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California Energy Commission

STAFF REPORT

California Plug-In Electric Vehicle Infrastructure Projections: 2017-2025

Future Infrastructure Needs for Reaching the State's Zero-Emission-Vehicle Deployment Goals

California Energy Commission

Edmund G. Brown Jr., Governor

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ABSTRACT

This report analyzes plug-in electric vehicle (PEV) infrastructure needs in California from 2017 to 2025 in a scenario where the state's zero-emission vehicle (ZEV) deployment goals are achieved by light-duty vehicles, primarily in residential use. The statewide infrastructure needs are evaluated by using the Electric Vehicle Infrastructure Projection tool, which incorporates representative statewide travel data from the *2010-2012 California Household Travel Survey*. The infrastructure solution presented in this assessment addresses two primary objectives: (1) enabling travel for battery-electric vehicles and (2) maximizing the electric vehicle-miles traveled for plug-in hybrid-electric vehicles. The analysis is performed at the county level for each year between 2017 and 2025 while considering potential technology improvements. The results from this study present an infrastructure solution that can promote market growth for PEVs to reach the state's ZEV goals by 2025. The results show a need for 99,000 to 133,000 destination chargers, including at workplaces and public locations, and 9,000 to 25,000 fast chargers. The results also show a need for home charging solutions at multifamily dwellings, which are expected to host about 121,000 PEVs by 2025. Therefore, the total number of chargers needed to support PEVs in California ranges from 229,000 to 279,000. This range does not account for chargers at single-family homes. An improvement to the scientific literature, this analysis evaluates the significance of infrastructure reliability and accessibility on the quantification of charger demand.

Keywords: Plug-in electric vehicles, zero-emission vehicles, charging infrastructure, charger projections, demand assessment

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EXECUTIVE SUMMARY

Transforming California's transportation system to consist primarily of zero-emission vehicles (ZEVs) that use low-carbon and renewable fuels is critical to reducing the impacts of climate change and meeting federal requirements to improve air quality. The transportation sector represents the largest source of air pollution in California, accounting for nearly 80 percent of the nitrogen oxide emissions and 90 percent of diesel particulate matter emissions. As of 2015, transportation, including indirect emissions from fossil fuel production and refining, accounted for nearly half of the greenhouse gas emissions in California. Specifically, direct fuel combustion emissions from light-duty vehicles accounted for more than one-quarter (26 percent) of the state's carbon footprint.

Numerous California energy policies and vehicle regulations have prioritized the drastic reduction of vehicle emissions to reduce harm to human health and the risk of climate change. Governor Edmund G. Brown Jr.'s Executive Order B-16-2012 punctuated statewide efforts to electrify the transportation sector, calling on the California Energy Commission and other state agencies to support benchmarks to achieve, principally among other goals, 1.5 million ZEVs on California's roads and to ensure that Californians have easy access to ZEV infrastructure by 2025. In California, as of the end of 2017, nearly 14,000 public chargers, including 1,500 direct current fast chargers (DCFC), served 350,000 plug-in electric vehicles. This report quantifies the current and future charging infrastructure necessary to attain California's near-term transportation electrification goals as identified in Executive Order B-48-18 "*to spur the construction and installation of 250,000 electric vehicle chargers, including 10,000 direct current fast chargers*." California's government agencies and the private sector will need to exceed these targets in order *"to put at least 5 million zero-emission vehicles on California roads by 2030."*

Electric Vehicle Infrastructure Projections Method Overview

Energy Commission staff worked with the National Renewable Energy Laboratory (NREL) to develop the Electric Vehicle Infrastructure Projection (EVI-Pro) computer simulation tool. The EVI-Pro quantifies the types of charging infrastructure needed to ensure that plug-in electric vehicle (PEV) drivers can meet their transportation needs. This study applies EVI-Pro in the context of the continuously evolving California market, chiefly in succession of the 2014 *California Statewide Plug-In Electric Vehicle Infrastructure Assessment*. This 2018 study fundamentally improves upon the 2014 Assessment, which used travel and charging data from early PEV adopters to predict the quantities of chargers needed in California. The new study builds upon recent methods that model the behaviors of PEV drivers to predict chargers needed. The principal specialization of EVI-Pro in quantifying charging needed is the ability to account for sources of variation and uncertainty in vehicle and charger technologies, user demographics and market adoption conditions, the shared-use of chargers, and travel and charging preferences while using an electric vehicle. The following is a high-level summary of the method and analysis of California's need, focusing on light-duty vehicles primarily on residential use.

A fundamental element in the EVI-Pro is the simulation of travel behavior of households that are representative of mainstream drivers, as opposed to that of early PEV adopters. A survey of real-world behaviors was used to derive origins, destinations, and schedules of mainstream drivers across California's 58 counties. The use of a statewide representative sample is essential to quantify the charging necessary to promote the widespread replacement of conventional fuel vehicles with electric vehicles.

An individual's charging requirements are subject to the driver's preferences for convenience and to reduce cost. To reflect mass-market convenience, the model assumes that drivers will have a low tolerance for modifying their driving schedules. In other words, drivers are not assumed to remain at a particular location longer than they would have otherwise to recharge their vehicles. Second, EVI-Pro simulates drivers as economically rational and with an ability to choose among multiple potential charging locations, including at home, based on the price of electricity. If drivers that have economical home charging are price-responsive and motivated to reduce their transportation costs, the total quantity of work and public charging required to serve a county can be reduced. For example, pricing nonresidential chargers can avoid a substitution effect where drivers charge for free at work who would otherwise charge at home at a low cost. This substitution among charger locations may block other users without home charging and increase the number and associated costs of work and public charging. Conservatively, EVI-Pro assumes that drivers will require their vehicle to maintain a predefined level of travel range, as a proxy to reduce "range anxiety," or the concern that driving with a battery of a certain range would be insufficient to complete a given trip. The aggregation, or collection, of driving simulations determines the number of vehicles that require chargers of varying power levels, among three types of locations: at home, at work, or at public locations.

Input Assumptions

Four major categories of inputs are needed to complete the driving and charging simulations. These categories include vehicle attributes, charger attributes, county-level household travel data, and the composition of the vehicle fleet (or PEV sales). This approach was used by the U.S. Department of Energy and NREL in their *National Plug-In Electric Vehicle Infrastructure Analysis* released in 2017. The analysis calculated charger-per-1,000 PEV ratios with various technology and market scenarios, many of which differ from assumptions summarized below. Stakeholders are encouraged to refer to this report as the primary reference for California-specific infrastructure planning.

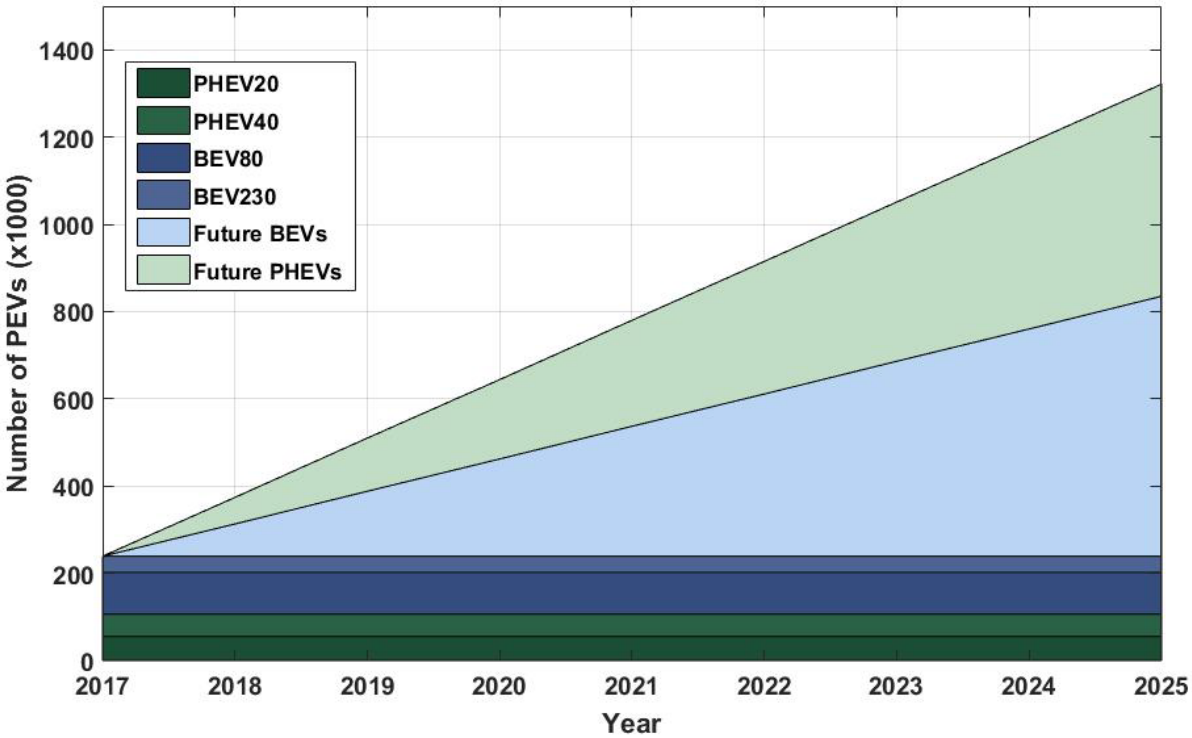
The principal vehicle technology assumption is the electric range of battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), which increase each year consistent with the California Air Resource Board's (CARB) technical review of vehicle battery technologies under the Advanced Clean Cars Program. The principal charger technology assumption is average dispenser power capacity, which varies by charger type and the capability of a vehicle to receive the power into the battery. For simplicity, all BEVs and no PHEVs are assumed capable of DC fast charging. Charge power increases each year linearly between ranges assessed by the Energy

Commission. As noted earlier, location-based driver preferences to charge their vehicles are input into the model; price signals are set relative to one another in the order of residential, workplace, and public charging to reflect the cost of infrastructure.

The *2010-2012 California Household Travel Survey* features 24-hour daily travel profiles representative of mainstream driving behaviors at the county level. In EVI-Pro, the availability for a simulated driver to charge at home is based on information on the driver's type of residence. Without detailed information about the availability of parking, all vehicles associated with single-family homes and multiunit dwellings with more than five units were assumed to have access to a residential charger.

Assumptions of the composition of the PEV fleet are derived from an interpolation between the actual shares of BEVs and PHEVs adopted as of 2017 and CARB's assumptions of the plug-in share of ZEV adoption defined in the Clean Technologies and Fuels Scenario by 2025. The ratio of the two PEV types adopted was held constant for the planning period under a linear growth assumption for the overall fleet (as seen on Figure ES.1). Vehicles were geographically distributed among the 58 counties in California with the assumption that the adoption rates of electric vehicles by county would converge toward the purchase rates of all new vehicles, as identified by 2012-2016 vehicle registration data from IHS Markit. As a result, by 2025 about 90 percent of the PEVs were distributed to the counties identified within the four largest metropolitan planning regions of California (Southern California, the San Francisco Bay Area, San Diego County, and the larger Sacramento area).

Figure ES.1: Shares of PEVs Input for the Default Scenario, 2017-2025



Source: California Energy Commission and NREL

Analysis and Results

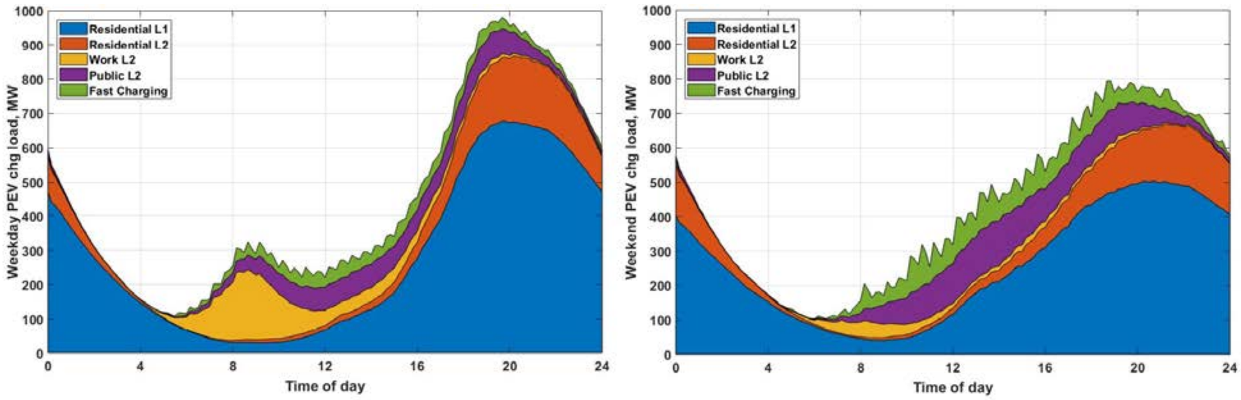
The number of chargers needed in a given county is based on the location and time when a charger is necessary to satisfy a driver's travel schedule. Therefore, EVI-Pro outputs electricity demand and the quantity of sessions at homes, workplaces, and in public. Both outputs are resolved hourly for each county and then aggregated for the entire state.

Weekday charging demand creates a more dynamic electricity demand profile compared to weekend charging demand. As seen on Figure ES.2, two peaks for the weekday load coincide with vehicles arriving at work in the morning and returning home during the evening. By 2025, workplace chargers demand more than 200 megawatts (MW) at the peak time of around 9 a.m., and residential chargers demand almost 900 MW at 8 p.m. In contrast, peak demands above 120 MW associated with both public Level 2 and fast chargers occur on the weekends.[1] Fast chargers peak before 11 a.m., and public Level 2 chargers peak after 1 p.m. By 2025, during weekdays, the aggregate demand from all charging types represents an increase of roughly 500 MW between 4 p.m. and 7 p.m., with a maximum demand of nearly 1,000 MW before 8 p.m. The subhourly electricity load shape for DC fast chargers is more volatile than other charging types, as indicated by statewide fast charging load more than doubling to peak demand within one

1 The term "charger" refers to a connector that can serve a vehicle at the full rated power capacity without any operational limitations. The rated power capacity is grouped into alternating current Level 1 (1.4 kW), Level 2 (3.6kW – 11.4 kW), and direct current (DC) fast chargers (50 – 105 kW).

hour. All types of charging loads will need to be integrated efficiently with the grid to prevent additional ramping generators and stress on distribution infrastructure.

Figure ES.2: PEV Charging Load Profiles in 2025



Source: California Energy Commission and NREL

To quantify the number of chargers, EVI-Pro calculates two outputs for each type of nonresidential location and charging power level. The first output is the total number of vehicle charging events over a 24-hour period. This charging session quantity is the basis for the "high estimate" of charging needed. The quantity of total sessions is divided by two to reflect the likelihood that a public charger is shared with at least one other vehicle, and a charging station operator's economic incentive to best use a public asset. In contrast with Level 2 chargers, this 2:1 sharing ratio in the high estimate is a very conservative proxy for the use of a fast charger. Higher sharing ratios for fast chargers were not used because of the limited sharing potential in some rural counties and the desire for consistent application of the method statewide.

The second output is the maximum number of vehicles that need to charge at any time over a given day. This peak vehicle quantity is the basis for the "low estimate" of charging needed insofar as it represents the minimum quantity of chargers that must be available to meet drivers' simultaneous need to charge. This minimum quantity is scaled to account for the total quantity of charging sessions over a day, in case that sessions needed at times other than during the peak time are sufficiently far away from each other and inhibit drivers' ability to share chargers.

By 2025, to support about 1.3 million PEVs, California needs between 99,000 and 133,000 destination chargers at or near workplaces and in public locations, between 9,000 and 25,000 public DC fast chargers, and 121,000 chargers at multiunit dwellings (MUDs). The total number of chargers needed to support PEVs in California ranges from 229,000 to 279,000. This range does not account for chargers at single-family homes. EVI-Pro results can be compared with actual or planned charger deployments. The quantity of fast chargers available in California in 2017 was less than the number of chargers calculated by EVI-Pro necessary to expand the market for battery electric vehicles (that is, the 1,500 existing fast chargers are at least 25 percent less than the 2,005-5,877 fast chargers listed "as of 2017" in Table ES. 1).

