ELECTRIC VEHICLES AND THE CALIFORNIA GRID

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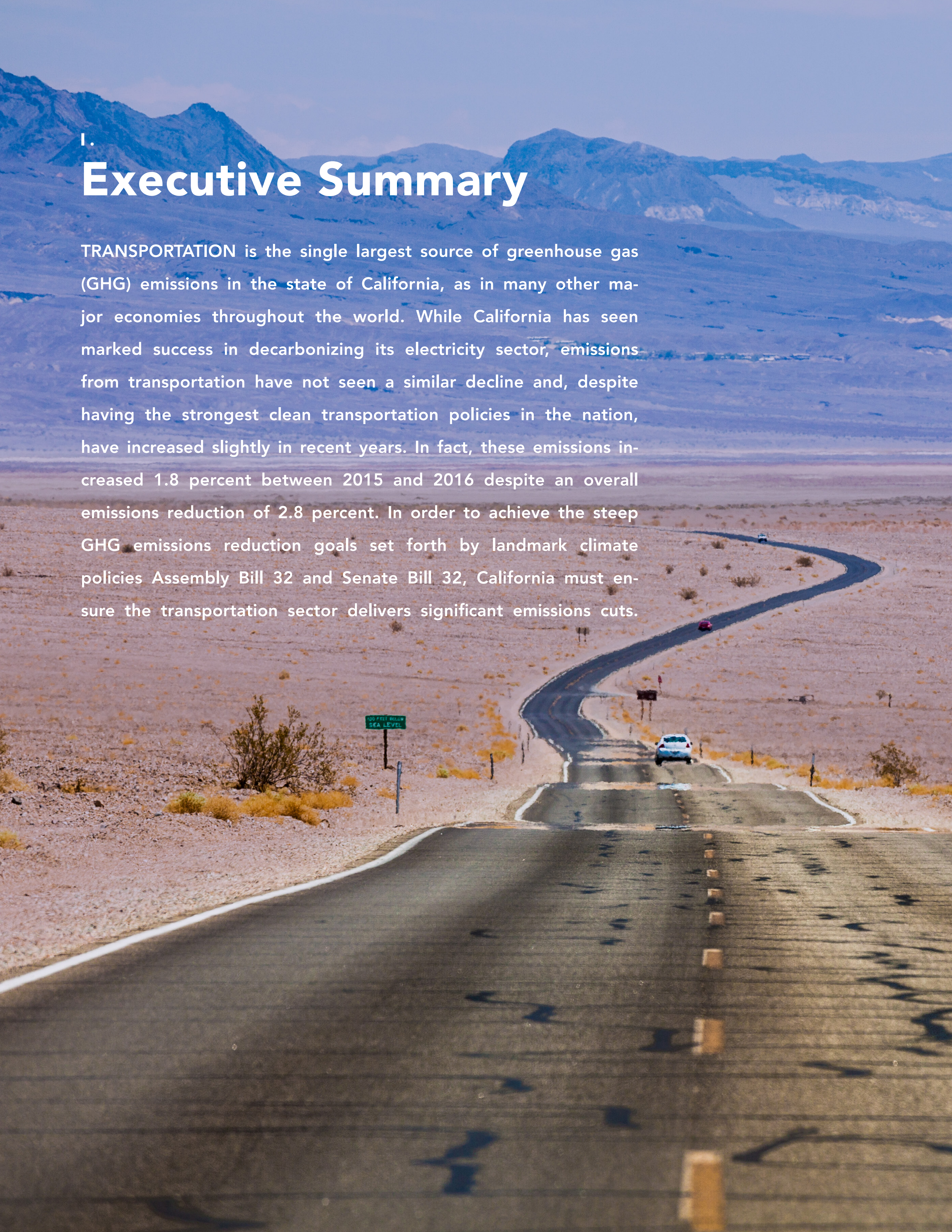
I.

Executive Summary

TRANSPORTATION is the single largest source of greenhouse gas (GHG) emissions in the state of California, as in many other major economies throughout the world. While California has seen marked success in decarbonizing its electricity sector, emissions from transportation have not seen a similar decline and, despite having the strongest clean transportation policies in the nation, have increased slightly in recent years. In fact, these emissions increased 1.8 percent between 2015 and 2016 despite an overall emissions reduction of 2.8 percent. In order to achieve the steep GHG emissions reduction goals set forth by landmark climate policies Assembly Bill 32 and Senate Bill 32, California must ensure the transportation sector delivers significant emissions cuts.



To that end, a variety of policies have been implemented to help electrify the transportation sector – from passenger vehicles to high speed rail. In his final "State of the State" address, Governor Jerry Brown announced a new electrification target: getting 5 million zero emission vehicles on the road by 2030.

As vehicle manufacturers and nations around the world move from internal-combustion engines to zero-emission vehicles (ZEVs), vehicle automation and greater utilization of mobility-on-demand services like ride-hailing are further disrupting transportation systems. As the state looks to add hundreds of thousands of electric vehicles to the grid each year, California's electricity system will need to evolve to accommodate shifting demand patterns and increased electrification of transportation.

Part of a series of briefs analyzing key issues facing the future of California's grid, this brief investigates trends in the electrification of the transportation sector along with mobility and charging infrastructure trends to determine the impacts policy leaders should be aware of and the strategies that can optimize grid performance as more electric vehicles hit the road.

Key takeaways include:

- **Electricity demand will increase only modestly as electric vehicles (EV) sales surge.**
  - » California currently has about 369,000 plug-in electric vehicles (PEVs)—including both fully battery electric vehicles and plug-in hybrid electric vehicles—on the road but is predicted to reach more than five million PEVs on the road by 2030.
  - » The California Energy Commission forecasts that 3.9 million PEVs will add about 15,500 GWh of charging demand, equivalent to about five percent of California's current total annual energy load.
- **Transportation trends towards automation and increased usage of mobility services like ride-hailing could rapidly expand the share of electric vehicles on the road, further increasing electricity demand.**
  - » The estimated share of total light-duty vehicle VMT from ride-hailing vehicles is growing rapidly nationwide - currently about 6 percent in the U.S. – and could double from 10 percent to 20 percent of total VMT between 2018 and 2020.
  - » If these companies move toward PEVs, critically important to decarbonize transportation, charging infrastructure needs and grid impacts would increase substantially. While ride-sharing companies are expected to complete 12 billion rides this year in the U.S., only one percent of the estimated 334 million total trip miles on the Uber and Lyft platforms in California were in an electric vehicle (in Q3 2017).
- **The growth of EVs in California will require upgrades to the energy system, but the long-run costs are likely to be low, when compared to the benefits.**
  - » As PEV adoption levels grow, there will be impacts to both the distribution system as well as the bulk power system. To date, the actual cost of distribution system upgrades as a result of added PEVs has been small: in 2017, PEVs caused only about 0.01 percent of total distribution system upgrade costs.
  - » A detailed analysis of the grid system and geographic distribution of future PEV sales found that the annual PEV-related distribution costs through 2030 are estimated to be only about one percent of the combined distribution revenue requirement of the three IOUs and SMUD (Sacramento Municipal Utility District).
  - » While upgrade costs to these systems as a result of added PEVs have been minimal thus far, that could change with greater adoption rates.

- **New management strategies can help optimize the potential benefits and minimize the potential risks that added EV demand will present.**
  - » Managed charging programs could alleviate stress on the distribution grid, lower wholesale operating costs, and serve as a resource to help integrate more intermittent renewable energy.
  - » Smart charging could deliver significant benefits: the authors' analysis found that when 2.5 million PEVs were added to the system, grid dispatch found that smart charging of all the vehicles could avoid 50 percent of incremental power system operating costs and reduce renewable energy curtailment by 27 percent annually, relative to when the charging of the same number of PEVs is left unmanaged.
  - » According to results from the CPUC's Integrated Resource Planning model, flexible PEV charging can yield total system resource cost savings of $100 - 200 million dollars per year and a reduction in renewable energy curtailment, compared to unmanaged PEV charging.
  - » EV batteries could provide a source of energy storage to the grid, and the CPUC should consider recognizing this value. In practice, due to the high value placed on mobility by PEV users, relying on EV batteries alone for grid storage is fraught with risk. The precipitous decline in battery prices makes it increasingly feasible for stationary battery storage to cost effectively provide distribution system support, load-shifting, and ancillary services, without the risks of managing a highly valuable mobile battery asset.

To ensure that California can meet its ZEV goals while maintaining an affordable and reliable electricity system, certain policy levers might be considered to optimize this transition. These include:

- Ensure that autonomous vehicles and mobility-on-demand services do not lead to increased GHG emissions while working to increase the overall level of electrification of the transportation sector.
- Increase the accessibility of charging infrastructure, which is paramount to increasing EV adoption rates.
  - » Focus financing and support to increase the deployment of fast chargers to support the electrification of medium-, heavy-duty and ridehailing vehicles.
  - » Focus incentives on lowering the installation and equipment costs for multifamily and public charging stations.
  - » Create a centralized, public database that tracks the cost, location, and utilization of home, multifamily, work, and public chargers by power level.
- Increase participation in existing and upcoming load management opportunities such as time-of-use (TOU) rates and smart charging programs.
  - » Design PEV-specific TOU rates with longer off-peak periods and bigger price differentials.
  - » Conduct more smart charging pilots.

This brief is intended to help provide background on how mobility, charging infrastructure, and energy management trends could influence the future management of PEVs on California's grid. The state's energy-related agencies and regulators, utilities, automakers, aggregators/demand response providers, and scheduling coordinators will need to work together to enable PEV grid services.

I.

Introduction

THE widespread electrification of the transportation sector can enable oil independence and lower greenhouse gas emissions.[1] Simultaneously increasing the share of renewable energy on the grid can help meet economy-wide greenhouse gas reduction goals.[2] California is a national and international leader in both of these decarbonization strategies. At the same time, technological change is leading to a shift toward automation, ride-hailing, and heavy-duty vehicle electrification in the transportation sector. With such changes in plug-in electric vehicle adoption, levels of renewable energy, and mobility paradigms, planning for interactions between vehicles, charging infrastructure, and the electric grid at both the distribution and bulk power system levels will become both increasingly important and complex. The growing electric load from the transportation sector could either be an added challenge or a resource for the integration of solar photovoltaic and wind onto the grid, depending on the timing and location of charging patterns, and the type of grid services the vehicles are able to provide through the charging infrastructure.

1 Richardson, D. B. (2013). Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. Renewable and Sustainable Energy Reviews, 19, 247–254. https://doi.org/10.1016/j.rser.2012.11.042

2 California has a target to reduce GHG emissions 40% below 1990 levels by 2030, and 80% below 1990 levels by 2050; Williams, J. H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W. R., ... Torn, M. S. (2012). The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. Science, 335(6064), 53–59. https://doi.org/10.1126/science.1208365

California's Mobility – Infrastructure – Charging – Grid Nexus

With about 369,000 plug-in electric vehicles (PEVs)—including both fully battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)—on the road,[3] California's sales account for about half of cumulative PEV sales in the United States, which ranks as the second country in the world after China in total number of PEVs.[4] As model options increase (there are currently more than 40 PEV models on the market)[5] and with the support of policy,[6] Governor Brown has set a revised target of 5 million PEVs on the road by 2030.[7] To catch up with this growth of PEVs in the state and to spur further sales, private companies, electric utilities, and government agencies are investing heavily in the buildout of charging infrastructure, especially in public areas, workplaces, and multi-family housing.[8] In the power sector, the Renewable Portfolio Standard (RPS) requires half of the state's electricity consumption be met by renewable energy sources by 2030, and with large additions of solar photovoltaic (PV) and wind generation, utilities are already several years ahead of schedule to meet this mandate.[9] In parallel to these decarbonization transitions, the transportation sector is undergoing a shift toward automation and dramatic increases in mobility-on-demand services (such as ride-hailing) which may further affect the use of PEVs and the demand for charging infrastructure. Electrification of medium-duty and heavy-duty vehicles is also becoming increasingly possible and would add substantial additional load to the electric grid. Depending on how the electrification, mobility and charging infrastructure transitions evolve, there may be value in managed charging strategies that shift charging to times that are more optimal for the grid, so that the vehicles provide grid services and serve as a resource for the integration of renewable energy onto the grid.

As outlined in the following section, and depicted graphically in Figure 1, this report develops a Mobility-Infrastructure-Charging-Grid Nexus framework to analyze how the future of PEV impacts on the California electric grid, specifically from the grid services provided by the vehicles, will depend on current and emerging trends in three key areas: mobility of people and goods, charging infrastructure development, and charging strategies.

3 Advanced Technology Vehicle Sales Dashboard. (n.d.). Retrieved May 8, 2018, from https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/

4 Lutsey, N. (2018). *ICCT Briefing: California's continued electric vehicle market development*. The International Council on Clean Transportation.; International Energy Agency. (2017). Global EV Outlook 2017: Two million and counting. Retrieved from https://www.iea.org/publications/freepublications/publication/Global_EV_Outlook_2017.pdf

5 EV Showroom | GoElectricDrive - Accelerate the Good, Powered by EDTA. (n.d.). Retrieved May 7, 2018, from https://www.goelectricdrive.org/you-buy/ev-showroom; Vlasic, B., & Boudette, N. E. (2017, October 2). G.M. and Ford Lay Out Plans to Expand Electric Models. *The New York Times*. Retrieved from https://www.nytimes.com/2017/10/02/business/general-motors-electric-cars.html; Luxury carmakers unveil electric plans. (2017, September 7). BBC News. Retrieved from http://www.bbc.com/news/business-41179332; Ewing, J. (2017, July 5). Volvo, Betting on Electric, Moves to Phase Out Conventional Engines. *The New York Times*. Retrieved from https://www.nytimes.com/2017/07/05/business/energy-environment/volvo-hybrid-electric-car.html

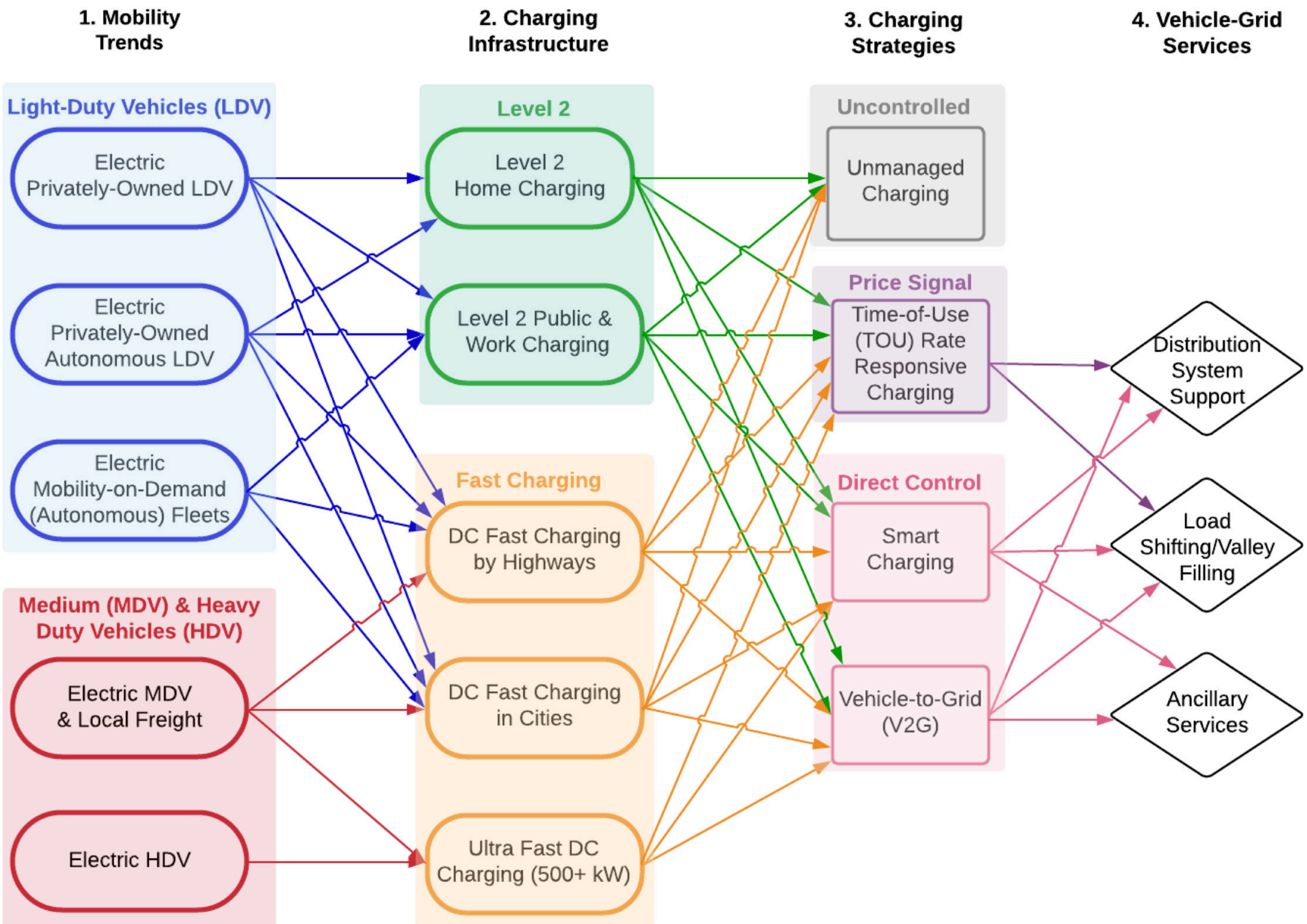
6 For example: Edmund G. Brown Jr., Governor of the State of California. Executive Order B-16-2012, Pub. L. No. EXECUTIVE ORDER B-16-2012 (2012).; CVRP Rebate Statistics. (2016). Retrieved November 12, 2016, from https://cleanvehiclerebate.org/eng/rebate-statistics; Zero Emission Vehicle (ZEV) Program. (n.d.). Retrieved December 4, 2017, from https://arb.ca.gov/msprog/zevprog/zevprog.htm

