an EV market share above 10 percent while three states had an EV market share under 2 percent; California was the only state above 20 percent.[7]

[2] States with more than a 10 percent market share of EVs: California, Colorado, District of Columbia, Washington, Oregon, Nevada, Hawaii, New Jersey, Vermont, Massachusetts, Connecticut, and Maryland.
[3] *Denotes states that have adopted California's ZEV program
[4] The seven states are: Delaware, Virginia, Arkansas, Missouri, Arizona, Massachusetts, and New Jersey
[5] Colorado taxpayers are eligible for a state tax credit of $5,000 for the purchase or lease of a new EV on or after July 1, 2023 with a manufacturer's suggested retail price (MSRP) up to $80,000. Lease agreements must have an initial term of at least two years. Beginning January 1, 2024, Coloradans purchasing an EV with an MSRP up to $35,000 will be eligible for an additional $2,500 tax credit.
[6] Oklahoma is often an outlier due to fleet registrations.
[7] Figures compiled by Alliance for Automotive Innovation with new registrations for retail and fleet data provided by S&P Global Mobility covering January 1, 2021 – June 30, 2024



*Denotes states that have adopted California's ZEV program

2024 EV Market Share by State (YTD Q2)[8]

1	CA*	25.78%	**11**	VT*	11.35%	**21**	GA	7.03%	**31**	MI	4.69%	**41**	IA	3.45%
2	DC	19.44%	**12**	CT*	11.15%	**22**	ME*	6.74%	**32**	NM	4.69%	**42**	KY	3.33%
3	WA*	19.03%	**13**	NY*	9.67%	**23**	MN*	6.74%	**33**	TN	4.64%	**43**	AK	2.93%
4	CO*	18.86%	**14**	AZ	9.30%	**24**	NC	6.65%	**34**	KS	4.50%	**44**	AL	2.89%
5	OR*	15.90%	**15**	DE	8.99%	**25**	PA	6.58%	**35**	ID	4.47%	**45**	WY	2.58%
6	HI	15.18%	**16**	UT	8.93%	**26**	TX	6.16%	**36**	IN	4.43%	**46**	AR	2.41%
7	NV*	14.09%	**17**	FL	8.53%	**27**	NH	5.44%	**37**	WI	4.32%	**47**	SD	2.25%
8	NJ*	12.63%	**18**	VA*	8.24%	**28**	OK	5.40%	**38**	SC	4.06%	**48**	WV	2.03%
9	MA*	11.37%	**19**	RI*	8.02%	**29**	MO	5.16%	**39**	NE	3.99%	**49**	LA	1.83%
10	MD*	11.36%	**20**	IL	7.31%	**30**	OH	4.70%	**40**	MT	3.84%	**50**	MS	1.72%
												51	ND	1.62%

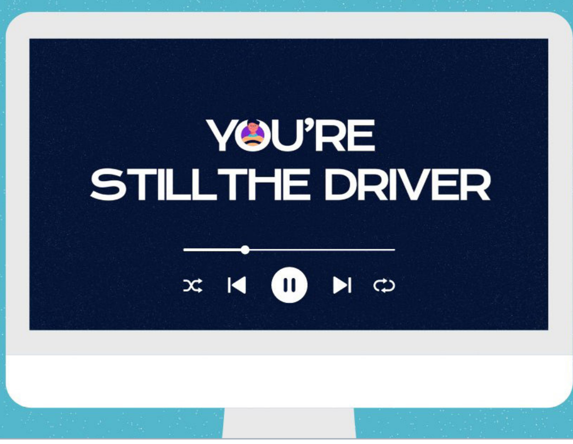
[8] *Denotes states that have adopted California's ZEV program; Figures compiled by Alliance for Automotive Innovation with new registrations for retail and fleet data provided by S&P Global Mobility covering January 1, 2024 – June 30, 2024

State	Second Quarter 2024, New Light-Duty Vehicle Registrations By Powertrain				Change In Market Share (2024 Q2 vs 2023 Q2), New Light-Duty Vehicle Registrations Powertrain			
	Advanced Powertrain Market Share				Advanced Powertrain Market Share (Percentage Point Change)			
	PHEV	BEV	FCEV	EV Total	PHEV	BEV	FCEV	EV Total
AK	0.66%	2.13%	0.00%	2.80%	-0.19	-0.43	0.00	-0.62
AL	0.57%	2.43%	0.00%	3.01%	0.01	0.64	0.00	0.65
AR	0.49%	2.14%	0.00%	2.63%	-0.06	0.55	0.00	0.50
AZ	1.13%	8.15%	0.00%	9.28%	-0.20	-0.19	0.00	-0.39
CA*	3.22%	23.48%	0.02%	26.72%	0.10	0.92	-0.21	0.80
CO*	5.49%	13.94%	0.00%	19.43%	1.23	6.49	0.00	7.72
CT*	3.86%	7.57%	0.00%	11.43%	0.64	1.48	0.00	2.11
DC	6.03%	13.32%	0.00%	19.35%	2.22	-1.53	0.00	0.69
DE	2.45%	5.11%	0.00%	7.56%	0.52	-2.26	0.00	-1.74
FL	1.28%	8.18%	0.00%	9.46%	0.43	2.17	0.00	2.60
GA	0.77%	6.83%	0.00%	7.60%	0.12	0.34	0.00	0.46
HI	4.54%	9.84%	0.01%	14.39%	3.57	1.34	0.00	4.91
IA	0.96%	2.69%	0.00%	3.65%	0.07	0.70	0.00	0.78
ID	1.19%	3.34%	0.00%	4.53%	-0.10	0.54	0.00	0.44
IL	1.30%	6.91%	0.00%	8.22%	0.23	0.51	0.00	0.74
IN	0.88%	3.76%	0.00%	4.64%	0.01	1.16	0.00	1.17
KS	1.04%	3.57%	0.00%	4.62%	0.19	-0.03	0.00	0.16
KY	0.67%	2.95%	0.00%	3.62%	-0.14	0.89	0.00	0.75
LA	0.42%	1.47%	0.00%	1.89%	0.03	0.21	0.00	0.24
MA*	3.60%	7.97%	0.00%	11.57%	-0.49	0.17	0.00	-0.32
MD*	2.40%	8.91%	0.00%	11.31%	-0.07	0.96	0.00	0.89
ME*	2.98%	3.88%	0.00%	6.86%	0.69	0.99	0.00	1.68
MI	1.04%	4.07%	0.00%	5.11%	-0.06	1.11	0.00	1.05
MN*	1.86%	5.05%	0.00%	6.90%	0.59	0.60	0.00	1.18
MO	2.71%	3.22%	0.00%	5.94%	-0.18	-0.31	0.00	-0.49
MS	0.39%	1.47%	0.00%	1.86%	-0.03	0.68	0.00	0.65
MT	1.12%	2.41%	0.00%	3.53%	0.12	0.61	0.00	0.73
NC	1.09%	5.89%	0.00%	6.98%	0.15	-0.08	0.00	0.07
ND	0.55%	1.12%	0.00%	1.67%	-0.02	0.62	0.00	0.60
NE	1.20%	2.93%	0.00%	4.13%	0.13	0.76	0.00	0.89
NH	2.41%	3.08%	0.00%	5.49%	0.85	0.14	0.00	0.99
NJ*	2.79%	10.45%	0.00%	13.25%	0.26	-0.52	0.00	-0.26
NM	1.06%	3.72%	0.00%	4.78%	-0.07	0.63	0.00	0.56
NV*	1.61%	13.79%	0.00%	15.40%	-0.08	4.77	0.00	4.70
NY*	3.66%	5.78%	0.00%	9.44%	0.33	0.79	0.00	1.13
OH	1.08%	3.95%	0.00%	5.03%	0.11	0.87	0.00	0.98
OK	3.49%	0.86%	0.00%	4.35%	2.86	-0.39	0.00	2.47
OR*	4.02%	11.95%	0.00%	15.97%	0.93	1.66	0.00	2.59
PA	2.19%	4.51%	0.00%	6.69%	0.06	0.23	0.00	0.29
RI*	3.37%	4.67%	0.00%	8.04%	0.43	0.79	0.00	1.22
SC	1.13%	2.97%	0.00%	4.09%	0.37	0.08	0.00	0.44
SD	0.79%	1.43%	0.00%	2.22%	0.01	0.48	0.00	0.49
TN	0.55%	4.65%	0.00%	5.20%	-0.07	1.43	0.00	1.36
TX	0.73%	5.38%	0.00%	6.11%	0.11	0.23	0.00	0.34
UT	1.55%	7.87%	0.00%	9.41%	0.11	2.17	0.00	2.27
VA*	1.60%	7.31%	0.00%	8.91%	0.31	-1.25	0.00	-0.95
VT*	4.37%	7.56%	0.00%	11.93%	0.99	2.45	0.00	3.44
WA*	2.73%	15.14%	0.00%	17.87%	-0.38	1.06	0.00	0.68
WI	1.04%	3.41%	0.00%	4.45%	0.13	0.42	0.00	0.55
WV	0.72%	1.38%	0.00%	2.10%	0.16	0.39	0.00	0.55
WY	0.78%	1.71%	0.00%	2.49%	0.03	0.55	0.00	0.58
U.S.	**1.96%**	**7.99%**	**0.00%**	**9.96%**	**0.28**	**0.65**	**-0.02**	**0.91**