The ranges (as seen on Table ES.1 and Figure ES.3) associated with each charger location are principally affected by the shape of the hourly electricity demand. Charging locations that experience a sharp increase in demand within a brief time frame, like workplaces, will have a smaller range in between the high and low estimates of chargers demanded. The finding regarding the difference in the high and low estimates, similarly with respect to locations of chargers, also applies geographically. For example, if a county's travel is predominantly associated with commutes to and from work, the peak demand associated with those charging behaviors will manifest themselves in a relatively small variation in total chargers needed. As seen on Table ES.1, this study considered only Level 2 chargers at workplace and public locations, as Level 2 chargers represent about 95 percent of existing installations accounted by the U.S. Department of Energy's Alternative Fuels Data Center. On the other hand, staff acknowledges that Level 1 chargers may be feasible for some use cases with long dwell times.

Given the total relative quantities of charger types, more than 80 percent of workplace and public Level 2 charging sessions were demanded by PHEV drivers. This result is primarily affected by the electric range limitation of the plug-in hybrids and the drivers' objective to minimize their fueling costs by recharging with electricity instead of using their conventional engines. Since PHEV drivers' actual motivations and charging behaviors will differ from modeled assumptions, this optional use aspect of public charging contrasts with that of BEV drivers, whose demand for fast charging is essential for completing their travel. On the other hand, chargers for PHEVs should be seen as essential for reaching the state's petroleum use reduction goals.

Table ES.1: Projections for Statewide PEV Charger Demand

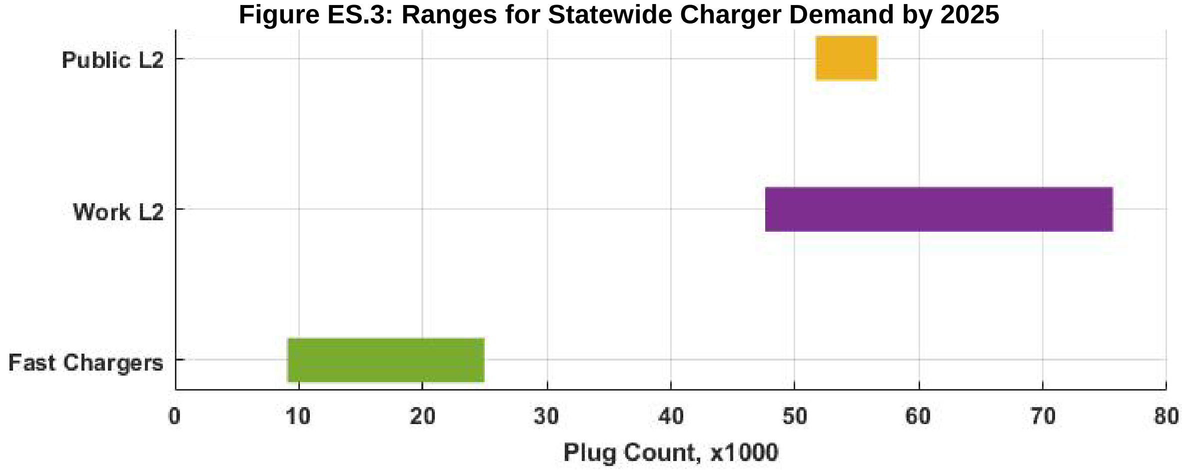
Demand for L2 Destination (Workplace and Public) Chargers (The Default Scenario)			
	Total PEVs	**Lower Estimate (Chargers)**	**Higher Estimate (Chargers)**
As of 2017	239,328	21,502	28,701
By 2020	645,093	53,173	70,368
By 2025	1,321,371	99,333	133,270
Demand for DC Fast Chargers (The Default Scenario)			
	Total BEVs	**Lower Estimate (Chargers)**	**Higher Estimate (Chargers)**
As of 2017	133,386	2,005	5,877
By 2020	356,814	4,881	13,752
By 2025	729,094	9,061	24,967

Source: California Energy Commission and NREL

In the default scenario, charging at home is the foundation for the majority of PEV travel, with more than 90 percent of simulated drivers engaging with either Level 1 or Level 2 charging, while the rest did not use residential charging under the given parking assumptions. However, given the simulations described, there are two cautions in interpreting the findings herein.

First, due to the wide variation in parking configurations and the lack of local information about parking availability, the study made simplifying assumptions about the potential charging at residence types and did not investigate the potential for sharing at residences. Given this, 10 percent of all residential charging, which corresponds to more than 121,000 vehicles, was completed at multiunit dwellings. Second, the EVI-Pro cost-minimization algorithm provided a driver with a Level 2 charger only if a Level 1 charger was not technically able to deliver the driver's energy requirement during their dwelling times. Further, the study did not incorporate drivers' value of time, their potential for unexpected trips, or range anxiety. Based on this assessment, staff found that a minimum of 65,584 PEVs from single-family homes and 6,874 PEVs from multifamily dwellings could not complete their travel with Level 1 charging at home. This group corresponds to nearly 6 percent of the overall PEV sample statewide.

Figure ES.3: Ranges for Statewide Charger Demand by 2025



Source: California Energy Commission and NREL

Finally, a sensitivity analysis of where drivers preferred public Level 2 over public DC fast charging resulted in a substitution in needed fast chargers in favor of destination chargers. However, the sensitivity revealed that compared to actual levels of fast charger deployment, this price preference does not reflect the focus of the charging industry's investments.

Toward 2030 and Beyond

This report quantifies the amount of charging infrastructure needed to stimulate the growth of the light-duty plug-in electric vehicle adoptions for mainstream personal travel patterns in California between 2017 and 2025. In addition to existing charging infrastructure demand modeling approaches, this model specializes in the ability to characterize spatiotemporal effects of demand on the shared use of chargers. An important conclusion is the assurance to drivers that charging will be visible, accessible, and reliably maintained—partly through real-time networking technologies. Networked technologies will be critical to improving the efficiency of charger installations by enabling the shared use of chargers. This has the potential to increase use and reduce the size of the network necessary to support the growing PEV fleet. Leveraging smart-charging technologies in combination with greater diversity in charging power and location- or time-variant prices can enable charging load to be shifted, thereby reducing any new electricity system costs associated with the charging scenario presented.

While the analysis identifies several sources of variance and uncertainty, policy makers and industry should develop consistent policies statewide and locally that ensure the immediate and steady growth in the deployment of chargers to close the gaps necessary for enabling widespread adoption, as envisioned by the 2012 executive order. Consistent with this recommendation, in 2018, CARB updated the *Climate Change Scoping Plan*, which calls for 4.2 million ZEVs on the road by 2030 and to "*comprehensively [facilitate] the market-wide transition to electric drive that we need to see materialize as soon as possible*." In the 2018 State of the State Address and in the subsequent Executive Order B-48-18, Governor Brown set a target with even greater ambition: to deploy 5 million ZEVs in California by 2030. Thus, the quantities of chargers identified for installation by 2025 in this projection should be followed with additional analyses of various infrastructure networks that can serve more than triple the number of PEVs within just five additional years. Simultaneous to the public and private deployments from 2018 to 2025, staff will complete subsequent iterations of EVI-Pro analyses to incorporate both actual and refined anticipated changes to the vehicle and charging technology markets, built environment characteristics, personal and fleet travel behavior, evolving mobility preferences, and interactions with other policies that affect transportation electrification.

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CHAPTER 1: Introduction

This report analyzes plug-in electric vehicle (PEV) infrastructure needs in California from 2017 to 2025 in a scenario where the state's zero-emission vehicle (ZEV) deployment goals are achieved by light-duty vehicles, primarily in residential use. The statewide infrastructure needs are evaluated by using the Electric Vehicle Infrastructure Projection (EVI-Pro) computer simulation tool. This modeling tool was developed by collaboration between the Energy Commission and NREL.[2] In this report, staff attempted to address the following question: "*How many chargers, by type and location, are needed in California to ensure that both battery-electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) drivers can travel primarily with electricity by 2025?"* The answer to this question may guide large-scale investments and policy making toward sustainable transportation.

The State of California has initiated several policy actions to support PEV infrastructure planning and deployment. Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) and Assembly Bill 109 (Núñez, Chapter 351, Statutes of 2008) directed the Energy Commission to accelerate the development and deployment of technologies to transform California's transportation system. The Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP) began in 2009 with $46 million annual funding to invest in electric drive technology. In 2010, the Commission initiated PEV regional readiness efforts to support electric vehicle infrastructure planning at the local level.

In 2012, Governor Edmund G. Brown Jr.'s Executive Order B-16-2012[3] targeted a deployment of 1.5 million ZEVs by 2025. Under this executive order, several state agencies were directed to ensure that infrastructure will be ready to support 1 million ZEVs by 2020. With the existing ARFVTP, the Energy Commission has been leading PEV infrastructure assessment and planning for the State. The Commission released its first statewide PEV infrastructure assessment in 2014 conducted by NREL.[4] Based on 2010-2013 PEV market data, the first assessment provided estimates for Level 1, Level 2, and fast chargers corresponding to a scenario of 1 million PEVs in California by 2020. In the following years, Governor Brown and the state Legislature have announced several other major policy actions such as Senate Bill 350: Clean Energy and Pollution Reduction Act (De León, Chapter 547, Statutes of 2015), Senate Bill 32 (Pavley, Chapter 249, Statues of 2016), and, most recently, Executive Order B-48-18,[5] which further supported

2 Agreement 600-15-001.

3 Office of Governor Edmund G. Brown Jr., Executive Order B-16-2012, March 23, 2012, https://www.gov.ca.gov/news.php?id=17472.

4 Melaina, Marc, and Michael Helwig. (National Renewable Energy Laboratory). 2014. *California Statewide Plug-in Electric Vehicle Infrastructure Assessment*. California Energy Commission. Publication Number: CEC-600-2014-003.

5 Office of Governor Edmund G. Brown Jr., Executive Order B-48-18, January 26, 2018, https://www.gov.ca.gov/2018/01/26/governor-brown-takes-action-to-increase-zero-emission-vehicles-fund-new-climate-investments/.

statewide efforts to spur the construction and installation of ZEV infrastructure. These efforts have been instrumental in the installation of nearly 14,000 public chargers, including 1,500 direct current fast chargers, and the use of 350,000 plug-in electric vehicles in California by the end of 2017.

The assessment of PEV infrastructure demand, based on electric vehicle driving and charging behavior, began on a large scale with the rollout of the Nissan Leaf and the Chevy Volt in 2010. The initial PEV infrastructure demonstrations, including the EV Project,[6] deployed an unprecedented number of vehicles and chargers. Concurrently and subsequently, various studies have been conducted to provide different approaches for quantifying infrastructure needs. These approaches illustrate need at a location of interest, with a focus on a specific infrastructure type such as residential, workplace, or public charging. (See Chapter 2.) Besides the infrastructure type and location, the scientific studies also differ in considerations for PEV fleet and modeling consumer behavior. Some studies present a more simplistic approach using "top-down" models. These models attempt to make inferences based on a survey or other big data applications without modeling specific vehicles or drivers. For instance, the 2014 Statewide Assessment used a top-down approach, where the EV Project data from early adopters were used to predict consumer preference for charging infrastructure. In contrast, the studies with a "bottom-up" approach model PEVs individually, then aggregate energy consumption from these vehicles to show high-level infrastructure needs. The bottom-up approach aims to characterize behavioral differences among individuals in more detail. It is especially useful for planning infrastructure for locations where obtaining demand data is difficult.

In this report, several terms are used heavily in describing electric vehicle and charger technologies. Most importantly, the term "charger" refers to a connector that can serve a vehicle at the full rated power capacity without any operational limitations. The rated power capacity is grouped into alternating current Level 1 (L1), Level 2 (L2), and direct current (DC) fast chargers. The assumptions for these power levels are described in Chapter 4. In addition, the infrastructure quantification approach applies to chargers only without accounting any other supply equipment such as pedestals or electrical service and grid-related hardware. The term "PEV" applies to both BEVs and PHEVs. On the other hand, the term ZEV is more comprehensive – it applies to both PEVs and fuel cell vehicles. Finally, the nonresidential charging demand for work-related and nonwork-related trips (workplace and public charging) are grouped into a category called "destination" charging. The designation of parking spaces at workplaces and public locations often overlaps such that the spaces have hybrid use cases (for example, parking garages serving multiple commercial locations).

The term "shared use of chargers" refers to the case where a charger serves more than one vehicle per day. The real-world implication of this concept can be seen in locations with shared parking such as workplaces, multifamily dwellings, and other public locations. The sharing

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6 Idaho National Laboratory. 2015. *Plug-in Electric Vehicle and Infrastructure Analysis.*

potential for a charger may be increased if the use of the charger is well-managed, where usage-based pricing can prevent the case where a driver remains at a charger while not actively charging, thereby inhibiting another driver's use. The reliability of equipment and accessibility of chargers are other important factors in sharing potential. For example, ensuring that chargers are maintained, enforcing parking ordinances to prevent idling of vehicles, and choosing locations with high visibility and accessibility can improve sharing potential.

This study evaluates infrastructure needs for vehicles from a residential usage perspective only, and it quantifies charging infrastructure necessary for stimulating the growth of the electric vehicle market. Regardless of household demographics and travel behaviors, the infrastructure solution presented in this study addresses two primary objectives: (1) enabling travel for BEVs and (2) maximizing the electric vehicle-miles traveled (eVMT) for PHEVs. In doing so, staff considered household travel data representative of the mainstream market of drivers, instead of restricting travel data to only early PEV adopters. Staff also considered drivers' ability to reduce the cost of infrastructure wherein the driver adopts economic charging behavior. The model incorporates a cost-minimization algorithm where individual PEV drivers minimize their fuel cost by responding to price signals set for each charger type and location type, without changing their travel behavior.

CHAPTER 2: Literature Review: Understanding the Uncertainty and Variance in PEV Infrastructure

The light-duty PEV market is in the early stage, with PEV shares among the entire vehicle stock accounting for around 1 percent in the leading California metro areas.[7] While anticipating PEV charging demand is crucial interest to robust infrastructure planning, it is imperative to acknowledge the variance between the technology and use of PEVs. Thus, modeling and planning are subject to large uncertainties. In this chapter, staff analyzes the scientific literature concerning how these studies dealt with variance and uncertainty in modeling "PEV-driver-charger" systems and quantified future charger demand. In addition, staff evaluates various dynamics that vary greatly among different geographies and individuals, even when applying consistent market growth assumptions.

Variance is a metric to measure the spread of a dataset or variable for any given time. On the other hand, *uncertainty* refers to the current and limited state of knowledge about future conditions. For instance, while the PEV market is growing at a fast pace, political, economic, and technological uncertainties will shape the evolution of the market in the coming years. Infrastructure assessment models, on the other hand, typically do not forecast market size. The number of PEVs is usually input to the models. The major sources of variance and uncertainty regarding PEV infrastructure are summarized in Table 1 below. These categories include PEV technology, PEV market trends, and, finally, consumers' travel and refueling behavior.

Table 1: Sources of Variance and Uncertainty on PEV Charging Demand

Area	Sources of Variance and Uncertainty
PEV technology	- Battery range - Powertrain efficiency - Charging power level
PEV market trends	- PEV buyer demographics (i.e., type of residence) - PEV fleet mix of BEVs and PHEVs - Vehicle ownership and innovative mobility trends
Travel and charging behavior	- Range anxiety (or state-of-charge [SOC] tolerance) - PHEVs' willingness to plug-in - Pricing and the shared-use of chargers (accessibility and reliability)

Source: California Energy Commission and NREL

7 U.S. Department of Energy (DOE). September, 2017. *National Plug-in Electric Vehicle Infrastructure Analysis.* https://www.nrel.gov/docs/fy17osti/69031.pdf. Accessed January, 12, 2018.

Besides the battery chemistry, the "real-world" range of PEVs is affected by a multitude of factors, including ambient temperature conditions, driver behaviors, and road or traffic attributes. Also, consumer perceptions such as range anxiety and value of time further affect the "effective" electric range of their vehicles and, in turn, could increase the need for charging infrastructure. On the other hand, technology development in the realm of charging power level, battery capacity, and vehicle efficiency could lower charging requirements.