7 Governor Brown Takes Action to Increase Zero-Emission Vehicles, Fund New Climate Investments can be found at: https://www.gov.ca.gov/2018/01/26/governor-brown-takes-action-to-increase-zero-emission-vehicles-fund-new-climate-investments/

8 Volkswagen, Group of America. (2017). *Volkswagen California ZEV Investment Plan: Cycle 1 - Electrify America* (Electrify America).; John, J. S. (2017, January 24). California Utilities Seek $1B to Build Out Electric Vehicle Infrastructure. Retrieved April 20, 2017, from https://www.greentechmedia.com/articles/read/california-utilities-seek-1b-to-build-out-electric-vehicle-infrastructure; Marcacci, S. (2016, February 25). How Utilities Are Planning Electric-Vehicle Infrastructure in California and Beyond. Retrieved from https://www.greentechmedia.com/articles/read/how-utilities-are-planning-for-electric-vehicle-infrastructure

9 *California Public Utilities Commission Renewables Portfolio Standard Annual Report*. (2017). California Public Utilities Commission. Retrieved from http://www.cpuc.ca.gov/uploadedFiles/CPUC_Website/Content/Utilities_and_Industries/Energy/Reports_and_White_Papers/Nov%202017%20-%20RPS%20Annual%20Report.pdf

FIG 1 Framework of Electric Mobility - Infrastructure - Charging - Grid Nexus



Source: Western Electricity Coordinating Council (WECC).[10]

1. MOBILITY TRENDS:

Mobility patterns are in a state of flux and there is significant uncertainty about the effects that technological and behavioral changes will have on spatial and temporal travel demands. In addition to increasing electrification of light-duty vehicles, the main mobility trends are summarized below:

- **Autonomous Vehicles:** Rapid advances in computing, sensors, and artificial intelligence are rapidly leading to an increasing number of autonomous driving features in vehicles. There is widespread expectation that fully autonomous vehicles will comprise a majority of the U.S. vehicle fleet within a few decades. Autonomous vehicles could potentially have negative climate impacts if they lead to a substantial increase in annual vehicle miles traveled (VMT) because travelers no longer need to focus on driving. On the other hand, increased VMT may make PEVs more attractive due to their substantially lower operating costs. It is unclear if widespread automation will result in a shift toward shared, centrally operated fleets or whether personal vehicle ownership will continue to dominate.

10 Made using Lucid Chart at https://www.lucidchart.com/

- **Mobility-on-Demand services:** The near ubiquitous use of smart phones and advances in information technology have spawned several types of mobility-on-demand services in recent years. The most dominant of these are ride-hailing services such as those provided by Lyft and Uber. The high daily VMT of ride-hailing vehicles also make a switch to electric highly attractive once charging infrastructure is widely available. The charging load curve for a mobility-on-demand fleet could be tilted toward much greater use of DC fast charging in urban centers, resulting in a different spatial and temporal load impact on the grid than today's largely privately owned PEV fleet, which primarily charges at lower power at home.
- **Electric medium-duty vehicles and heavy-duty vehicles:** Battery costs have fallen to a level where substantial electrification of medium-duty and heavy-duty vehicles appears feasible over a much earlier time horizon than previously imagined. While this would result in a significant local air pollution and climate benefit, electrification of these segments will add large loads to the grid as high-powered charging will become necessary.

2. CHARGING INFRASTRUCTURE:

The outcomes of the mobility trends above will influence the number, types, and spatial distribution of charging infrastructure that will be deployed. Chargers can be categorized by their maximum power output and typical application:

- **Level 1 charging (up to 3.3 kW):** Any regular wall outlet, if used for PEV charging, is a Level 1 charger. Level 1 chargers are the least expensive (usually just used for home charging) but are not very practical because their charging speeds are very slow. In the future, PEVs will almost always need Level 2 or higher rate chargers.
- **Level 2 charging (typically 6.6 kW for most vehicles, but up to 19.2 kW for some vehicles):** The majority of charging for privately-owned PEVs takes place at home, at Level 2 rates. Grid interactions and impacts will differ if electrification of the light-duty vehicle fleet proceeds with automation, and if the cars are fleet operated. More home charging would be required with private ownership, whereas more DC fast charging would be used with automated fleet vehicles because of tradeoffs between meeting travel demand and charging demand.
- **DC Fast charging (up to 350 kW) and Ultra-Fast charging (500+ kW):** DC fast charging stations, which could be along highway routes or in city centers, allow for much quicker charging for light-duty vehicles and local freight vehicles. Battery electric medium-duty and heavy-duty vehicles would likely need DC fast charging along highways, as would light-duty vehicles on longer trips. Transit or freight medium-duty and long-haul heavy-duty vehicles, which have high opportunity costs of idling and have large batteries, may need Ultra-Fast charging stations (currently under development) with charging rates exceeding 500 kW.

3. CHARGING STRATEGIES:

Currently, most PEV charging is unmanaged, wherein the vehicle is charged at full power as soon as it plugs in until the battery reaches full charge. As the penetration of electric light-duty, medium-duty, and heavy-duty vehicles increases to a level that imposes a significant load on the California grid, various managed charging strategies may be needed to manage the grid more cost-effectively. The type of managed charging strategies that are technically feasible and likely to be adopted depend on the mobility trends and the type of deployed charging infrastructure:

- **Time-of-use (TOU) charging:** Drivers or site hosts of PEV chargers shift the timing of their charging to off-peak hours, when electricity prices are lowest. Any type of charger could be signed up for a TOU rate if available for the particular rate class (i.e., residential, commercial, etc.). Most commonly, including in California, TOU rates have fixed time periods that are designated as peak or off-peak, but some regions around the world have real-time pricing with dynamically determined peak and off-peak times. Existing residential TOU rates in California have been very effective in moving charging to off-peak hours, but only a small share of all PEV drivers have enrolled in such rates.
- **Smart charging:** Active PEV charging is remotely turned on or off through the PEV or charger software, to coincide with low wholesale prices or other events such as times of high RE generation. Smart charging is usually part of a demand response (DR) program for an aggregation of many PEVs and/or charging sites. All levels of charging infrastructure could participate. There have been several small-scale smart charging demonstration programs in California.
- **Vehicle-to-grid (V2G) charging:** As an extension of smart charging, V2G allows for bi-directional power flow between the vehicle and grid such that the vehicle can both discharge excess energy to the grid and charge from the grid. V2G would be controlled through the charger or vehicle software and requires fast, networked communications and metering, and a more expensive inverter as part of the charging infrastructure. V2G has been piloted with a fleet at a military base in California but has yet to be implemented at scale.

4. VEHICLE-GRID SERVICES:

Through the charging infrastructure, the PEV charging strategies above can provide various services when integrated with the grid:

- **Distribution system support:** Charging strategies can be optimized to smooth utilization of distribution system assets to avoid overloading and increase load factors.
- **Load-shifting/valley filling:** Charging strategies can avoid coinciding with non-PEV related loads at peak times. Charging can be shifted to off-peak times (valleys), which could be during times of renewable energy over-generation or during overnight hours with low load.
- **Ancillary services:** Fast-responsive charging controls through V2G primarily (but also with some types of smart charging) could provide ancillary services such as regulation and load-following (where the battery discharges and recharges over the course of a few seconds or minutes) to help the grid balance and manage uncertainties in supply and demand.

Widespread electrification of transportation and the emergence of new trends such as automation and mobility-on-demand will influence how the state develops and uses charging infrastructure, and subsequently, the ability and willingness of electric light-duty, medium-duty, and heavy-duty vehicles to participate in managed charging programs and provide grid services. The resulting grid impacts, at the distribution and the bulk power system levels, will also depend on how California's generation mix and load management policies evolve. With at least 50 percent renewable energy by 2030, a growing deployment of stationary battery storage, and more widespread distributed and flexible energy resources besides PEVs, the needs of the grid and interactions with PEVs may change over time. This report summarizes each of these segments of the mobility-infrastructure-charging-grid nexus framework and presents policy considerations and recommendations for robust vehicle-grid integration in California in light of these current and emerging trends.

II.

Mobility Trends

PASSENGER mobility is undergoing three revolutions: (1) surging demand for mobility-on-demand services, (2) accelerating adoption of automated vehicle technologies, and (3) increasing electrification of vehicles. If these revolutions combine to dramatically reduce vehicle ownership and increase shared rides, the spatial and temporal charging demand from a centrally managed automated fleet to service mobility would most likely be dominated by the use of high-powered chargers that could be smartly coordinated with periods of high renewable power production. On the other hand, if the three revolutions simply increase VMT and private ownership continues to dominate, night-time, Level 2 home charging demand would dramatically increase making it harder to integrate solar onto the grid. Alongside these light-duty vehicle trends, rapidly dropping battery prices are making electrified road freight movement increasingly feasible. If medium and heavy-duty vehicles across the state also became electric, the demand for ultra-fast charging (>500kW), would dramatically increase the load on the California grid. However, because these vehicles are centrally dispatched, with the right policies and incentives, they could be smartly charged to assist grid management.

Historical trends in the United States

Historically, the mobility needs of the U.S. population have been met primarily through privately owned and operated light-duty vehicles (cars and light trucks). The light-duty vehicle ownership rate in the U.S. is 817[11] vehicles per 1,000 people and the corresponding number for California is 775,[12] primarily due to the relatively higher level of urbanization in the state. The average annual VMT for each of these private light-duty vehicles is approximately 15,000 miles, which means that Californians travel 460 billion miles each year in their personal vehicles. The share of all other modes is minor, even in the denser cities like Los Angeles and San Francisco.

Freight movement in the U.S. and California has also been dominated by medium-duty and heavy-duty diesel trucks. Commercial medium-duty and heavy-duty vehicles only make up 16 percent of California's vehicle fleet but are responsible for almost 40 percent of the state's transportation greenhouse gas emissions due to the substantially higher annual average VMT of these vehicles. The share of marine and rail-based freight movement within and to/from the state is minor.

In the future, it is entirely possible that the overall mode shares and ownership models for mobility will remain largely unchanged. However, due to the advent of mobility-on-demand services; vehicle automation technology; and increasing urbanization, online shopping and online socializing; the future of mobility could be very different. The state of these technologies, and the behavioral patterns of travelers and shoppers are in a state of flux, making it difficult to predict the dominant modes of goods and people movement in a decade. Unfortunately, the evolution of mobility trends will causally influence the spatial and temporal distribution of power demand from vehicles as the share of PEVs increase, making it a planning challenge for grid operators and infrastructure providers who typically make decisions over long time-scales. This section describes the main factors causing changes in mobility trends and electrification of modes.

11 Fact #962: January 30, 2017 Vehicles per Capita: Other Regions/Countries Compared to the United States | Department of Energy. (n.d.). Retrieved May 31, 2018, from https://www.energy.gov/eere/vehicles/fact-962-january-30-2017-vehicles-capita-other-regionscountries-compared-united-states

12 California Department of Motor Vehicles Statistics. (n.d.). Retrieved from https://www.dmv.ca.gov/portal/wcm/connect/fafd3447-8e14-4ff6-bb98-e85f3aa9a207/ca_dmv_stats.PDF?MOD=AJPERES

Automated Vehicles

With substantial investment of time and effort from both Silicon Valley and the traditional automakers, vehicle automation technology has advanced rapidly in the last decade. Most vehicle models in the market today feature some automated or driver assist technologies. Vehicle automation technologies are classified into five levels by the Society of Automotive Engineers (SAE):[13]

- **Level 0: No automation.** The vehicle has no features that share any level of control with the driver. Traditional cruise control, reversing cameras, and blind-spot warning are all technologies are not considered automation technologies and therefore fall into this category.
- **Level 1: Driver assistance required.** The vehicle includes features that control the vehicle but the driver's continuous engagement is necessary. Adaptive cruise control and lane-keep assistance technologies fall into this category.
- **Level 2: Partial automation options available.** The vehicle will be able to manage both speed and steering under a limited number of conditions, like highway driving on a clear day with clear road markings. Tesla Autopilot, Volvo PilotAssist, etc., fall into this category. The driver must keep eyes on the road at all times.
- **Level 3: Conditional automation.** The vehicle will take over the monitoring of the environment and will operate the vehicle without any intervention by the driver but in specific, limited conditions. For example, the Audi AI traffic jam pilot can drive the vehicle at speeds lower than 37 miles per hour. In this level, drivers will be called on to take over control after not paying attention, making it a higher risk level than others.
- **Level 4: High automation.** The vehicle will be able to handle most operating tasks without driver support except in limited conditions and unusual environments. Hence, there will still be a steering wheel, brake and accelerator pedals.
- **Level 5: Full automation.** All humans in the vehicle are passengers, eliminating the need for any driving equipment like steering wheels, etc.

Each increasing level of automation lowers the burden of driving, although this effect will be much greater when moving from Level 3 to Level 4 and from Level 4 to Level 5 than at lower levels. There is a concern that while easing the mental strain and fatigue caused by driving and traffic is beneficial to human health and productivity, automation could substantially increase VMT, which will correspondingly increase transportation energy demand. On the other hand, especially in the heavy-duty vehicle sector with long-haul tractor-trailers, automation of highway operation could allow for platooning,[14] thereby substantially increasing fuel efficiency.

If VMT does increase due to automation, ensuring that the vehicles are powered by low-carbon fuels like electricity becomes even more critical from a climate perspective. Fortunately, if a vehicle has high VMT, the economics tilt significantly in favor of PEVs, since they are three to four times more fuel-efficient than internal combustion engine vehicles. However, overall electricity demand would be significantly higher, which is an important consideration for power sector and grid planners.

13 Understanding SAE automated driving – levels 0 to 5 explained. Retrieved May 31, 2018 from https://www.gigabitmagazine.com/ai/understanding-sae-automated-driving-levels-0-5-explained

14 A platoon is a group of vehicles that can travel closely and safely together at high speed. Each vehicle communicates with the other vehicles in the platoon and there is a lead vehicle that controls the speed and direction, with all following vehicles responding to the lead vehicle's movement. The primary energy efficiency advantage stems from the substantially superior aerodynamics of the platoon when compared to individual trucks traveling separately at highway speeds.

Mobility-on-Demand Services

Over the last five years, there has been a surge in mobility-on-demand services worldwide. Mobility-on-demand is an umbrella term that includes the following services:

- Ride-hailing (Lyft, Uber, Didi, etc.)
- Car sharing (GIG, Zipcar, Getaround, Turo, etc.)
- Bike sharing
- Demand-responsive commuter services (Chariot, etc.)
- Demand-responsive bus services
- Vertical takeoff and landing aircraft for urban mobility (Uber Elevate, etc.)

Of these, ride-hailing services provided by transportation network companies (TNCs) like Uber and Lyft have seen the most growth in many countries. Figure 3 shows the dramatic recent increases in rides completed by TNCs in China, India and the U.S., including the companies' own projections to 2018. A significant share of the U.S. trips were in California, although there are no reliable sources of how many rides were specifically in the state.

The estimated share of total light-duty vehicle VMT from ride-hailing vehicles is also growing rapidly in all countries. Figure 2 shows that it is already estimated to be about 6 percent in the U.S., with rapid growth rates projected - doubling from 10 percent in 2018 to 20 percent of total VMT between by 2020.