*Denotes states that have adopted California's ZEV program
Source: Figures compiled by Alliance for Automotive Innovation with new registrations for retail and fleet data provided by S&P Global Mobility covering January 1 – June 30, 2023, and January 1 – June 30, 2024

WHO's DRIVING?

a public service announcement



State	2024 New Light-Duty Vehicle Registrations By Powertrain (YTD Q2) — Advanced Powertrain Market Share				Change In Market Share (2024 vs 2023 YTD Q2), New Light-Duty Vehicle Registrations Powertrain — Advanced Powertrain Market Share (Percentage Point Change)			
	PHEV	BEV	FCEV	EV Total	PHEV	BEV	FCEV	EV Total
AK	0.62%	2.31%	0.00%	**2.93%**	-0.26	-0.45	0.00	**-0.72**
AL	0.59%	2.30%	0.00%	**2.89%**	-0.06	-0.43	0.00	**0.50**
AR	0.46%	1.95%	0.00%	**2.41%**	0.07	-0.34	0.00	**0.27**
AZ	1.44%	7.86%	0.00%	**9.30%**	-0.24	0.10	0.00	**0.13**
CA*	3.49%	22.25%	0.03%	**25.78%**	-0.20	-0.79	0.17	**0.81**
CO**	6.20%	12.66%	0.00%	**18.86%**	-2.27	-4.61	0.00	**6.88**
CT*	3.98%	7.17%	0.00%	**11.15%**	-1.00	-0.85	0.00	**1.84**
DC	5.21%	14.24%	0.00%	**19.44%**	-1.16	1.11	0.00	**0.05**
DE	2.41%	6.59%	0.00%	**8.99%**	-0.55	-0.14	0.00	**0.70**
FL	1.14%	7.39%	0.00%	**8.53%**	-0.26	-1.55	0.00	**1.81**
GA	0.88%	6.15%	0.00%	**7.03%**	-0.19	0.16	0.00	**0.03**
HI	5.54%	9.64%	0.00%	**15.18%**	-4.55	0.03	0.00	**4.52**
IA	0.98%	2.47%	0.00%	**3.45%**	-0.14	-0.41	0.00	**0.55**
ID	1.36%	3.11%	0.00%	**4.47%**	-0.12	-0.24	0.00	**0.36**
IL	1.36%	5.95%	0.00%	**7.31%**	-0.26	0.35	0.00	**-0.08**
IN	1.01%	3.42%	0.00%	**4.43%**	-0.15	-0.65	0.00	**0.80**
KS	1.14%	3.37%	0.00%	**4.50%**	-0.33	0.06	0.00	**0.27**
KY	0.66%	2.66%	0.00%	**3.33%**	0.10	-0.41	0.00	**0.31**
LA	0.54%	1.30%	0.00%	**1.83%**	-0.11	0.17	0.00	**-0.06**
MA*	3.90%	7.46%	0.00%	**11.37%**	-0.29	0.08	0.00	**0.21**
MD*	2.70%	8.66%	0.00%	**11.36%**	-0.40	-0.78	0.00	**1.17**
ME*	3.23%	3.52%	0.00%	**6.74%**	-0.94	-0.48	0.00	**1.42**
MI	1.04%	3.65%	0.00%	**4.69%**	0.06	-0.77	0.00	**0.72**
MN*	1.77%	4.97%	0.00%	**6.74%**	-0.51	-0.49	0.00	**1.00**
MO	1.83%	3.33%	0.00%	**5.16%**	0.17	0.12	0.00	**-0.29**
MS	0.41%	1.30%	0.00%	**1.72%**	-0.05	-0.40	0.00	**0.46**
MT	1.23%	2.61%	0.00%	**3.84%**	-0.21	-0.56	0.00	**0.77**
NC	1.07%	5.57%	0.00%	**6.65%**	-0.07	0.34	0.00	**-0.27**
ND	0.57%	1.06%	0.00%	**1.62%**	0.05	-0.46	0.00	**0.41**
NE	1.27%	2.73%	0.00%	**3.99%**	-0.22	-0.56	0.00	**0.78**
NH	2.44%	3.01%	0.00%	**5.44%**	-0.90	0.04	0.00	**0.86**
NJ*	2.90%	9.73%	0.00%	**12.63%**	-0.60	0.66	0.00	**-0.06**
NM	1.05%	3.64%	0.00%	**4.69%**	0.09	-0.32	0.00	**0.23**
NV*	1.66%	12.42%	0.00%	**14.09%**	-0.02	-1.36	0.00	**1.38**
NY*	4.44%	5.23%	0.00%	**9.67%**	-1.39	-0.68	0.00	**2.06**
OH	1.17%	3.53%	0.00%	**4.70%**	-0.24	-0.61	0.00	**0.85**
OK	4.50%	0.90%	0.00%	**5.40%**	-3.92	0.32	0.00	**3.60**
OR*	4.47%	11.43%	0.00%	**15.90%**	-1.20	-0.24	0.00	**1.43**
PA	2.49%	4.09%	0.00%	**6.58%**	-0.69	-0.10	0.00	**0.79**
RI*	3.63%	4.39%	0.00%	**8.02%**	-0.98	-0.56	0.00	**1.53**
SC	1.04%	3.01%	0.00%	**4.06%**	-0.26	-0.16	0.00	**0.42**
SD	0.78%	1.48%	0.00%	**2.25%**	0.04	-0.35	0.00	**0.31**
TN	0.56%	4.08%	0.00%	**4.64%**	0.08	-0.01	0.00	**-0.07**
TX	0.85%	5.31%	0.00%	**6.16%**	-0.19	-0.06	0.00	**0.25**
UT	1.58%	7.36%	0.00%	**8.93%**	-0.13	-0.78	0.00	**0.91**
VA*	1.50%	6.74%	0.00%	**8.24%**	-0.24	1.78	0.00	**-1.54**
VT*	4.30%	7.05%	0.00%	**11.35%**	-1.25	-1.68	0.00	**2.93**
WA*	3.21%	15.81%	0.00%	**19.03%**	-0.20	-1.75	0.00	**1.96**
WI	0.94%	3.38%	0.00%	**4.32%**	-0.05	-0.47	0.00	**0.52**
WV	0.68%	1.35%	0.00%	**2.03%**	-0.12	-0.35	0.00	**0.47**
WY	0.86%	1.72%	0.00%	**2.58%**	-0.10	-0.64	0.00	**0.73**
U.S.	**2.13%**	**7.52%**	**0.00%**	**9.66%**	**-0.50**	**-0.32**	**0.02**	**0.81**

