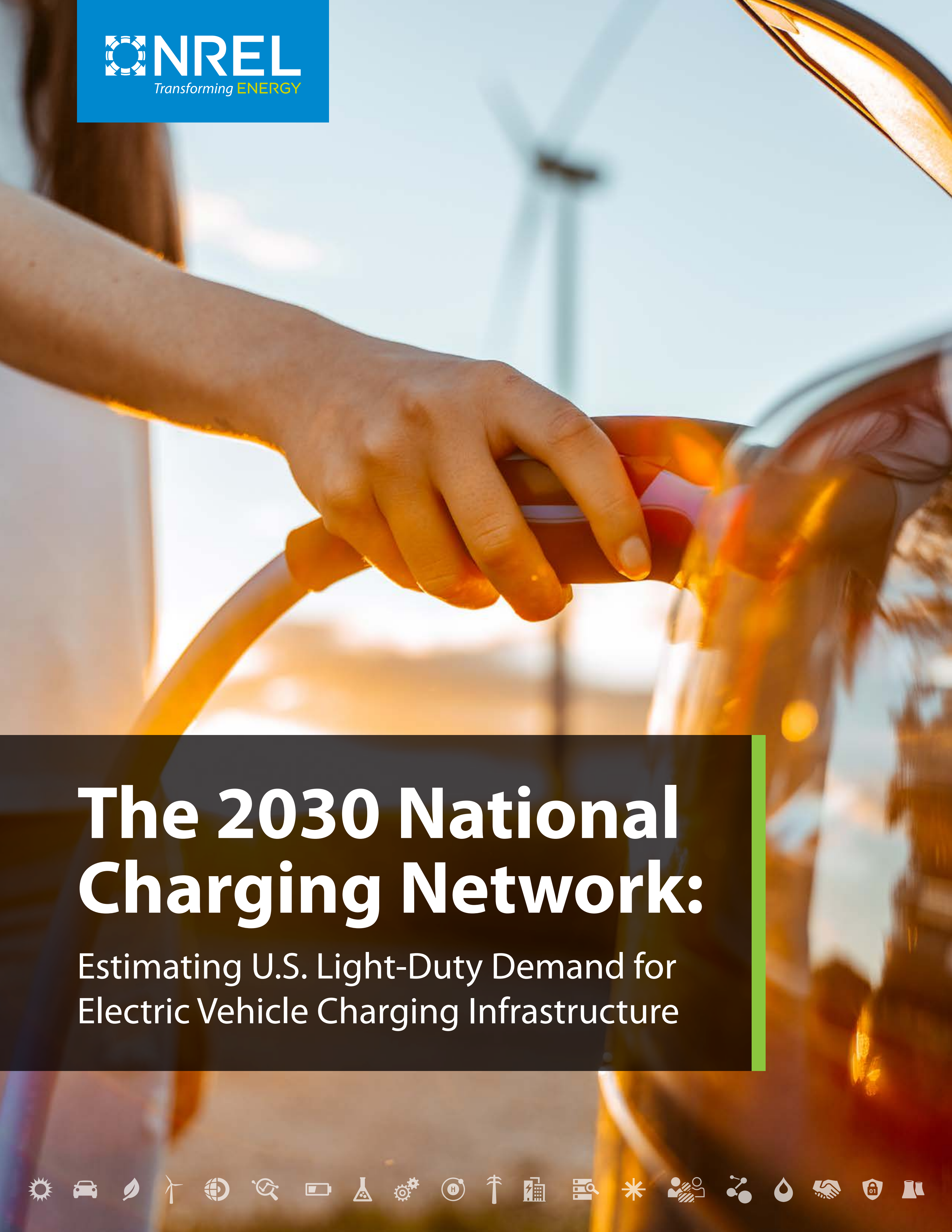

NREL
Transforming ENERGY

The 2030 National Charging Network:

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

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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.

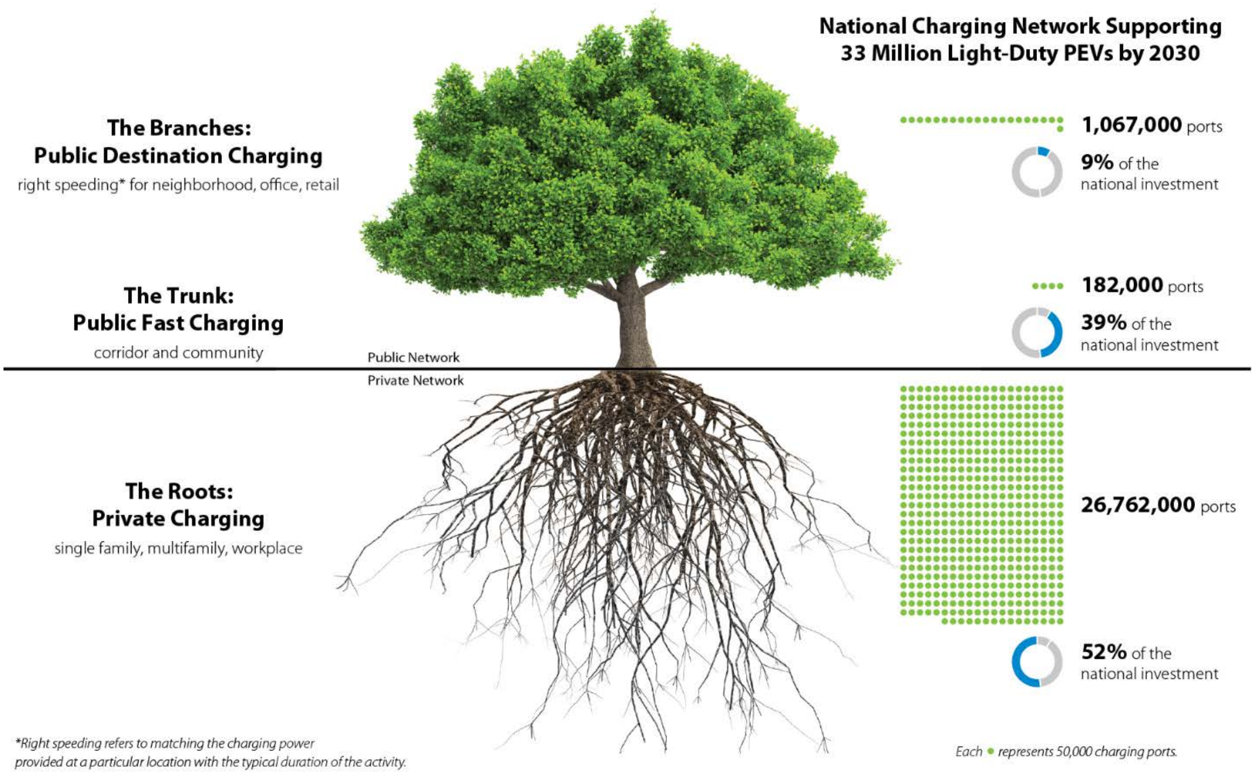

Figure ES-1. Conceptual illustration of national charging infrastructure needs

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.

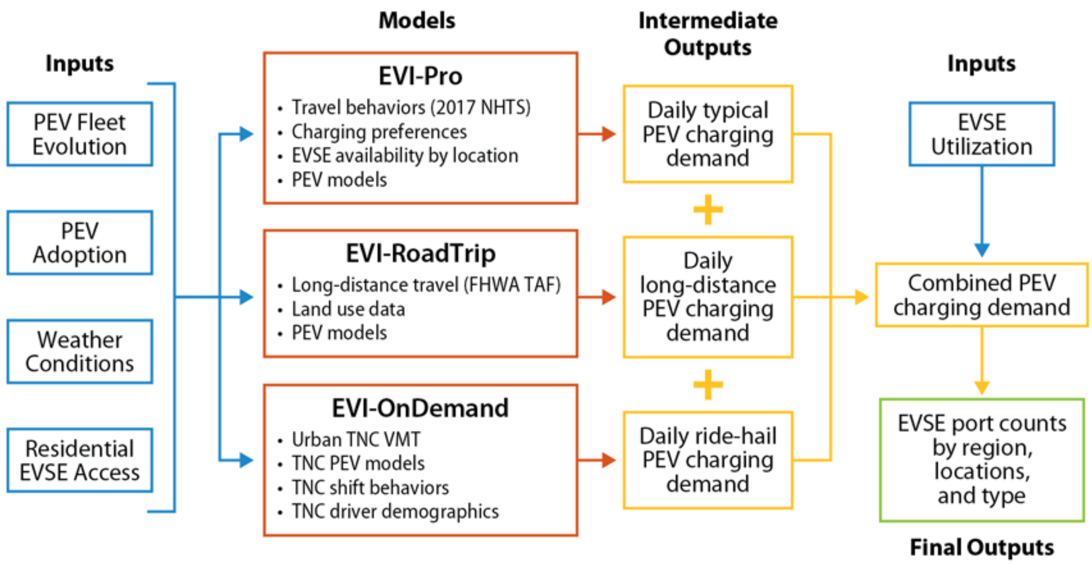

Figure 1. Shared simulation pipeline integrating EVI-Pro, EVI-RoadTrip, and EVI-OnDemand

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).