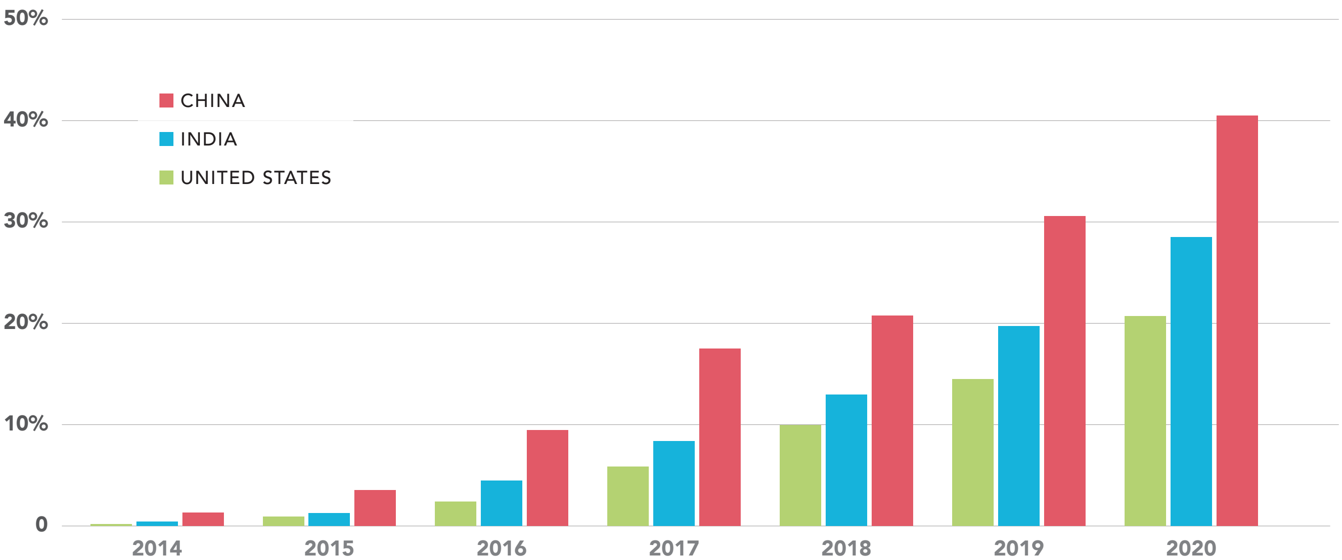
The future growth of mobility-on-demand services depends on numerous factors such as pricing, economic feasibility beyond urban core areas, and state and city regulations, among other factors. It is far from certain that mobility-on-demand services replace personal car trips rather than transit trips.[16] However, due to their high VMT, the economic case for ride-hailing vehicles to be electric is compelling, provided that drivers are confident about charging infrastructure availability and find electricity prices and refueling times attractive. In an effort to transition more TNC vehicles to electric, the California State Legislature is currently reviewing a bill that would mandate GHG reduction targets and facilitate ZEV adoption programs for TNCs.[17] Just as the future growth and electrification of TNCs is uncertain, the future adoption of concurrent pooling on ride-hailing trips is also uncertain and could depend greatly on the price difference between pooled and single-occupant trips. Vehicle automation could dramatically lower the price of ride-hailing services (from elimination of driver labor costs) but also the price difference between pooled and single-occupant trips.

To improve the sustainability of passenger transportation, many experts see a solution in the merging of automation, ride-hailing, and electric vehicles, if that results in dramatic reductions in the personal ownership of vehicles and increases in pooled rides. While such an outcome is entirely possible, other mobility outcomes are equally possible. From a grid and charging infrastructure perspective, the various mobility outcomes could result in dramatically different spatial and temporal charging patterns as well as charging infrastructure types and layouts.

16 Giovanni Circella, Farzad Alemi, Kate Tiedeman, Susan Handy, & Patricia Mokhtarian. (2018). The Adoption of Shared Mobility in California and Its Relationship with Other Components of Travel Behavior. National Center for Sustainable Transportation Research. Retrieved from https://ncst.ucdavis.edu/project/the-adoption-shared-mobility-in-california-and-relationship-with-other-components-travel-behavior/

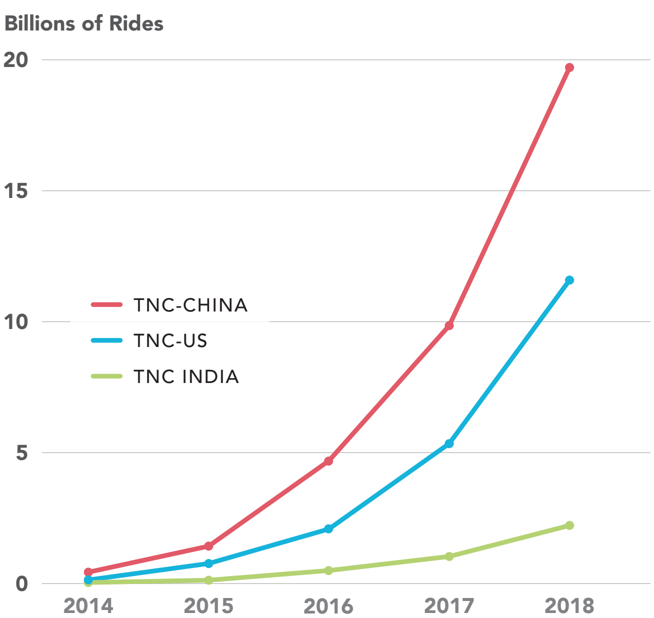
17 California Clean Miles Standard and Incentive Program: Zero-emission Vehicles, SB-1014. Introduced by Senator Nancy Skinner, California Legislature (2017–2018 Regular Session). Retrieved from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB1014

FIG 2 Estimated and Projected Share of Passenger Car VMT from Ride-Hailing Vehicles in the U.S., India, and China



Source: U.S. Department of Transportation, et al.[15]

FIG 3 Number of annual completed (2014-17) and projected (2018) TNC rides



Source: U.S. Department of Transportation, et al.[15]

15 The ride numbers data are directly from Uber, Lyft (for the US), Uber and Ola (for India) and Didi Chuxing (for China). The estimated VMT share is calculated by us based on assuming that each ride share vehicle drives 52,500 miles per year while the average private car drives 11,500 miles per year and the vehicle fleet numbers are estimated based on number of rides given and the private fleet is estimated from DOT data.

Electric Medium-Duty Vehicles and Heavy-Duty Vehicles

Dramatic reductions in battery prices[18] and increases in battery energy density in the past several years have improved the technical and economic feasibility of battery electric medium-duty and heavy-duty vehicles. Urban freight movement and short-haul heavy-duty vehicles like drayage trucks need much smaller battery capacities and hence could feasibly be electrified in a few years.

Recognizing the importance of addressing freight movement in its climate policy, California is developing a sustainable freight action plan.[19] The plan directs state agencies to work together to develop policies, regulations, and other programs that help transition the state toward zero emission freight movement. Separately, the California Air Resources Board (CARB) has an Innovative Clean Transit[20] program that targets all buses in the state to be zero emission by 2040. Several California cities and transit agencies, including Los Angeles, which has the second largest bus fleet in the nation, plan to completely transition their bus fleets to zero emission by 2025.

Electrification of medium-duty and heavy-duty vehicles provide California the opportunity to decarbonize freight movement. The power system can accommodate heavy-duty vehicle electrification but it will require anticipation of load growth and advance planning. If long-haul road freight is electrified, Ultra-Fast (>500kW) charging stations will be needed along the main freight corridors of the state. Integrating this high-powered load while the share of renewables on the grid continues to increase is likely to add a significant challenge to grid planners and operators. Fortunately, the logistics and operation of medium-duty and heavy-duty vehicles are centrally planned and therefore, the implementation of smart charging and other managed charging strategies could be easier.

18 Nykvist, B., & Nilsson, M. (2015). Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change, 5(4), 329–332. https://doi.org/10.1038/nclimate2564

19 The California Sustainable Freight Action Plan, Retrieved May 31, 2018 from http://www.dot.ca.gov/casustainablefreight/theplan.html

20 California Air Resources Board: Innovative Clean Transit, Retrieved June 11, 2018 from https://arb.ca.gov/msprog/ict/ict.htm

III.

Charging Infrastructure Deployment and Policies

THE mobility trends above will influence the number, type (Level 1, Level 2, DC fast, or Ultra-Fast), and location of new charging infrastructure likely to be deployed in California. These PEV charging stations are a key determinant of vehicle-grid integration outcomes because they directly connect the vehicle to the power system. Currently, the vast majority of charging for light-duty PEVs occurs at home with either Level 1 or Level 2 chargers, but faster public and workplace chargers are also seen as important to alleviate range anxiety and to encourage PEV adoption beyond early purchasers. However, compared with other states and countries, California has lagged in the construction of public charging stations relative to the number of PEVs on the road, likely due to expensive installation and operating costs. Such public infrastructure has been developed by a combination of private companies, automakers, government agencies, and (more recently) utilities. If mobility trends move toward automation, mobility-on-demand, and electrification of medium and heavy-duty vehicles, even more public and faster charging infrastructure will likely be needed, along both highway traffic corridors and in urban centers.

TABLE 1 Capabilities of Charger Types[21]

Level	**Voltage and Power**	**Typical Application**	**Charging Ports**
Level 1 AC	110/120 volts AC; 1.4 to 1.9 kW (12 to 16 amps)	Standard household AC plug; typically used in residential applications when only a wall outlet is available.	J1772 
Level 2 AC	208/240 volts AC; typically, 6.6 kW, but up to 19.2 kW for some vehicles (typically 30-40 amps, but 16-80 amps possible)	Home or workplace/public charging; Level 2 AC chargers use the same port as Level 1. Tesla vehicles have adaptors for the J1772 charge port.	J1772 
DC Fast charging	AC - DC conversion; typically, 50 kW and 120-150 kW (Tesla), but can go up to 350 kW	Usually at public stations along high traffic corridors (along highways or in city centers). Three are three different types of DC fast charging systems depending on the vehicle: the Society of Automotive Engineers (SAE) J1772 combo or Combo Charging System plug supported by Audi, BMW, Chevrolet, Daimler, Ford, GM, Honda, Hyundai, Porsche, Volvo and Volkswagen; the CHAdeMO plug supported by Renault-Nissan, Kia, Mitsubishi and Toyota; Tesla plug exclusively for Tesla. Faster chargers for all three DC fast charging standards are under development are able to charge at higher power levels. CHAdeMO is planning a 150 kW charging protocol, and 350 kW chargers are under development by both Tesla and a coalition of Ford, BMW, Mercedes and Volkswagen.[22]	J1772 combo/ CCS  CHAdeMo  Tesla combo 
Ultra-Fast DC charging	500 kW+	Some companies are developing Ultra-Fast chargers of 500 kW or more, which could be well suited for MDV and HDV.	

Source: U.S. Department of Energy[21]

21 Alternative Fuels Data Center: Developing Infrastructure to Charge Plug-In Electric Vehicles. (n.d.). Retrieved May 8, 2018, from https://www.afdc.energy.gov/fuels/electricity_infrastructure.html; California Energy Commission. (2017). *California Energy Commission Tracking Progress: Renewable Energy* (Tracking Progress). Retrieved from http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf; Smith, M., & Castellano, J. (2015). *Costs Associated with Non-Residential Electric Vehicle Supply Equipment: Factors to consider in the implementation of electric vehicle charging stations.* Prepared by New West Technologies, LLC for the U.S. Department of Energy Vehicles Technologies Office.

22 Elkind, E. (2017). *Plugging Away: How to Boost Electric Vehicle Charging Infrastructure.* Berkeley Law Center for Law, Energy & the Environment and UCLA School of Law's Emmett Institute on Climate Change and the Environment.

Types of Chargers

Charger types are categorized based on their charging speeds, typical applications, and ports as shown in Table 1.

Charging standards consist of the electronic communications protocol between the vehicle and charger, and the physical charging connector.[23] While Level 1 and Level 2 charging ports work across all PEV types, as shown in Table 1, there are competing DC fast charging standards for certain car manufacturers that are each not interoperable between vehicle types. In addition, China has its own set of DC fast charging standards (not pictured here) called GB/T. Aside from the standards specifically for communication between the vehicle and the charger, there are also communications standards/protocols that enable various components of the vehicle-grid interaction for use cases including smart charging, V2G, interaction between vehicle and building energy management system, etc. (see Appendix). Based on a California working group of government agencies, charging station providers, automakers and other stakeholders, the California Public Utilities Commission (CPUC) has decided not to recommend a single charging communications protocol for utilities developing charging infrastructure at this time.

Higher powered chargers are also under development. CHAdeMO is planning a 150 kW charging protocol, and 350 kW chargers are being designed by both Tesla and a coalition of Ford, BMW, Mercedes and Volkswagen. Some companies are even developing Ultra-Fast charging capability of 500 kW or more, which would be well suited for medium-duty and heavy-duty vehicles, including transit and freight vehicles that have both a high opportunity cost of being out of service while charging, and very large batteries to fill up.

Historical and Current Charging Infrastructure Deployment

One of the milestones of Governor Brown's Executive Order B-16-2012, which set an initial target of 1.5 million zero emission vehicles[24] (ZEVs) in California by 2025, is charging infrastructure to support up to 1 million ZEVs by 2020. Thus far, early PEV adopters have conducted 74-80 percent of their charging at home, but publicly available charging stations (which are either Level 2 or DC fast chargers as described in Table 1) are seen as critically important in diminishing range anxiety, and subsequently in improving public perception and increasing broader adoption of PEVs.[25] A survey of consumer preferences indicated that the availability of charging infrastructure is as important a factor in buying a PEV as the upfront cost of the vehicle itself.[26] Ubiquitous charging stations will also be increasingly important because the majority of new PEV sales will likely be fully battery electric BEVs without a back-up gasoline engine (unlike PHEVs).[27] Further, if emerging mobility trends result in reduced personal vehicle ownership and toward fleets of electric autonomous vehicles, expanded networks of public fast charging infrastructure will be essential.

California's public charging stations are primarily located around major traffic corridors or highways, or where there is high PEV density (Figure 4).[28] However, public charging station construction has not kept pace with the existing and expected magnitude of PEV deployment across the state. This shortage of charging stations threatens to become a critical bottleneck

23 Li, J. (2017, October 23). *Compatibility and Investment in the US Electric Vehicle Market*. Working paper, Cambridge, MA: Harvard University, Department of Economics.

24 ZEVs are defined by this policy measure as hydrogen fuel cell vehicles (FCEVs), plug-in hybrid vehicles (PHEVs), and battery electric vehicles (BEVs)

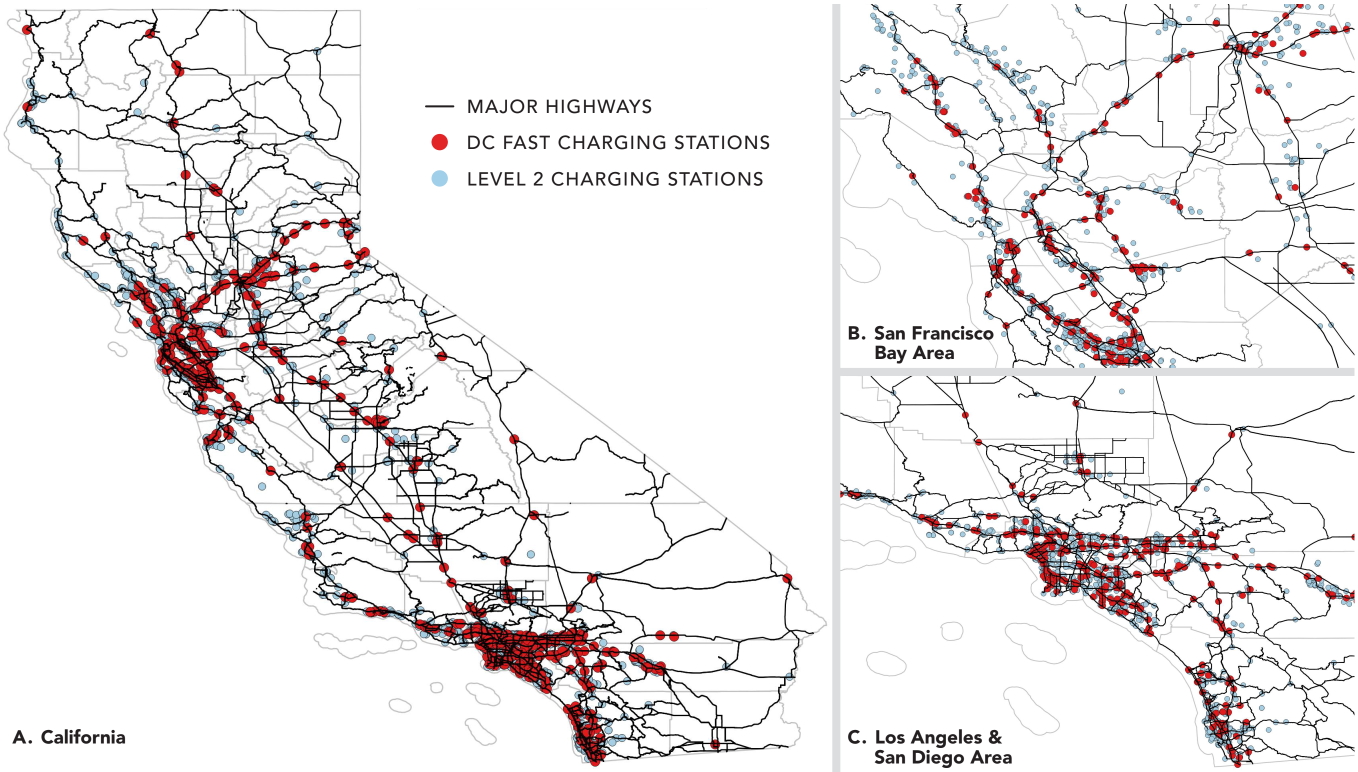
25 Prepared by ICF International and E3. (2014). California Transportation Electrification Assessment: Phase 2: Grid Impacts.; Idaho National Laboratory. (2016). Plugged In: How Americans Charge Their Electric Vehicles Findings from the largest plug-in electric vehicle infrastructure demonstration in the world. Retrieved from https://avt.inl.gov/sites/default/files/pdf/arra/PluggedInSummaryReport.pdf.