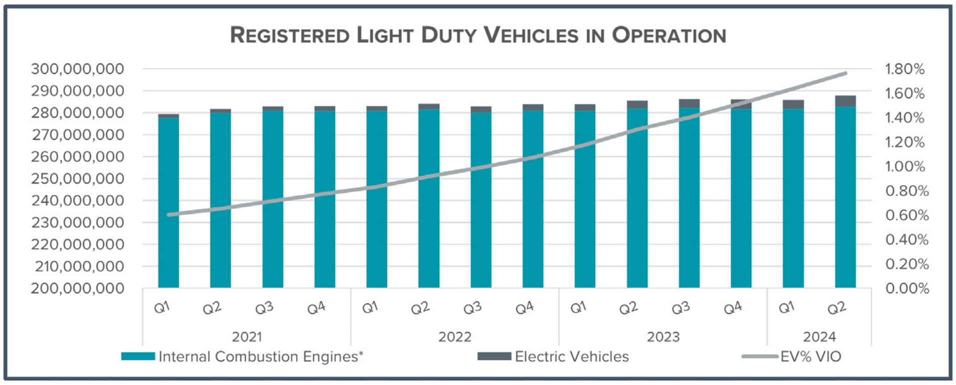
*Denotes states that have adopted California's ZEV program

Source: Figures compiled by Alliance for Automotive Innovation with new registrations for retail and fleet data provided by S&P Global Mobility covering January 1 – June 30, 2023, and January 1 – June 30, 2024

**Note: Colorado taxpayers are eligible for a state tax credit of $5,000 for the purchase or lease of a new EV on or after July 1, 2023 with a manufacturer's suggested retail price (MSRP) up to $80,000. Lease agreements must have an initial term of at least two years. Beginning January 1, 2024, Coloradans purchasing an EV with an MSRP up to $35,000 will be eligible for an additional $2,500 tax credit.

REGISTRATIONS AND CHARGING / REFUELING

Share of Registered EVs In U.S. Light-Duty Fleet Continues to Increase Incrementally. As sales of EVs increase, so does the total number of EVs operating on U.S. roads. There are now nearly 5.1 million EVs in operation in the United States (1.76 percent of all light vehicles in operation). EVs represented more than 1 percent of total vehicles in operation (VIO) for the first time at the end of 2022. The electric vehicles in operation (E-VIO) of 1.76 percent is an increase of 0.46 pp since the second quarter of 2023 and nearly three times the EV VIO from the first quarter in 2021 (0.60 percent).[9]



U.S. Public Charging Infrastructure: Overview

While the U.S. Department of Energy notes that roughly 80 percent of all EV charging occurs at home, reliable and convenient access to workplace and public charging and refueling stations help to support customers who purchase EVs or are considering purchasing an EV. Workplace and public charging infrastructure not only eases perceived "range anxiety" concerns but also increases consumer awareness of the technology. In addition, achieving the EV market share envisioned by state and/or federal regulators will require moving beyond customers who have access to charging via privately-owned single-family dwellings.

How Available are NEVI Funded Chargers?

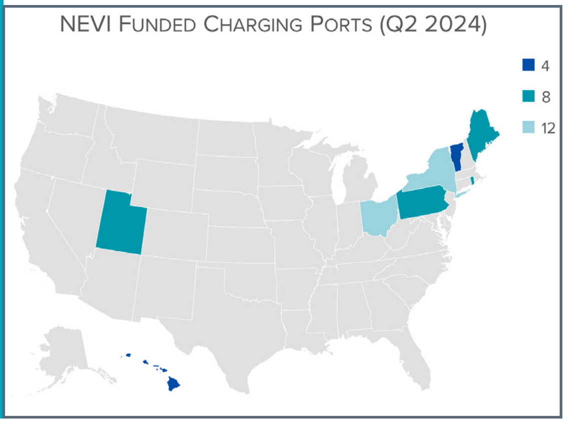
Through Q2 of 2024:

- 8 States Have Installed Charging Ports
- 64 Fash Charging Ports Intalled in 15 Locations

States with NEVI funded charging ports:

1. New York (12)
2. Ohio (12)
3. Maine (8)
4. Pennsylvania (8)
5. Rhode Island (8)
6. Utah (8)
7. Hawaii (4)
8. Vermont (8)

The bipartisan Infrastructure Investment and Jobs Act (IIJA) that was signed into law in November 2021 includes $5 billion in funding for states to establish a nationwide EV charging network (NEVI) every 50 miles along highway corridors and provides $2.5 billion in competitive grants to deploy publicly available EV charging and other alternative fuel stations through 2026. NEVI funding provides funding to states to strategically deploy charging infrastructure and to establish an interconnected network of publicly available charging. There are currently 45,592 distinct locations with 133,939 Level 2 (L2) ports and/or 43,391 DC Fast charging ports. See more on charging locations by state below.



Here is a snapshot of publicly available EV charging and refueling infrastructure[10] available across the United States at the end of the second quarter of 2024[11]:

[9] Registered vehicles in operation compiled by Alliance for Automotive Innovation with data provided by S&P Global Mobility as of June 30, 2024
[10] "Stations" denotes stations as counted and identified by U.S. Department of Energy Alternative Fuels Data Center. Stations Differs from number of locations as many stations can be at a singular location. Locations denotes unique addresses.
[11] Charging information from U.S. Department of Energy Alternative Fuels Data Center, stations in operation as of June 30, 2024

Electronic Filing: Received, Clerk's Office 11/27/2024

Level 2: 56,002 Locations, 133,939 EVSE Ports
DC Fast: 10,338 Locations, 43,391 EVSE Ports
Hydrogen Refueling: 58 Stations (57 are in California)
***U.S. Total:** 65,083[12] Locations, 177,330 EVSE Ports*

See Recommended Attributes for EV Charging Stations

State	Locations	L2 Ports	DC Fast Ports	State	Locations	L2 Ports	DC Fast Ports
AK	60	91	30	MT	119	188	207
AL	322	626	431	NC	1,303	3,236	1,168
AR	285	731	155	ND	84	125	92
AZ	908	2,605	1,042	NE	218	387	180
CA	8,896	34,569	11,664	NH	194	399	203
CO	1,631	4,227	1,048	NJ	999	2,696	1,130
CT	936	2,814	537	NM	239	441	299
DC	260	992	62	NV	407	1,350	746
DE	168	377	234	NY	3,111	10,691	1,611
FL	2,733	7,500	2,539	OH	1,286	2,958	909
GA	1,336	3,871	1,248	OK	308	450	844
HI	279	709	85	OR	1,011	2,331	891
IA	337	534	352	PA	1,339	3,437	1,119
ID	177	329	162	RI	208	644	95
IL	1,016	2,426	1,075	SC	452	977	506
IN	491	1,001	620	SD	92	134	118
KS	309	886	240	TN	638	1,576	580
KY	268	595	233	TX	2,508	6,668	2,748
LA	212	457	265	UT	589	2,003	447
MA	1,799	6,661	871	VA	1,116	3,188	1,184
MD	1,381	3,788	994	VT	326	859	177
ME	404	836	242	WA	1,503	4,526	1,261
MI	1,094	2,622	765	WI	514	1,024	479
MN	679	1,517	577	WV	126	288	151
MO	691	2,183	519	WY	91	134	123
MS	139	282	133	US. Total	45,592	133,939	43,391