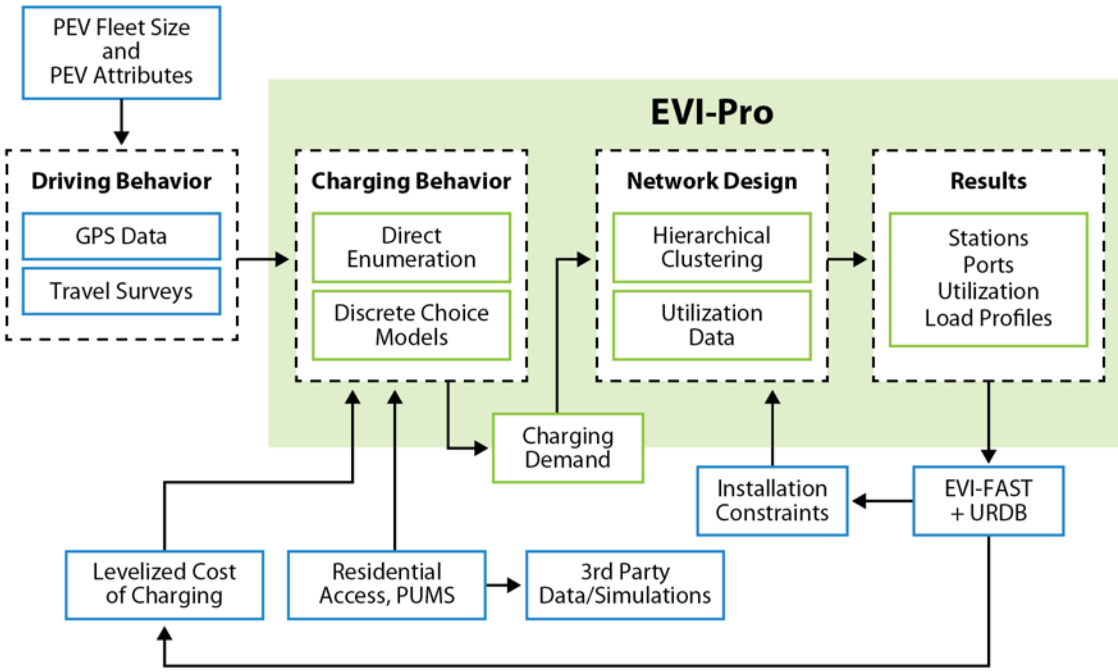

Figure 2. EVI-Pro block diagram for charging behavior simulations and network design

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).

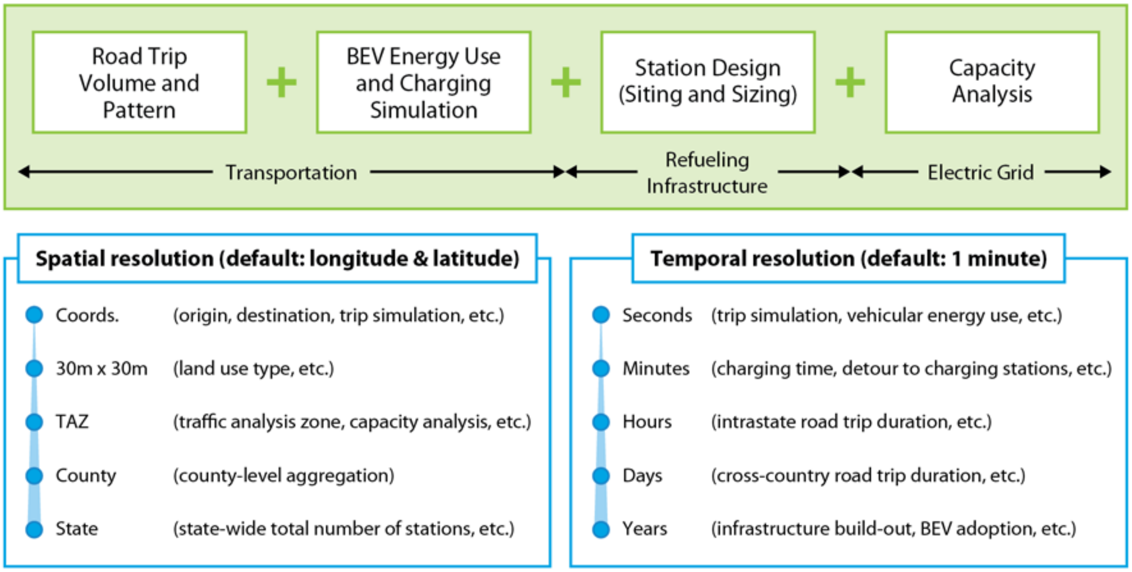

Figure 3. EVI-RoadTrip block diagram for traffic generation, charging behavior simulations, and network design

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.

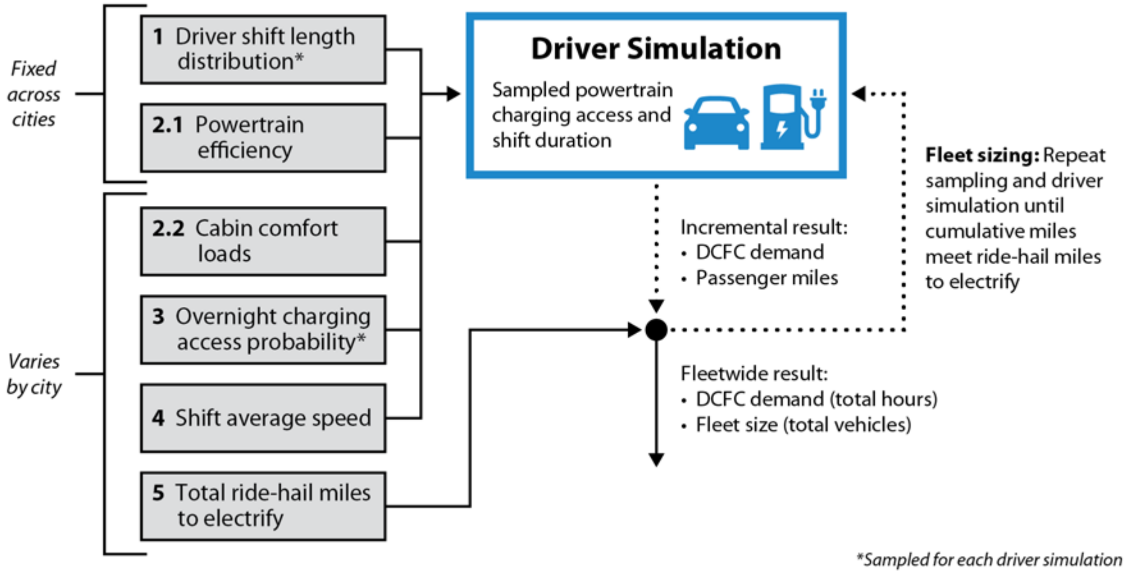

Figure 4. EVI-OnDemand block diagram for driver simulations and related assumptions

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.

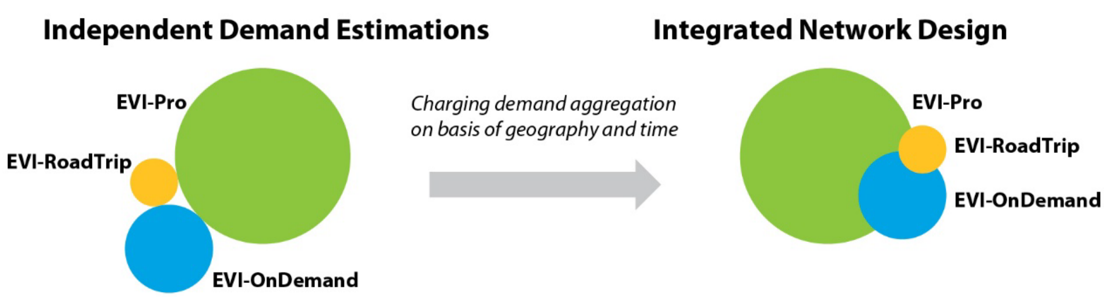

Figure 5. Conceptual diagram illustrating independent demand estimations, demand aggregation, and integrated network design

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.

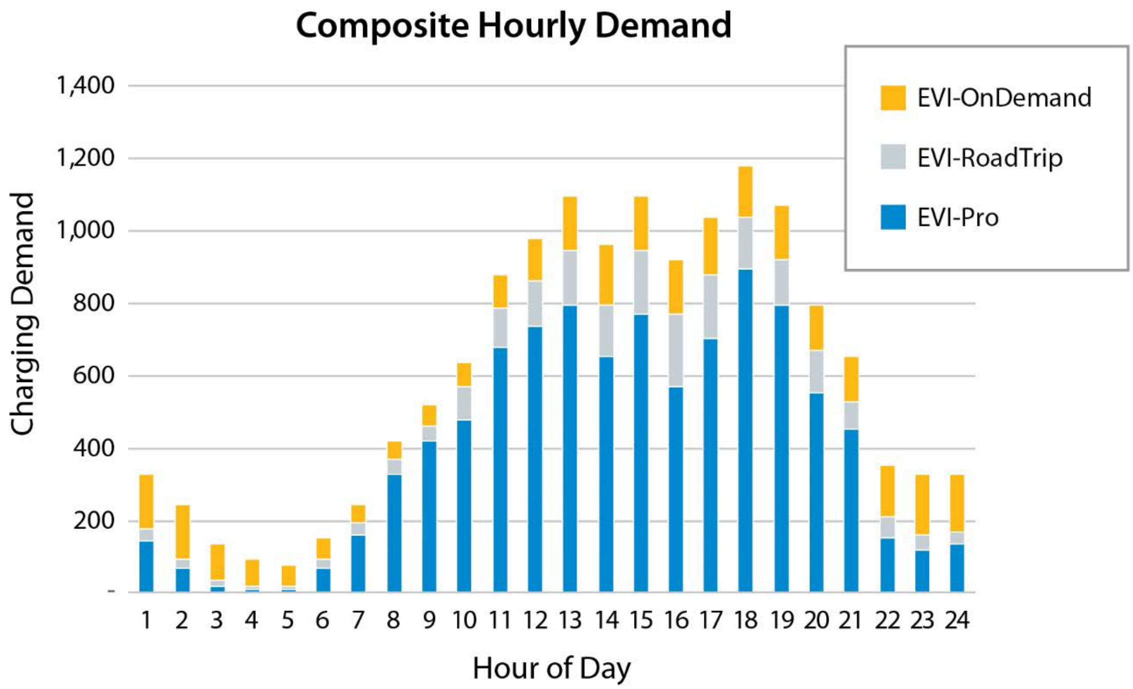

Figure 6. Composite hourly demand for DC charging by use case for an illustrative region

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.