26 Baumhefner, M., Hwang, R., & Bull, P. (n.d.). *Driving Out Pollution: How Utilities Can Accelerate the Market for Electric Vehicles* (No. R:16-05-B). Natural Resources Defense Council

27 Lutsey, N. (2018). *ICCT Briefing: California's continued electric vehicle market development*. The International Council on Clean Transportation.

28 Alternative Fuels Data Center: Electric Vehicle Charging Station Locations. (n.d.). Retrieved May 1, 2018, from https://www.afdc.energy.gov/fuels/electricity_locations.html#/analyze?region=CA&fuel=ELEC

FIG 4 A) California, B) San Francisco Bay Area, and C) Southern California PEV Charger Distribution



Source: CalTrans; U.S. Department of Energy[29]

to mass adoption of PEVs, particularly when it comes to meeting Governor Brown's new extended goal (set by Executive Order B-48-18) of five million zero emission vehicles by 2030.[30] There are currently only about 4,200 public non-residential charging stations in California, with about 15,000 charging outlets,[31] which amounts to approximately only 0.04 public outlets per PEV. Without even considering the potential widespread adoption of electric autonomous vehicles, the California Energy Commission (CEC) estimates that by 2025 the state will need 99,000 to 133,000 public/workplace chargers and 9,000 to 25,000 fast chargers to support the number of expected PEVs on the road.[32] And while 80 percent of current PEV owners live in single-family homes, to encourage PEV sales beyond early adopters, there is also a need for additional chargers at multi-unit residences, where about 40 percent of Californians live.[33] Assuming a continued trend of personal vehicle ownership at least in the near future, the CEC projects that multi-family homes will host about 121,000 PEVs (and chargers) by 2025.[34]

29 Maps created in QGIS (attached CA_DC_Fast_and_L2_stations_May2018.qgs file) using shapefiles of the major highways from Cal-Trans open data (http://www.dot.ca.gov/hq/tsip/gis/datalibrary/Metadata/NHS.html), shapefiles of the California county boundaries (https://data.ca.gov/dataset/ca-geographic-boundaries), and the lat and long locations of the EVSE from the alternative fuels data center (https://www.afdc.energy.gov/stations).

30 Governor Brown Takes Action to Increase Zero-Emission Vehicles, Fund New Climate Investments – Governor Edmund G. Brown Jr. (n.d.). Retrieved May 9, 2018, from https://www.gov.ca.gov/2018/01/26/governor-brown-takes-action-to-increase-zero-emission-vehicles-fund-new-climate-investments/

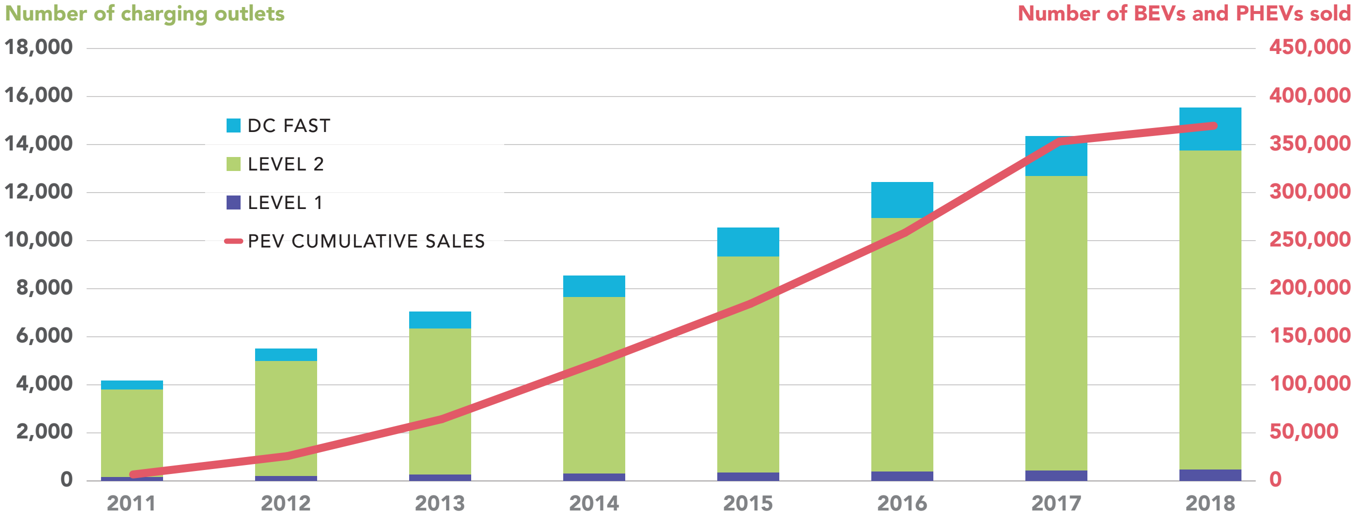
31 Alternative Fuels Data Center: Electric Vehicle Charging Station Locations. (n.d.). Retrieved May 1, 2018, from https://www.afdc.energy.gov/fuels/electricity_locations.html#/analyze?region=CA&fuel=ELEC

32 Bedir, A., Crisostomo, N., Allen, J., Wood, E., & Rames, C. (2018). *California Plug-In Electric Vehicle Infrastructure Projections: 2017-2025* (No. CEC-600-2018-001). California Energy Commission.

33 Elkind, E. (2017). *Plugging Away: How to Boost Electric Vehicle Charging Infrastructure*. Berkeley Law Center for Law, Energy & the Environment and UCLA School of Law's Emmett Institute on Climate Change and the Environment.

34 Bedir, A., Crisostomo, N., Allen, J., Wood, E., & Rames, C. (2018). *California Plug-In Electric Vehicle Infrastructure Projections: 2017-2025* (No. CEC-600-2018-001). California Energy Commission

FIG 5 Cumulative EVSE Charging Outlets and PEV Sales in California



Source: U.S. Department of Energy; Auto Alliance[35]

TABLE 2 California has one of lowest charger-to-PEV ratios among top PEV states in U.S.[36]

State	Number of PEVs	Number of Public Charging Outlets	Ratio of Outlets to PEVs
TX	23,781	2,648	0.11
CO	13,263	1,470	0.11
MA	14,462	1,446	0.10
FL	27,870	2,243	0.08
OR	16,044	1,205	0.08
IL	15,643	1,133	0.07
GA	28,444	1,895	0.07
WA	29,989	1,988	0.07
NY	32,082	2,077	0.06
MI	15,300	987	0.06
PA	12,642	764	0.06
CA	369,626	15,577	0.04
NJ	17,576	565	0.03

Source: Source: U.S. Department of Energy; Auto Alliance[37]

35 Alternative Fueling Station Locator data can be found at: https://www.afdc.energy.gov/stations and ATV sales can be found at: https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/

36 Alternative Fuels Data Center: Electric Vehicle Charging Station Locations. (n.d.). Retrieved May 1, 2018, from https://www.afdc.energy.gov/fuels/electricity_locations.html#/analyze?region=CA&fuel=ELEC; Advanced Technology Vehicle Sales Dashboard. (n.d.). Retrieved May 8, 2018, from https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/

37 Alternative Fueling Station Locator data can be found at: https://www.afdc.energy.gov/stations and ATV sales can be found at: https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/

Figure 5 shows the cumulative deployment of public chargers by type and of PEV sales since 2011 when data became available. While home charging opportunities can mitigate some of the infrastructure gap, Table 2 shows that California also has one of the lowest rates of public charger-to-PEV ratios in the country, despite having the highest number of PEVs in the United States.

California also lags in public charging station development in the global context, despite leading in PEV sales worldwide. Compared to the California cities with the highest cumulative PEV adoption (Los Angeles, San Jose and San Francisco)—which had 25 to 35 PEVs per public charging station in 2017—the Chinese cities with the most PEVs (including Shanghai, Beijing and Shenzhen) had only five to ten PEVs per charging station. The PEV-to-public-charger ratio is also much lower in several European cities (2-8 PEVs per charger)—including Utrecht, Rotterdam-The Hague, Amsterdam, and Paris—than in California cities.[38] China, which has the largest and also one of the most dense public charging networks,[39] also has a very high share (16 - 45%) of public chargers that are DC fast chargers compared to one to two percent in the Netherlands, which has one of the highest concentrations of public charging stations. San Francisco and San Jose do have higher portions of chargers at workplaces compared to other cities because of installation by technology firms.[40]

Charging Infrastructure Costs

While the cost of non-residential charging (at public locations or workplaces) equipment has dropped substantially in recent years, installation and operating costs still remain a major barrier for widespread deployment, varying widely from site to site depending on site location, charger type (including power level, number of ports, level of communications, and payment features), required electrical upgrades at the site, permitting and engineering design, and labor costs.[41] A recent study claimed that charging station business models relying solely on PEV charging revenues, especially DC fast chargers, were not financially viable given the high costs for both capital and operating expenses.[42]

NON-RESIDENTIAL CHARGING INFRASTRUCTURE COSTS

According to a 2015 national study, a single-port non-residential charging unit costs range $300 - $1,500 for Level 1, $400 - $6,500 for Level 2, and $10,000 - $40,000 for DC fast charging.[43] Multiple-port charging units are more expensive, as are added communications capabilities, which can allow for data collection and communication with the driver, site host, grid system operator, and the internet. Other added charging station features on the higher end of the cost range include demand response (DR) capabilities, access control, advanced displays, and networked energy

38 Hall, D., Cui, H., & Lutsey, N. (2017). *Electric vehicle capitals of the world: What markets are leading the transition to electric?* The International Council on Clean Transportation.

39 China's EV Charging Point Network Grew 51% In 2017. (2018, January 23). Retrieved May 15, 2018, from https://cleantechnica.com/2018/01/23/chinas-ev-charging-point-network-grew-51-2017/

40 Ibid

41 Smith, M., & Castellano, J. (2015). *Costs Associated with Non-Residential Electric Vehicle Supply Equipment: Factors to consider in the implementation of electric vehicle charging stations.* Prepared by New West Technologies, LLC for the U.S. Department of Energy Vehicles Technologies Office.

42 Nigro, N., & Frades, M. (2015). *Business Models for Financially Sustainable EV Charging Networks.* Center for Climate and Energy Solutions (C2ES)

43 Smith, M., & Castellano, J. (2015). *Costs Associated with Non-Residential Electric Vehicle Supply Equipment: Factors to consider in the implementation of electric vehicle charging stations.* Prepared by New West Technologies, LLC for the U.S. Department of Energy Vehicles Technologies Office

management software. Installation costs altogether amount to an additional $0 - $3,000 for Level 1, $600 to $12,700 (about $3,000 on average) for Level 2, and $4,000 to $51,000 (about $21,000 on average) for DC fast charging above the cost of the non-residential charging station equipment.[44] The installation cost can be on the higher end of the range if extensive trenching and electrical upgrades such as transformer installations are required. DC fast charging and multi-unit Level 2 charging sites are more likely to need an electrical service upgrade for added feeder capacity.

On average, charging station installation has been more expensive in California than in other geographic regions because of higher labor and permitting costs. A recent Los Angeles Department of Water and Power installation of DC fast chargers found installation costs including equipment and labor to be on average $85,000 each, and Southern California's Charge Ready pilot program found "customer-side" installation costs to be $10,397, and $2,129 for "utility-side" costs for a charger's "make-ready" infrastructure per Level 2 port. Make-ready infrastructure includes the service connection and supply infrastructure to support the charging station, including both "equipment on the utility-side (e.g., transformer) and customer-side (e.g., electrical panel, conduit, wiring) of the meter." Business models differ, but in this case the utility paid for and owns the infrastructure on the "utility-side."

After the upfront equipment and installation costs, charging station operators must pay for operation and maintenance (O&M), which mainly consists of electricity usage. In addition to the energy cost ($/kWh), commercial electricity rate plans typically include a demand charge based on peak consumption at the site during the billing period, which is meant to cover the fixed cost of additional infrastructure needed to support higher electricity usage. Some demand charges can be avoided by charging at off-peak times, but that may not be possible for public charging stations. If charging loads do coincide with a site's existing peak load, demand charges can be exacerbated and be a disincentive for installing charging stations at commercial sites. This is particularly problematic with DC fast chargers, which cause large spikes in demand, often at sites that otherwise don't have high energy usage to spread the demand chargers over many kilowatt-hours. One study claimed that a charging station site can experience demand charges of more than $2,000 per month.

Policy discussions and possible reforms to commercial electricity rates are underway, especially so that demand charges do not discourage charging station installation. For example, the Sacramento Municipal Utility District (SMUD) has a flat energy-only rate that merges energy and demand costs.[45] In May 2018, the CPUC approved Southern California Edison's (SCE), proposed tariff to recover charging costs through volumetric charges. The tariff would waive the commercial demand charge for charging sites for the first five years of implementation, phasing in demand charges between years 6 and 11.[46] San Diego Gas & Electric (SDG&E) has a day-ahead, hourly time-varying energy rate for the participants of its Power Your Drive program, and SCE and Pacific Gas & Electric (PG&E) have TOU rates for the site hosts through their Charge Ready and EV Charge Network programs.[47]

44 Elkind, E. (2017). *Plugging Away: How to Boost Electric Vehicle Charging Infrastructure.* Berkeley Law Center for Law, Energy & the Environment and UCLA School of Law's Emmett Institute on Climate Change and the Environment.; Smith, M., & Castellano, J. (2015). *Costs Associated with Non-Residential Electric Vehicle Supply Equipment: Factors to consider in the implementation of electric vehicle charging stations.* Prepared by New West Technologies, LLC for the U.S. Department of Energy Vehicles Technologies Office.

45 Business electric vehicles. (n.d.). Retrieved May 16, 2018, from https://www.smud.org/en/Going-Green/Electric-Vehicles/Business

46 Decision 18-05-040 on the Transportation Electrification Standard Review Projects in Application of San Diego Gas & Electric Company (U 902E) for Approval of SB 350 Transportation Electrification Proposals And Related Matters. (California Public Utilities Commission May 2018). Retrieved from http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442457637

47 Decision 16-01-045 Regarding Underlying Vehicle Grid Integration Application and Motion to Adopt Settlement Agreement: Application of San Diego Gas & Electric Company (U902E) for Approval of its Electric Vehicle-Grid Integration Pilot Program And Related Matter. (California Public Utilities Commission February 4, 2016); Decision 16-01-023 Regarding Southern California Edison Company's Application for Charge Ready and Market Education Programs: Application of Southern California Edison Company (U338E) for Approval of its Charge Ready and Market Education Programs. (California Public Utilities Commission January 25, 2016).; Decision 16-12-065 In the Matter of the Application of Pacific Gas and Electric Company for Approval of its Electric Vehicle Infrastructure and Education Program (U39E). Directing Pacific Gas & Electric Company to Establish an Electric Vehicle Infrastructure and Education Program (California Public Utilities Commission December 21, 2016).