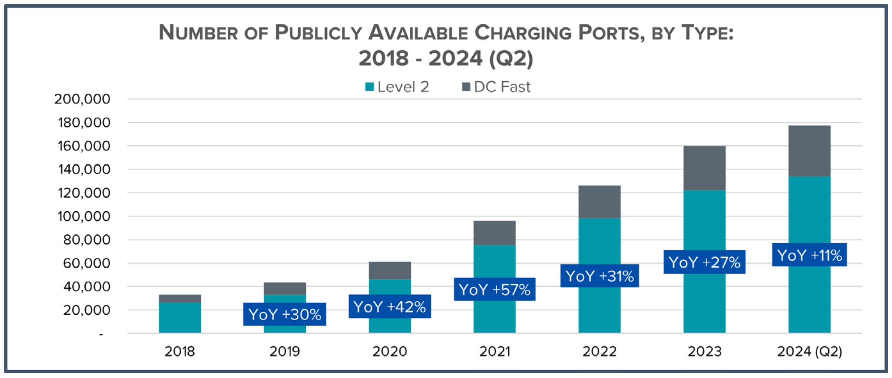
Level 2 Chargers and DC Fast Chargers. Both Level 2 and DC Fast charging play important roles in electrifying the light-duty vehicle fleet. However, the key difference between Level 2 and DC Fast chargers is how quickly each will charge an EV's battery. Level 2 equipment is common for home, workplace, and public charging with longer dwell times. Level 2 chargers can fully charge a BEV from empty in 4-10 hours and a PHEV from empty in 1-2 hours. DC Fast charging equipment enables rapid charging of BEVs in 20 minutes to 1 hour along heavy-traffic corridors, in city centers, at transportation hubs, and fleet depots. Wider installation of Level 2 chargers, DC Fast chargers, and hydrogen fueling will be necessary to support wider-scale adoption of EVs.

The number of public Level 2 charging increased 10 percent at the end of the second quarter of 2024 over 2023. DC Fast chargers increased 14 percent. Total charging ports increased 11 percent from the end of 2023.[13] (For context, E-VIO increased 17 percent from the end of 2023 to the end of the second quarter of 2024.)

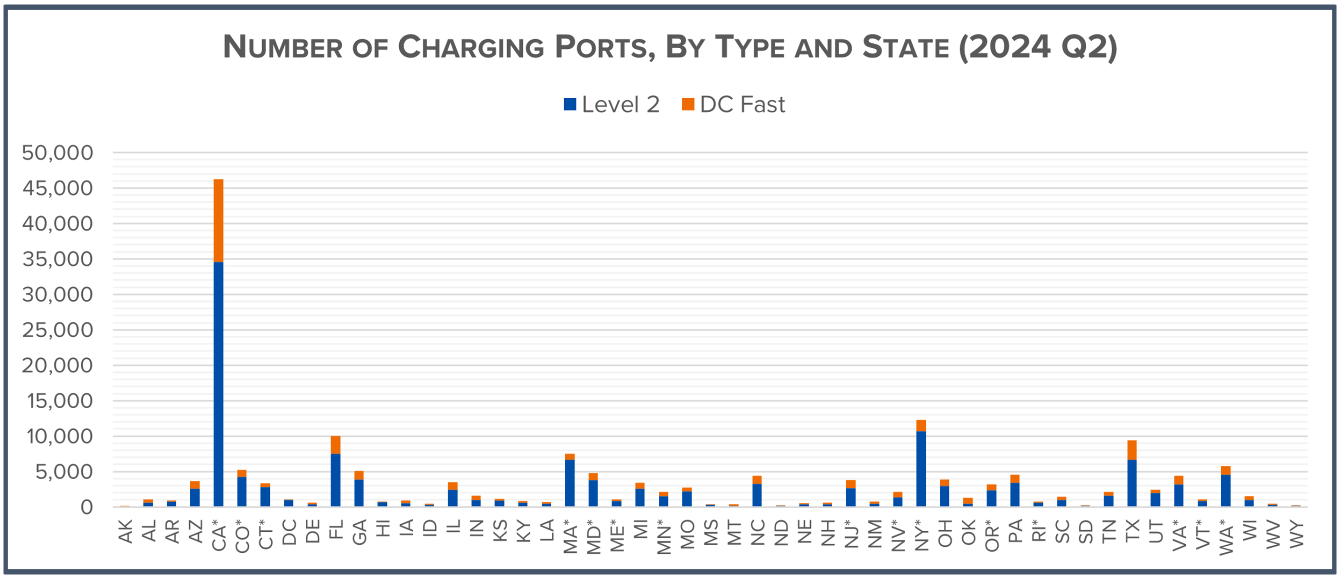
Through June 30, 2024, 60 Percent of Installed DC Fast Charging Ports Were on the Tesla Network (North American Charging Standard)[14]:

» **After Tesla opened their previously proprietary chargers (in November 2022), at least 18 EV manufacturers have announced that they will move to Tesla's North America Charging Standard.**

DC Fast Charger Ports by Network		
Network	**Ports**	**%Total**
Tesla (NACS)	25,967	60%
All Other Networks	17,424	40%
Total	43,391	100%



Note: prior editions of this report excluded proprietary chargers, however Tesla opened their previously proprietary chargers in November 2022 and their "North American Charging Standard" will be widely adopted by automakers.
[12] Some station locations have both Level 2 and DC Fast installed.
[13] Charging information from U.S. Department of Energy Alternative Fuels Data Center, stations in operation as of 6/30/2024
[14] Charging information from U.S. Department of Energy Alternative Fuels Data Center, 6/30/2024; does not include J1772 or CHAdeMO connectors



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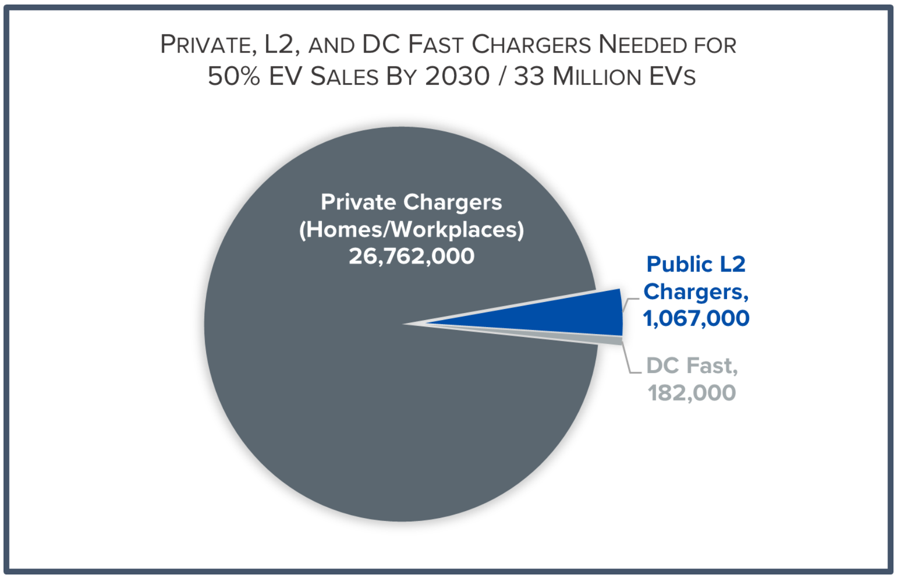
Infrastructure Investment Necessary

An assessment by the U.S. National Renewable Energy Laboratory (NREL) released in June 2023 estimated that a network of 28 million charging ports would be necessary to support 50 percent EV sales by 2030 (and 33 million EVs on the road).[16] NREL estimates that 96 percent of those charging ports would be privately accessible L1 and L2 chargers located at single-family homes, multifamily properties, and workplaces. The remaining 4 percent (1,249,000 ports) would be split between public L2 and high-speed DC Fast charging ports, with L2 making up 85 percent of those public chargers.