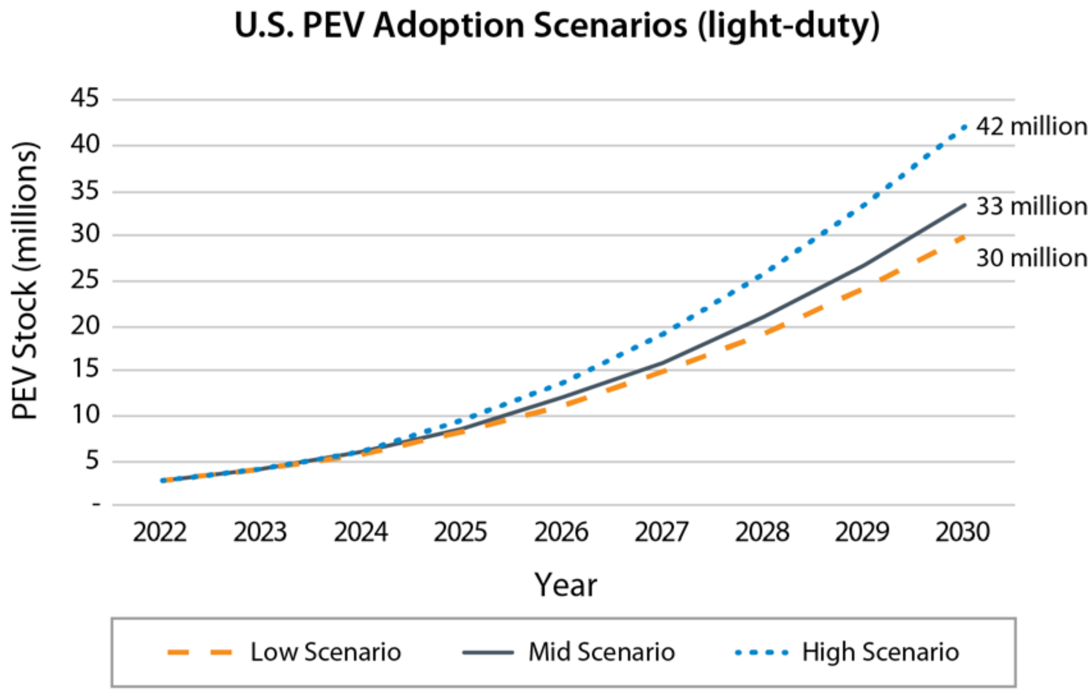

Figure 7. U.S. national light-duty PEV stock under three adoption scenarios

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.

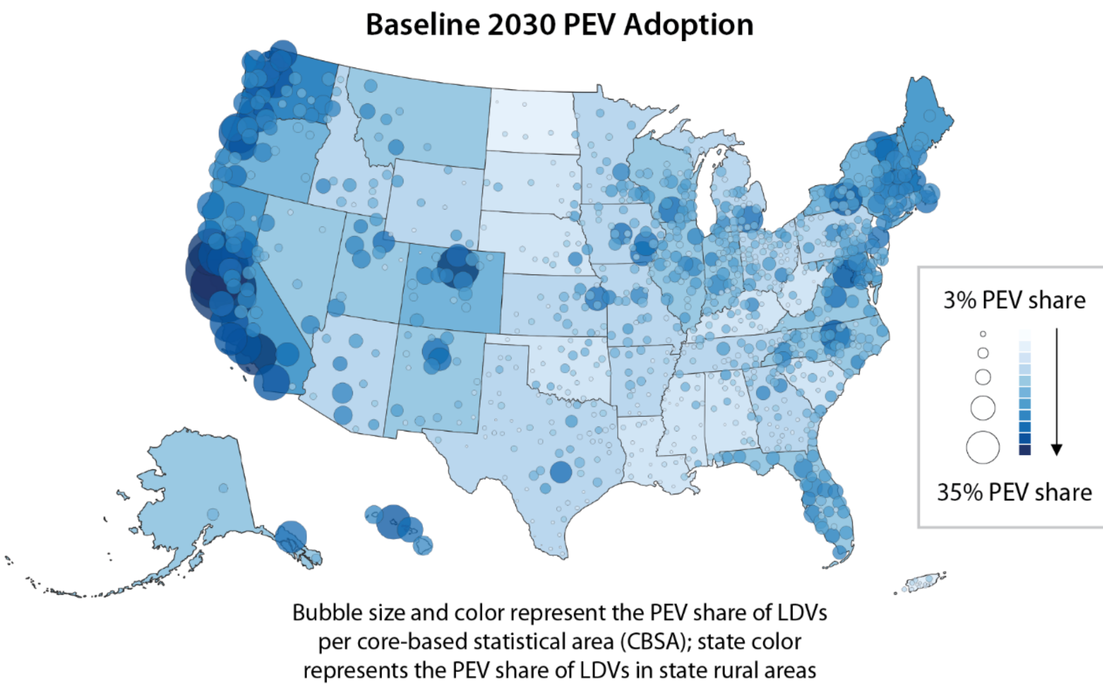

Figure 8. Assumed spatial distribution of 33 million PEVs in 2030 by CBSA and state

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.

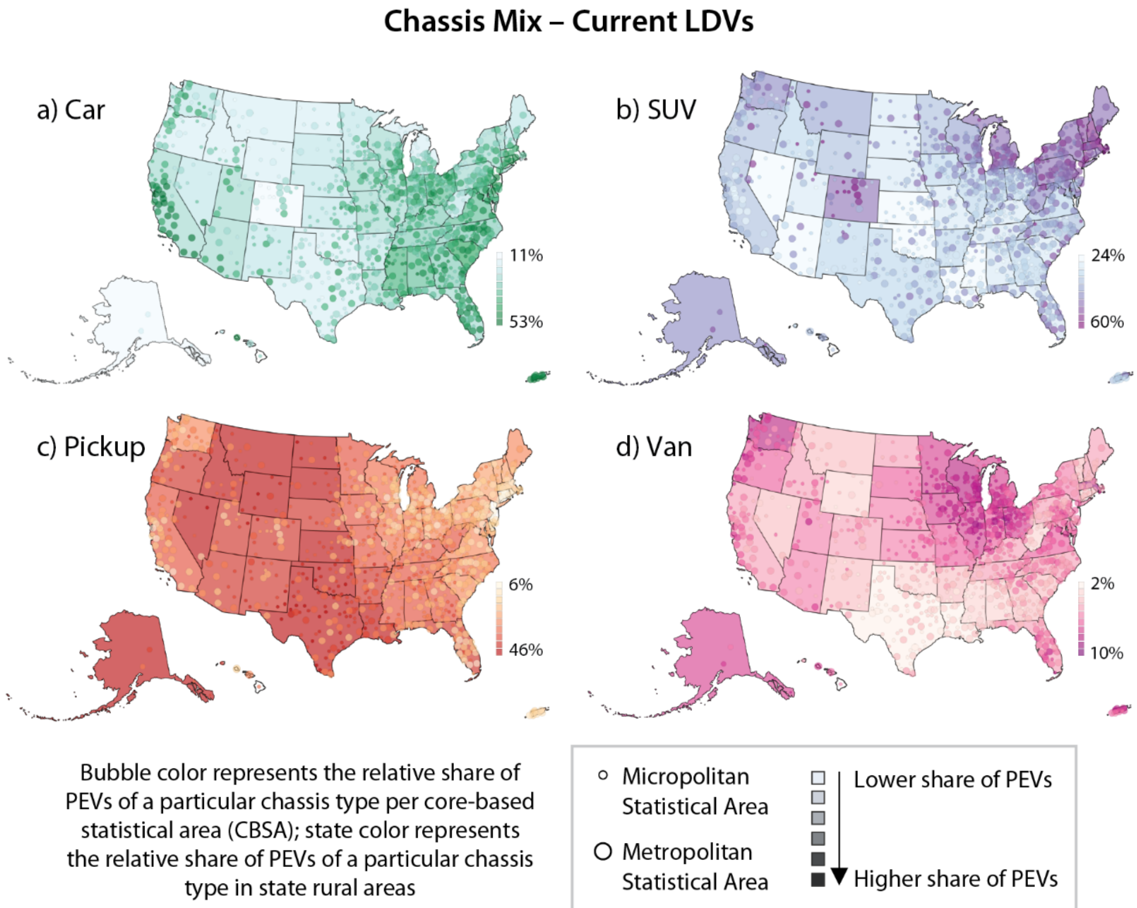

Figure 9. Spatial distribution of new (2019–2022) LDV registrations by body type.

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.