RESIDENTIAL CHARGING INFRASTRUCTURE COSTS

The cost of Level 2 home charger equipment and installation is together about $1,400 on average, depending on a home's age, other loads, and circuit capacity.[48] A limited number of local or regional government agencies in California, such as air quality districts or municipal utilities, currently offer incentives to defray some of the installation cost (additional incentives are available to residential customers for the purchase of the PEV itself).[49] In terms of charging costs, depending on a particular utility's offerings, for residential rates PEV drivers could remain on their standard tiered rate, adopt a TOU rate that is for both the PEV load and non-PEV load, or adopt a PEV-specific rate that is separately metered (much less popular option for PEV rate customers because the customer has to pay for any electrical upgrades necessary for a second meter).[50] If mobility trends do shift toward increased mobility-on-demand and electric autonomous vehicle fleets, the need for residential chargers for personal vehicles could decline in favor of public DC fast charging at commercial sites, but it is widely expected that overnight-at-home charging will continue to play a critical role as any transition to such transportation paradigms will not occur overnight.

Investment Pathways to Support Charging Infrastructure Expansion

A combination of private companies, utilities, government agencies, and other private actors have made or are planning investments to accelerate deployment of the charging infrastructure necessary to catch up with the growth of PEVs on the road.

PRIVATE SECTOR INFRASTRUCTURE DEVELOPMENT

The majority of California's public charging infrastructure has thus far been developed and operated by a number of private companies (Table 3), including automakers, with a variety of business models, prices for charging, charging levels and geographic distribution. Charging networks are commonly membership-based (with a monthly subscription fee), pay-per-charge, or free. Membership benefits could include visibility into charging station availability, automated payments and exclusive access.[51]

UTILITY-LED INFRASTRUCTURE DEVELOPMENT

Based on the lagging rate of charging station construction relative to PEV sales (Figure 5), it appears that private development alone has not been sufficient to meet infrastructure demands. In the last 5 years, electric utilities in California have led further charging station development. First, a CPUC December 2014 decision set aside a prohibition that had prevented investor-owned

48 Idaho National Laboratory. (2016). Plugged In: How Americans Charge Their Electric Vehicles Findings from the largest plug-in electric vehicle infrastructure demonstration in the world. Retrieved from https://avt.inl.gov/sites/default/files/pdf/arra/PluggedInSummaryReport.pdf

49 Define Your Incentives Search. (n.d.). Retrieved May 22, 2018, from http://www.driveclean.ca.gov/pev/Incentives.php

50 California Public Utilities Commission. (2017). *Load Research Report Compliance Filing of San Diego Gas & Electric Company (U 902-M), Southern California Edison Company (U 338 - E), and Pacific Gas and Electric Company (U 39E) Pursuant to Ordering Paragraph 2 of D.16-06-011*

51 Smith, M., & Castellano, J. (2015). *Costs Associated with Non-Residential Electric Vehicle Supply Equipment: Factors to consider in the implementation of electric vehicle charging stations.* Prepared by New West Technologies, LLC for the U.S. Department of Energy Vehicles Technologies Office.

TABLE 3 Private charging station providers in California

Company	Number of Level 1 Chargers	Number of Level 2 Chargers	Number of DC Fast Chargers	Total Number of Chargers
ChargePoint	354	7,854	194	8,402
Tesla	9	1,224	440	1,673
eVgo	0	155	877	1,032
Blink	0	813	70	883
SemaCharge	0	746	0	746
EV Connect	0	450	7	457
Greenlots	25	145	80	250
GE WattStation	0	57	0	57
OpConnect	1	37	2	40

Source: U.S. Department of Energy[52]

utilities (IOUs) from owning charging infrastructure (the prohibition had meant to prevent the "crowding out" of non-utility charging station providers from the market) and ruled that it would use a case-by-case approach to evaluate IOU involvement.[53] Then, in 2015, California's legislature formalized its GHG goal and commitment to PEVs by passing a bill (SB 350) which directed the major utilities in the state to file applications for programs and investments to "accelerate widespread transportation electrification to reduce dependence on petroleum, meet air quality standards, … and reduce emissions of greenhouse gases."[54]

In 2016, the CPUC approved SCE, SDG&E, and PG&E transportation electrification applications proposing programs and investments to develop charging infrastructure for light-duty vehicles, especially at multi-family, workplaces, and in disadvantaged communities across their respective service territories.[55] The CPUC authorized SCE to spend $22 million to develop up to 1,500 chargers at multi-unit dwellings, workplaces and public areas in its Charge Ready pilot, SDG&E to spend $45 million to build 3,500 chargers at multi-unit dwellings and workplaces in its Power Your Drive pilot, and PG&E to build 7,500 chargers at multi-unit dwellings and workplaces for $130 million in its EV Charge Network pilot.[56] Each of the IOUs have a unique plan for ownership of the charging infrastructure and electric rates related to light-duty PEVs: SDG&E will own, install, and maintain the chargers and offer a vehicle-grid integration rate to the driver or site host; site hosts will own the chargers in SCE's territory (SCE will own and operate the supporting make-ready infrastructure) and will be offered a TOU rate; and PG&E will only own up to 35 percent of the pilot's chargers in multifamily or disadvantaged communities but otherwise the chargers will be owned by the site hosts, who can participate in a TOU rate (PG&E will

52 https://www.afdc.energy.gov/stations

53 Phase 1 Decision Establishing Policy to Expand the Utilities' Role in Development of Electric Vehicle Infrastructure in Application of SAN DIEGO GAS & ELECTRIC COMPANY (U902E) for Approval of its Electric Vehicle-Grid Integration Pilot Program. (California Public Utilities Commission December 22, 2014).

54 De León. SB-350 Clean Energy and Pollution Reduction Act of 2015, Pub. L. No. SB 350, Chapter 547, Statutes of 2015 (2015)

55 Anne C. Mulkern, ClimateWire. (2016, August 26). California Utility Wants to Install Huge Number of Electric Car Chargers. *Scientific American*. Retrieved from https://www.scientificamerican.com/article/california-utility-wants-to-install-huge-number-of-electric-car-chargers/; Baumhefner, M. (n.d.). CA Greenlights Big Utility Effort to Electrify Transport [Natural Resources Defense Council]. Retrieved June 27, 2018, from https://www.nrdc.org/experts/max-baumhefner/ca-greenlights-big-utility-effort-electrify-transport

56 John, J. S. (2016, December 15). Compromise Plan Approved for PG&E's Record-Setting EV Charger Deployment. *Greentech Media*. Retrieved from https://www.greentechmedia.com/articles/read/compromise-plan-approved-for-pges-record-setting-ev-charger-deployment

own up to and including the make-ready infrastructure regardless of who owns the charging infrastructure).[57] At least 10 to 15 percent of the chargers are required to be installed in disadvantaged communities. Depending on who owns the charging infrastructure, the IOUs require varying levels of payments by participating sites or offer rebates for hosts to offset a portion of the charger cost.

In addition to this initial round of pilots focused on light-duty vehicle charging infrastructure, in January 2018, the CPUC approved the three IOUs to collectively spend up to $42.8 million on 15 "priority review" pilot projects focused on electrification of medium-duty or heavy-duty vehicles including those related to airport ground support, port operations and transit.[58] These pilots also include some incentives for dealerships, rebates for residential customers to offset the cost of infrastructure and permitting fees for Level 2 home charging, funds to develop urban DC fast chargers, and support for customer education resources.[59] Most recently in May 2018, the CPUC authorized the "standard review" round of IOU charging infrastructure spending totaling $738 million for: SDG&E to provide rebates to install up to 60,000 residential Level 2 charging stations; PG&E to install make-ready infrastructure for about 300 DC fast charging outlets for up to $22 million, and to install infrastructure for about 6,500 medium-duty or heavy-duty vehicles with a budget of $236 million; and SCE to install make-ready infrastructure to support charging of about 8,500 medium-duty or heavy-duty vehicles with a budget up to $342 million as well as new TOU rates for commercial PEV customers, initially without a demand charge.[60]

GOVERNMENT AGENCY INFRASTRUCTURE SUPPORT

Local, state, and federal government agencies have also enacted a number of ZEV and charging infrastructure policies and incentives. For example, the California AB 118 program (consisting of the Alternative and Renewable Fuel and Vehicle Technology Program and Air Quality Improvement Program or ARFVTP founded in 2007), has supported clean vehicles by funding various initiatives, such as vehicle rebates, medium and heavy-duty bus and truck demonstrations, alternative vehicle manufacturing, and workforce training.[61] As of July 2016, $51 million in funding has been provided through ARFVTP for the installation of 8,530 charging connectors across all sectors and charging levels.[62] Additional funding and research by the California State Legislature, U.S. Department of Energy (DOE) and local governments have also promoted the development of vehicles, charging infrastructure and business models to encourage increased adoption. For example, the California Capital Access Program (CalCAP) Electric Vehicle Charging Station (EVCS) Financing Program started in 2015 to provide small businesses and landlords of multi-unit dwellings and in disadvantaged

57 Decision 16-01-045 Regarding Underlying Vehicle Grid Integration Application and Motion to Adopt Settlement Agreement: Application of San Diego Gas & Electric Company (U902E) for Approval of its Electric Vehicle-Grid Integration Pilot Program And Related Matter. (California Public Utilities Commission February 4, 2016).; Decision 16-01-023 Regarding Southern California Edison Company's Application for Charge Ready and Market Education Programs: Application of Southern California Edison Company (U338E) for Approval of its Charge Ready and Market Education Programs. (California Public Utilities Commission January 25, 2016); Decision 16-12-065 In the Matter of the Application of Pacific Gas and Electric Company for Approval of its Electric Vehicle Infrastructure and Education Program (U39E). Directing Pacific Gas & Electric Company to Establish an Electric Vehicle Infrastructure and Education Program (California Public Utilities Commission December 21, 2016).

58 Decision on the Transportation Electrification Priority Review Projects: Application of San Diego Gas & Electric Company (U 902E) for Approval of SB 350 Transportation Electrification Proposals And Related Matters, No. A.17-01-020, et (California Public Utilities Commission January 11, 2018).

59 Ibid.

60 Decision 18-05-040 on the Transportation Electrification Standard Review Projects in Application of San Diego Gas & Electric Company (U 902E) for Approval of SB 350 Transportation Electrification Proposals And Related Matters. (California Public Utilities Commission May 2018). Retrieved from http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442457637

61 California Energy Commission Tracking Progress: Zero-Emission Vehicle and Infrastructure 2016. California Energy Commission.; Governor's Interagency Working Group on Zero-emission Vehicles. (2013). *ZEV Action Plan: A roadmap toward 1.5 million zero-emission vehicles on California roadways by 2025.*

62 California Energy Commission Tracking Progress: Zero-Emission Vehicle and Infrastructure 2016. California Energy Commission.

communities loans of up to $500,000 to build work or home charging stations.[63] Additionally, local incentives such as the EVSE Incentives of San Joaquin Valley and Electric Vehicle Charging Station Infrastructure Program for Santa Barbara County also support charging infrastructure development.[64]

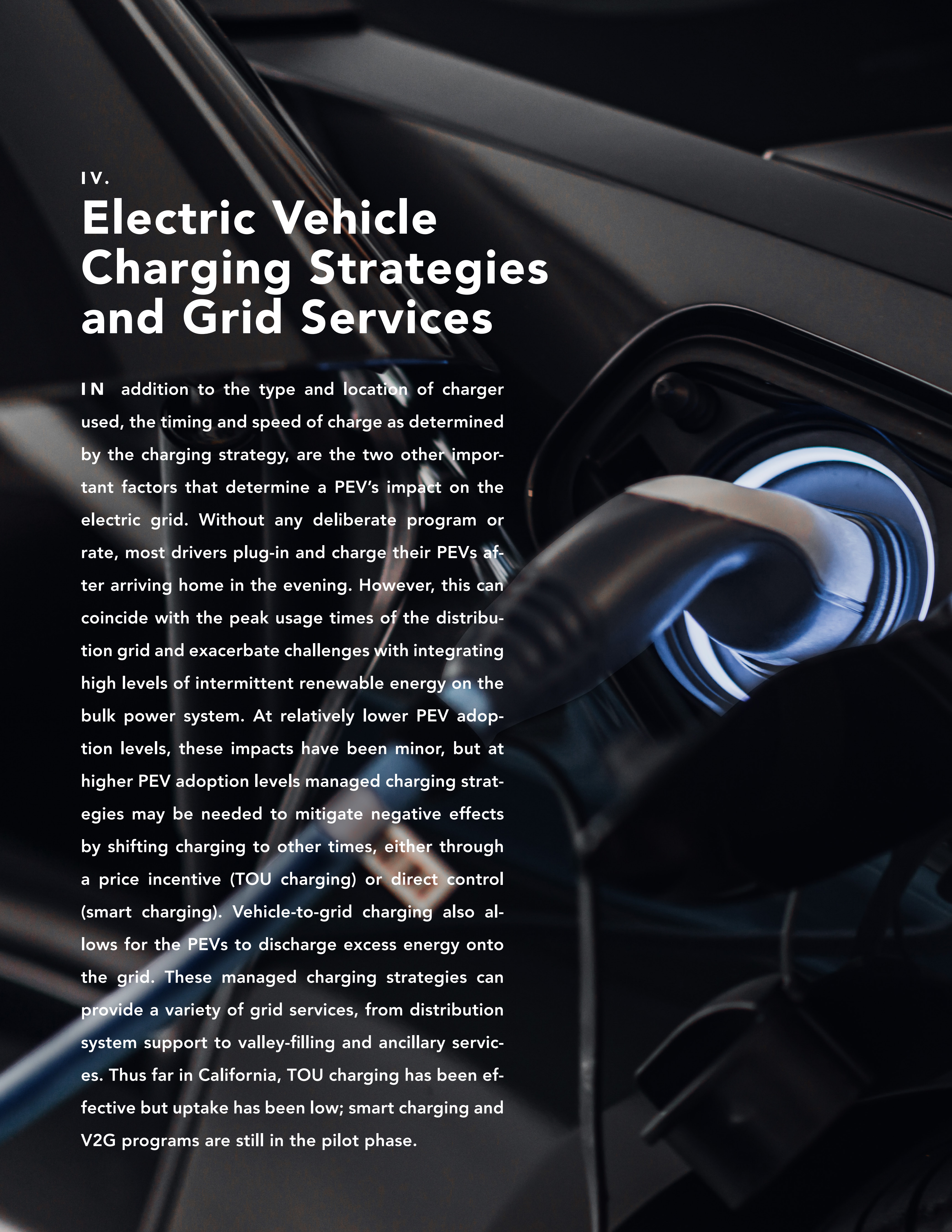
OTHER PRIVATE INVESTMENT IN CHARGING INFRASTRUCTURE

Finally, two other rounds of charging infrastructure investment have resulted from legal settlements with California regulatory agencies. In 2012, in a settlement with the CPUC related to claims from the California Energy Crisis, the energy company NRG agreed to install $102.5 million of chargers (through its subsidiary eVgo), including 200 DC fast charging stations and make-ready infrastructure for 10,000 chargers at 1,000 multi-family, public or workplace sites. Volkswagen, as part of its 2016 settlement with CARB from its diesel emission scandal, has committed to spend $800 million in the next 10 years for ZEV infrastructure and public education campaigns about benefits of ZEVs in California. In its first investment cycle starting Q1 2017, Volkswagen plans to spend approximately $120 million on installing 2,000 to 3,000 chargers across more than 400 stations for community charging and a long-distance DC fast charging highway network.[65]

63 Elkind, E. (2017). *Plugging Away: How to Boost Electric Vehicle Charging Infrastructure*. Berkeley Law Center for Law, Energy & the Environment and UCLA School of Law's Emmett Institute on Climate Change and the Environment. Retrieved from https://scholarship.law.berkeley.edu/cleepubs/41

64 Ibid.; Electric Vehicle Charging Station Infrastructure Program. (n.d.). Retrieved May 9, 2018, from https://www.ourair.org/ev-charging-program/

65 Volkswagen, Group of America. (2017). *Volkswagen California ZEV Investment Plan: Cycle 1 - Electrify America* (Electrify America).



IV.