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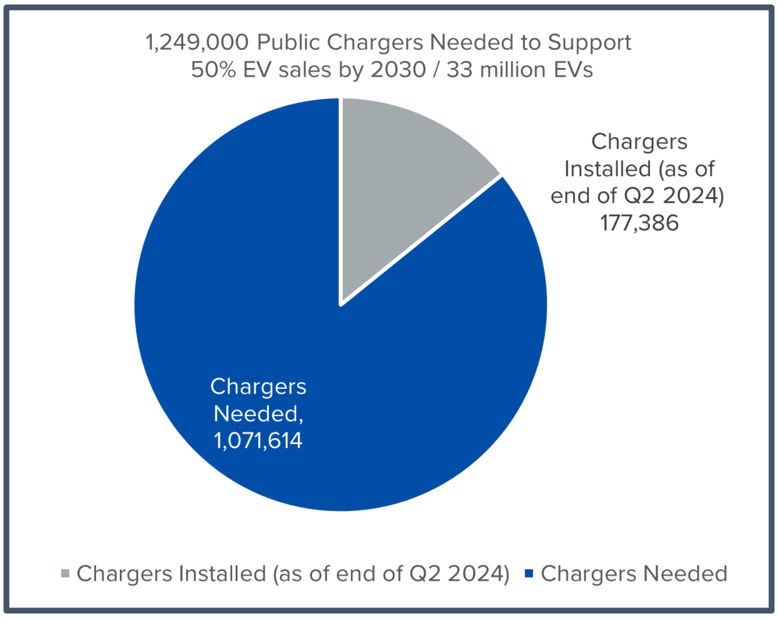
At the end of Q2 2024, there were about 177,000 public charging ports across the country and 5.1 million EVs on the road. Total installed public charging ports are about 17 percent of the needed estimate to support EV penetration by 2030 according to NREL.

More than 1 million additional public chargers (933,061 L2 and 138,609 DC Fast) will need to be installed to satisfy the necessary infrastructure estimate by 2030. This means that between the end of Q2 2024 and December 31, 2030, 451 chargers need to be installed every day, for the next 6.5 years. Or 3 chargers every 10 minutes through the end of 2030.

[15] Charging information from U.S. Department of Energy Alternative Fuels Data Center, stations in operation as of 6/30/2024; *Denotes states that have adopted California's ZEV program.
[16] National Renewable Energy Laboratory, "The 2030 National Charging Network: Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure," June 2023
[17] National Renewable Energy Laboratory, "The 2030 National Charging Network: Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure," June 2023



Between the end of Q2 2024 and December 31, 2030, 451 chargers need to be installed every day, for the next 6.5 years. Or 3 chargers every 10 minutes through the end of 2030.

The Cost of This Substantial Infrastructure Necessity Will Largely Fall on Consumers and Commercial Real Estate Owners as They Install Home and Workplace Charging. According to NREL, a national capital investment of $53–$127 billion in charging infrastructure is needed by 2030 (including as much as $72 billion for private residential charging) to support 33 million EVs.[18] The large range of potential costs is a result of variable and evolving equipment and installation costs across charging networks, locations, and site designs[19]. Notably, the estimates exclude the cost of grid upgrades and distributed energy resources. The estimated cumulative capital investment includes[20]:

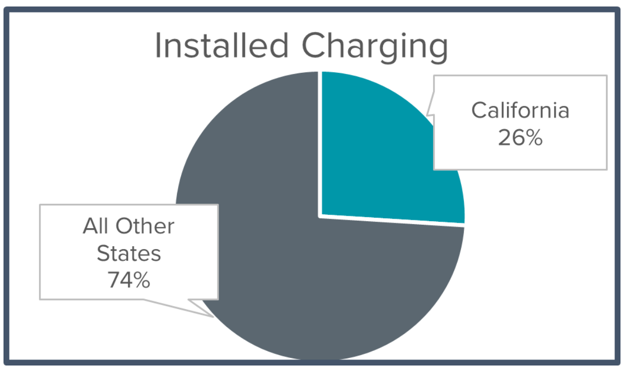
» $22–$72 billion for privately accessible Level 1 and Level 2 charging ports

» $27–$44 billion for publicly accessible fast charging ports

» $5–$11 billion for publicly accessible Level 2 charging ports

Infrastructure Disparities by Geography
Geographic disparities in charging infrastructure are pervasive. At the end of Q2 2024, more than a quarter of all public charging infrastructure was in California, which had 34 percent of all registered EVs.

Alliance for Automotive Innovation is proactively engaging to enable the automotive industry's transformation to electric vehicles through state-level engagement actions such as participation in the Joint Office of Energy and Transportation's Electric Vehicle Working Group, development of a lithium-ion battery recycling policy framework, recommendations for attributes of EV charging stations, and recommendations for the implementation of IRA EV tax credits[21].



[18] National Renewable Energy Laboratory, "The 2030 National Charging Network: Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure," June 2023
[19] Various state and federal incentives are available to consumers or businesses that install EV charging infrastructure, including from power utilities.
[20] National Renewable Energy Laboratory, "The 2030 National Charging Network: Estimating U.S. Light-Duty Demand for Electric Vehicle Charging Infrastructure," June 2023
[21] Alliance for Automotive Innovation, Blog, What We Know (and Don't Know) About the New EV Tax Credit Rules, 12/20/2022; Alliance for Automotive Innovation, blog Foreign Entity of Concern: Finally... Some Clarity, 12/1/2023

Vehicles in Operation and Charging by State

Public Charging Outlets And Registerd EVs (as of 6/30/2024)