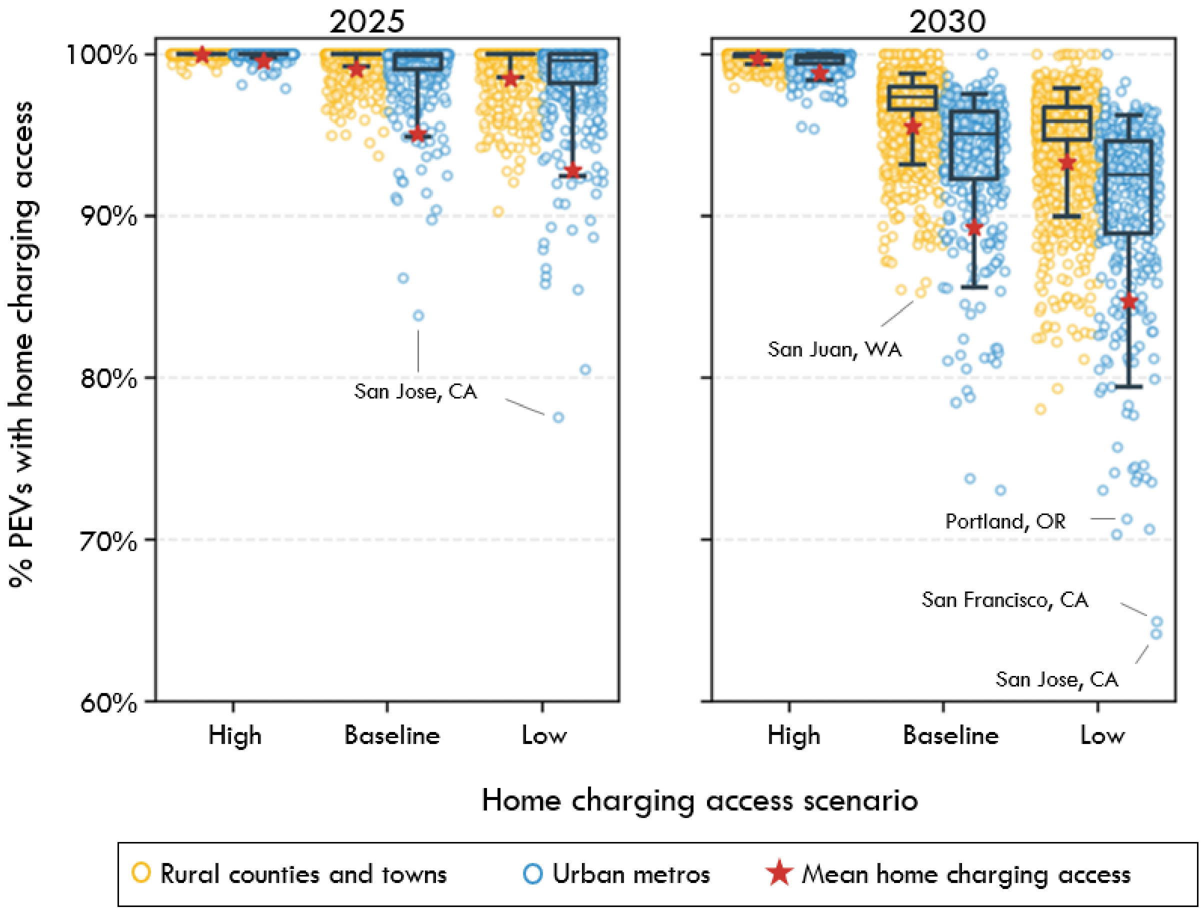

Figure 10. Residential charging accessibility scenarios as a function of PEV stock share. In the boxplot figure, the box reflects the inner quartile range (25%–75%), with the horizontal line reflecting the median value. Whiskers represent the 5th and 95th percentile values, respectively.

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.

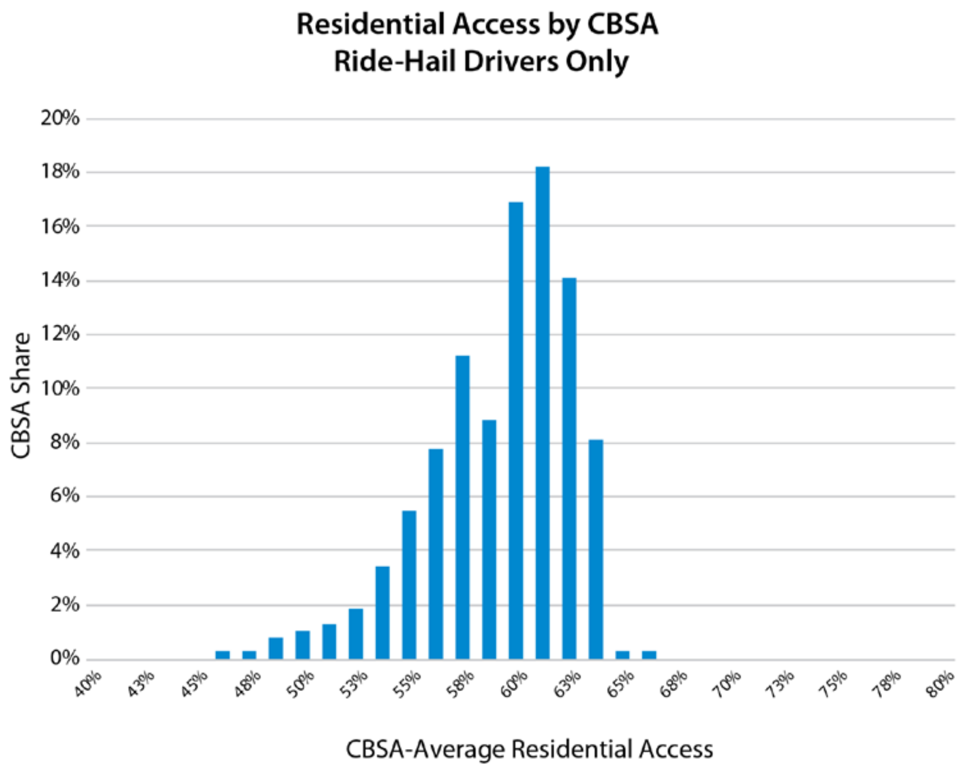

Figure 11. Likelihood of overnight charging access for ride-hailing drivers for the baseline scenario across all metropolitan CBSAs

[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.

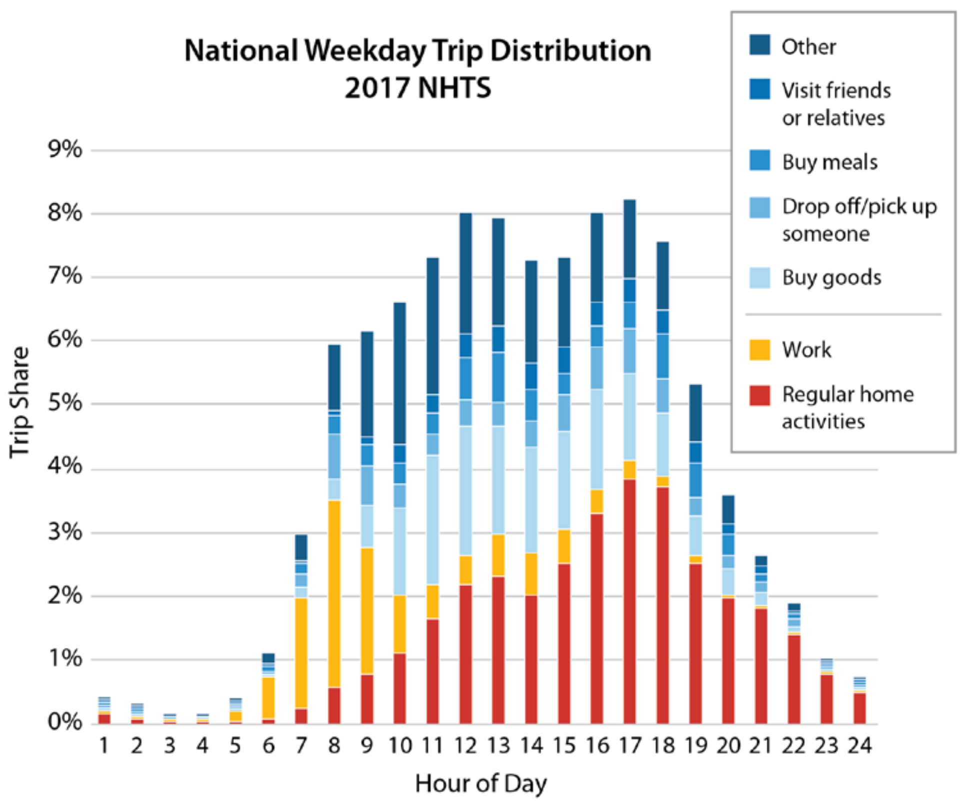

Figure 12. 2017 NHTS auto weekday trip distribution by hour of day and activity type ("other" activities include general errands, buy services, exercise, recreational activities, health care visits, religious or community activities, work-related meetings, volunteer activities, paid work from home, attending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

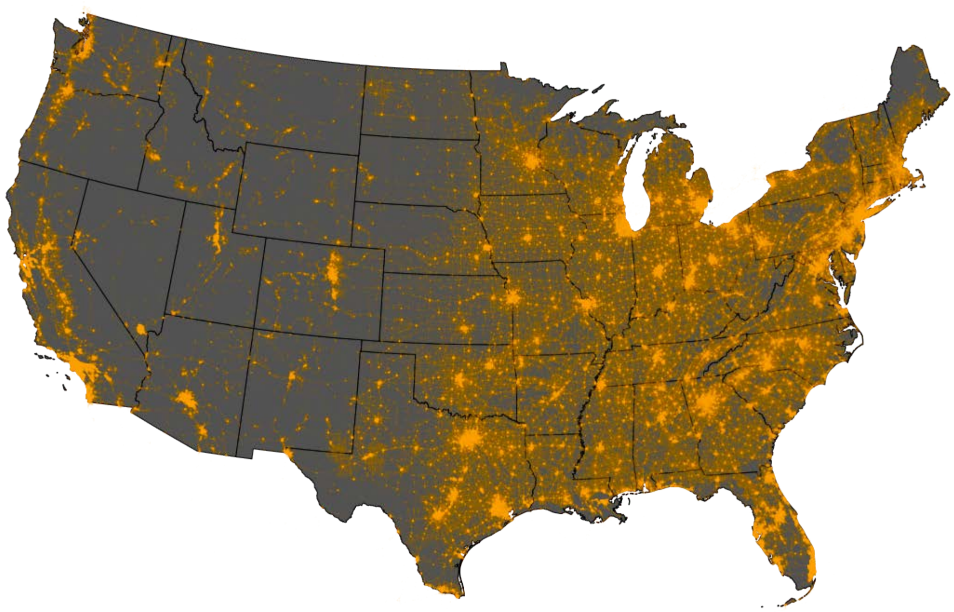

Figure 13. National origin-destination data set from Jan.–Feb. 2020 (licensed from INRIX)

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.