Electric Vehicle Charging Strategies and Grid Services

IN addition to the type and location of charger used, the timing and speed of charge as determined by the charging strategy, are the two other important factors that determine a PEV's impact on the electric grid. Without any deliberate program or rate, most drivers plug-in and charge their PEVs after arriving home in the evening. However, this can coincide with the peak usage times of the distribution grid and exacerbate challenges with integrating high levels of intermittent renewable energy on the bulk power system. At relatively lower PEV adoption levels, these impacts have been minor, but at higher PEV adoption levels managed charging strategies may be needed to mitigate negative effects by shifting charging to other times, either through a price incentive (TOU charging) or direct control (smart charging). Vehicle-to-grid charging also allows for the PEVs to discharge excess energy onto the grid. These managed charging strategies can provide a variety of grid services, from distribution system support to valley-filling and ancillary services. Thus far in California, TOU charging has been effective but uptake has been low; smart charging and V2G programs are still in the pilot phase.

Unmanaged Charging Behavior and Managed Charging Strategies

Absent any price incentive or programmatic intervention, PEVs typically participate in unmanaged or uncoordinated charging whereby charging occurs at the fastest rate permitted by the charger, as soon as the vehicle is plugged in. If the battery is full prior to departure, and there is no queue at the charger, the PEV typically remains grid-connected until unplugged. Several studies based on both simulated and empirical data show that unmanaged charging typically occurs during the evening, when drivers plug-in after arriving home from their commute.[66] This pattern increases load during peak times on the grid, which can negatively impact the grid by increasing peak capacity requirements and stressing distribution system infrastructure.[67]

While unmanaged charging can have negative grid consequences if coincident with non-PEV peak loads, the necessity of managing or controlling the charging from private PEVs and the optimal type and configuration of such strategies is still an open question for California, depending on many circumstances, such as the magnitude of PEV adoption and the cost and availability of alternative measures to cope with added load. There are three main types of "managed charging" options for PEVs, which adjust the time and speed of charge as compared to the unmanaged alternative. These options are explained in brief below, and then explored further in this section:

- **Time-of-use (TOU) Charging:** Drivers are incentivized by a lower electricity rate to charge during off-peak hours, usually pre-programming the start time through the charger or PEV. Most commonly, including in California, TOU rates have fixed time periods that are designated as peak or off-peak, but some regions have real-time pricing with dynamically determined peak and off-peak times. Residential TOU rates in California have off-peak hours in the middle of the night, and the exact start and duration of the off-peak period varies by utility. Spring day-time off-peak periods may be added for some utilities to encourage charging during times of high solar PV generation.
- **Smart Charging (V1G referring to unidirectional power flow to vehicle from grid):** The PEV participates in a demand response (DR) program that controls active charging to be on or off or at a different speed through the charger or vehicle software but does not allow for the discharging of the PEV battery back to the grid. Under a DR program, electricity usage is adjusted (typically reducing use or shifting use to other times in the day) at certain times in response to price signals or other conditions. An aggregator (utility or private company) usually directly controls charging for many vehicles at once to shift charging to times that provide the most grid benefit, when prices are low or renewable energy is abundant,[68] bidding the aggregated flexible load of many PEVs into the wholesale electricity market. Ancillary services, like frequency regulation and others, can also be provided by V1G applications but not to the same extent as V2G.
- **Vehicle-to-grid (V2G referring to bi-directional power flow between vehicle and grid):** An aggregation of PEVs (similar to smart charging) act like storage to the grid by charging over some hours, storing the energy in the car battery, and then discharging some energy back to the grid. Under V2G, PEVs could also provide some ancillary services to the grid, such as regulation, load-following, and spinning reserves.[69]

66 Sheppard, C., Waraich, R., Gopal, A., Campbell, A., & Pozdnukov, A. (2017). *Modeling plug-in electric vehicle charging demand with BEAM, the framework for behavior energy autonomy mobility* (No. 2017_EV_BEAM). Lawrence Berkeley National Laboratory.; Muratori, M. (2018). Impact of uncoordinated plug-in electric vehicle charging on residential power demand. Nature Energy, 3(3), 193–201. https://doi.org/10.1038/s41560-017-0074-z; California Public Utilities Commission. (2017). *Load Research Report Compliance Filing of San Diego Gas & Electric Company (U 902-M), Southern California Edison Company (U 338 - E), and Pacific Gas and Electric Company (U 39E) Pursuant to Ordering Paragraph 2 of D.16-06-011.*

67 Muratori, M. (2018). Impact of uncoordinated plug-in electric vehicle charging on residential power demand. Nature Energy, 3(3), 193–201. https://doi.org/10.1038/s41560-017-0074-z

68 Richardson, D. B. (2013). Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. *Renewable and Sustainable Energy Reviews, 19,* 247–254. https://doi.org/10.1016/j.rser.2012.11.042

69 Kempton, W., & Tomic, J. (2005). Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. *Journal of Power Sources, 144*(1), 280–294. https://doi.org/10.1016/j.jpowsour.2004.12.022

GRID SERVICES FROM MANAGED CHARGING STRATEGIES

Managed charging strategies can provide a variety of services when integrated with the grid, including these main services below:

- **Distribution system support:** Charging strategies can be optimized to smooth utilization of distribution system assets and increase load factors (and utility revenues), helping to defer or avoid asset upgrades such as transformers or distribution lines and putting downward pressure on customers' rates.[70] This can be achieved with smart and V2G charging strategies if controls are optimized to consider distribution system impacts, or with TOU if non-PEV loads are diversified and non-coincident with PEV loads. However, if TOU rates encourage all PEVs on a feeder to start charging simultaneously, the off-peak periods could exacerbate, rather than help with distribution system impacts.
- **Load-shifting/valley filling:** TOU (through price incentives) and smart and V2G (through automated control) strategies can shift charging to off-peak times or valleys, which could be during renewable over-generation or overnight hours with low load. As a result, the grid can possibly save on expensive and inefficient peaking generation, lower emissions, and avoid renewable energy curtailment.
- **Ancillary services:** Fast-responsive charging controls through V2G primarily could provide ancillary services such as regulation and load-following to help the grid balance and manage variation and forecast uncertainties in supply and demand. Regulation services are used to maintain fluctuations in grid frequency, typically within seconds, to meet North American Electric Reliability Corporation (NERC) standards. Load-following reserves respond to fluctuating load and/or generation at the minute time scale. By starting, stopping or varying the level of charging, smart charging could also provide ancillary services.

Managed Charging Experiences to Date

TOU

California's real-world experience demonstrates that PEVs on appropriate TOU rates charge almost exclusively during off-peak hours, which maximizes fuel cost savings and improves the utilization of the grid to the benefit of all utility customers.[71] Participating residential customers with Level 1 or Level 2 chargers usually adjust to TOU rates by programming a timer on their charger or vehicle. Unfortunately, for all three IOUs, the vast majority of PEV drivers remain on default standard rates (for example, SDG&E estimates that 64 percent of PEV owners are not on TOU rates).[72] This means most PEV drivers not on TOU rates are likely not realizing the fuel cost savings numerous consumer research surveys reveal are the primary motivator of PEV purchases.

More research is needed to better understand and address the user acceptance barriers to mass adoption of TOU rates. In addition, there are a number of other considerations with TOU rates: 1) the rate periods are not dynamic and can only be adjusted through a multi-year regulatory process to accommodate any shift in off-peak periods for the system (i.e., from nighttime to daytime off-peak due to renewable overgeneration), 2) the distribution system could be overloaded by a new, second peak if many drivers start charging their PEVs all at the same time during the start of the off-peak period,[73] and 3) default TOU rates that are not designed for PEVs do not necessarily provide sufficient fuel cost savings relative to gasoline, nor do they provide sufficiently high on-peak to off-peak price ratios to encourage PEV drivers to charging almost exclusively during off-peak hours.

70 Adam Langton, & Noel Crisostomo. (2014). *Vehicle-Grid Integration: A Vision for Zero-Emission Transportation Interconnected throughout California's Electricity System Adam.* Energy Division, California Public Utilities Commission; Baumhefner, M., Hwang, R., & Bull, P. (n.d.). *Driving Out Pollution: How Utilities Can Accelerate the Market for Electric Vehicles* (No. R:16-05-B). Natural Resources Defense Council.

71 California Public Utilities Commission. (2017). Load Research Report Compliance Filing of San Diego Gas & Electric Company (U 902-M), Southern California Edison Company (U 338 - E), and Pacific Gas and Electric Company (U 39E) Pursuant to Ordering Paragraph 2 of D.16-06-011

72 Ibid.

73 Hodge, C. (2017). *Aligning PEV Charging Times with Electricity Supply and Demand* (No. NREL/TP-5400-68623). National Renewable Energy Laboratory.

Some of these concerns can be managed with deliberate TOU rate/program design. Lengthening the off-peak period can help spread the charging more evenly and avoid load spikes. A recent report noted that SCE, which has a longer TOU off-peak period (10 hours), has the greatest diversity of PEV charging loads, compared to SDG&E, which has a much shorter off-peak period (5 hours).[74] The second peak impact can also be mitigated through the use of "charge-by" options included in PEVs, whereby the driver indicates in the vehicle software when it should complete charging by rather than when it should start charging.[75] Because vehicles all arrive at their destinations with differing states of charge, this provides a natural staggering effect that can prevent artificial peaks at the beginning of off-peak periods. An SDG&E pilot also showed that a larger price differential (6:1) between peak and off-peak pricing for EV TOU rates resulted in 90 percent of PEV drivers shifting their charging loads to off-peak hours, compared to 70 percent when the price differential was 2:1.[76]

In addition to residential chargers, commercial sites with Level 2, city and highway DC fast, and medium-duty/heavy-duty vehicle Ultra-Fast chargers could also be on a TOU rate, but charging station site hosts would need to pass time-varying prices through to PEV drivers' charging fees for their behavior to adjust. Individual drivers may have different incentives than site hosts and not be as responsive to TOU rates at a commercial site as they would be at home.

SMART CHARGING

For smart charging, typically an aggregating entity or administrator has a "master controller" that can limit overall power draw and apportion between connected PEVs.[77] If the goal of the smart charging program is to minimize wholesale electricity market costs, the utility could send a price signal to the aggregator to encourage charging or to delay charging, and this could be implemented by the aggregator using an automated control algorithm. Adding up the loads across many vehicles would allow the aggregator to diversify its resource, more easily secure minimum bid size required for participation in the California Independent System Operator (CAISO) day-ahead and real-time energy market (100 kW) and extend the duration of the load-shifting resource.[78] Smart charging programs could also be used to reduce stress on the distribution system, lower demand charges at commercial sites, or achieve other objectives. Depending on the program, PEV drivers may input a desired minimum state-of-charge (SOC) of their battery and expected departure time into a smart phone application or interface on the charger or vehicle, so that the algorithm could ensure that the vehicle still meets a drivers' preferences by the end of the charging session.[79] Smart charging programs could also have an override function if a driver has an urgent travel need and does not want to have charging interrupted.

Smart charging programs have the potential to mitigate negative impacts of PEVs (for example, if charging is otherwise coincident with peak loads, or is overloading the distribution system infrastructure) and

74 California Public Utilities Commission. (2017). *Load Research Report Compliance Filing of San Diego Gas & Electric Company (U 902-M), Southern California Edison Company (U 338 - E), and Pacific Gas and Electric Company (U 39E) Pursuant to Ordering Paragraph 2 of D.16-06-011.*

75 Idaho National Laboratory. (2016). Plugged In: How Americans Charge Their Electric Vehicles Findings from the largest plug-in electric vehicle infrastructure demonstration in the world. Retrieved from https://avt.inl.gov/sites/default/files/pdf/arra/PluggedInSummaryReport.pdf

76 Idaho National Laboratory. (2015). *Residential Charging Behavior in Response to Utility Experimental Rates in San Diego* (No. INL/MIS-15-35158).

77 Hodge, C. (2017). *Aligning PEV Charging Times with Electricity Supply and Demand* (No. NREL/TP-5400-68623). National Renewable Energy Laboratory.

78 Adam Langton, & Noel Crisostomo. (2014). *Vehicle-Grid Integration: A Vision for Zero-Emission Transportation Interconnected throughout California's Electricity System Adam.* Energy Division, California Public Utilities Commission.; California ISO - Demand response and load. (n.d.). Retrieved June 27, 2018, from http://www.caiso.com/participate/Pages/Load/Default.aspx

79 Schmalfuß, F., Mair, C., Döbelt, S., Kämpfe, B., Wüstemann, R., Krems, J. F., & Keinath, A. (2015). User responses to a smart charging system in Germany: Battery electric vehicle driver motivation, attitudes and acceptance. Energy Research & Social Science, 9, 60–71. https://doi.org/10.1016/j.erss.2015.08.019

leverage the vehicle load as a grid resource. However, depending on the implementation, PEV owners and users may also view smart charging as an inconvenience. For example, two possible barriers to acceptance of such "Smart Grid" programs include inadequate communication by utilities about the justification for the program, and failure to address participants' privacy concerns.[80] Other studies show that programs should emphasize non-monetary aspects, such as environmental benefits, to promote smart charging, and the fear of losing flexibility and control over mobility should be addressed.[81]

Provided that the charging infrastructure is networked and equipped with communications equipment, all levels of chargers could participate in smart charging. The smart charging could also occur through the communications software of the vehicle. In any case, given that smart charging delays active charging or limits the speed of charge while a PEV is plugged in, smart charging is most likely to be effective at charging locations where a vehicle could be plugged in for a longer period of time but still achieve the same final SOC by the end of the charging session. Therefore, Level 2 home chargers, where a PEV would have longer dwell-times and medium power levels, are good candidates for smart charging. PEVs participating in a California pilot program were found to be connected to their residential Level 2 chargers for about 12 hours a day but only actively charging 20 percent of that time, allowing for shifting within that time window.[82] Level 2 chargers at work or public places are also possible, but given that there is often a queue to use the charger or a fine for not moving the car after active charging, smart charging is less likely unless there is an abundance of chargers. Similarly, smart charging is also possible with DC fast charging, but PEVs would not necessarily be plugged in for a long duration to allow for shifting energy. Electric medium-duty and heavy-duty vehicles could be good candidates for smart charging because of their larger loads, but drivers may not be willing to have charging delayed given the high opportunity cost of not driving.

In accordance with CPUC decision D.12-04-045, the three IOUs have recently conducted a number of pilots to evaluate smart charging implementations:

- **PG&E's BMW i ChargeForward Pilot:**[83] This July 2015 - December 2016 smart charging pilot used 96 aggregated BMW i3 loads and a second-life battery system (from eight used PEV batteries totaling 225 kWh) to provide DR services as a flexible grid resource. For each DR event, BMW provided PG&E with 100kW of grid resource for a one-hour duration through a combination of deferring PEV charging and discharging energy from the stationary battery system to the grid. The PEV loads were controlled by BMW through the vehicles' telematics system. On average the PEVs delivered 20 percent of the 100 kW resource (80% came from the battery), although the PEV share increased to 50 percent when the DR event took place overnight when the majority of the PEVs were incentivized to charge due to TOU rates. The program's evaluation reported that 98 percent of participating customers were satisfied with the program, which primarily operated in the background without much active participant involvement. Participants were willing to join the program as long as it was not inconvenient or interfered with use of their PEV. Participants received both a $1,000 incentive upfront for enrollment and up to $540 throughout the program for each day of not opting out of DR events. A second phase of this program is underway now to pilot more active load control, including of charging events that are not at home.

80 Oliver, J., & Sovacool, B. (2017). The Energy Trilemma and the Smart Grid: Implications Beyond the United States. Asia & the Pacific Policy Studies, 4(1), 70–84. https://doi.org/10.1002/app5.95

81 Will, C., & Schuller, A. (2016). Understanding user acceptance factors of electric vehicle smart charging. *Transportation Research Part C: Emerging Technologies*, *71*, 198–214. https://doi.org/10.1016/j.trc.2016.07.006

82 Adam Langton, & Noel Crisostomo. (2014). Vehicle-Grid Integration: A Vision for Zero-Emission Transportation Interconnected throughout California's Electricity System Adam. Energy Division, California Public Utilities Commission.