In addition to the number of PEVs on the road, buyer demographics may greatly affect infrastructure requirements. For instance, most residents of MUDs typically do not have reliable access to specified off-street parking at their homes. PEV drivers residing at MUDs will thus rely more heavily on public and workplace charging infrastructure.

Another important dynamic is the PHEV drivers' willingness to plug in their vehicles. PHEVs are equipped with an internal combustion engine that allows them to drive on gasoline by choice or once their battery is empty. PHEV drivers' willingness to recharge their vehicles outside their home also has a drastic effect on requirements for nonresidential charging. Consumers' willingness and ability to share available chargers, especially at their workplace, could potentially halve the number of chargers required to satisfy workplace charging needs.

Finally, on the electricity supply side, policies and incentives will have a geographically heterogeneous impact on infrastructure requirements. Utilities will have a central role in shaping load profiles from charging through designing time-of-use rate structures. In California, the widespread adoption of solar energy has led to a major dip in grid load around midday. This so-called "duck-curve" effect may encourage the deployment of workplace charging, which could absorb this excess energy. Advantageous pricing or even free charging at certain times or locations will likely affect consumers' charging decisions. This study focuses on the charging demand side only and does not deal with variance and uncertainties on the electricity supply side that could influence charging behavior. Staff summarizes a selected number of scientific studies regarding PEV infrastructure in Table 2.

From the nine studies reviewed, two approaches to infrastructure planning emerge: (1) quantifying the need for chargers for predetermined driver travel behavior and (2) quantifying the electric miles achieved for a given number of chargers supplied. From the PEV users' perspective, PEV powertrain models, coupled with real-world or synthetic travel data and electricity price signals, are used by Wang et al. (2017), Ji et al. (2015), Saxena et al. (2015), and Zhang et al. (2013 and 2015). In contrast, from an infrastructure supplier's perspective, Ahn and Yeo (2015), Dong et al. (2014), and Xi et al. (2013) developed optimization algorithms to minimize installation and operational costs while maximizing electrified VMT. This literature review did not include micrositing infrastructure models, similar to a recent study from the Luskin Center (2017),[8] which have significantly different inputs and outputs. The micrositing models focus on the street-level traffic and other constraints, such as local grid capacity.

8 Luskin Center. 2017. *Siting Analysis for Plug-in Electric Vehicle Charging Stations in the City of Santa Monica.* http://innovation.luskin.ucla.edu/content/siting-analysis-plug-electric-vehicle-charging-stations-city-santa-monica. Accessed January 12, 2018.

This literature review shows that several dynamics, which may be a significant source of variance and uncertainty, have been neglected in projecting future PEV charger demand. These dynamics include parking availability, shared use of chargers, and new mobility paradigms affecting travel and vehicle ownership patterns). Accounting for these dynamics will be crucial in designing a future-proofed charging infrastructure network. While not all questions are answered in this report, the focus of the EVI-Pro modeling framework – the assessment of the shared use of chargers – could be used to provide insight into these issues. (See Chapter 5 for a detailed discussion on EVI-Pro's contributions to the literature.)

Table 2: Summary and Comparison of the Scientific Literature

Author(s)	Infrastructure Focus	Geography	Fleet Scenario(s) (Range/Battery)	Sources of Variance and Uncertainty Explored
Xi et al. (2013)	Destination (workplace and public) L1&L2	Columbus Region, Ohio	Various BEV fleet (BEV73)	• Charger type & availability by location
Zhang et al. (2013)	Destination (workplace and public) L1&L2	California	Various PEV fleet (PHEV35, BEV60)	• Charger type &availability by location • Electricity pricing
Dong et al. (2014)	Destination (public L1, L2 & DCFC)	Seattle, WA region	Various BEV fleet (BEV100)	• Range anxiety • Daily travel (in miles)
Zhang et al. (2015)	Corridor DCFC planning	California	Various BEV fleet (BEV60, BEV100, BEV200)	• Electricity pricing • Battery range
Ahn and Yeo (2015)	Destination DCFC planning for taxis	Daejeon, South Korea	Various BEV fleet (22 kWh)	• Battery range • Charging power level
Saxena et al. (2015)	Travel demand satisfied by L1 charging	United States	Various BEV fleet (24 kWh)	• Powertrain efficiency • Daily travel (in miles)
Ji et al. (2015)	Corridor DCFC planning	California	250k BEV80, 125k BEV150, 125k BEV300	• Battery range • PEV fleet mix • Charger type & availability by location
Metcalf et al. (2016)	Destination DCFC siting	California, Pacific Gas & Electric service area	Various PEV fleet (PHEV40, BEV 100, BEV200)	• PEV market size
Wang et al. (2017)	Charging demand forecasting	Synthetic U.S. travel data	Various BEV fleet (18kWh, 24kWh, 28kWh, 32kWh)	• Battery range • Electricity pricing • Daily travel (in miles)

Source: California Energy Commission and NREL

Xi et al. (2013) used a linear-integer program to simulate the number of L1 (1.4 kilowatts [kW]) and L2 (4 kW) charging stations required at work and public locations, optimizing either to maximize the number of EVs charged or maximize the energy throughput from the chargers, both under a budget constraint. EV adoption and travel patterns in the region were predicted using a linear regression model with sociodemographic and macroeconomic variables in conjunction with 2010 Mid-Ohio Regional Planning Commission survey data. The available budget is varied under both optimization goals to yield different bounds for the optimal charging station and plug counts.

In contrast, Zhang et al. (2013) modeled different L1 and L2 charging scenarios for PHEVs and BEVs, assuming that a PEV driver's charging behavior aims to minimize his or her cost. They evaluated various time-of-use (TOU) charging strategies and charger needs at home, work, and public locations. The authors used *2009 National Household Travel Survey* (NHTS) travel data and existing electricity rates from Pacific Gas and Electric Company. Smart-charging strategies, responding to TOU rates, were shown to yield significant savings for PHEV drivers. Sensitivities to battery range, electricity rate structure, and infrastructure availability at home, work, or public locations are presented.

Dong et al. (2014) optimized the locations for a given number of chargers using genetic programming (an algorithm that mimics natural selection) under budget constraints. An activity-based assessment for driving and charging behavior aimed to quantify the effect of public charging infrastructure on range anxiety. Considering a case study of the Seattle region, the authors illustrated the effects of different levels of investment on infrastructure deployment and the corresponding reduction in range-constrained trips.

Zhang et al. (2015) estimated the demand for interregional corridor DC fast charging stations through a set-cover problem and analyzed the use of these stations for various charging strategies. The candidate sites for DCFC were selected from a pool of 3,000 freeway exits and highway intersections in California. Different charging scenarios were investigated: random and late-charging increase the grid demand in the afternoon, while early reserve strategies with dynamic pricing evenly distribute charging throughout the day. Sensitivity to battery range is also evaluated.

Ahn and Yeo (2015) derived optimal public DCFC density by minimizing a cost function (the sum of additional trip cost, cost of delay time, installation, and operating cost of charging stations) for a given unit area. Real-world taxi trajectory data from Daejeon in South Korea was used to generate an optimal map of charging station density to serve 90-mile range electric taxis in that city. The authors investigated the following variances for different sizes of a BEV fleet: charging station density, numbers of plugs per station, peak-time charging demand, charging power levels, and electric range.

Saxena et al. (2015) built an EV powertrain model to estimate the fraction of typical U.S. driving days – from NHTS data – that can be accommodated with L1 charging at home only or at home and workplaces. They ran sensitivity analyses for the following sources of variance: unexpected trips beyond normal daily driving, ancillary loads such as air conditioners, battery degradation over time, and effects of road grade and elevation. While the distinction between weekday and weekend travel patterns is made in this analysis, charging availability at MUDs wasn't studied, and only one PEV type was simulated, with a sub-100-mile range (24 kilowatt-hour [kWh] battery).

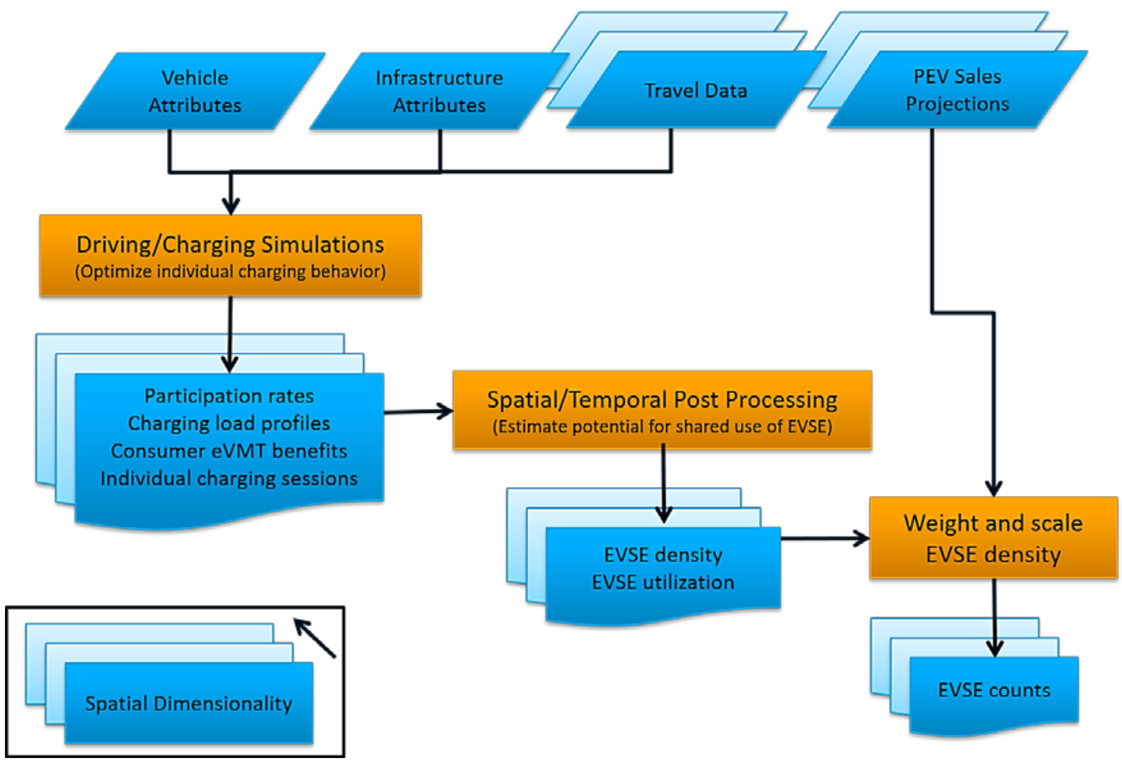
Ji et al. (2015) projected fast charging demand for connecting major California metropolitan areas by aggregating charge windows derived from long-distance travel data from the *2012 California Household Travel Survey*. Charger utility was assessed for two fleet scenarios. The present-day scenario corresponded to the PEV adoption rate from the Clean Vehicle Rebate Project (CVRP) data and DCFC availability from the Alternative Fuels Data Center (AFDC), while the future scenario projected 500,000 BEVs in California. The authors evaluated the effects of different battery range and availability of workplace charging on DCFC corridor charging demand.

In another study, Metcalf et al. (2016) provided the prioritized DCFC site locations for PG&E's service territory based on highest unmet PEV charging need. Their macrositing model used data including household travel and existing charging networks. The model considered two PEV adoption scenarios by 2025. As a significant improvement to the siting models, the authors considered the available transformer capacity for the sited locations to reduce installation costs and improve site host acceptance. The transformer capacity, which is a very important factor, was often neglected in other infrastructure siting models.

CHAPTER 3: Method: The Electric Vehicle Infrastructure Projections (EVI-Pro)

EVI-Pro used a "bottom-up" approach to estimate PEV charging requirements with the conceptual flow of information visualized below in Figure 3.1. The primary processing steps in EVI-Pro included 1) conducting individual PEV driving/charging simulations over real-world 24-hour driving days, 2) spatiotemporal post processing of individual charging events to derive charger-to-PEV ratios, and 3) scaling charger to PEV ratios per a PEV stock goal or projection. This approach was recently used by U.S. Department of Energy (DOE)/NREL in their *National Plug-In Electric Vehicle Infrastructure Analysis*[7] for calculating *charger-per-1000 PEV* ratios with various technology and market scenarios, many of which differ from assumptions employed in this report. Thus, the DOE/NREL report is not interchangeable with this analysis. Stakeholders are encouraged to refer to this report as the primary reference for California-specific infrastructure planning.

Figure 3.1: Inputs/outputs and data flow in EVI-Pro



Source: California Energy Commission and NREL Staff

The fundamental element of EVI-Pro simulations is 24-hour daily driving schedules from real-world vehicles. While these driving schedules are typically sourced from gasoline vehicles, EVI-Pro simulated each driving day as if it were attempted in a PEV. By applying real-world travel data from gasoline vehicles to simulated PEVs, EVI-Pro attempted to estimate charging solutions that enable future PEVs to serve as a direct replacement for the gasoline vehicles that represent the present-day majority of the light-duty vehicle fleet.

Charging solutions to complete days of driving were estimated by identifying charging opportunities that were consumer-oriented for both convenience and cost. Convenience is achieved by simulating charging events as occurring only during dwell times present in the original travel data. The EVI-Pro method implies that the mainstream PEV drivers will have a low tolerance for altering travel behavior regularly to accommodate charging their vehicle. When the price of charging is equivalent for two or more locations, EVI-Pro assumes that consumers prefer to charge at locations with long dwell times. This approach implied a greater energy transfer per charging event and helped minimize the number of charging events per day. Simulated consumers in EVI-Pro were modeled as being economically efficient, preferring to charge their vehicles at locations that help minimize charging costs. Simulated consumers were provided with charging cost ($/kWh) information and the energy needed to complete their next trip, so each simulated PEV driver could decide whether a charging event was needed at their location. Once feasible charging solutions were identified, the model iterated through driving/charging events until the battery SOC at the start and end of the simulated day were consistent.

In addition to the objective of minimizing cost, simulated consumers were also subject to constraints on battery SOC. For each simulated driving day in EVI-Pro, BEVs were required to maintain battery state of charge above a predefined level, defined by users as a reasonable proxy for minimizing range anxiety. This minimum state-of-charge level may decrease gradually as the electric range of BEVs increases. Since PHEVs can operate with a depleted battery in charge sustaining mode, EVI-Pro did not place a constraint on the minimum allowable state of charge for PHEVs but instead attempted to maximize eVMT and minimize gasoline consumption. The authors performed the EVI-Pro driving/charging simulations only for vehicles that had participated in the California Household Travel Survey (CHTS) that is completed every 10 years.[9] The number of PEVs input by EVI-Pro users may be different than the number of CHTS vehicle-days simulated. In this case, EVI-Pro scaled charger-to-PEV ratios (derived from simulation of CHTS vehicle-days) concerning the number and type of PEVs defined by users. The charger-to-PEV ratios tended to vary by location type (home, work, public) and by region (county) and were sensitive to model inputs.

While the driving and charging simulations determined the number of vehicles that used each charger type, the amount of infrastructure required to satisfy charging demand depended on the spatial/temporal coincidence of charging. For example, consider a fixed number of charging events at public L2 chargers. If these charging events happened at the same location and were

9 California Department of Transportation (Caltrans). 2013. *2010-2012 California Household Travel Survey Final Report Appendix*. http://www.dot.ca.gov/hq/tpp/offices/omsp/statewide_travel_analysis/files/CHTS_Final_Report_June_2013.pdf. Accessed January 12, 2018.

uniformly distributed throughout the day, a minimal amount of infrastructure could meet the demand (corresponding to the high utilization of a small number of chargers). Conversely, if the same number of charging events occurred in isolated locations at the same time, a much larger amount of infrastructure was required (corresponding to the low use of a large number of chargers).