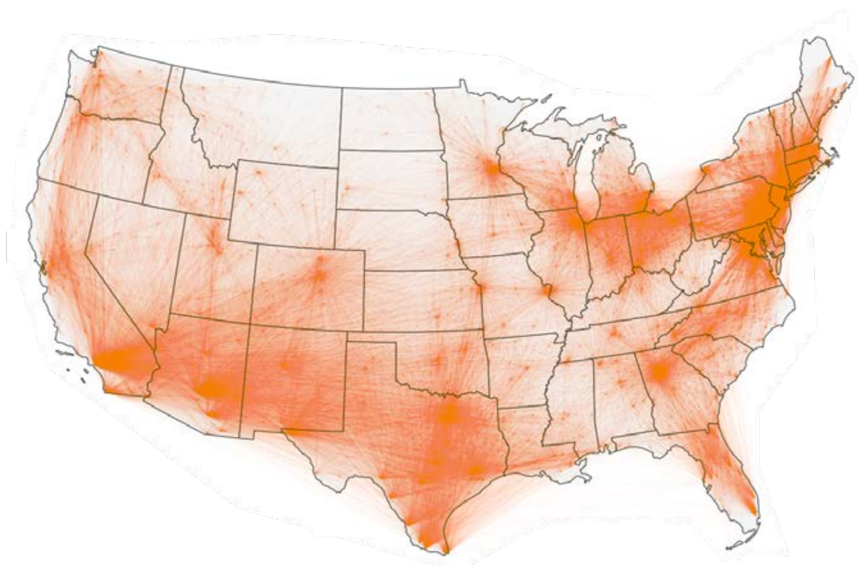

Figure 14. County-to-country origin-destination flows visualized from the FHWA TAF data set

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.

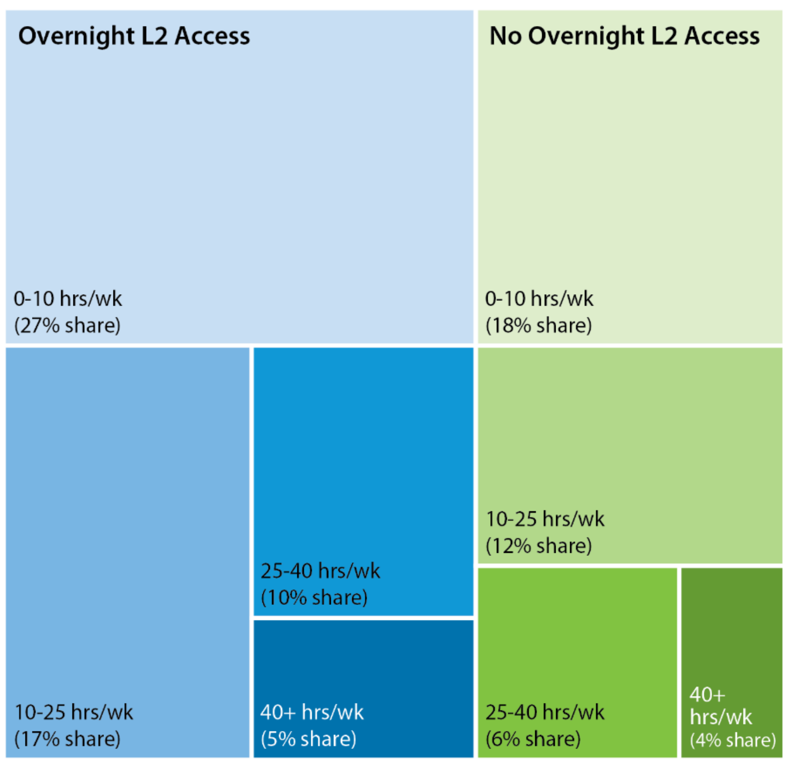

Figure 15. Assumed national composition of ride-hailing drivers by shift type and residential charging access

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]

[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).

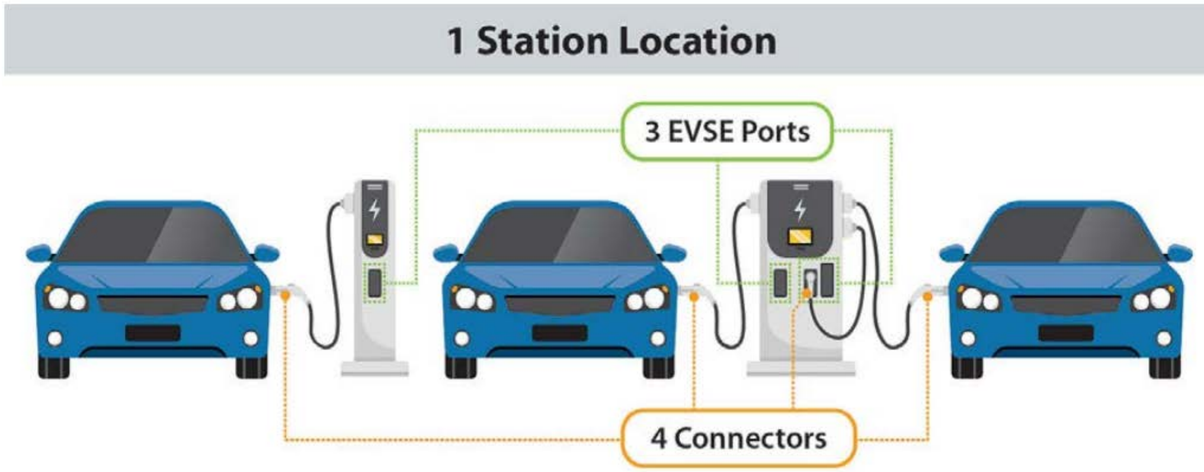

Figure 16. PEV charging infrastructure hierarchy.

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.

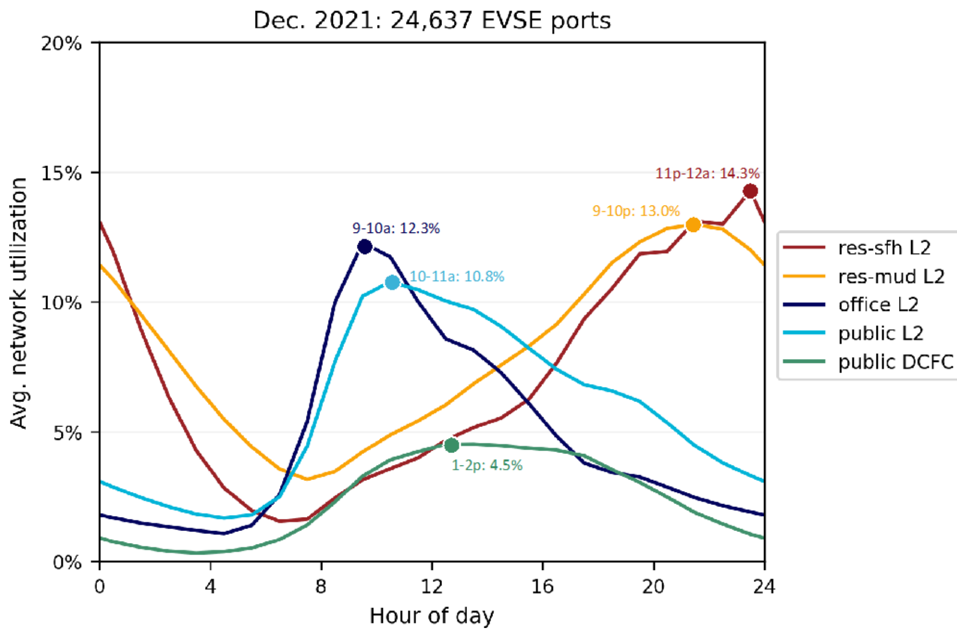

Figure 18. Average network utilization across 24,637 ports from December 2021 by location and EVSE type.

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.

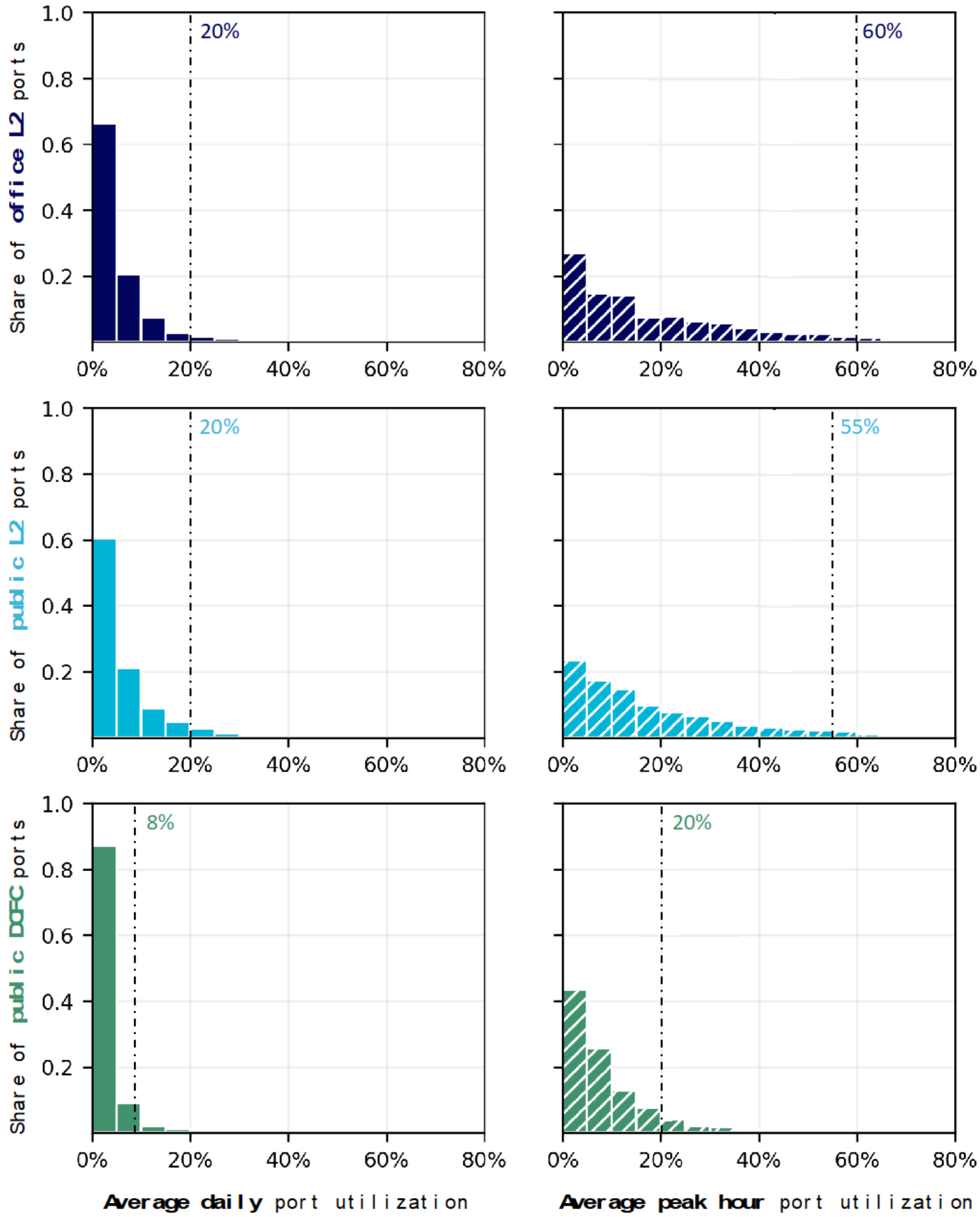

Figure 19. Distribution of average daily port utilization and average peak hour port utilization by location and EVSE type.