83 Kaluza, Sebastian, David Almeida, and Paige Mullen. (2017). BMW I ChargeForward: PG&E's Electric Vehicle Smart Charging Pilot. BMW Group and PG&E.; BMW ChargeForward. (n.d.). Retrieved April 6, 2017, from https://www.bmwchargeforward.com/

- **SCE's Workplace Charging Pilot:**[84] SCE conducted a pilot to test and evaluate workplace charging, DR programs at workplace chargers, and related business models. The pilot launched in October 2014 and ran until December 2015, with various phases of the experiment rolled out over that time at nine company sites. SCE tested TOU pricing, 19 weekday DR events to curtail PEV charging, an occupancy penalty for overstaying at a charging spot, text message communications with drivers, and peak pricing. The pilot found that majority of drivers charged between 5:00 AM and noon, and about 75 percent of drivers participated in the DR events in both the on-peak and off-peak hours. However, there was significant variation in charging station utilization by site, time, facility staffing, work schedules, etc. which made planning for DR baselines challenging. Survey results of participants confirmed that the probability and frequency of workplace charging correlated with commute distance and also related to convenience; 33 percent of PEV owners charged their vehicle at work daily. Occupancy penalties did encourage space turnover and more optimized charging station use.
- **SCE's Smart Charging Pilot:**[85] SCE conducted a smart charging pilot from mid-2013 to end of 2014 to test and evaluate residential smart charging technologies at ten employee homes and create a set of standards and requirements for future load management programs. SCE conducted nine DR events and notified participants through email and text. Three events occurred when no PEVs were charging, five were throttling events to lower the rate of charge, and four were complete charge curtailment events. 22 percent of events had an opt-out by participants, suggesting the importance of flexibility to participants.

V2G

As an extension of smart charging, PEVs participating in V2G with bi-directional power flow could provide energy storage to the grid as well as ancillary services benefits for various products such as regulation up and down, and load-following up and down.[86] However, studies diverge in quantifying the marginal economic benefit of V2G over smart charging, given the additional cost and complexity of implementation as well as likely accelerated PEV battery degradation.[87] Because of the two-way power flow and frequent use, V2G participation may actually void the warranty on the battery with the automaker.

In theory, all levels of chargers could participate in V2G, but the participation in ancillary services markets requires CAISO-grade metering, utilizes a much faster communications network, and would likely only be effective in locations where the PEVs would be plugged-in for longer periods of time. V2G would also require an inverter to convert the power from DC to AC for discharge to the grid. In addition, there is not a clear vehicle-grid communications standard for V2G (more on the communications standards in the Appendix). Having a centralized operator for a whole fleet, rather than many individual drivers would ease implementation of the controls as well. In California, SCE in collaboration with the Department of Defense, conducted a first-of-its-kind V2G pilot to test the ability of a PEV fleet to provide ancillary services to the CAISO grid:

84 Gonzalez, N. (2016). *Southern California Edison Plug-In Electric Vehicle (PEV) Workplace Charging Pilot.* Southern California Edison.

85 Martinez, M. (2016). Southern California Edison Company's (U 338-E) Plug-In Electric Vehicle (PEV) Smart Charging Pilot Final Report. Southern California Edison. Retrieved from http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442453597.

86 Kempton, W., & Tomic, J. (2005). Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. *Journal of Power Sources, 144*(1), 280–294. https://doi.org/10.1016/j.jpowsour.2004.12.022

87 Peter Alstone, Jennifer Potter, Mary Ann Piette, Peter Schwartz, Michael A. Berger, Laurel N. Dunn, … Ankit Jain. (2016). *Final Report on Phase 2 Results, 2015 California Demand Response Potential Study: Charting California's Demand Response Future.* Lawrence Berkeley National Laboratory, Energy and Environmental Economics, and Nexant; Peterson, S. B., Whitacre, J. F., & Apt, J. (2010). The economics of using plug-in hybrid electric vehicle battery packs for grid storage. *Journal of Power Sources,* 195(8), 2377–2384. https://doi.org/10.1016/j.jpowsour.2009.09.070.

- **Department of Defense V2G Pilot:**[88] The pilot at the Los Angeles Air Force Base tested the ability of the base's 41-PEV fleet to bid directly into the energy and ancillary services market of the CAISO. Each charging station in the pilot was capable of bi-directional power flow and began participating in the CAISO market in December 2015. The fleet submitted regulation up and down ancillary services bids almost every day of the pilot, and awards were usually equal to the bid amounts: from January 30, 2016 to Sept. 30, 2017 the fleet provided 255 MWh of regulation up and 118 MWh of regulation down. During this period the total energy for charging was 321 MWh and 72 MWh for discharging (including regulation up and down and testing). Because there were no off-the-shelf V2G solutions, the pilot program developed a new charger support system and set of protocols. This added challenges but the pilot was ultimately deemed successful in advancing the state of V2G engineering and software. However, the pilot incurred more fees from CAISO than revenue earned for its energy services demonstrating that a small V2G program is currently not cost-effective, although a larger PEV aggregation could meaningfully participate in the CAISO market.

88 Southern California Edison. (2017). *Southern California Edison Company's Department of Defense Vehicle-to-grid Final Report.*

V.

Electric Vehicle Grid Services and Impacts in California

PEV charging loads—depending on their participation in managed charging programs, type and location of infrastructure used, and overall magnitude as described above—can have varying impacts on the distribution system and bulk power system. On the distribution system, PEV impacts could be positive (higher utilization of infrastructure) or negative (for example, voltage excursions or transformer overloading). At lower PEV adoption levels, thus far the distribution system upgrade costs have been minimal. On the bulk power system, PEV loads are also still a relatively small share of overall load. However, at forecasted levels of PEV adoption, managed charging programs could alleviate stress on the grid, lower wholesale operating costs, and serve as resource to help integrate more intermittent renewable energy.

Types of Impacts

DISTRIBUTION SYSTEM IMPACTS

PEV charging loads can have numerous positive and negative impacts on the distribution grid, depending on the PEVs spatial and temporal behavior, and characteristics of the distribution infrastructure including age, utilization, peak load, and presence of other distributed resources such as solar PV.[89] Added PEV loads could have the benefit of increasing the load factor (utilization) of grid assets, spreading capital costs for peak demand (kW) across more load (kWh), lowering electricity rates and bills to the benefit of all utility customers.[90] However, depending on their location, saturation and timing, high levels of PEV charging loads could cause voltage to be out of range, lines to be overloaded/over current, transformers to be overloaded, and cause possible power quality issues.[91] Downsides could be more acute when PEV loads are clustered on certain feeders and geographic areas.[92] For example, PEV customers in the PG&E service territory are currently concentrated in the SF Bay Area and in the Central Coast,[93] which tend to be higher income areas. In SCE's service territory PEV owners are concentrated in coastal areas with milder climates. As mentioned above, there is also a potential for the distribution feeder to be overloaded if many customers in the same area start charging simultaneously.

Additionally, while charging loads for customers on TOU rates tend to peak while non-PEV customers have their lowest usage, the PEV charging during the peak period must still be accommodated on the distribution grid because PEV drivers do occasionally charge during those times.

Despite these concerns, to date, the actual cost of distribution system upgrades purely as a result of added PEVs has been small: in 2017, PEVs caused $500,000 out of total distribution system investments of $5 billion for the three IOUs combined – about 0.01 percent of upgrade costs.[94] As of October 2017, when about 270,000 PEVs were on the road in California, only 460 or 0.16 percent of the PEVs required a service line and/or distribution system upgrade.[95] Another study suggests that even with clustering of PEVs in certain residential areas under aggressive PEV adoption (about 4 million PEVs), California's distribution system upgrade costs will be minimal. Based on a detailed analysis of utility circuits, feeders and substations, and a forecast of the geographic distribution of future PEV sales, the annual PEV-related distribution costs through 2030 are estimated to be only about one percent of the combined distribution revenue requirement of the three IOUs and SMUD.[96] This study did not consider the spike in load at the start of a TOU off-peak period (though as mentioned above this can be mitigated by encouraging the use of the "charge-by" setting in many

89 Adam Langton, & Noel Crisostomo. (2014). *Vehicle-Grid Integration: A Vision for Zero-Emission Transportation Interconnected throughout California's Electricity System Adam.* Energy Division, California Public Utilities Commission.

90 Prepared by ICF International and E3. (2014). *California Transportation Electrification Assessment: Phase 2: Grid Impacts.*

91 García-Villalobos, J., Zamora, I., San Martín, J. I., Asensio, F. J., & Aperribay, V. (2014). Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches. *Renewable and Sustainable Energy Reviews, 38*(Supplement C), 717–731. https://doi.org/10.1016/j.rser.2014.07.040; Green, R. C., Wang, L., & Alam, M. (2011). The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook. *Renewable and Sustainable Energy Reviews, 15*(1), 544–553. https://doi.org/10.1016/j.rser.2010.08.015

92 Muratori, M. (2018). Impact of uncoordinated plug-in electric vehicle charging on residential power demand. *Nature Energy,* 3(3), 193–201. https://doi.org/10.1038/s41560-017-0074-z

93 California Public Utilities Commission. (2017). *Load Research Report Compliance Filing of San Diego Gas & Electric Company (U 902-M), Southern California Edison Company (U 338 - E), and Pacific Gas and Electric Company (U 39E) Pursuant to Ordering Paragraph 2 of D.16-06-011.*

94 Allison, A., & Whited, M. (2018). *Electric Vehicles Still Not Crashing the Grid: Updates from California.* Prepared by Synapse Energy Economics, Inc. on behalf of Natural Resources Defense Council.

95 California Public Utilities Commission. (2017). *Load Research Report Compliance Filing of San Diego Gas & Electric Company (U 902-M), Southern California Edison Company (U 338 - E), and Pacific Gas and Electric Company (U 39E) Pursuant to Ordering Paragraph 2 of D.16-06-011.*

96 Prepared by ICF International and E3. (2014). *California Transportation Electrification Assessment: Phase 2: Grid Impacts.*

PEVs),[97] and instead found that TOU rates yielded the lowest distribution system cost compared to standard tiered rates because of charging when non-PEV loads were lowest. The study also assumes predominantly at home L1 and L2 charging, and with new mobility trends and a higher share of DC and Ultra-Fast charging may increase costs. It is also unclear what the threshold is in PEV adoption and geographic concentration for distribution system impacts to be more significant, especially because the charging patterns of the next generation of PEV drivers may be different than those of current early adopters.

TABLE 4 Projected 2030 CA PEV stock, CEC's 2017 California Energy Demand Forecast.

Scenario	PEV Stock	Annual Energy
Low	2.6 million	11,000 GWh
Mid	3.3 million	14,500 GWh
High	3.9 million	15,500 GWh

Source: California Energy Commission[95]

BULK POWER SYSTEM IMPACTS

In addition to the distribution system level, added PEV loads have impacts on California's bulk power system, at the transmission or wholesale grid level. Under the CEC's load forecast[99] (Table 4), the projected 2030 PEV stock could reach 3.9 million in the high case. The CEC forecasts 3.9 million PEVs to add about 15,500 GWh of charging load, or about five percent of California's approximately 300 TWh total annual load, net of energy efficiency.

While the aggregate PEV load is not significant in the context of the whole California system, PEV charging may change the shape of the load profile in a way that may impact the bulk power system,[100] especially with an increasingly renewable generation mix. California's RPS requires half of electricity consumption be met by renewable energy sources by 2030.[101] The majority of existing and expected renewable energy generation is from intermittent wind and solar photovoltaic (PV) sources.[102] The resulting grid flexibility and ramping needs are illustrated in the "duck curve" (so named because of its shape) produced by the CAISO, showing net load—load minus solar and wind generation—over the course of 24 hours of a typical spring day during the years 2012 to 2020 (Figure 6). As the penetration of solar and wind generation on California's system increases over time there will be greater need for:

1. Steep downward ramping of resources in the morning,
2. Upward ramping of resources in the evening,
3. Fossil generators to turn off or operate at minimum levels to avoid over-generation and/or curtailment of RE in the middle of the day,
4. Resources to meet peak loads, and
5. Ancillary services resources to provide intra-hour flexibility at the minute and second response time.[103]

Renewable energy curtailment can maintain grid stability and help especially with challenges one through three, but also increases system operating costs. Subsequently, utilities deliver less renewable energy to comply with RPS requirements, necessitating added renewable energy capacity or flexible resources to compensate.

The academic literature shows that PEVs can potentially help (typically with managed charging) or worsen (typically

97 Idaho National Laboratory. (2016). Plugged In: How Americans Charge Their Electric Vehicles Findings from the largest plug-in electric vehicle infrastructure demonstration in the world. Retrieved from https://avt.inl.gov/sites/default/files/pdf/arra/PluggedInSummaryReport.pdf

98 California Energy Demand 2018 - 2030 Revised Forecast (Page 38 to 40) can be found at: https://efiling.energy.ca.gov/getdocument.aspx?tn=222287

99 Kavalec, C., Gautam, A., Jaske, M., Marshall, L., Movassagh, N., & Vaid, R. (2018). *California Energy Demand 2018 - 2030 Revised Forecast* (No. CEC-200-2018-002-CMF).

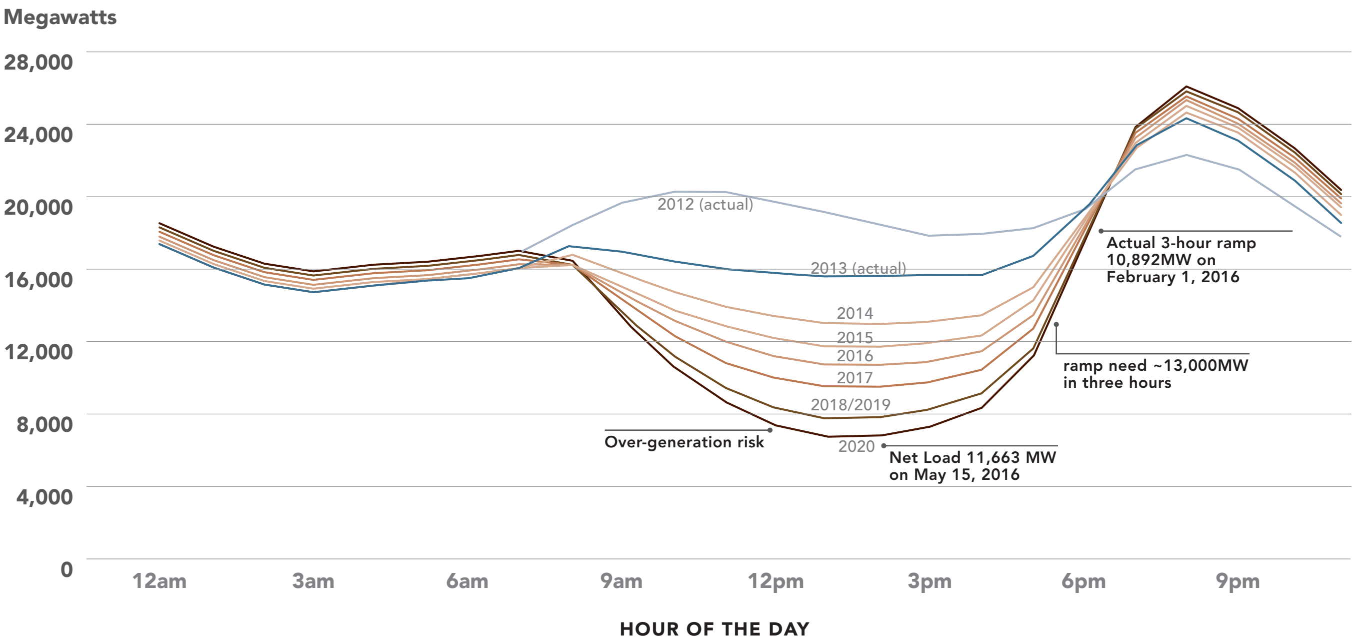
100 Muratori, M. (2018). Impact of uncoordinated plug-in electric vehicle charging on residential power demand. Nature Energy, 3(3), 193–201. https://doi.org/10.1038/s41560-017-0074-z

101 De León. SB-350 Clean Energy and Pollution Reduction Act of 2015, Pub. L. No. SB 350, Chapter 547, Statutes of 2015 (2015).

102 California Energy Commission Tracking Progress: Renewable Energy 2017. Tracking Progress. California Energy Commission.

103 Prepared by ICF International and E3. (2014). California Transportation Electrification Assessment: Phase 2: Grid Impacts.

FIG 6 Projected 2030 CA PEV stock, CEC's 2017 California Energy Demand Forecast.



Source: California Independent System Operator[101]

with unmanaged charging) all of these renewable [104]energy operational challenges on the grid.[105] Since there are no places with large-scale PEV adoption, especially with managed charging, the majority of the studies compare the cost and other grid impacts of different charging behaviors using simulation-based tools.[106] For example, a California electrified transport paper estimates that with 40 percent renewable energy and PEVs charging under a residential non-TOU rate, the majority of the PEV load would occur in the late afternoon and evening, after the predominant commute home and coinciding with the typical evening peak of the system's load net of PV, solar thermal, and wind generation. This suggests that if the majority of PEVs were left unmanaged, challenges with upward evening ramping (2), minimum generation (3), and meeting the peak (4) could be exacerbated. When PEVs instead respond to TOU rates, by design, the same simulation shows that charging is concentrated overnight at the start of the off-peak period, and also occurs up to the late morning as vehicles arrive at work. Such TOU charging avoids peak load times but also most times of renewable energy over-generation or curtailment.[107] A dynamic "vehicle-grid integration" program such as smart charging can shift charging to the late night/early morning to reduce the morning ramp, and to the early afternoon to utilize peak solar generation.[108] Both TOU and smart charging achieve load shifting, reduce peak loads, and lower grid generation cost relative to unmanaged charg-

104 California ISO Fast Facts. Available at https://www.caiso.com/documents/flexibleresourceshelprenewables_fastfacts.pdf.