EVI-Pro provided two important outputs used in quantifying charger demand. First was the sum of all charging events for a 24-hour period from all simulated vehicles with distinguishing each location type (residential, work, public). Each charging event was associated with a unique vehicle to prevent double counting in identifying the potential charger needs. The second important output was the sum of charging events occurring during peak-demand time (weekday or weekend) for each location type. The participants in CHTS were asked to provide one day-long trip information assigned randomly for a weekday or a weekend. All outputs described above were calculated separately for typical driver behaviors on weekdays and weekends. The charger estimates in results were not based on the average of weekday and weekend simulations. The results were based on weekday *or* weekend trips, depending on which day has the higher charging demand for a particular location type.

The Energy Commission staff used a 2:1 PEV-to-charger ratio to derive the high estimate for nonresidential charger counts. In this case, the total daily charging events for each location type were divided by two. This 2:1 sharing ratio used in the high estimates should be seen as a conservative proxy for the use of a fast charger, particularly when compared to a Level 2 charger, but higher ratios were not used due to two factors: 1) the convergence with the minimum quantity of chargers needed (mostly in rural areas) and 2) the geospatial uncertainty as to whether drivers were in practice willing to travel to use fast chargers, if they were not sufficiently distributed.

The low estimate is equal to the 10th percentile between the peak-time total charging events and the high estimate. Therefore, the low estimates are obtained by scaling the peak charging demand up using the daily total number of charging sessions. The Energy Commission's approach for low estimates intends to account for the case when the charging events during nonpeak times occur at geographically distant locations, inhibiting shared use. Thus, additional chargers beyond those required to meet peak demand may be needed. The mathematical model for the higher estimate (H.E.) and lower estimate (L.E.) of charger counts are provided below:

$$H.E._{i,j} = \frac{\sum_{k=1}^{144} C.E._{i,j,k}}{2}$$

$$L.E._{i,j} = C.E._{i'j}^{p} + \frac{\left(H.E._{i,j} - C.E._{i'j}^{p}\right)}{10}$$

i = location type (residential, work or public)

j= type of day (weekday or weekend)

C.E. = Total Charging Events occurring within any 10-minute time interval

k= time interval (up to 24x6 for a 24 hour period [by increments of 10-minutes])

$C.E.^p$ = Total Charging Events occurred during the 10-minute time interval associated with peak demand

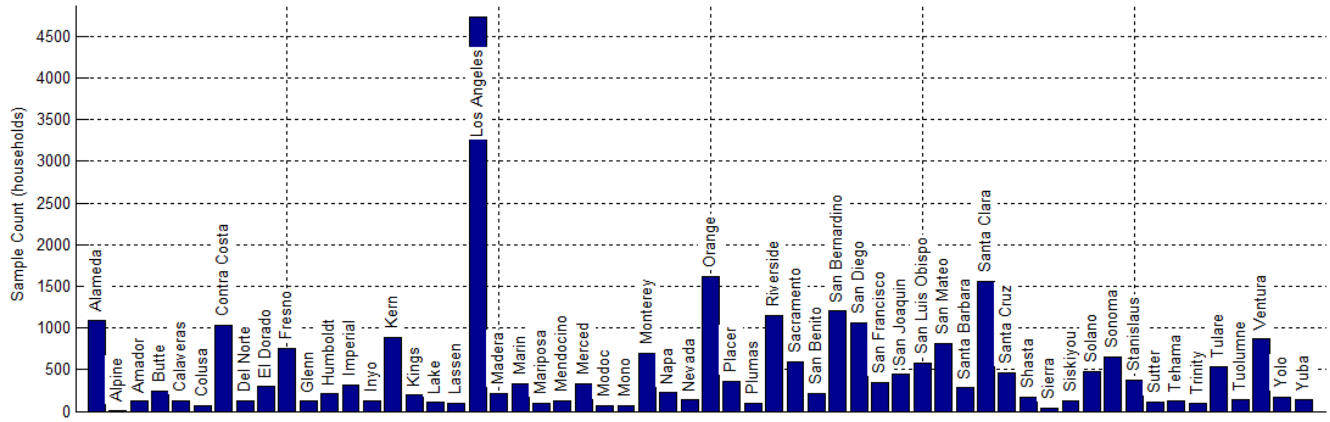
The Input Selections. The four groups of input data necessary for an EVI-Pro simulation included t (1) PEV attributes, (2) infrastructure attributes, (3) travel data, and (4) PEV fleet projections.

Input 1: PEV attributes. The vehicle attributes that can be specified in EVI-Pro included the electric range (in miles), vehicle drive efficiency (watt-hours per mile), minimum range tolerance (in miles), onboard charger efficiency, and maximum AC charging power. In this assessment, some of these inputs were assumed constant, while others were assumed to change over time (annually). The assumptions on PEV attributes are provided in Chapter 4.

Input 2: Infrastructure attributes. The authors segmented charging infrastructure by location type as home (single-unit or multiunit dwelling), workplace, and public (any destination not classified as either a home or work destination). For each location type, up to three charging power levels may be available depending on the scenario provided by users. For all simulated charging opportunities, a minimum dwell time for the driver to consider plugging in (at all location types, including home) can also be specified by users, though simulated consumers may not plug in at every opportunity, depending on their daily charging needs. The inputs for fuel pricing were also included under the infrastructure attributes. Staff developed scenarios where attributes of new chargers evolve annually and described in Chapter 4. While charger technologies improve annually, during this eight-year planning horizon for simplicity, staff did not consider decay rates to characterize the actual useful lifetime of equipment (for example, warranty, durability, malfunction, theft).

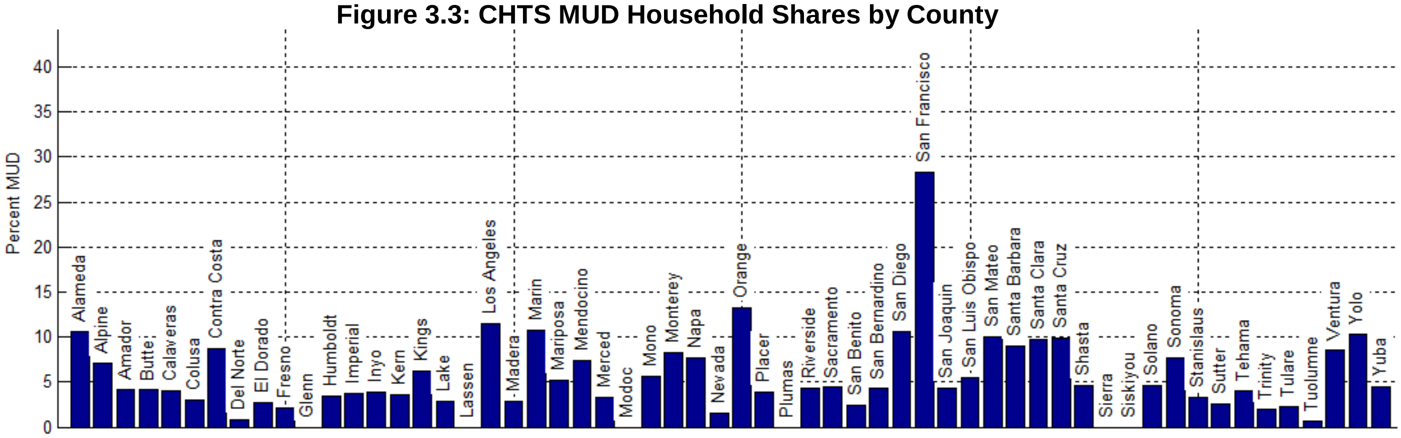
Input 3: Travel data. Driving and charging simulations were conducted in EVI-Pro using 24-hour travel profiles from the 2012 CHTS.[6] The CHTS contains 24-hour travel logs from 47,559 vehicles across 32,300 households in California. With coverage across all 58 California counties, the CHTS data contained 184,476 driving trips. County distributions of CHTS household counts and MUD shares are shown in Figures 3.2 and 3.3.

Figure 3.2: CHTS Household Counts by County



Source: California Energy Commission and NREL

Figure 3.3: CHTS MUD Household Shares by County



Source: California Energy Commission and NREL

Input 4: PEV fleet projections. The authors used county-level sales projections for BEVs and PHEVs to scale the charger-to-PEV ratios calculated by EVI-Pro. PEV fleet projections used in this study are discussed in Chapter 4. In addition to the number and type of PEVs by county, an assumption had to be made regarding the availability of home charging. This assumption is central to modeling the charging behavior as most residential vehicles are parked at home during overnight hours. This long-duration parking can be a significant opportunity for PEV charging, which is lost on individuals without residential parking or access to an outlet nearby. To this end, residence type information for CHTS households was used as a proxy for the potential for a driver to use home charging. Table 3.1 shows the statewide shares of CHTS vehicles by residence type, the classification of residences as a MUD, and the assumption of the availability of home charging used in this study. EVI-Pro simulated CHTS vehicles that did not have access to home charging as relying solely on workplace and public charging infrastructure, which represented about 5 percent of the sample (per the assumed relationship between residence type and potential for home charging).

Table 3.1: CHTS Statewide Sampling by Residence Type and Assumed Home Charging Potential

Residency Type/Code	Description	Vehicle Count	Percent of Sample	EVI-Pro MUD	EVI-Pro Home Charging Option
1	Single-family house not attached to any other house	39,018	82.0%	no	yes
2	Single-family house attached (each unit separated by a ground-to-roof wall)	2,887	6.1%	no	yes
3	Mobile home	1,055	2.2%	yes	no
4	Building with 2–4 apartments/condos/studios/rooms	1,234	2.6%	yes	no
5	Building with 5–19 apartments/condos/studios/rooms	1,701	3.6%	yes	yes
6	Building with 20 or more apartments/condos/studios/rooms	1,612	3.4%	yes	yes
7	Boat, RV, van, etc.	12	0.0%	yes	no
97,98,99	Other; Don’t know; Refused	30	0.0%	yes	no

Source: California Energy Commission and NREL

CHAPTER 4: Analysis and Results

The Default Scenario Formulation

Step 1: Fleet input: Total PEVs and annual growth rate. Fleet assumptions followed the state's ZEV deployment goals for 2025. This study did not forecast future levels of ZEV adoption. The Energy Commission's report *Transportation Energy Demand Forecast, 2018-2030* includes statewide forecast of ZEV and conventional vehicle population to 2030.[10] Rather, the study took a policy perspective to achieve the 1.5 million ZEV target in Executive Order B-16-2012. As discussed in Chapter 3, vehicle quantities were exogenous inputs for EVI-Pro. Following the 1.5 million ZEV target, staff used the relative shares of Fuel Cell Vehicles and PEVs projected in CARB's "Clean Technologies and Fuels (CTF)" scenario following the 2016 *Mobile Source Strategy.*[11] This scenario (also called "Natural Turnover Scenario" or "Scenario-2") assumed 200,779 FCEVs among 1,686,000 ZEVs by 2025. This amount corresponded to a market share of 11.9 percent for FCEVs. This analysis considered the same 11.9 percent FCEV adoption rate to apply over 1.5 million ZEVs, which resulted in a statewide population of 1,321,371 PEVs by 2025 used in EVI-Pro simulations.

The analysis was performed at the county level and by year. The PEV fleet defined as of January 1, 2017, was gathered from the CVRP online database,[12] accounting for rebate participation rates at the county level. Staff assumed that upon this initial fleet of 239,215 PEVs at the start 2017, 135,269 PEVs were added annually through the end of 2024 to reach 1.3 million PEVs by 2025. The annual increase was assumed linear, as presented in Figure 4.1. The authors chose linear adoption over exponential adoption for simplicity. Furthermore, because EVI-Pro quantified charging in proportion to PEV quantity, when comparing linearly and exponentially increasing functions between equivalent fleets in 2017 and 2025, a modeling assumption of linear growth may have caused infrastructure to "lead" real-world PEV adoption. Otherwise stated, a linear annual increase in modeled PEV adoption promoted readiness for actual PEV adoption, because infrastructure demanded by linearly-modeled adoption consistently results in more chargers required in a given year compared to an exponential adoption curve.

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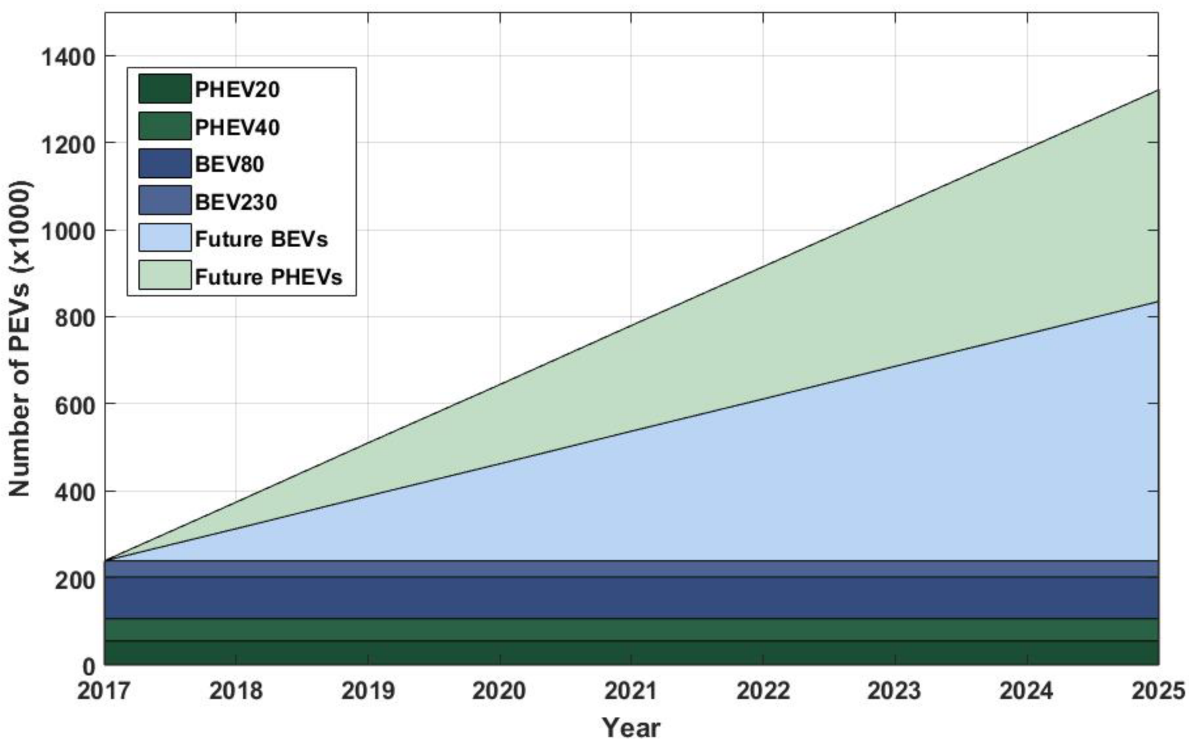
10 The Energy Commission's *Transportation Energy Demand Forecast* includes forecast of electricity demand associated with ZEV population forecast, in different incentive and clean vehicle technology scenarios and the current regulatory environment. The "Low Demand" case achieves about 1.6 million ZEVs by 2025, of which about 1.5 million vehicles are PEVs. For details see California Energy Commission. November, 2017. *Transportation Energy Demand Forecast, 2018-2030.* http://docketpublic.energy.ca.gov/PublicDocuments/17-IEPR-05/TN221893_20171204T085928_Transportation_Energy_Demand_Forecast_20182030.pdf. Accessed February 13, 2018.

11 California Air Resources Board. May, 2016. *Mobile Source Strategy.* https://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc.pdf. Accessed January 12, 2018.

12 Clean Vehicle Rebate Program Website. https://cleanvehiclerebate.org. Accessed January 12, 2018.

Step 2: Distribution of PEVs by county. The fleet distribution followed the current distribution of PEVs for the first set of simulations for 2017. The first set of simulations for 2017 included four types of PEVs, which were identified as a proxy to the existing market. (See Appendix D for details.) The annual PEV shares by county were assumed to converge to the new vehicle adoption distribution (including non-PEVs), as derived from 2016 vehicle registration data provided by IHS Markit.[13] The new vehicle adoption for a given year was defined as the average of new vehicle sales during the last five-year period. The assumption of convergence toward the new vehicle adoption distribution intended to model the outcome where PEVs become a mainstream market product by 2025. For details on existing and new vehicle distributions by county, refer to Appendix A and Appendix B, respectively.