	EV Level 2	EV DC Fast	H2** Fueling	Total	Percent EVs of Total VIO***	Share of Registered EVs****	EVs Per Charger	EVs Per 10K Residents
AK	91	30	-	121	0.65%	0.07%	31	51.23
AL	626	431	-	1,057	0.38%	0.38%	18	38.20
AR	731	155	-	886	0.37%	0.21%	12	34.39
AZ	2,605	1,042	-	3,647	1.85%	2.52%	35	172.30
CA*	34,569	11,664	57	46,290	5.51%	33.85%	37	440.89
CO*	4,227	1,048	-	5,275	2.49%	2.70%	26	232.72
CT*	2,814	537	-	3,351	1.69%	1.03%	16	144.38
DC	992	62	-	1,054	3.66%	0.25%	12	183.93
DE	377	234	-	611	1.43%	0.26%	21	125.90
FL	7,500	2,539	-	10,039	1.73%	6.60%	33	148.11
GA	3,871	1,248	-	5,119	1.23%	2.32%	23	106.61
HI	709	85	1	795	3.05%	0.68%	44	241.90
IA	534	352	-	886	0.49%	0.31%	18	49.32
ID	329	162	-	491	0.71%	0.28%	29	72.72
IL	2,426	1,075	-	3,501	1.37%	2.73%	40	110.28
IN	1,001	620	-	1,621	0.65%	0.80%	25	58.88
KS	886	240	-	1,126	0.62%	0.36%	16	61.34
KY	595	233	-	828	0.43%	0.35%	21	38.77
LA	457	265	-	722	0.34%	0.26%	18	28.31
MA*	6,661	871	-	7,532	2.20%	2.39%	16	172.97
MD*	3,788	994	-	4,782	2.12%	2.14%	23	175.92
ME*	836	242	-	1,078	1.21%	0.32%	15	116.14
MI	2,622	765	-	3,387	0.88%	1.48%	22	74.89
MN*	1,517	577	-	2,094	1.06%	1.10%	27	97.11
MO	2,183	519	-	2,702	0.72%	0.81%	15	66.70
MS	282	133	-	415	0.20%	0.12%	15	20.86
MT	188	207	-	395	0.44%	0.15%	19	67.10
NC	3,236	1,168	-	4,404	1.05%	2.03%	23	94.88
ND	125	92	-	217	0.23%	0.04%	9	23.76
NE	387	180	-	567	0.54%	0.22%	20	57.29
NH	399	203	-	602	1.25%	0.33%	28	119.20
NJ*	2,696	1,130	-	3,826	2.42%	3.55%	47	194.01
NM	441	299	-	740	0.79%	0.32%	22	75.83
NV*	1,350	746	-	2,096	2.56%	1.28%	31	203.87
NY*	10,691	1,611	-	12,302	2.01%	4.54%	19	117.77
OH	2,958	909	-	3,867	0.76%	1.59%	21	68.48
OK	450	844	-	1,294	1.32%	1.20%	47	150.59
OR*	2,331	891	-	3,222	2.54%	1.94%	31	232.58
PA	3,437	1,119	-	4,556	1.07%	2.33%	26	91.22
RI*	644	95	-	739	1.35%	0.23%	16	107.57
SC	977	506	-	1,483	0.58%	0.62%	21	58.38
SD	134	118	-	252	0.31%	0.06%	12	33.99
TN	1,576	580	-	2,156	0.70%	0.96%	23	68.22
TX	6,668	2,748	-	9,416	1.19%	5.81%	31	96.69
UT	2,003	447	-	2,450	1.83%	1.10%	23	163.93
VA*	3,188	1,184	-	4,372	1.46%	2.23%	26	129.73
VT*	859	177	-	1,036	2.57%	0.28%	14	221.14
WA*	4,526	1,261	-	5,787	2.89%	3.98%	35	258.56
WI	1,024	479	-	1,503	0.71%	0.76%	26	65.56
WV	288	151	-	439	0.30%	0.10%	11	27.30
WY	134	123	-	257	0.31%	0.04%	8	35.70
U.S.	**133,939**	**43,391**	**56**	**177,386**	**1.76%**	**100.00%**	**29**	**151.53**

REGISTRATIONS

EV registrations as a share of all registered light-duty vehicles are 1.76 percent (as of June 30, 2024). There are more than 287 million registered light-duty vehicles in the U.S.

At the end of Q2 2024, California accounted for 34 percent of all registered light-duty EVs in the U.S.

States with highest portion of total EVs registered:

1. CA* (1,717,934, 5.51%)
2. DC (12,488, 3.66%)
3. HI (34,716, 3.05%)
4. WA* (202,013, 2.89%)
5. VT* (14,318, 2.57%)
6. NV* (65,121, 2.56%)
7. OR* (98,460, 2.54%)
8. CO* (136,786, 2.49%)
9. NJ* (180,249, 2.42%)
10. MA* (121,104, 2.20%)

States with worst ratio of registered EVs per public charger:

1. OK
2. NJ*
3. HI
4. IL
5. CA*
6. AZ
7. WA*
8. FL
9. TX
10. NV

Read more about automaker plans for an ***ELECTRIC FUTURE HERE***

*Denotes states that have adopted California's ZEV program; **Hydrogen count denotes stations
*** VIO is vehicles in operation; **** State share of U.S. Total
Source: Figures compiled by Alliance for Automotive Innovation with registered vehicle data provided by S&P Global Mobility as of June 30, 2024; Charging information from U.S. Department of Energy Alternative Fuels Data Center, as of 6/30/2024

SPOTLIGHT ON:
THE IMPORTANCE OF SECURING THE EV SUPPLY CHAIN

Leadership in automotive technology and manufacturing has underpinned a century of U.S. economic growth and innovation. However, the continued leadership of the auto industry in the United States and our global competitiveness is not a forgone conclusion. The ability of the auto industry to maintain its position in the global economy will be determined, in part, by the transition to electrification. And the success of that transition will hinge on the ability to secure, localize and diversity the EV supply chain.

Nations around the world are moving aggressively to lead the development and deployment of electrified technologies. These same nations have clearly recognized that those that lead the development and deployment of these technologies will also guide the development of international standards, control supply chains, and drive international markets. For example, China, with a 15-year head start on electrification, currently controls the market on major segments of the global EV supply chain – including mining and processing of critical minerals like lithium, cobalt and graphite used in EV batteries.

The transition to electrification is not just a tectonic shift within the industry, but also a harbinger of vast opportunities: rewriting global supply chains, rebuilding the domestic industrial base, creating jobs, and underpinning American economic and national security. However, for the U.S. to realize the full potential of the opportunities that come with this shift, the EV supply chain needs to be secured, localized, and diversified. Failure to do so will risk being left dependent on and exposed to foreign competitors and their ability to manipulate the market for materials, components, or finished products through market dominance and trade distorting practices.

Reducing Exposure to Dependency on Foreign Sources

The EV supply chain, particularly for battery components and critical minerals (lithium, cobalt, nickel, graphite), is heavily dependent on foreign sources, especially from countries like China. This dependency makes the U.S. vulnerable to geopolitical risks, trade disputes, and supply chain disruptions. By localizing and diversifying the supply chain, the U.S. can reduce its vulnerability over time to these external pressures and ensure a more stable and secure supply of essential materials.

Automakers and battery manufacturers have invested heavily in EVs, with much of their $125 billion commitment focused downstream – on finished vehicles and battery cell production. Over 900 GWhs of battery cell production are expected to be added in the U.S. by 2030 (more than an 800% increase over current capacity). As important as these investments are, much more attention needs to be focused on upstream and midstream supply chain development – specifically critical mineral mining and processing.

"Converting mined mineral supplies into chemicals suited to the battery industry is mostly dominated by production in China.

- "Lithium chemicals are the only critical battery minerals in which less than 75% of this year's supply is forecast to be located outside of China.
- "Despite so much mined manganese having no Chinese involvement, 97% of manganese sulphate suitable for batteries is produced in China.
- "Although there is significant synthetic graphite production spread around the world, supply of material suitable for use in battery anodes is mostly located in China, with only 2% located outside of the country."[22]

Four U.S. Graphite Mines in the Works:

"At present, the US produces no natural graphite but has four mines in various stages of development, according to Benchmark's Natural Graphite Forecast. The four assets are operated by Redbird Bluebird, Westwater Resources, Graphite One Resources, and South Star Battery Metals."