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)

Access	Port (thousands)	EVSE / Location	Port (thousands)
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.

Access	Access Cost	EVSE Cost	Type / Location	Cost (% of total)
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).

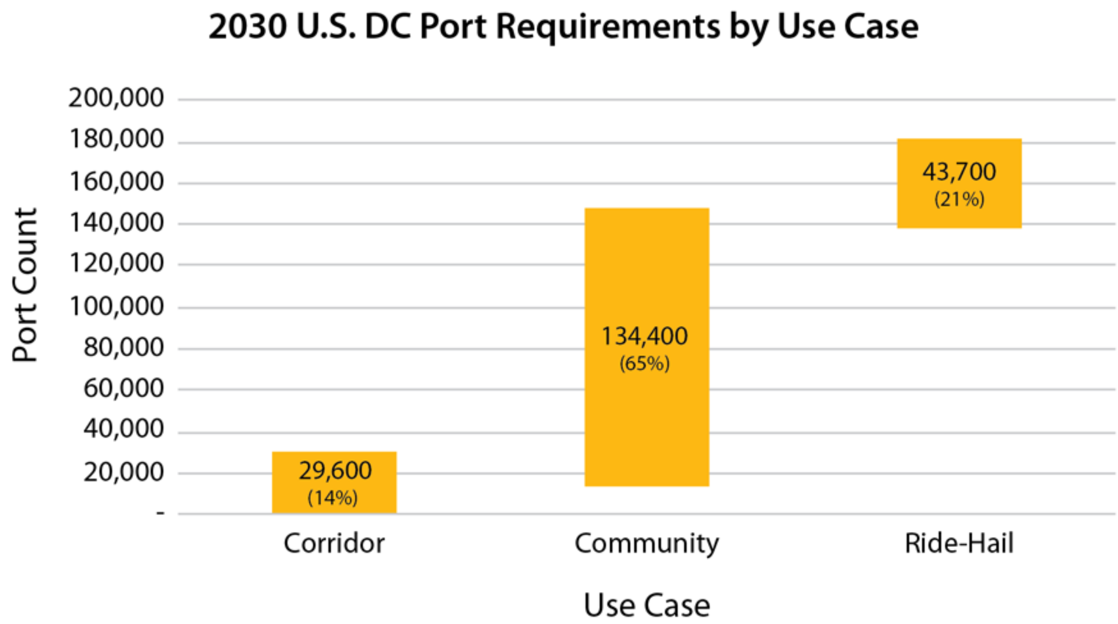

Figure 20. Simulated national DC charging network sized individually by use case and sized by consolidating demand

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.

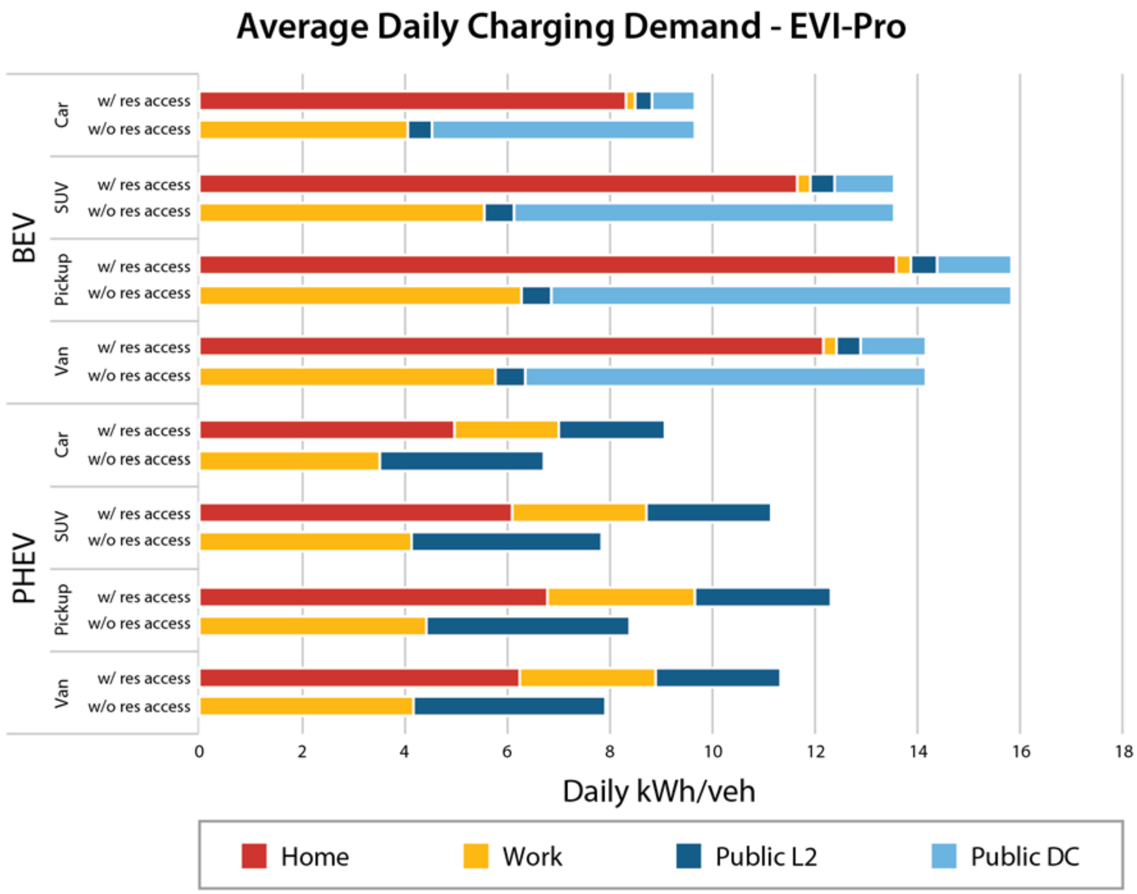

Figure 21. Average daily charging demand simulated by EVI-Pro for typical daily travel, broken out by powertrain type, body style, and residential access

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.

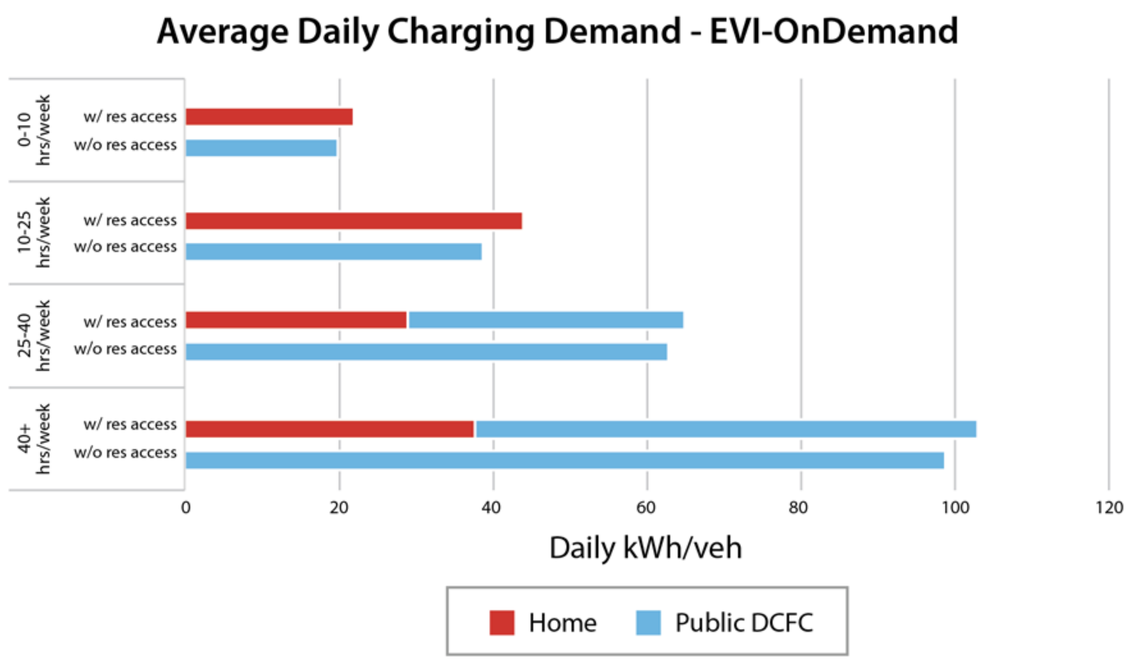

Figure 22. Average daily charging demand simulated by EVI-OnDemand for ride-hailing use cases, broken out by shift duration and residential access

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

CBSA	PEVs	Public L2 Ports: 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

CBSA	PEVs	Public DC Ports: 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**