Figure 4.1: Shares of PEVs Input for the Default Scenario, 2017-2025



Source: California Energy Commission and NREL

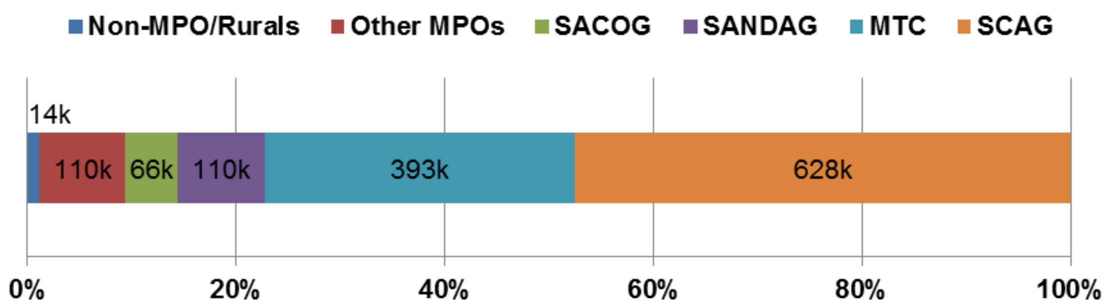
Step 3: Shares of BEV and PHEV at the county level. The PEV fleet included BEVs and PHEVs. Given the wide range of automotive manufacturer announcements and anticipated PEV releases during the modeled time frame and county-level variability in available PEV models for sale, staff did not assume substantive changes in the relative rate of adoption of BEVs and PHEVs. Therefore, the BEV-PHEV split was assumed consistent through 2025. This assumption resulted in a statewide PEV fleet composed of 45 percent PHEVs and 55 percent BEVs. The authors applied the existing BEV and PHEV proportions for each county on the annual PEV fleet

13 IHS Markit. 2017. “Market Insight: Registrations and Vehicles-in-Operation.” https://www.ihs.com/products/automotive-market-data-analysis.html. Accessed June 2017.

distributed for each county described. Because some counties had very high BEV or PHEV rates, the authors applied a filter for BEV-PHEV splits. This filter limited PHEV adoption to between 35-55 percent for a given county. Therefore, some counties with very low or high adoption rates for BEVs or PHEVs were assumed closer to the statewide average of BEV and PHEV split for adoptions for 2018 through 2025.

In Figure 4.2, the total PEV fleet was grouped by metropolitan planning organization (MPO) regions: the Southern California Association of Governments (SCAG), the Metropolitan Transportation Commission (MTC) of the Bay Area, the San Diego Association of Governments (SANDAG), the Sacramento Council of Governments (SACOG), and other smaller MPO regions. The rural counties without a desginated MPO were listed under "Non-MPO" areas.[14] The intent of applying these distributions was for the model to consider a distribution of the PEV fleet that converges from an early adopter market toward the mainstream new vehicle buyer's market, where overall Southern California and the Bay Area regions comprise more than three-quarters of all PEVs adopted in California. Finally, about three-quarters of all PEVs adopted in Other MPOs are located within the Central Valley[15], while the rest of the fleet is located within the Central Coast[16]. A complete list of counties and their regional classification is included within Appendix F.

Figure 4.2: Regional Distribution of the 2025 PEV Fleet



Source: California Energy Commission and NREL

Step 4: PEV and charger technology projections through 2025. Technological improvements were applied for PEV electric range (in miles) and charging power levels (in kilowatts). The device-level assumptions, such as vehicle and charger efficiencies, were assumed constant through 2025. (See Appendix C.) The assumptions for improvements in electric miles were

14 California Department of Transportation (Caltrans). 2009. "California Metropolitan Planning Organizations (MPOs) and Regional Transportation Planning Agencies (RTPAs)." http://www.dot.ca.gov/hq/tpp/offices/orip/index_files/Updated%20Files/MPO-RTPA_1-10.pdf. Accessed February 13, 2018.

15 The Central Valley counties within Other MPOs include Butte, Fresno, Kern, Madera, Merced, San Joaquin, Shasta, Stanislaus, and Tulare.

16 The Central Coast counties within Other MPOs include Monterey, San Luis Obispo, and Santa Barbara.

based on the CARB Advanced Clean Cars Midterm Review.[17] The CARB midrange scenario projected that the average electric range will increase to 210 miles for BEVs, 30 for short-range PHEVs, and 55 miles for long-range PHEVs. The authors assumed the improvements in electric range and power levels to follow a linear increase and applied them to the vehicles and chargers for a given year. Table 4.1 presents technological improvement assumptions for newly deployed vehicles and chargers for 2017 and 2025. (See Appendix D for annual values.) For example, by 2025, new PHEVs were assumed to have an average electric range of 40 miles and be capable of accepting L2 AC power from residential chargers at a rate of 5 kW. Accounting for the onboard charger efficiency resulted in a 10 percent reduction in power delivered from L1 and L2 chargers. Although BEV fast charging (controlled through an off-board charger) was not subject to the onboard charger efficiency of the vehicle, BEVs usually cannot accept full power during a fast charging event. The charging power level usually decreases as the state of charge increases for a BEV battery.[18] Therefore, the authors also applied a 10 percent power reduction to rated charge power levels to characterize this technical limitation for DC fast charging.

Table 4.1: Annually Applied Technology Projections for Newly Deployed PEVs and Chargers

Electric Range and Charger Power Level Projections			
PHEVs	**(As-of-2017)**		**(By 2025)**
Electric Range (miles):	29.6	→	40.0
Residential L2 (kW):	3.6	→	4.9
Destination L2 (kW):	3.6	→	4.9
BEVs	**(As-of-2017)**		**(By 2025)**
Electric Range (miles)	121.8	→	210.0
Residential L2 (kW)	6.6	→	11.4
Destination L2 (kW)	6.6	→	6.6
Fast Charging (kW)	50.0	→	105.0

Source: California Energy Commission and NREL

Step 5: Fuel pricing. The fuel pricing was another important input for scenario formulation, which had a major effect on consumer preferences. The electricity pricing was relative and varied by location. Prices were assumed to follow the relative capital costs for infrastructure installation, where residential charging is cheaper than workplace charging, and workplace charging is cheaper than public charging.[19] While DC fast charging has higher capital costs than Level 2 charging, BEV drivers were assumed to prefer public fast charging over public L2 charging. This is input in the scenario as $Price_{Public\ DCFC} < Price_{Public\ Level\ 2}$. This assumption was

17 California Air Resourced Board. 2017. *California's Advanced Clean Cars Midterm Review.* https://www.arb.ca.gov/msprog/acc/mtr/acc_mtr_finalreport_full.pdf. Accessed January 12, 2018.
18 Idaho National Laboratory (INL). 2016. 2013 Nissan Leaf BEV – VINs 0545, 0646, 7885 & 9270: Advanced Vehicle Testing –DC Fast Charging at Temperature Test Results. Idaho Falls: INL. https://avt.inl.gov/sites/default/files/pdf/fsev/2013LeafDCFCAtTempBOT.pdf. Accessed January 12, 2018.
19 For instance, see Table-9 within National Renewable Energy Laboratory (NREL). 2016. *National Economic Value Assessment of Plug-in Electric Vehicles.* https://www.nrel.gov/docs/fy17osti/66980.pdf. Accessed February 14, 2018.

made due to consumers' generally higher expectations for equipment reliability and accessibility for a fast charger compared to an L2. This assumption was evaluated by a sensitivity analysis in the section "Locational Fuel Price Sensitivity Analysis." In the default scenario, the electric fuel pricing (cent/kWh) provided to the PEV drivers was as follows:

$$Price_{Residential} < Price_{Workplace} < Price_{Public}$$

The assumption that chargers are consistently priced may not accurately reflect the existing infrastructure market. Only 59 percent of destination L2 chargers in California are priced for use in some manner[20] (for example, per use of space, energy delivered, time spent).

Results

Total Charging Load for Weekdays and Weekends

EVI-Pro produced two outputs that were used in a spatial/temporal postprocessing assessment of the shared use of chargers. These outputs were hourly electricity demand and hourly total charging sessions created at each location type (residential, workplace, and public). Figure 4.3 presents the total electricity load from each location type for weekdays. The load profiles for each location type were initially calculated for each county, and the results were aggregated up to the state level.

Peak electricity demand at each charging location and the time the peak occurred varied according to the day of the week, as tabulated in Table 4.2. Residential charging was the largest load segment, from 669 MW to 867 MW, and the peak demand fluctuated according to when people arrived home during the evening (about 8:00 or 9:00 p.m.). Nonresidential locations had the largest variation in charging demand and the time at which drivers' needs to charge occur. Workplace demand peaked between 8:00 a.m. and 9:00 a.m., regardless of the day of the week, but weekday demand for this segment was more than 300 percent greater than weekend demand. Fast charging demand peaked between 10:00 a.m. and 11:00 a.m. on weekends. Fast charging infrastructure was used about twice as much on weekends as weekdays. Furthermore, the fast charger fleet had wide intrahourly variation in load, depending on the day. For example, during the hour starting at 10:00 a.m.[21] on weekends, fast charging load had an increase of 71 MW compared to 27 MW on weekdays.

Peak demand for Public L2 charging varied the least among the nonresidential charging locations, but it was needed more often in the afternoon on weekends compared to the evening on weekdays. Overall, the maximum charging load (from the total of all segments) of 981 MW occurred at 7:40 p.m. weekdays. Peak load occurred at 6:50 p.m. on weekends, albeit at a lower level due to decreased residential charging needs. These load profiles do not reflect consumer incentives or energy resources to manage charging load (such as time-variant pricing, solar generation, or energy storage).

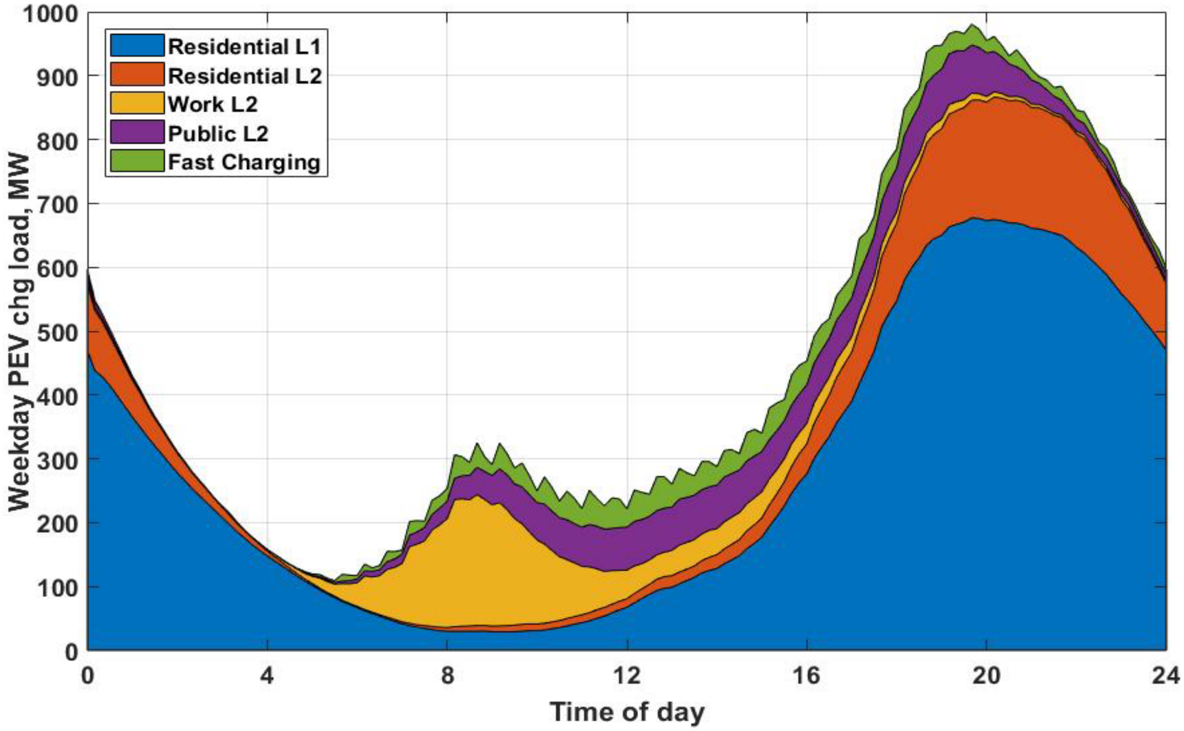
20 Jenks, Ray (PlugShare), email of January 4, 2018, to the Fuels and Transportation Division staff.
21 The change in absolute load between and 10:00 a.m. to 10:40 a.m. was the greatest for the representative 24-hour demand profiles, regardless of day of the week.

Table 4.2: Peak Charging Load and Time Occurring in 2025

Location	Weekday		Weekend	
	Demand (MW)	Time	Demand (MW)	Time
Residential Total (L1&L2)	867	8:10 p.m.	669	9:10 p.m.
Work L2	205	8:40 a.m.	50	8:10 a.m.
Public L2	80	7:20 p.m.	134	1:20 p.m.
Fast Charging	55	5:10 p.m.	120	10:40 a.m.
Total PEV Charging Load	981	7:40 p.m.	794	6:50 p.m.

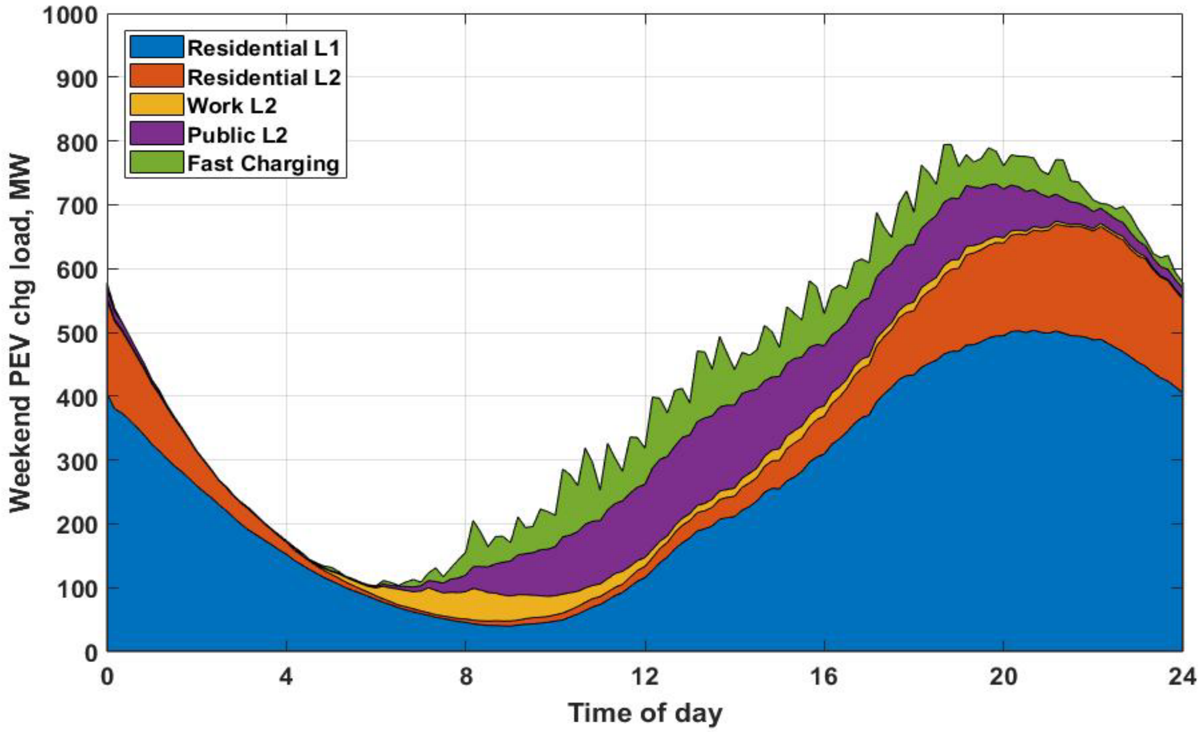
Source: California Energy Commission and NREL

Figure 4.3: The Statewide Aggregated Electricity Load for a Typical Weekday



Source: California Energy Commission and NREL

Figure 4.4: The Statewide Aggregated Electricity Load for a Typical Weekend



Source: California Energy Commission and NREL

Lower Estimates for Chargers Demanded

The total number of charging events demand that occur during the peak time was the first output used in the assessment of shared-use chargers. The authors calculated peak-time charging events for each location type and for each county as the lower estimates for the required infrastructure. The authors assumed that, for each location type, the infrastructure deployed in a county should be higher than the number of chargers being used during the peak time. As noted above, the peak time may occur during a weekday or weekend, depending on the location type.