-Benchmark Mineral, 8/21/2024

[22] How Much Of The Global Battery Supply Chain Is Owned By Chinese Companies?" Benchmark Mineral, 8/22/2024

"Very little active material and cell production has no Chinese involvement

- "This year 99% of cathode active material and 93% of anode active material production are forecast to be produced either in China or involve a Chinese company. This is forecast by Benchmark to drop to 85% for both by 2030.
- "Chinese involvement in cell production is forecast to drop from 84% today to 70% in 2030."[23]

Economic Growth and Job Creation

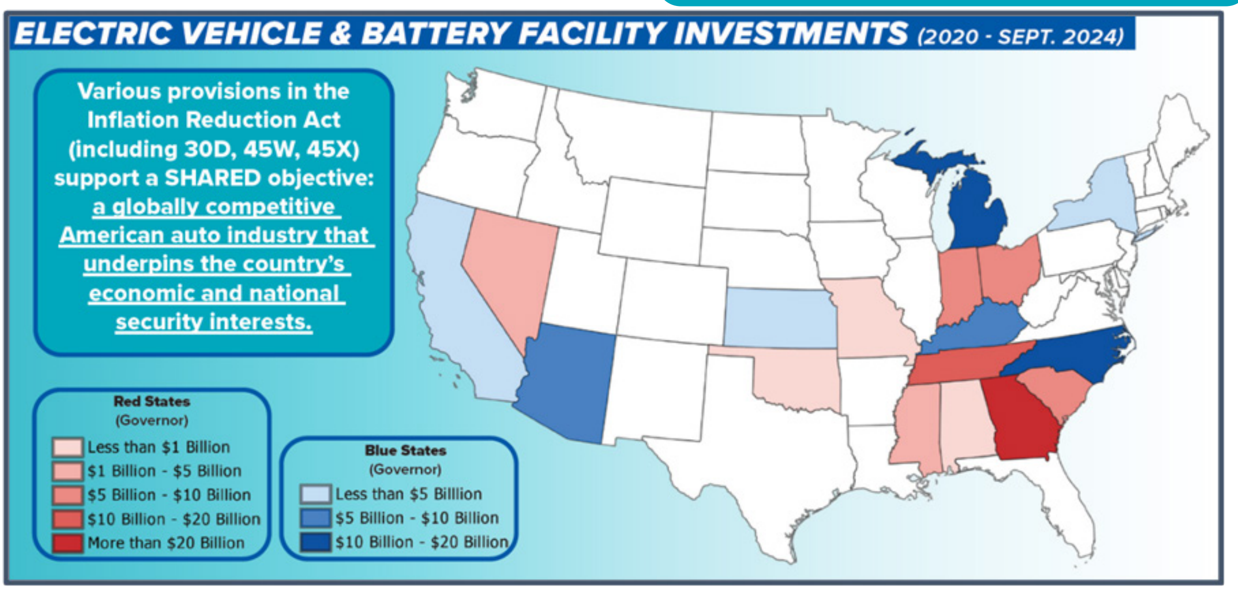
The auto industry is a major driver of the U.S. economy, supporting 10 million jobs coast-to-coast. Every direct job in vehicle manufacturing creates another 10.5 American jobs. These are not just auto jobs – these are jobs throughout communities and the economy necessary to support our manufacturing sector – which provides $650 billion in payroll compensation as well as more than $220 billion in federal and state revenue annually. As a result, every $1 added to the economy by vehicle manufacturing creates an additional $3.45 in economic value. It's not only imperative that the auto sector's economic contributions be preserved throughout the transition to expanded electrification, but also strengthened by capitalizing on new growth opportunities.

Localizing and diversifying the EV supply chain will promote domestic manufacturing, catalyzing significant economic growth. It can create new jobs not just in manufacturing, but also mining, research and development, and other related sectors. By fostering a localized supply chain, including key allies and partners, the U.S. can further strengthen the domestic auto industry and drive innovation and economic competitiveness.

As noted earlier, automakers and battery manufacturers have made considerable investments downstream, committing to $125 billion in investments and outlaying more than $123.7 billion for more than 80 projects and creating 114,000 jobs across 18 states[24]:

- More than $90 billion has been outlaid for EV battery production facilities in the U.S., creating an estimated 65,000 jobs.
- An additional $33 billion has been committed to EV assembly projects creating an additional 48,000 jobs.
- $68.3 billion in the South
- $41.8 billion in the Midwest
- $13.3 billion in the West
- $0.3 billion in the Northeast

See more on the EV Investment Dashboard



[23] "How Much Of The Global Battery Supply Chain Is Owned By Chinese Companies?" Benchmark Mineral, 8/22/2024
[24] Compiled from company reports, press statements, and other media; investments from 2020 – September 2024

With a localized and diversified supply chain, companies and research institutions can collaborate more closely, leading to faster advancements in technology and innovation within the EV sector.

» E2 estimates an additional $128 million committed to clean vehicle R&D in the past two years, with more than 1,200 jobs associated with those announcements.[25]

Each of these jobs and investments will create indirect and induced benefits throughout the communities, states, and regions where they are located.

CASE STUDY: AESC | BATTERY MANUFACTURING PLANT | FLORENCE, SC

In 2022, AESC announced the construction of a new battery manufacturing plant in Florence, South Carolina. Initially, AESC committed $810 million in 2022, followed by another $810 million announced in December 2023, and then an additional $1.5 billion was announced in March 2024, bringing the overall investment to $3.12 billion by 2026. With operations slated to begin in 2027, AESC plans to employ 2,700 people when fully operational.

The annual operations of the proposed AESC battery plant would support a total of **4,900** jobs (direct, indirect, and induced) across the South Carolina region.

$406 million in Labor Income would be supported in South Carolina due to annual operations of the AESC battery plant.

The annual spending on operations would support **$628 million** in contribution to GDP and **$1.6 billion** in output across South Carolina.

Approximately **$143.7 million** in local, state, and federal tax revenue would be generated by annual operations, including sales tax and income tax.

This study used IMPLAN 2022 Data and the IMPLAN calculation process to estimate the economic impact from operations of the AESC – Battery Plant (Storage Battery Manufacturing) in Florence, SC on the South Carolina region. The financial expenditures and assumptions used to generate the results included in this report were imputed and entered into IMPLAN by Alliance for Automotive Innovation. All results are reported in 2024 dollars.

Global Competitiveness

The global EV market is highly competitive, with countries like China and members of the European Union making significant investments. By localizing and diversifying the supply chain, the U.S. can enhance its competitiveness in the global EV market and ensure it remains a key player in the automotive industry of the future.

Two decades ago, the U.S. was the leading manufacturer of automobiles in the world. Today, it remains one of the global leaders, manufacturing approximately 10 million vehicles in the U.S., and more than 16 million across North America. But the U.S. position in the global market has been dramatically outpaced by China. At the turn of the century, China was manufacturing around 2 million vehicles. Today, it manufactures 30 million vehicles and has capacity for nearly 50 million. Almost one-third of that production was for new energy – or electrified – vehicles. Put differently, China is manufacturing EVs on a scale equivalent to the entire vehicle manufacturing output of the U.S. auto industry.

Almost 14 million new EVs were registered globally in 2023, accounting for around 18 percent of all vehicles sold, an increase from 14 percent in 2022 and only 2 percent in 2018. **Nearly 95 percent of all global EV sales were in China (60 percent), Europe (25 percent) and the United States (10 percent).**

[25] E2, https://e2.org/announcements/, Accessed 9/4/2024

While China's domestic sales of EVs have increased (nearly one-third of all new vehicles sales in 2023), so too have their EV exports. In fact, China's EV exports are nearly as high as all U.S. vehicle exports: In 2023, China exported 1.5 million EVs.[26] The U.S. exports (average of last 5 years of data) 1.7 million new vehicles, across all powertrain types.