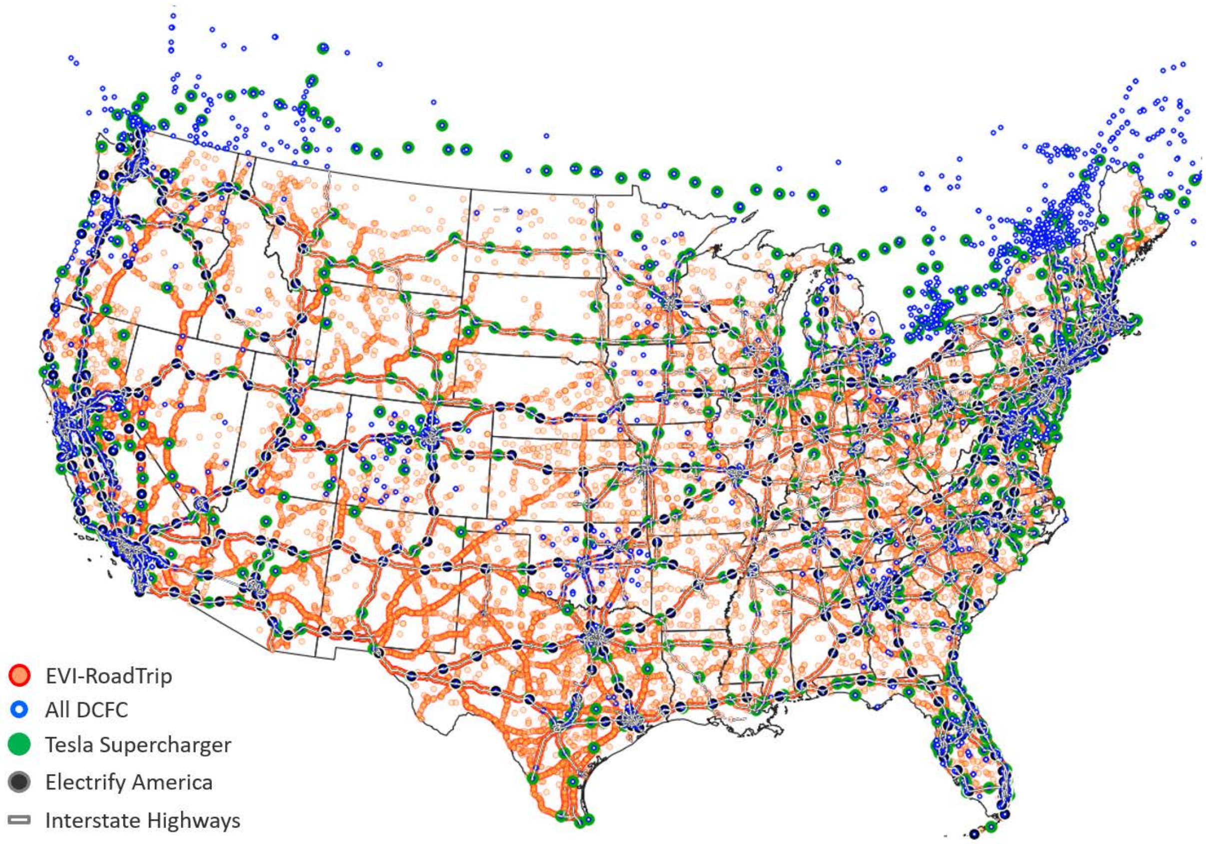

Figure 23. Example charging demand from EVI-RoadTrip overlaid with locations of existing DC stations, including those part of the Tesla Supercharger and Electrify America networks

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.

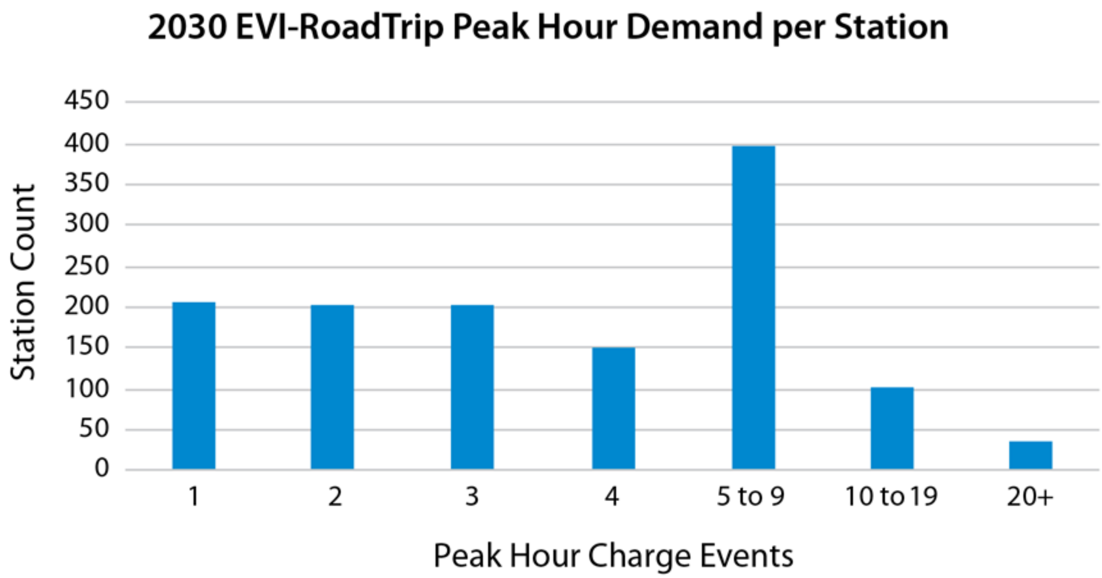

Figure 24. Distribution of peak hourly utilization across corridor stations as simulated by EVI-RoadTrip

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.

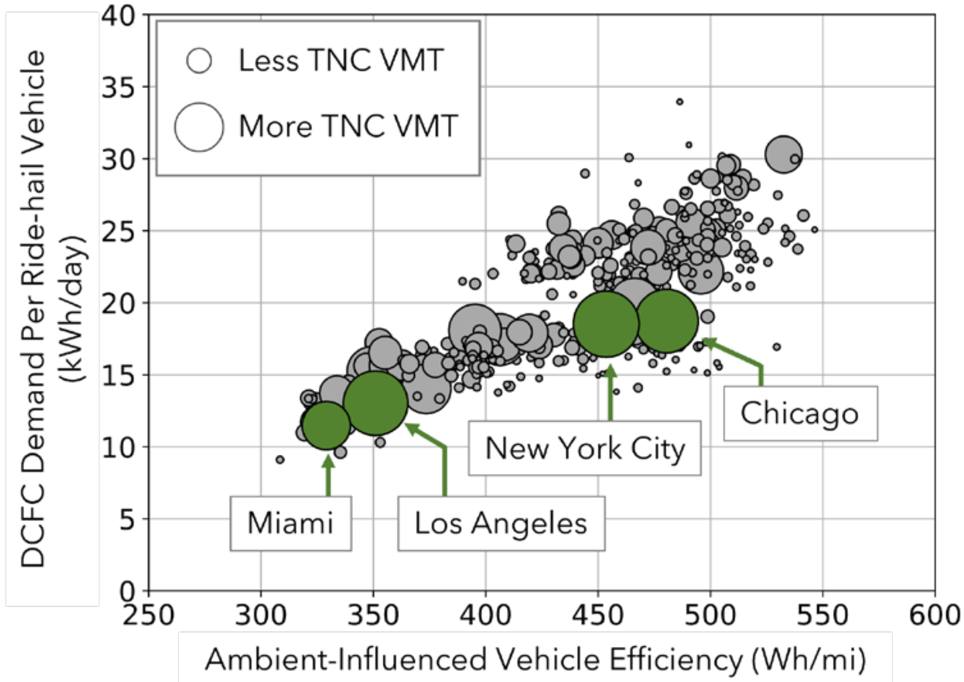

Figure 25. Normalized DC charging demand across CBSAs as a function of worst-case ambient conditions

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).

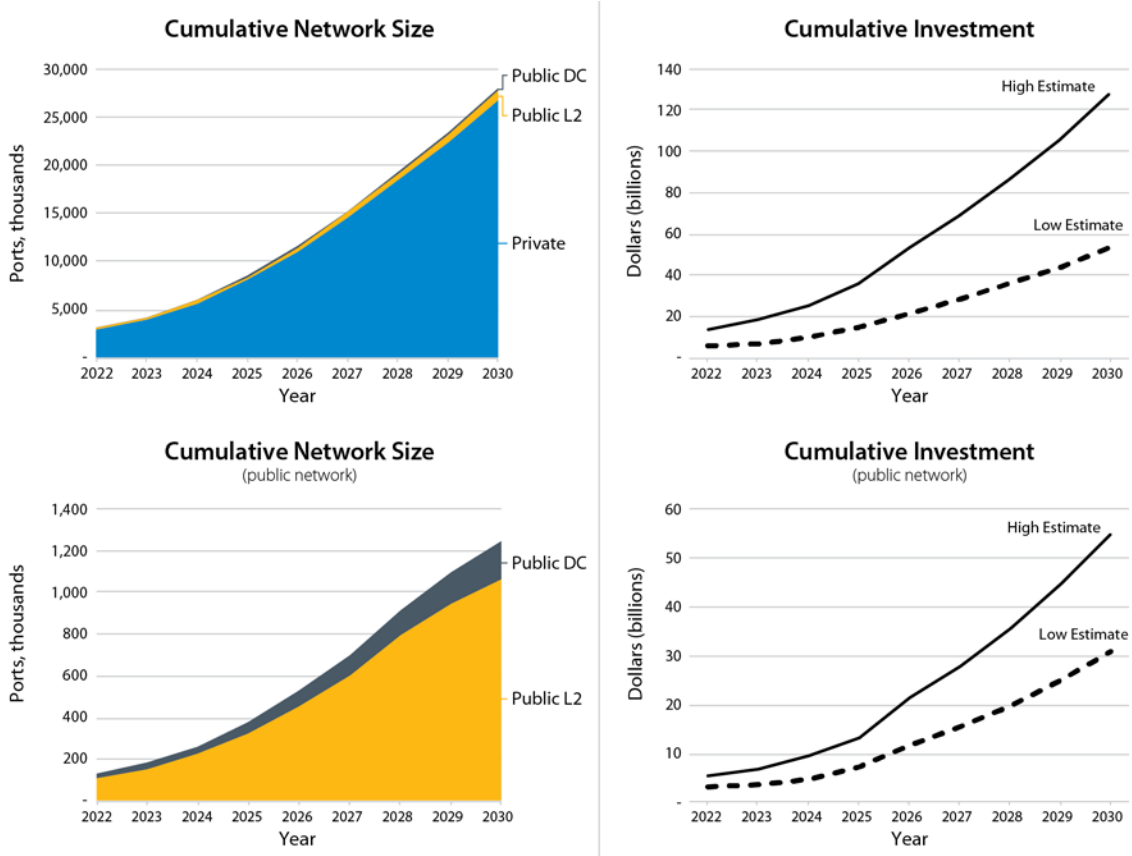

Figure 26. Simulated cumulative network size (left column) and cumulative investment (right column) between 2022 and 2030. Both private and public infrastructure estimates are shown in the top row, while the bottom row isolates the public network result.