Higher Estimates for Chargers Demanded

After quantifying the weekday and weekend hourly electricity load, EVI-Pro calculated the total number of charging sessions demanded over 24 hours from PEVs for each location type (home, work, and public). Total charging events over 24 hours were used for the high estimate of shared chargers. Staff assumed that the deployed infrastructure for nonresidential charging should serve at least two vehicles, on average over 24 hours, reasoning that driver demands to use a particular charger within a given county would be sufficiently temporally differentiated to allow multiple vehicles to share the charger. In other words, more than one driver will be able to use the same charger during different times of the day. Therefore, the infrastructure solution identified for a given location type presented in this study did not exceed half of the total charging sessions demanded during the weekdays or weekends, whichever was higher. As described earlier, this 2:1 ratio for high estimates can be seen as a very conservative estimate for the use of a fast charger and should be interpreted separately from the high estimate results for Level 2 chargers.

Estimates to Account for Load Shape

The difference between a lower estimate (representing peak-time charging events) and a higher estimate (representing total charging sessions demanded over 24 hours) was affected by the shape of the load profile. A charging load profile with steep peak demand, as is the case for workplace charging (Figure 4.3), had a relatively smaller difference between the estimates and contrasted with a load profile where the demand was distributed evenly during the day, as was the case for public L2 charging. As described earlier, the authors assumed that the lower estimate for an infrastructure solution should be higher than the charging demand during peak time, and the increase should be proportional to the total daily use.

The ratio of lower estimates to the total charging demand during peak time provided the expected peak usage rates for the infrastructure by location type. The 10th percentile assumption for calculating the lower estimates results in peak-time usage rates of chargers of between 87 percent and 100 percent for destination chargers and between 70 percent and 98 percent for fast chargers, depending on the county.

Table 4.3: Projections for Statewide PEV Charger Demand

Demand for L2 Destination (Workplace and Public) Chargers (The Default Scenario)			
	Total PEVs	**Lower Estimate (Chargers)**	**Higher Estimate (Chargers)**
As of 2017	239,328	21,502	28,701
By 2020	645,135	53,173	70,368
By 2025	1,321,371	99,333	133,270
Demand for DC Fast Chargers (The Default Scenario)			
	Total BEVs	**Lower Estimate (Chargers)**	**Higher Estimate (Chargers)**
As of 2017	133,446	2,005	5,877
By 2020	356,814	4,881	13,752
By 2025	729,150	9,064	24,967

Source: California Energy Commission and NREL

Residential Charging

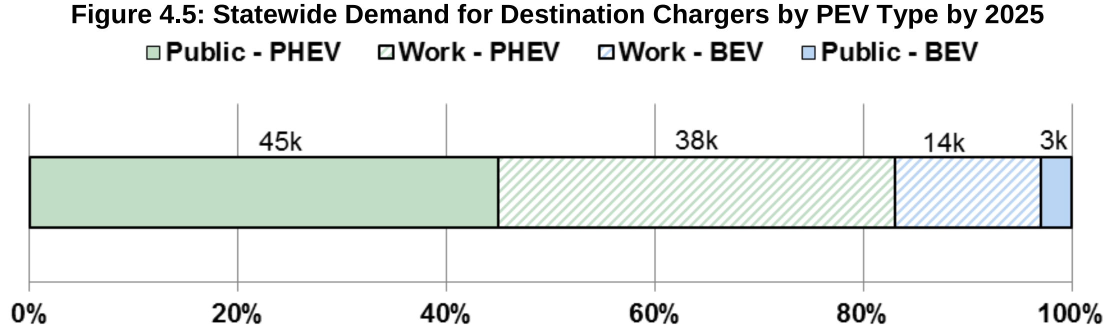
The EVI-Pro simulations also provided demand for residential charging. About 92 percent of the PEVs engaged in residential charging. The ability of a PEV to charge at home is very sensitive to the parking assumptions discussed in Chapter 3 and detailed in Table 3.1. Among the residential PEV group, about 10 percent of the charging was done at multifamily dwellings. Therefore, 120,800 PEVs required residential charging at or near multifamily dwellings. This quantity of PEVs associated with MUDs could be interpreted as a proxy estimate for the chargers needed in this segment (in other words, 1 charger: 1 PEV). At the time of running simulations, no data representative of county-level parking availability were accessible for use. In addition, the wide spectrum of parking configurations at multifamily dwellings and single-family homes limited an assessment of sharing potential. Therefore, this analysis did not assess the potential for shared use in any residential charging.

In the cost-minimization algorithm, PEV drivers were provided with a Level 2 charger only if Level 1 chargers were not adequate due energy requirements associated with long-distance travel, short dwelling time, or both. Based on this assessment, staff found that a minimum of 65,584 PEVs from single-family homes and 6,874 PEVs from multifamily dwellings could not complete their travel with Level 1 charging. Please refer to the last column in Appendix E. This analysis did not estimate the demand for residential Level 2 chargers because it did not incorporate the value of time for PEV consumers that desired higher power level chargers due to their unpredictable travel patterns or range anxiety. Furthermore, the demand for Level 2 chargers from single-unit dwellings and multifamily dwellings should be expected to be higher due to differences in parking configurations that may increase the need to share chargers.

Destination Charging and PHEV Participation

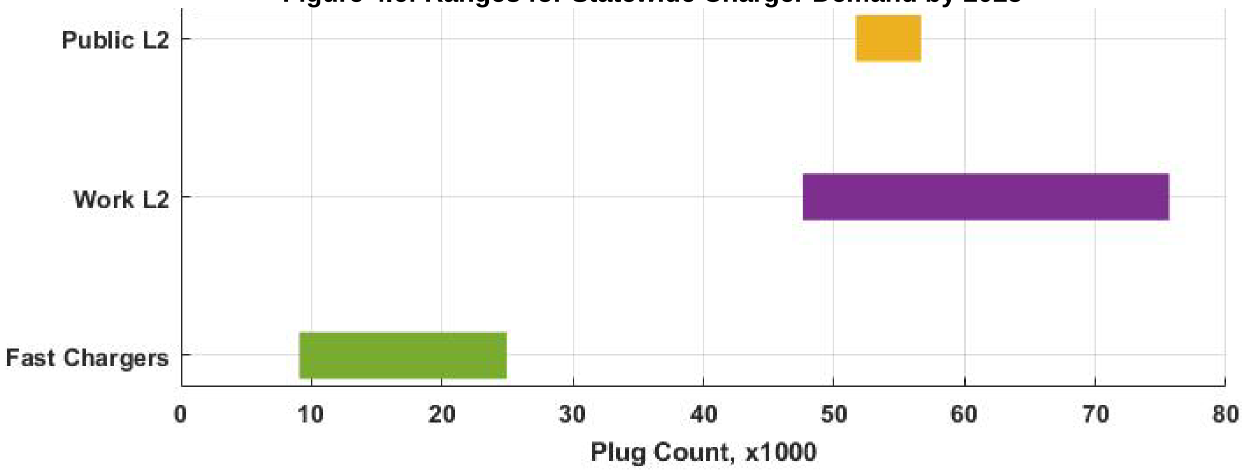
The analysis shows that the majority (83 percent) of the destination charging sessions will be associated with serving the needs of PHEVs, as shown in Figure 4.5. The fleet of PHEVs is responsible for a large portion of sessions because these vehicles typically have a lower electric range (30 to 40 miles) and are assumed incapable of using fast charging. On the other hand, this analysis assumes that PHEVs, if parked in a workplace or public location more than 30 minutes, will prefer to plug in their vehicle to minimize fuel cost. However, the actual charging behavior of PHEV drivers may be much more complicated. PHEV drivers may plug in their cars based on their perception of the utility received from nonresidential charging. Therefore, the results should be interpreted that the majority of destination chargers will be used in supporting the electric travel of the PHEVs; however, it is not a required fuel supply for those PHEV drivers. The optional use aspect of Level 2 destination charging for PHEVs makes it very different in comparison to the use of fast chargers, which are essential to enable BEV travel. The statewide ranges for workplace, public, and fast chargers are presented in Figure 4.6.

Figure 4.5: Statewide Demand for Destination Chargers by PEV Type by 2025



Source: California Energy Commission and NREL

Figure 4.6: Ranges for Statewide Charger Demand by 2025



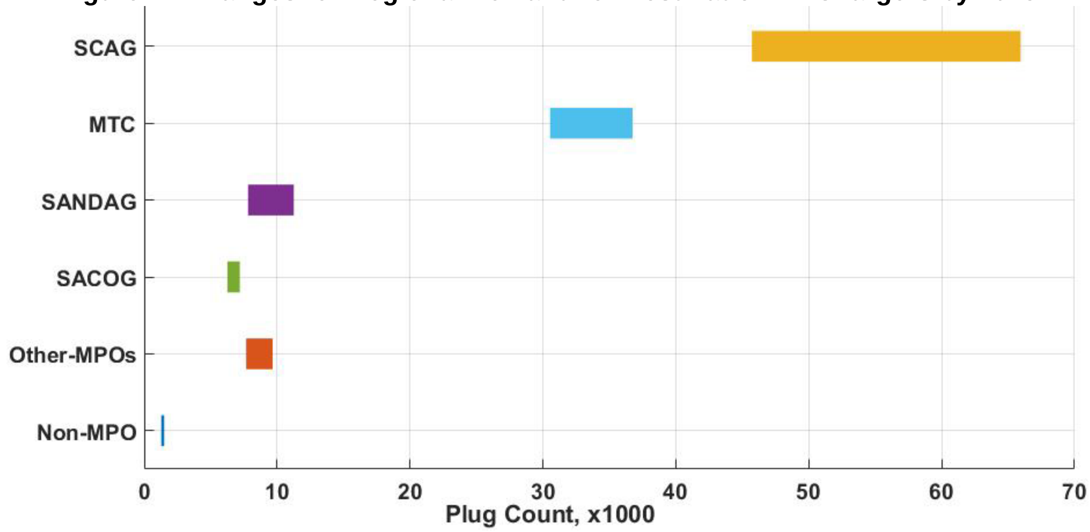
Source: California Energy Commission and NREL

The Regional Analysis

The authors performed EVI-Pro simulations at the county level, and differences in regional travel behavior significantly affected infrastructure demand. Figures 4.7 and 4.8 present the aggregated charging demand at the metropolitan regions for destination charging and fast charging, respectively. These bar charts also show that the size of the estimates can be narrower or wider, depending on the regional travel patterns. For instance, if a region has a dominance of work-related travel, then the range for the lower and higher charger estimates will be narrower due to higher peak-time demand, which is the basis for the lower estimate. This implies that the PEV drivers have a limited opportunity for sharing the available infrastructure. Appendix E and Appendix F present lower and higher estimates of charger counts for each county, which can be used to quantify charger-per-vehicle values.

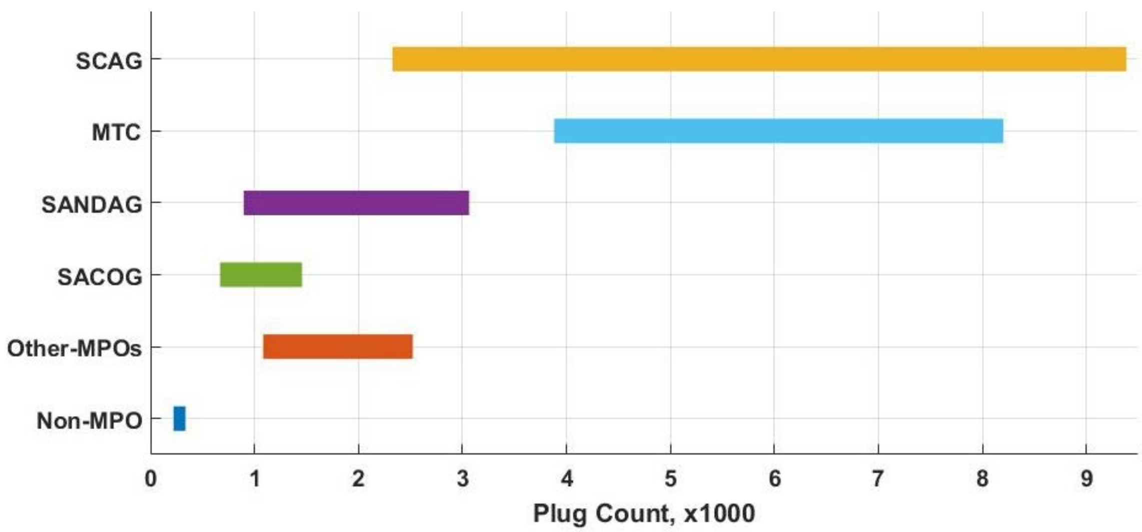
For comparison, the Southern California region has the highest amount of new vehicle adoptions and always has a higher need for destination chargers. On the other hand, the peak time-related demand (lower estimate) for fast charging is higher in the Bay Area than in Southern California. This difference may exist due to differences in regional and interregional travel behavior of BEV drivers, the relative of prevalence of housing types, the geographic area of the combined counties and development density, or combinations thereof. Finally, about 70 percent of both destination level 2 chargers and fast chargers within Other MPOs are located in the Central Valley area, while about 30 percent of the chargers are located in the Central Coast. Staff will continue to reevaluate the regional demand to answer these questions, including through the application of updated CHTS data expected to be released in 2018.

Figure 4.7: Ranges for Regional Demand for Destination L2 Chargers by 2025



Source: California Energy Commission and NREL

Figure 4.8: Ranges for Regional Demand for Fast Chargers by 2025



Source: California Energy Commission and NREL

Location Fuel Price Sensitivity Analysis

Staff performed a sensitivity analysis where PEV driver behaviors were simulated with a minor difference in their charging preferences. In this scenario, all other inputs described in "The Default Scenario Formation" section (also Appendix C and Appendix D) are consistent. The only difference is that BEV drivers preferred public L2s over fast chargers, instead of the converse. To implement this scenario, relative charging prices were input as $Price_{Public\ Level\ 2} < Price_{Public\ DCFC}$ in contrast to the description within "The Default Scenario Formation" section. This scenario may provide an infrastructure solution with a lower unit equipment cost. However, the assumption that fast chargers are perceived as the last option for enabling BEV travel may not be reflected in current market deployment conditions. As seen in Table 4.4, the demand for fast charging is shifted to public L2 chargers. The estimate for number of fast chargers needed by 2025 decreased to 3,700-8,500 from 9,000-25,000 calculated previously under the default scenario. The overall results present an increase in the reliance on destination charging. In comparing the new scenario results for fast charging to the actual quantity of fast chargers for 2017, staff concluded that this pricing scenario does not reflect the current market status. Fast charging deployment is more than two times higher than the lower estimate and more than 80 percent of the higher estimate derived from the alternative pricing scenario (compare 1,601 existing chargers[22] to between 759 and 1,949 from EVI-Pro). At a high level, this sensitivity could be used to compare the relative tradeoffs of developing fewer fast chargers in favor of more public L2 chargers (for example, land acquisition, site management, and electricity demand).