While Chinese EV exports to the U.S. are minimal, Chinese EV exports to Europe have soared in recent years. More than 438,000 EVs were imported from China into the EU in 2023. And China's market share in EU battery-electric sales has climbed from around 3 percent to over 20 percent in the past three years.[27]

The cost advantage provided by China's early entry into the EV space cannot be overstated: "EVs sell in China for the equivalent of $34,400, considerably lower than the $55,242 average selling price in the US.[28]" Due to government subsidies, cheap labor rates, increased scale, vertical integration, and importantly less expensive battery prices, Chinese exports (even with tariffs) provide an attractive cost comparison for consumers.

Bringing down the cost of batteries, and thus EVs, through supply chain localization, diversification, and vertical integration (to further provide for innovation, cost cutting, and business efficiencies) will be imperative if the U.S. wants to continue to compete in the global market.

Energy Independence

A localized EV supply chain supports the broader goal of reducing dependency on foreign oil, hence aligning with the U.S. strategy of achieving greater energy independence. Localizing battery production is essential for securing the energy infrastructure needed to support a growing number of electrified vehicles.

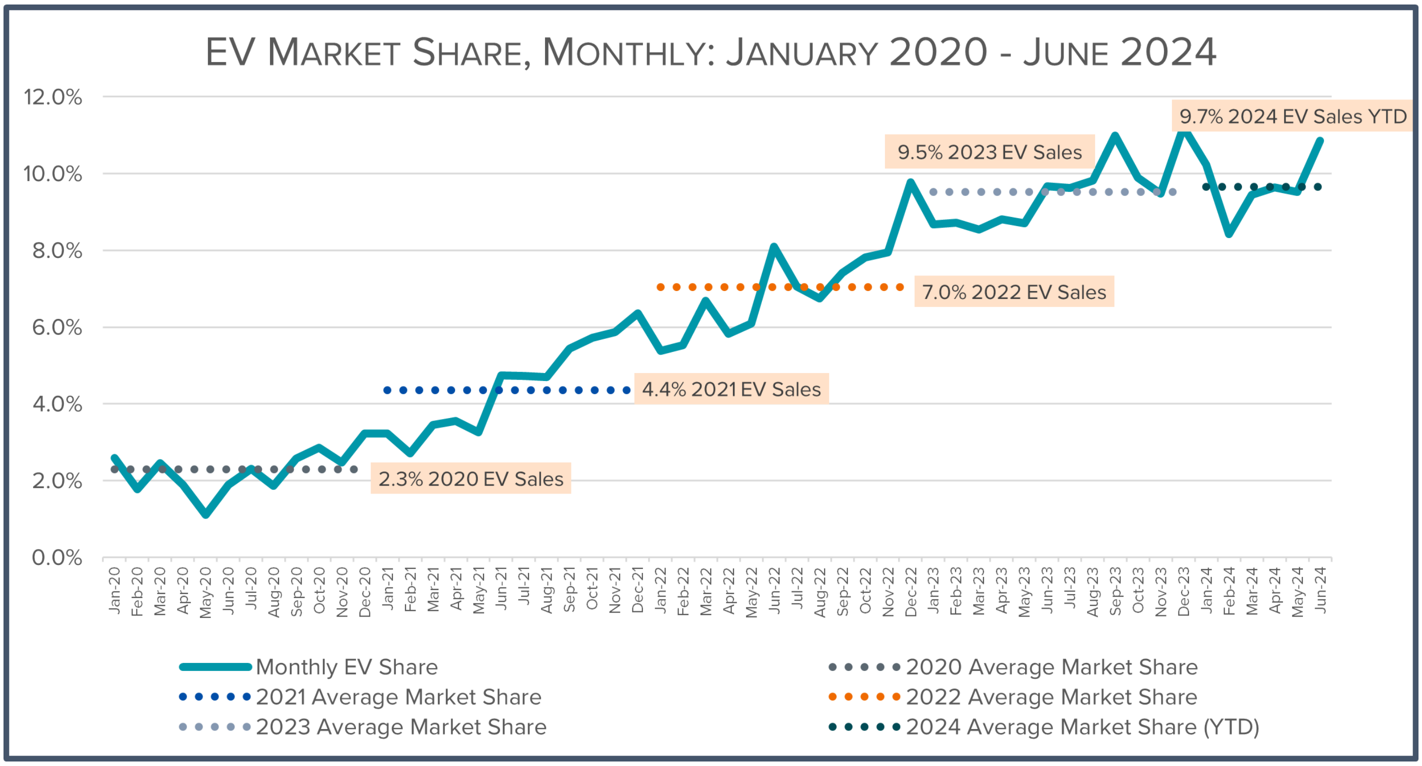
According to the U.S. Department of Energy[29], "the transportation sector accounts for approximately 30% of total U.S. energy needs and 70% of U.S. petroleum consumption. Using more energy efficient vehicles like hybrid and electric vehicles supports the U.S. economy and helps diversify the U.S. transportation fleet. The multiple fuel sources used to generate electricity results in a more secure energy source for the electrified portion of the transportation sector. All of this adds to our nation's energy security."

Since the electricity to power EVs in the U.S. is produced from domestic and diverse sources, localized production can help support the shift away from foreign sources of oil and toward renewable energy sources.

While the next decade will define which nations shape the future of automotive innovation and manufacturing, actions taken to localize the supply chain now will help the U.S. remain at the forefront of innovation that is critical to our national and economic security.

[26] "How The EU Could Tackle Subsidised Imports Of Chinese EVs," Benchmark Minerals, 4/10/2024
[27] ACEA, Fact Sheet: EU-China Vehicle Trade, Accessed 9/5/2024
[28] Shiv Shivaraman, "China Has An Electric Vehicle Advantage But Can It Maintain Its Edge?," World Economic Forum, 6/17/2024
[29] U.S. Department of Energy, Alternative Fuels Data Center, Accessed 9/5/2024

APPENDIX - A


EV MARKET SHARE, MONTHLY: JANUARY 2020 - JUNE 2024
12.0%
10.0%
8.0%
6.0%
4.0%
2.0%
0.0%
9.7% 2024 EV Sales YTD
9.5% 2023 EV Sales
7.0% 2022 EV Sales
4.4% 2021 EV Sales
2.3% 2020 EV Sales
Jan-20 Feb-20 Mar-20 Apr-20 May-20 Jun-20 Jul-20 Aug-20 Sep-20 Oct-20 Nov-20 Dec-20 Jan-21 Feb-21 Mar-21 Apr-21 May-21 Jun-21 Jul-21 Aug-21 Sep-21 Oct-21 Nov-21 Dec-21 Jan-22 Feb-22 Mar-22 Apr-22 May-22 Jun-22 Jul-22 Aug-22 Sep-22 Oct-22 Nov-22 Dec-22 Jan-23 Feb-23 Mar-23 Apr-23 May-23 Jun-23 Jul-23 Aug-23 Sep-23 Oct-23 Nov-23 Dec-23 Jan-24 Feb-24 Mar-24 Apr-24 May-24 Jun-24
Monthly EV Share
2020 Average Market Share
2021 Average Market Share
2022 Average Market Share
2023 Average Market Share
2024 Average Market Share (YTD)