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.

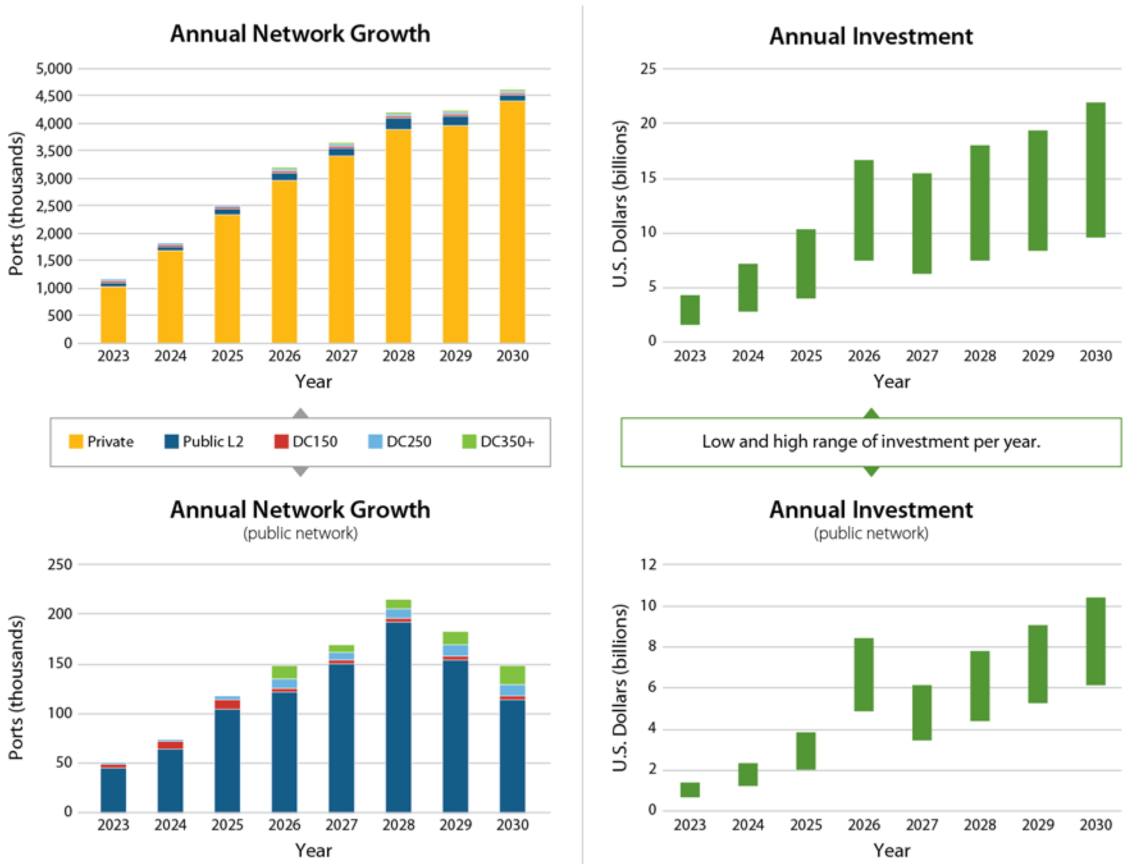

Figure 27. Simulated annual network growth (left column) and investment need (right column) between 2023 and 2030. Both private and public infrastructure estimates are shown in the top row, while the bottom row isolates the public network result.

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).

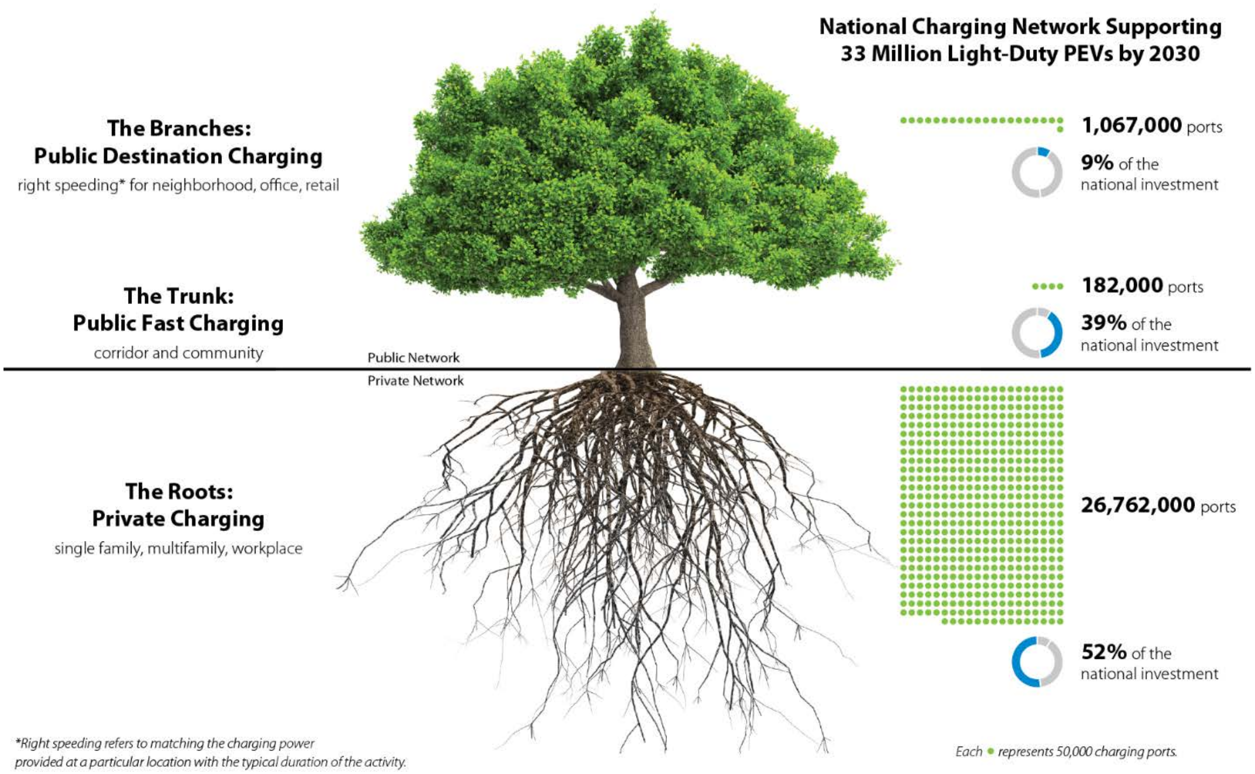

Figure 28. Conceptual illustration of national charging infrastructure needs

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.

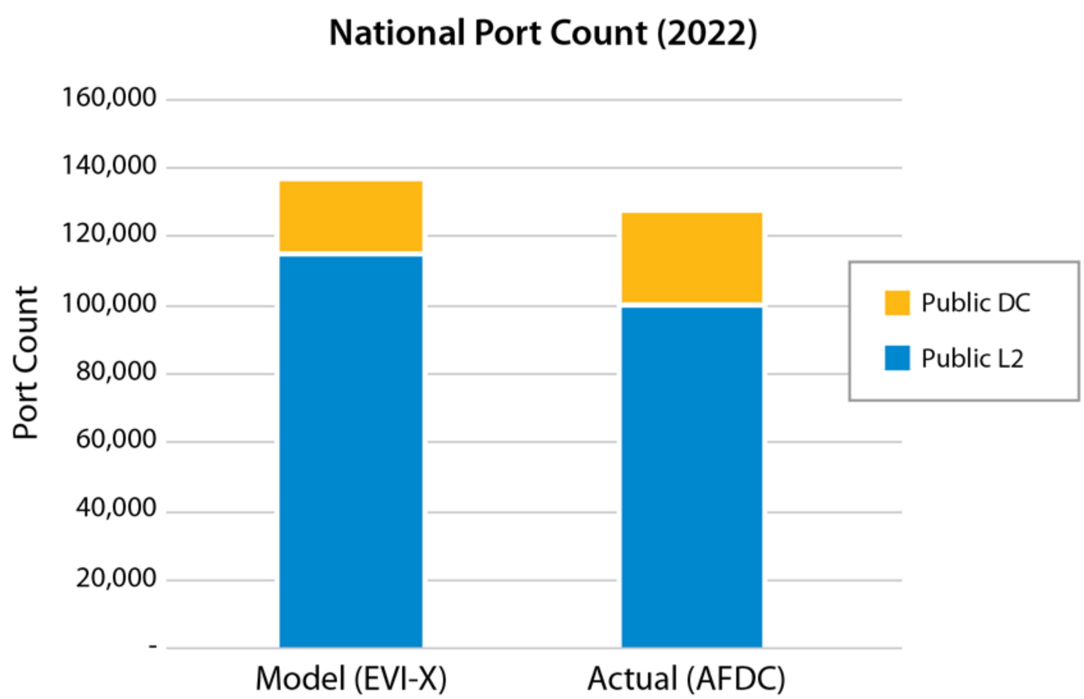

Figure A-1. Size of the 2022 national charging network as simulated in the national pipeline compared to the actual network as measured by the Alternative Fuels Data Center

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