Table 4.4: Results From the Location Fuel Price Sensitivity

Demand for L2 Destination (Workplace & Public) Chargers (Alternative Pricing Scenario)			
	Total PEVs	**Lower Estimate (Chargers)**	**Higher Estimate (Chargers)**
As of 2017	239,328	24,891	34,506
By 2020	645,093	63,333	84,934
By 2025	1,321,371	122,347	160,161
Demand for DC Fast Chargers (Alternative Pricing Scenario)			
	Total BEVs	**Lower Estimate (Chargers)**	**Higher Estimate (Chargers)**
As of 2017	133,446	759	1,949
By 2020	356,814	1,965	4,579
By 2025	729,094	3,726	8,504

Source: California Energy Commission and NREL

22 U.S. Department of Energy (DOE). 2017. "Alternative Fueling Station Locator." http://www.afdc.energy.gov/locator/stations. Accessed February 2018.

CHAPTER 5: Conclusions and Future Work

Conclusions

Overall Statewide Charger Needs by 2025

This staff report analyzed the PEV charging infrastructure needed for enabling BEV travel and maximizing electric miles for PHEVs. The authors performed the analysis at the county level for each year from 2017 through 2025 while considering potential technological improvements. They gathered the statewide results for 2025 from county-level simulations done for each year. The results from this study present an infrastructure solution that can promote market growth for PEVs to reach the state's ZEV goals by 2025. The overall results show a need for 99,000 to 133,000 destination chargers, including workplaces and public locations, and 9,000 to 25,000 fast chargers. Different from fast chargers, the majority (83 percent) of destination chargers serve PHEVs, which typically have shorter electric range. Although it is not required for enabling travel, destination chargers for PHEVs should be seen as a critical tool for reducing petroleum use in accordance with the state's environmental goals. The results also show a need for dedicated or shared residential charging solutions at multifamily dwellings. It is estimated that, by 2025, about 121,000 PEV drivers will reside at multifamily dwellings. Therefore, the total number of chargers needed to support PEVs in California ranges from 229,000 to 279,000. This range does not account for chargers located at single-family homes. EVI-Pro results can be compared with actual or planned charger deployments. The number of fast chargers available in California in 2017 was fewer than the number of chargers calculated by EVI-Pro necessary to expand the market for battery electric vehicles (that is, the 1,500 existing fast chargers is at least 25 percent less than the 2,005-5,877 fast chargers listed "As of 2017" within Table ES. 1). Staff should work with CARB and other agencies, including those at the regional and municipal levels, to specify the numbers of chargers needed at residential locations after conducting a detailed geospatial analysis that quantifies any limitations to charging posed by the local built environment, with specific attention to parking availability.

Need for Ongoing Analysis and Immediate Action

Staff has discussed numerous issues that create variance and uncertainty within the modeling framework. However, stakeholders need to evaluate these results in the context of continuously changing technologies and markets. Charging infrastructure industry participants and policy makers should target an approach that uses stable policy frameworks and that ensures incremental and steady growth in PEV infrastructure that is consistent throughout California. Meanwhile, tracking changes in vehicle and charging technology and consumer preferences can improve future modeled estimates and functionalities. Updated data and input from stakeholders will be essential to calibrate the model to characterize network growth and provide insight on the adequacy of service. To immediately promote the adoption of electric vehicles, current charging technologies should be used to close gaps in needed infrastructure.

Energy Commission staff will continue to develop analyses, policies, and investment programs to support improved accessibility and deployment of charging across California.

Shared Use of Chargers Is Critical to Ensure Efficient Investment

Representing an improvement to the scientific literature, this analysis presents the significance of infrastructure reliability and accessibility on the quantification of charger demand. Higher reliability and accessibility of chargers will promote efficient sharing and reduce overall costs. The savings from cost reductions can be evaluated by comparing the lower and higher estimates from EVI-Pro. For instance, higher reliability and accessibility of chargers could reduce the cost of equipment for fast charging by 60 percent (comparing 25,000 to 9,000 DCFC). Ensuring the reliability and accessibility of chargers to achieve savings in the charging segments depends on several site-level issues, such as visibility for drivers, use of networking and real-time tracking technologies to ensure chargers are maintained, and parking enforcement for internal combustion cars that block PEV access to chargers.

Widespread Charger Deployments Should Be Efficiently Integrated With the Electric System

This analysis simulated the use of 1.3 million PEVs for a typical weekday and weekend given driver travel schedules and drivers' consideration of electric range and refueling prices. Staff found that the PEV charging load from residential and nonresidential locations accounts for nearly 1 GW during the peak-demand period of the grid. The extent to which residential demand can be shifted temporally and among locations to, for example, shape load to better fit a solar generation profile will depend on the use of charging technologies and price incentives that aid dispatch ability and avoid substantive changes to driver travel and behaviors. Two enabling factors include 1) increasing the heterogeneity and rated capacity of the assumed residential chargers to permit shifting demand to the early morning and 2) the use of chargers in nonresidential areas to reduce the need for additional grid ramping capacity and operational costs associated with the charging scenario examined. Networking technologies that enable shared use should be leveraged to automate demand responsive charging.

These load profiles may have significant impacts at the local level. While the spatial distribution of chargers among sites within a county was not the focus of this analysis, future installations should recognize the likelihood for grid impacts and thus proactively manage costs. The travel simulations of EVI-Pro indicate that weekend DC fast charger demand would more than double within one hour to peak load of 120 MW. This sharp increase in DC fast charging demand, albeit dispersed among local sites, should be managed with appropriate electrical service and distributed generation and storage resources to effectively prevent system overloading and to avoid utility peak demand charges.

Future Analyses and Improvements

Commission staff intends to use EVI-Pro to track progress on the state's goals for transportation electrification infrastructure. Using EVI-Pro as a consistent reference point, particularly in the context of diverse publicly and privately supported investments in charging infrastructure, can provide insight into the adequacy of the network necessary to support PEV travel or identify where additional targeted investments are needed. A Web-based portal housing the 2018-2025 infrastructure demand results of EVI-Pro will be published in association with this report for electricity, air quality, and transportation planning (Appendix G). To ensure relevance for policy making and improve the accuracy and transparency of the results, the Energy Commission will establish a platform for stakeholders to engage with scenario development. Ongoing stakeholder engagements can contribute valuable information that improves EVI-Pro. Examples include the identification of prospective charging station installations and data enabling analysis of network adequacy and reliability. In addition, staff will provide annual updates that incorporate information about both public and private charging deployments and county-level PEV sales.

Staff intends to run additional EVI-Pro simulations to ensure adequate characterization of changes to the functioning of the transportation and charging markets and emissions reduction policy. Results from this analysis may be sensitive to changes in environmental regulation, the performance and cost of PEV technologies, consumer preferences, and information about the built environment, among other factors. Key new data and trends that can improve EVI-Pro include, but are not limited to:

- Updates to the *California Household Travel Survey* and new data on commercial and government vehicle travel.
- Representative and localized information about the availability of electricity nearby residential parking, defined at least at the county level.
- Improvements in PEV and charging technology projections, including light-duty vehicle class- and powertrain-specific charging and range capabilities, depending on the availability of data about new or expected models.
- Improvements in assumptions affecting the potential for the shared use of chargers (for example, geospatial distribution of currently deployed and anticipated investments in charging, pricing, and shared use of residential chargers, pricing of and access to workplace and public charging, connector/vehicle interoperability, and equipment decay rates).
- Surveys or models that reveal the range, time value, and load-shifting preferences of drivers who have purchased PEVs or intend to in the future.
- Changes in light-duty vehicle use due to shared or automated mobility.

Likewise, changes to other state agency or local municipal programs and policies that can affect and be informed by EVI-Pro include:

- Advanced Clean Cars Program regulations for model years 2026 and beyond.
- Expansion of charging infrastructure through the Low Carbon Fuel Standard Program.
- Clean Vehicle Rebate Program and other geo-targeted consumer incentives for vehicles and infrastructure.
- Electric utility transportation electrification investments and integrated resource planning, including time-variant pricing tariffs.
- Implementation of sustainable communities strategies and transportation plans by local governments.

- *Vehicle-Grid Integration Roadmap.*[23]
- California Green Building Standards Code[24] requirements for the new construction and retrofit of existing buildings.
- California Transportation Plan and others.

The extent to which these policies interact with charger demand is not known at this time. For example, Senate Bill 375: the Sustainable Communities and Climate Protection Act (Steinberg, Chapter 727, Statues of 2008) could affect housing patterns and single-occupancy vehicle travel demand, which are key inputs affecting demand for infrastructure. Beyond California, national and international electrification trends and experience will inform modeling efforts and deployment strategies. Coordination around EVI-Pro can improve the state's understanding of interactive effects across mobility, the electricity system, and private investment to support expeditious charging deployment.

More important, the Executive Order B-48-18 target to more than triple the number ZEVs deployed between 2025 and 2030 will require close coordination among the agencies, researchers and the Energy Commission. Commission staff looks forward to working collaboratively to maintain and use EVI-Pro to continuously spur the construction and installation of charging infrastructure essential for widespread PEV adoption in California.

23 California Independent System Operator. February, 2014. *Vehicle-Grid Integration Roadmap.* http://www.caiso.com/documents/vehicle-gridintegrationroadmap.pdf. Accessed February 27, 2018.
24 California Building Standards Commission. 2018. "*California Green Building Standards Code (Cal. Code Regs., Title 24, Part 11).*" http://www.bsc.ca.gov/Home/CALGreen.aspx. Accessed February 2018.

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Acronyms and Abbreviations

Original Term	Acronym/Abbreviation
Alternative Fuels Data Center	AFDC
Battery electric vehicle	BEV
California Air Resources Board	CARB
California Household Travel Survey	CHTS
Clean technologies and fuels	CTF
Clean Vehicle Rebate Project	CVRP
Direct current	DC
Direct current fast charger	DCFC
(United States) Department of Energy	U.S. DOE
Electric vehicle-miles traveled	eVMT
Electric Vehicle Infrastructure Projections	EVI-Pro
Fuel cell electric vehicle	FCEV
Kilowatt/kilowatt-hour	kW/kWh
Level 1/Level 2	L1/L2
Metropolitan Transportation Commission	MTC
Metropolitan Planning Organization	MPO
Multiunit dwellings	MUD
Megawatt	MW
National Household Travel Survey	NHTS
National Renewable Energy Laboratory	NREL
Plug-in hybrid electric vehicle	PHEV
Plug-in electric vehicle	PEV
Sacramento Council of Governments	SACOG
San Diego Association of Governments	SANDAG
Southern California Association of Governments	SCAG
State of charge	SOC
Time of use	TOU
Zero-emission vehicle	ZEV

APPENDIX A:
Existing PEV Fleet Distributed by County

The data below are based on the Clean Vehicle Rebate Project (CVRP) data from January 1, 2017, accounting for the rebate participation rates at the county level. The rebate participation rates for each BEV and PHEV buyer are reported by CVRP for the period of 2010-2015. Statewide average participation is applied for the seven counties with insufficient data.

The existing PHEV: PEV ratio is used in projecting the future shares of BEVs and PHEVs for 2017. Moving forward, an adjustment is made to keep existing outliers within an early PEV market within 10 percent of the state average (44 percent). Therefore, the counties that exceed the 54 percent PHEV:PEV ratio is kept at 54 percent, while the counties that have a ratio below 34 percent are kept at 34 percent.

Table A.1: Estimates for the Existing PEV Fleet Distributed by County

COUNTY	PEV20	PEV40	PEV80	PEV230	PEV Totals	PEV% of the State	PHEV:PEV Ratio
Alameda	3480	3429	10200	2141	19250	8.04%	0.36
Alpine	2	0	3	0	5	0.00%	0.40
Amador	11	13	26	6	56	0.02%	0.43
Butte	53	39	87	31	210	0.09%	0.44
Calaveras	17	10	22	17	66	0.03%	0.41
Colusa	2	2	3	2	9	0.00%	0.44
Contra Costa	2564	1770	3528	1538	9400	3.93%	0.46
Del Norte	5	3	5	0	13	0.01%	0.62
El Dorado	260	203	310	133	906	0.38%	0.51
Fresno	238	306	1583	127	2254	0.94%	0.24
Glenn	5	2	2	3	12	0.01%	0.58
Humboldt	233	91	144	27	495	0.21%	0.65
Imperial	13	10	9	15	47	0.02%	0.49
Inyo	6	2	0	3	11	0.00%	0.73
Kern	261	155	500	76	992	0.41%	0.42
Kings	11	14	45	2	72	0.03%	0.35
Lake	34	22	41	3	100	0.04%	0.56
Lassen	0	2	3	0	5	0.00%	0.40
Los Angeles	14525	16423	21704	10073	62725	26.21%	0.49
Madera	21	34	150	18	223	0.09%	0.25
Marin	862	641	1756	736	3995	1.67%	0.38
Mariposa	3	3	10	5	21	0.01%	0.29
Mendocino	163	90	133	36	422	0.18%	0.60
Merced	59	40	100	21	220	0.09%	0.45

Modoc	2	0	2	0	4	0.00%	0.50
Mono	3	3	0	2	8	0.00%	0.75
Monterey	293	215	329	240	1077	0.45%	0.47
Napa	184	155	243	195	777	0.32%	0.44
Nevada	66	47	115	64	292	0.12%	0.39
Orange	8503	5862	8668	5305	28338	11.84%	0.51
Placer	418	421	664	257	1760	0.74%	0.48
Plumas	2	3	5	0	10	0.00%	0.50
Riverside	2173	1699	1726	657	6255	2.61%	0.62
Sacramento	1152	810	2047	406	4415	1.84%	0.44
San Benito	91	45	42	29	207	0.09%	0.66
San Bernardino	1691	1238	1444	457	4830	2.02%	0.61
San Diego	4078	3075	8269	3079	18501	7.73%	0.39
San Francisco	1391	657	2689	1123	5860	2.45%	0.35
San Joaquin	323	296	660	183	1462	0.61%	0.42
San Luis Obispo	223	223	427	149	1022	0.43%	0.44
San Mateo	1593	1483	4499	2419	9994	4.18%	0.31
Santa Barbara	295	389	561	329	1574	0.66%	0.43
Santa Clara	6109	7162	18083	5516	36870	15.41%	0.36
Santa Cruz	646	475	826	303	2250	0.94%	0.50
Shasta	49	45	81	12	187	0.08%	0.50
Sierra	2	0	3	0	5	0.00%	0.40
Siskiyou	5	3	6	9	23	0.01%	0.35
Solano	570	386	375	151	1482	0.62%	0.65
Sonoma	1014	819	1764	319	3916	1.64%	0.47
Stanislaus	131	166	397	67	761	0.32%	0.39
Sutter	23	13	13	10	59	0.02%	0.61
Tehama	13	6	13	3	35	0.01%	0.54
Trinity	3	2	3	0	8	0.00%	0.63
Tulare	39	35	179	29	282	0.12%	0.26
Tuolumne	9	17	11	7	44	0.02%	0.59
Ventura	1027	1459	1296	819	4601	1.92%	0.54
Yolo	222	171	380	86	859	0.36%	0.46
Yuba	10	17	18	6	51	0.02%	0.53
TOTALS	**55181**	**50701**	**96202**	**37244**	**239328**	**100%**	**0.44**

Source: California Energy Commission and NREL

APPENDIX B:
New Vehicle Adoption Distributed by County

The data below are from a consulting firm, IHS' annual vehicle registration survey data for 2016 (released in 2017). The concept of "new vehicles" applied for the vehicles that are sold during the last five years. Therefore, staff considered the cumulative vehicle registrations from the last five-year period (2012-2016) to find the new vehicle adoption split presented below.

Table B.1: New Electric Vehicle Adoption Distributions by County

County	New Vehicle Adoption Rate (% of the State Total)
Alameda	3.82%
Alpine	0.00%
Amador	0.08%
Butte	0.38%
Calaveras	0.10%
Colusa	0.05%
Contra Costa	2.94%
Del Norte	0.04%
El Dorado	0.47%
Fresno	1.81%
Glenn	0.05%
Humboldt	0.23%
Imperial	0.45%
Inyo	0.04%
Kern	1.96%
Kings	0.29%
Lake	0.11%
Lassen	0.05%
Los Angeles	26.94%
Madera	0.26%
Marin	0.76%
Mariposa	0.04%
Mendocino	0.17%
Merced	0.43%
Modoc	0.02%
Mono	0.03%
Monterey	0.83%
Napa	0.35%

Nevada	0.21%
Orange	10.04%
Placer	1.11%
Plumas	0.04%
Riverside	6.02%
Sacramento	3.96%
San Benito	0.13%
San Bernardino	5.00%
San Diego	9.05%
San Francisco	1.77%
San Joaquin	1.43%
San Luis Obispo	0.66%
San Mateo	2.59%
Santa Barbara	0.93%
Santa Clara	5.25%
Santa Cruz	0.55%
Shasta	0.36%
Sierra	0.00%
Siskiyou	0.07%
Solano	1.14%
Sonoma	1.19%
Stanislaus	0.99%
Sutter	0.20%
Tehama	0.12%
Trinity	0.02%
Tulare	0.81%
Tuolumne	0.10%
Ventura	2.37%
Yolo	1.05%
Yuba	0.13%
TOTAL	**100.00%**

Source: California Energy Commission and NREL

APPENDIX C:
All Vehicle-Level Assumptions

Table C.1: All Vehicle-Level Assumptions

Input	Unit	Assigned Values	PEV Type
Vehicle Drive Efficiency	Watt-hour/mile	250	PHEV & BEV
Vehicle On-Board Charger Efficiency	%	90	PHEV & BEV
Min. Range Tolerance	miles	20	BEV-only
Min. Vehicle Dwell Time to Consider Charging (L1&L2 only)	minutes	30	PHEV & BEV
PHEV Cost of Gasoline Operation	$/mile	$3.00 gal / 40 mpg	PHEV-only
Max. AC Charging Power Level	kW	Varies annually	PHEV & BEV
Battery/Electric Range	Miles	Varies annually	PHEV & BEV
Maximum State of Charge (SOC) to Consider Fast Charging	%	85	BEV-only
Fast Charging SOC Cut-off	%	95	BEV-only

Source: California Energy Commission and NREL

APPENDIX D:

Annual Technology Projections for New Vehicles and Chargers

The technology projections for the electric range are consistent with California Air Resources Board's Mid-Term Review projections as detailed in Chapter 4.1. These values are considered as a reasonable estimate for the average range and charging power level limitations through 2025. Note that the PEV ranges for the 2017 fleet for the Energy Commission's assessment are different than the As-of-2017 values provided below. As-of-2017 values are used as the initial point upon which linear improvements in technology are projected.

Table D.1: PEV Technology Projections

Existing Fleet (As of 2017)		Vehicles	Range (miles)	Residential L2 (kW)	Destination L2 (kW)	Public DC (kW)
Group1	BEV80	96202	80	6.6	6.6	50.0
Group2	BEV230	37244	230	6.6	6.6	105.0
Group3	PHEV20	55181	20	3.6	3.6	N/A
Group4	PHEV40	50701	40	3.6	3.6	N/A
Future Fleet (2018-2025)		**Vehicles**	**Range**	**Residential**	**Destination**	**Public DC**
Group1	BEV-2018	74463	132.8	7.2	6.6	66.4
Group2	BEV-2019	74463	143.9	7.8	6.6	71.9
Group3	BEV-2020	74463	154.9	8.4	6.6	77.4
Group4	BEV-2021	74463	165.9	9.0	6.6	83.0
Group5	BEV-2022	74463	176.9	9.6	6.6	88.5
Group6	BEV-2023	74463	188.0	10.2	6.6	94.0
Group7	BEV-2024	74463	199.0	10.8	6.6	99.5
Group8	BEV-2025	74463	210.0	11.4	6.6	105.0
Group9	PHEV-2018	60806	30.9	3.8	3.8	N/A
Group10	PHEV-2019	60806	32.2	3.9	3.9	N/A
Group11	PHEV-2020	60806	33.5	4.1	4.1	N/A
Group12	PHEV-2021	60806	34.8	4.2	4.2	N/A
Group13	PHEV-2022	60806	36.1	4.4	4.4	N/A
Group14	PHEV-2023	60806	37.4	4.5	4.5	N/A
Group15	PHEV-2024	60806	38.7	4.7	4.7	N/A
Group16	PHEV-2025	60806	40.0	4.9	4.9	N/A
	TOTAL	**1321371**				

Source: California Energy Commission and NREL

APPENDIX E:
County-Level Results for Residential Charging

Table E.1: County-Level Results From EVI-Pro for Residential Charging Demand by 2025

County	Number of PEVs by 2025 (Input)	PEVs Participating in Residential Charging	Residential Charging Participation Rate	PEVs Participating in Residential Charging at MUDs	PEVs Participating in Residential Level 2 Charging
Alameda	80622	75734	94%	7185	4466
Alpine	27	27	100%	0	0
Amador	647	602	93%	0	68
Butte	2928	2676	91%	110	229
Calaveras	801	769	96%	7	89
Colusa	300	300	100%	0	58
Contra Costa	45873	42544	93%	2426	2655
Del Norte	255	231	91%	0	6
El Dorado	5580	5220	94%	133	369
Fresno	17703	16270	92%	780	869
Glenn	352	308	88%	9	21
Humboldt	2863	2627	92%	191	133
Imperial	2878	2517	87%	105	138
Inyo	281	230	82%	0	9
Kern	14872	13305	89%	550	897
Kings	1987	1921	97%	16	175
Lake	963	811	84%	0	74
Lassen	299	263	88%	0	16
Los Angeles	350881	320971	91%	49960	16982
Madera	2230	2093	94%	53	217
Marin	16518	16062	97%	2204	812
Mariposa	268	243	91%	0	33
Mendocino	2300	2171	94%	39	55
Merced	3266	2974	91%	40	182
Modoc	98	85	87%	0	4
Mono	185	154	83%	0	11
Monterey	8274	7460	90%	528	374
Napa	4434	3998	90%	252	226
Nevada	2137	2004	94%	33	212
Orange	145559	131538	90%	11215	7404

Placer	11976	11210	94%	403	695
Plumas	276	255	92%	12	14
Riverside	55287	50080	91%	1772	4397
Sacramento	37240	35507	95%	1576	2764
San Benito	1422	1340	94%	0	137
San Bernardino	44846	41230	92%	1749	3133
San Diego	110227	103516	94%	11489	5925
San Francisco	28222	23610	84%	6518	1367
San Joaquin	13035	12366	95%	520	1228
San Luis Obispo	7046	6255	89%	275	328
San Mateo	45544	43366	95%	3948	2010
Santa Barbara	10333	9420	91%	752	479
Santa Clara	141786	131768	93%	11533	6267
Santa Cruz	10066	9120	91%	468	696
Shasta	2765	2420	88%	113	93
Sierra	40	40	100%	0	6
Siskiyou	511	447	87%	5	36
Solano	11345	10778	95%	616	897
Sonoma	18918	17861	94%	929	1649
Stanislaus	8277	7831	95%	210	636
Sutter	1400	1400	100%	35	136
Tehama	797	786	99%	63	63
Trinity	131	108	82%	0	5
Tulare	5770	5281	92%	86	442
Tuolumne	758	641	85%	28	33
Ventura	28096	25730	92%	1071	1403
Yolo	8957	8830	99%	762	773
Yuba	909	864	95%	42	62
TOTAL	**1321371**	**1218182**	**92%**	**120811**	**72458**

Source: California Energy Commission and NREL

APPENDIX F:
County-Level Results for Nonresidential Charging

The table below shows EVI-Pro results at the county level. In some cases, the assumption of the shared use of chargers between two vehicles reduces the high estimate below what is required to serve the total number of vehicles needing to charge during the peak period (defined as the Low Estimate in Chapter 3). In the counties in which this convergence occurs, during post-processing staff equated the high estimate to the low estimate. For more detail about counties with zero or low ranges in chargers demanded, see discussion in Chapter 4.

Table F.1: County-Level Results From EVI-Pro for Destination Chargers and Fast Chargers Demand 2025

County	Workplace L2		Public L2		Destination L2 (Work & Public)		Fast Chargers		Metro (MPO) Region
	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	
Alameda	3853	3853	2629	3581	6482	7434	645	1740	MTC
Alpine	0	0	1	4	1	4	1	3	Non-MPO
Amador	20	30	39	52	59	82	14	29	Non-MPO
Butte	122	123	132	184	254	307	37	77	MPO-Other
Calaveras	21	25	45	45	66	70	16	20	Non-MPO
Colusa	13	13	20	20	33	33	7	9	Non-MPO
Contra Costa	1195	1507	2107	2420	3301	3927	352	674	MTC
Del Norte	1	8	11	17	11	25	1	6	Non-MPO
El Dorado	92	115	306	330	397	445	59	108	SACOG
Fresno	598	598	418	774	1016	1372	135	382	MPO-Other
Glenn	8	12	15	15	23	27	5	6	Non-MPO
Humboldt	78	79	166	236	244	315	24	57	Non-MPO
Imperial	96	114	95	117	190	231	26	43	SCAG
Inyo	7	15	14	16	21	31	2	5	Non-MPO
Kern	499	557	506	722	1005	1279	131	313	MPO-Other
Kings	75	75	139	139	214	214	32	75	Non-MPO
Lake	43	43	62	79	105	122	15	21	Non-MPO
Lassen	12	12	9	14	21	26	7	11	Non-MPO
Los Angeles	14497	16298	11695	20479	26192	36777	1097	5073	SCAG
Madera	48	62	50	65	97	127	30	57	MPO-Other
Marin	562	638	914	914	1476	1552	296	336	MTC
Mariposa	3	9	8	9	11	17	1	6	Non-MPO
Mendocino	110	127	150	181	260	307	38	48	Non-MPO
Merced	90	90	115	152	205	242	30	59	MPO-Other

Modoc	0	2	5	5	5	7	1	3	Non-MPO
Mono	15	11	15	24	30	34	5	11	Non-MPO
Monterey	341	363	350	490	691	853	63	139	MPO-Other
Napa	165	176	262	262	427	438	70	91	MTC
Nevada	43	48	111	143	154	191	41	54	Non-MPO
Orange	5829	6806	4653	9560	10482	16366	644	2375	SCAG
Placer	451	502	640	817	1090	1318	107	292	SACOG
Plumas	6	9	12	14	18	23	6	6	Non-MPO
Riverside	1397	1589	2537	4014	3934	5603	297	1003	SCAG
Sacramento	2024	2024	1656	2705	3680	4729	311	826	SACOG
San Benito	11	16	58	58	69	74	9	11	MTC
San Bernardino	1848	1997	1444	2669	3293	4666	156	598	SCAG
San Diego	4066	4034	3746	7224	7812	11258	896	3064	SANDAG
San Francisco	1379	1489	1498	1929	2877	3418	584	1281	MTC
San Joaquin	520	520	538	677	1058	1197	156	317	MPO-Other
San Luis Obispo	244	268	258	452	501	719	67	179	MPO-Other
San Mateo	1582	1695	1402	1468	2985	3163	614	775	MTC
Santa Barbara	389	425	583	725	972	1150	153	344	MPO-Other
Santa Clara	6532	7591	4190	6612	10722	14202	1045	2780	MTC
Santa Cruz	221	282	381	632	602	914	83	212	MTC
Shasta	107	136	165	250	273	386	49	105	MPO-Other
Sierra	0	0	0	2	0	2	1	1	Non-MPO
Siskiyou	24	28	20	24	45	52	12	15	Non-MPO
Solano	413	408	489	642	902	1050	72	139	MTC
Sonoma	449	703	940	1157	1389	1860	201	388	MTC
Stanislaus	251	277	210	334	461	611	65	150	MPO-Other
Sutter	69	69	75	89	144	158	12	17	SACOG
Tehama	21	25	51	37	73	62	4	8	Non-MPO
Trinity	0	3	6	7	6	10	1	3	Non-MPO
Tulare	135	156	130	225	265	381	43	107	MPO-Other
Tuolumne	32	35	33	58	65	93	8	19	Non-MPO
Ventura	716	884	915	1418	1631	2301	105	296	SCAG
Yolo	377	377	545	577	922	954	169	204	SACOG
Yuba	35	35	37	42	71	77	13	13	SACOG
TOTAL	**51737**	**57375**	**47596**	**75895**	**99333**	**133270**	**9064**	**24967**	

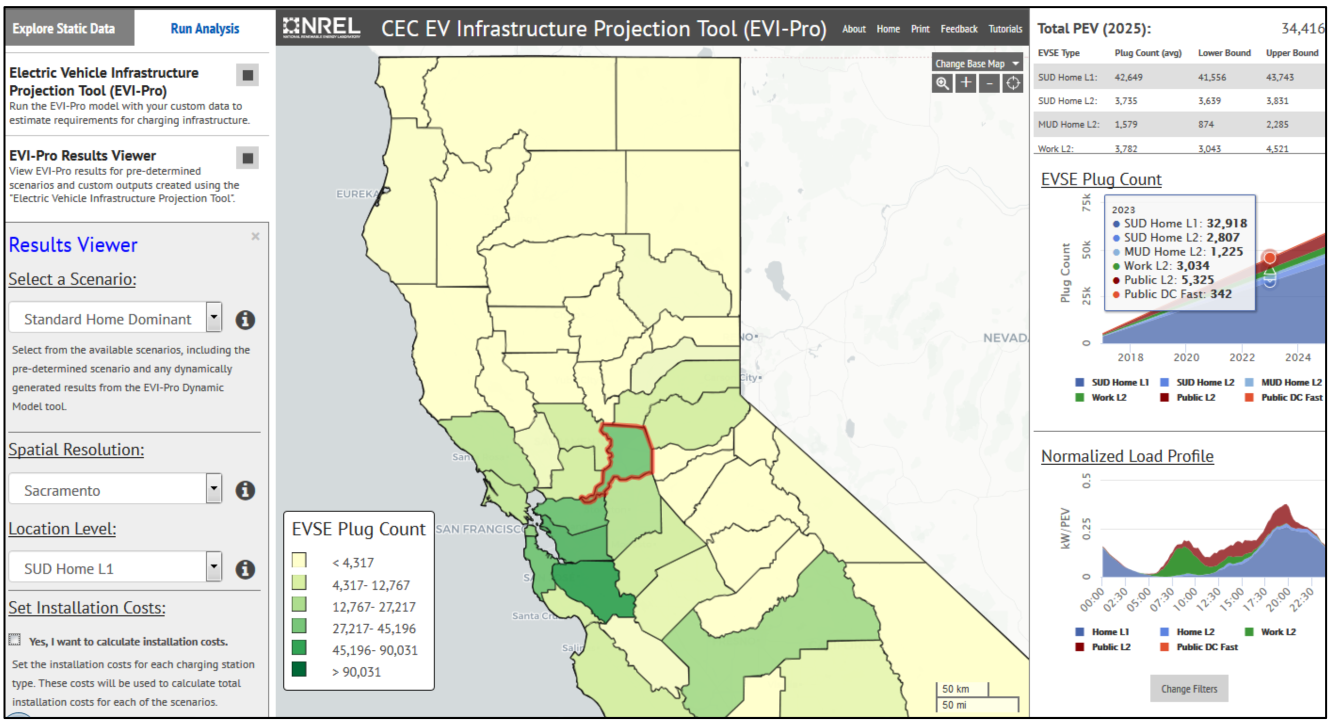
***Metropolitan Planning Organization (MPO) regions are classified under six; (1) Metropolitan Transportation Commission (MTC) representing the Bay Area, (2) Sacramento Council of Governments (SACOG), (3) Southern California Association of Governments (SCAG), (4) San Diego Association of Governments (SANDAG), (5) Other MPO regions, and, finally, (6) Rural non-MPO regions.**

Source: California Energy Commission and NREL

APPENDIX G:
EVI-Pro Web Portal

The screenshot below shows EVI-Pro results through an interactive Web interface. For instance, stakeholders will be able to view charging station quantities, load shapes, and infrastructure cost estimates resulting from the scenarios described in this report. In addition, a chloropleth map will be sortable by spatial resolution, location type, and other parameters. The EVI-Pro Web portal will be accessible on the Commission Web page.

Figure G.1: A Snapshot of the EVI-Pro Web Portal



Source: California Energy Commission and NREL