105 A sample of literature: Wang, J., Liu, C., Ton, D., Zhou, Y., Kim, J., & Vyas, A. (2011). Impact of plug-in hybrid electric vehicles on power systems with demand response and wind power. Energy Policy, 39(7), 4016–4021. https://doi.org/10.1016/j.enpol.2011.01.042; Kiviluoma, J., & Meibom, P. (2011). Methodology for modelling plug-in electric vehicles in the power system and cost estimates for a system with either smart or dumb electric vehicles. Energy, 36(3), 1758–1767. https://doi.org/10.1016/j.energy.2010.12.053; Stanton W. Hadley. (2006). Impact of Plug-in Hybrid Vehicles on the Electric Grid (No. ORNL/TM-2006/554). Oak Ridge National Laboratory. Retrieved from https://info.ornl.gov/sites/publications/files/Pub3198.pdf; Dallinger, D., & Wietschel, M. (2012). Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. Renewable and Sustainable Energy Reviews, 16(5), 3370–3382. https://doi.org/10.1016/j.rser.2012.02.019

106 Richardson, D. B. (2013). Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. Renewable and Sustainable Energy Reviews, 19, 247–254. https://doi.org/10.1016/j.rser.2012.11.042

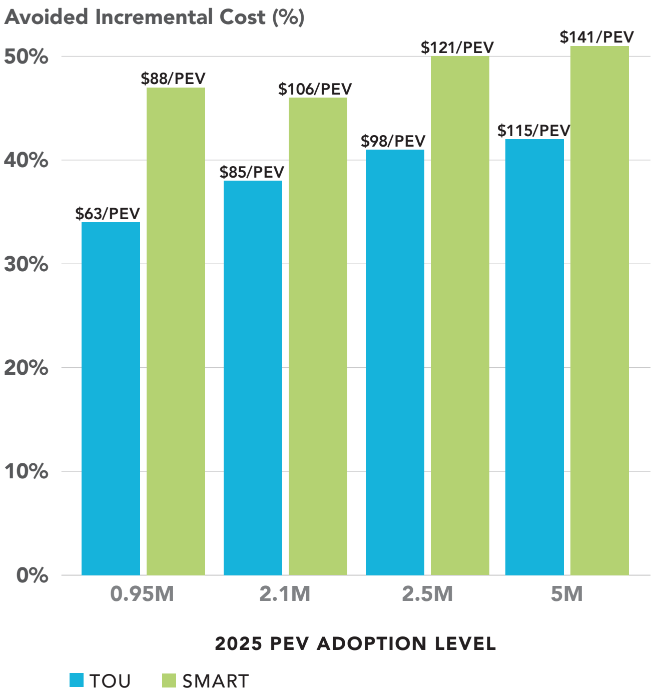
107 Prepared by ICF International and E3. (2014). *California Transportation Electrification Assessment: Phase 2: Grid Impacts.*

108 Ibid.

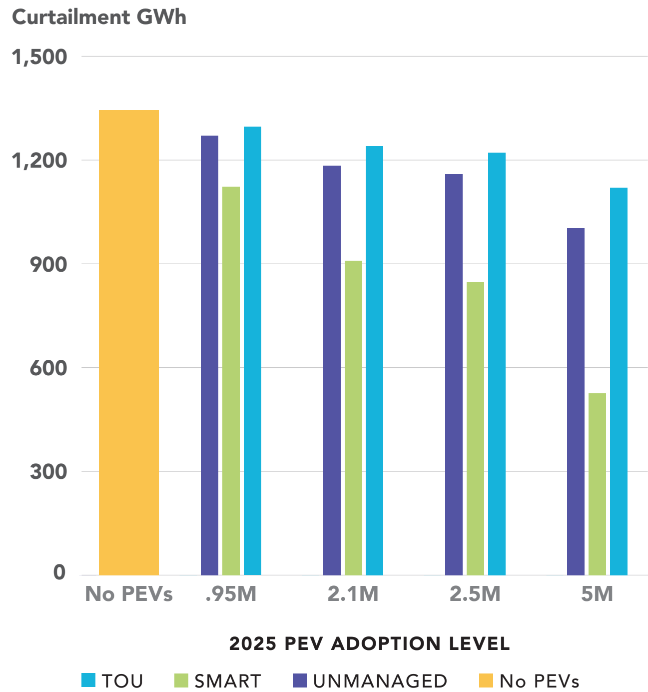
109 New footnote language forthcoming.

FIG 7 California Avoided System Costs & Renewable Curtailment with Managed PEVs.

Avoided total system cost increases relative to Unmanaged PEVs



Annual California renewable energy curtailment



Lawrence Berkeley National Lab[110]

ing, but smart charging is better able to adjust to seasonal changes in renewable energy over-generation and ramping needs.

Another analysis conducted by the authors of this brief simulated detailed PEV driving and charging behavior,[111] and the resulting California grid impacts of smart and TOU charging strategies compared to unmanaged charging at levels of PEV adoption ranging from 0.95 million to five million vehicles in 2025 with a 50 percent renewable energy grid. When 2.5 million PEVs were added to the system, the analysis of grid dispatch found that smart charging of all the vehicles avoids 50 percent of incremental system operating costs and reduces renewable energy curtailment by 27 percent annually relative to when the charging of the same number of PEVs is left unmanaged (Figure 7). Overnight TOU charging provides similar cost savings (although not curtailment reductions) relative to unmanaged charging. While both managed charging strategies achieve large grid operating cost savings in aggregate compared to unmanaged PEVs, that savings per vehicle is minimal (up to $140 per vehicle). Additionally, even when there are high levels of curtailment and negative pricing in the middle of the day, which would be ideal times for PEV loads, smart charging is limited by the relative scarcity of workplace and public chargers. Most load flexibility is still in the middle of the night when drivers are parked for longer periods at their homes (and where most drivers have a charger). Such simulations underscore the need to further develop public charging infrastructure and the capability to participate in managed charging at those locations.

The current California Integrated Resource Planning modeling exercise also includes a "flexible electric vehicle scenario" that allows for shifting of PEV charging loads within a single day, subject to constraints on the vehicle's avail-

110 Forthcoming report from Lawrence Berkeley National Laboratory. Authors areJulia Szinai, Colin Sheppard, Nikit Abhyankar and Anand R. Gopal.

111 Sheppard, C., Waraich, R., Gopal, A., Campbell, A., & Pozdnukov, A. (2017). *Modeling plug-in electric vehicle charging demand with BEAM, the framework for behavior energy autonomy mobility* (No. LBNL-2001018). Lawrence Berkeley National Laboratory. Retrieved from https://eetd.lbl.gov/publications/modeling-plug-in-electric-vehicle-cha

ability. Preliminary results show under increasingly stringent GHG caps, flexible PEV charging yields incremental total system resource cost (which are annualized incremental generation and transmission fixed costs and generation operating costs over the course of the analysis, 2018-2030) savings of $100 - 200 million dollars per year and a reduction in renewable energy curtailment--and subsequent renewable overbuild and storage development--compared to the reference scenario with unmanaged PEVs.[112]

V2G impacts on energy and ancillary services markets have also been simulated in a number of studies for a wide range of geographies, with the majority indicating an annual profit per vehicle in the range of $100-300.[113] In California, the recent CPUC Demand Response Potential Study evaluated the value of DR resources in 2025 (such as what would be enabled with V2G) providing second to minute responses for ancillary service products,[114] and found that DR resources were cost-competitive with traditional generators and could provide about $20 million/year of value for load-following up to 600 MW, and $20 million/year of value up to 600 MW for regulation, but also found that the value of DR in the ancillary services markets decreases as more DR is added. Another study suggests that the California ancillary service markets would be saturated with the V2G participation of only about 45,000 PEVs with Level 2 chargers.[115] Even if the demand for ancillary services grows as more intermittent renewable generators are added to the California grid, it is still unclear whether the size of the overall ancillary services markets are large enough to justify the complexity of V2G participation, even without consideration of battery degradation impacts and questions of consumer acceptance.

Grid Scenarios with Increased Stationary Storage & Distributed Energy Resources

The value of grid services from PEVs, whether through price signals such as TOU rates or active control through smart charging or V2G programs, also will depend on the alternative resources that can provide flexibility to the grid and the demand for flexibility itself.

As the renewable energy penetration in California approaches and potentially exceeds 50 percent in the next decade, the demand for low-carbon flexible resources, on either the demand-side or supply-side of the electricity system will increase. With dropping prices of lithium ion batteries,[116] in part because of technology advancements and increased volumes of PEV manufacturing, stationary battery storage may reach grid parity with fossil generation sooner than anticipated. Stationary battery storage can be used instead of PEVs to provide distribution system support, load-shifting, and ancillary services, without the opportunity cost of mobility demands and any inconvenience to a driver. California has a mandate to add about 1.3 GW of stationary storage to the grid, and most recently, a study compared the potential value of this level of stationary storage (from batteries) with smart charging and V2G enabled-PEVs to mitigate the challenges of the state's Duck Curve (Figure 6) in 2025.[117] The study found that the smart charging capability of PEVs to be

112 CPUC Energy Division. (2017, July). Preliminary RESOLVE Modeling Results for Integrated Resource Planning at the CPUC. Retrieved from http://www.cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/UtilitiesIndustries/Energy/EnergyPrograms/ElectPowerProcurementGeneration/irp/17/CPUC_IRP_Preliminary_RESOLVE_Results_2017-07-19_final.pdf

113 Richardson, D. B. (2013). Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. *Renewable and Sustainable Energy Reviews,* 19, 247–254. https://doi.org/10.1016/j.rser.2012.11.042

114 Alstone, P., Potter, J., Piette, M. A., Schwartz, P., Berger, M. A., Dunn, L. N., … Jain, A. (2017). *Final Report on Phase 2 Results, 2015 California Demand Response Potential Study: Charting California's Demand Response Future*. Lawrence Berkeley National Laboratory, Energy and Environmental Economics, and Nexant.

115 Baumhefner, M., Hwang, R., & Bull, P. (n.d.). *Driving Out Pollution: How Utilities Can Accelerate the Market for Electric Vehicles* (No. R:16-05-B). Natural Resources Defense Council.

116 Kittner, N., Lill, F., & Kammen, D. M. (2017). Energy storage deployment and innovation for the clean energy transition. *Nature Energy,* 2(9), 17125. https://doi.org/10.1038/nenergy.2017.125

117 Coignard, J., Saxena, S., Greenblatt, J., & Wang, D. (2018). Clean vehicles as an enabler for a clean electricity grid. Environmental Research Letters, 13(5), 54031. https://doi.org/10.1088/1748-9326/aabe97

valued at $1.45-$1.75 billion, and the value of V2G to be the equivalent to the what could be provided with $12.8 to $15.4 billion of stationary storage. However, this valuation is overestimated because PEV grid services are compared to battery costs that have since dropped dramatically (from 2013 $500/kWh levels to about $200/kWh now), and the $15 billion value of V2G reported corresponds to the cost of 5 GW of storage, which is more than the capacity required by the mandate and demanded by the grid. In addition, the study does not account for the behavioral/user acceptance barriers that constrain some of the potential participation for any managed charging programs, which do not exist with stationary storage. It remains to be seen how advances in these grid-scale battery storage technologies and smaller scale distributed energy resources (DERs) like smart devices (thermostats, refrigerators, pumps, etc. that could also provide flexibility services to the distribution and bulk power systems)[118] will truly compete in cost, convenience, and performance as alternative sources of flexible grid services for California, without having to "chase a moving battery" of a PEV.

118 Alstone, P., Potter, J., Piette, M. A., Schwartz, P., Berger, M. A., Dunn, L. N., … Jain, A. (2017). *Final Report on Phase 2 Results, 2015 California Demand Response Potential Study: Charting California's Demand Response Future.* Lawrence Berkeley National Laboratory, Energy and Environmental Economics, and Nexant.

VI.

Policy Considerations

IN order to reach California's GHG reduction goals and achieve synergistic clean energy transitions in the transportation and the power sector, this report's authors suggests a number of goals, metrics to track, and policy recommendations related to each of the areas of California's Mobility-Infrastructure-Charging-Grid Nexus. For each area, there are a variety of stakeholders across the transportation, energy, and urban/land-use planning sectors.

TABLE 5 Key Goals, Metrics and Policies for PEV and Infrastructure in California (1 of 2)

	GOALS	METRICS	POLICY RECOMMENDATIONS
Mobility	Increased PEV and electrified medium- and heavy-duty vehicle adoption	• # of PEVs, medium- and heavy-duty vehicles on the road • Electric VMT • Transportation sector emissions	• Zero emission vehicle (ZEV) regulation extended to MDVs and HDVs (i.e., require that a share of vehicles sold to California buyers be zero emission) • Advance the date of converting bus fleet to ZEV from 2040 to 2025 • Continue PEV rebates with the aim of sunsetting
	Electrified Automated vehicles and Mobility-on-Demand	• Level of AV technology by make and model by year and powertrain • Rides completed by ride-hailing in CA • Electric VMT	• Adopt policies to ensure that all Level 4 and higher automated vehicles must be electric • CPUC directs IOUs to deploy fast chargers in urban core areas • Mandate that a minimum percentage of miles completed by ride-hailing companies be zero emission (proposed in SB-1014)
Charging Infrastructure	Widespread and convenient charger availability	• # of home chargers, multi-family chargers, work chargers, public chargers by Level • Installation (including equipment) and operating costs for chargers • # of PEVs per public charger	• Focus incentives on lowering the installation and equipment cost for multi-family and workplace chargers, in addition to public chargers, and for medium-duty and heavy-duty vehicle chargers. • Reform demand charge and PEV-related rate structure to encourage fast charging stations • Work on alignment with charging plug/communications standards so that more chargers can be shared across PEV types • CPUC rules and programs to encourage installation of DC fast chargers for passenger vehicles and Ultra-Fast chargers for freight vehicles.

TABLE 5 Key Goals, Metrics and Policies for PEV and Infrastructure in California (2 of 2)

	GOALS	METRICS	POLICY RECOMMENDATIONS
Charging Strategies	Greater participation in load management	• Enrollment in TOU rates and smart charging programs • # of chargers deployed with smart charging capability • # of vehicle makes and models that are V2G enabled	• Mandatory opt-out TOU rates for PEVs, and design PEV-specific TOU rates with longer off-peak periods and bigger price differentials. • Pilot daytime off-peak charging rates • Conduct more smart charging pilots, including at workplaces to target daytime renewable energy generation • Design rules that allow PEVs to count toward the grid storage mandate
Grid	Limited negative distribution system impacts	• # of PEVs on each feeder • Distribution system upgrade costs attributable to PEVs • Instances of transformer overloads, voltage excursions	• Standardize notification process to utilities of PEV purchases to facilitate distribution system planning • Monitor default TOU rate impacts on distribution feeders
	PEVs as a grid resource for the bulk power system	• Added ramping requirements • Change in peak load • RE curtailment	• Simplify the process of CAISO market participation • Investigate the opportunity to do DR programs on electrified medium-duty and heavy-duty vehicles • Allow fleet operators to access real-time power market prices to enable easier integration of renewables

Source: U.S. Department of Energy

Goals, Metrics, and Policy Recommendations

MOBILITY

The primary goals in the mobility area are to increase the overall level of electrification in the light-duty, medium-duty, and heavy-duty vehicle sectors, and to ensure that autonomous vehicles and mobility-on-demand services do not result in increased GHG emissions. The success of these goals can be tracked by the number of PEVs, electric medium-duty vehicles, and electric heavy-duty vehicles adopted, the average electric VMT (eVMT) of these vehicles, and transportation sector emissions. For PEVs, these metrics should be specifically disaggregated for PEV drivers in multi-family homes and drivers living in disadvantaged communities, especially as increased local/community air pollution monitoring has recent legislative support.[119] Closely tracking such vehicle adoption and driving metrics will then be useful in planning and siting additional charging infrastructure needed to relieve range anxiety and further increase PEV adoption and utilization. Additionally, if mobility trends move toward automation and greater use of ride-hailing services, tracking the VMT and eVMT will indicate whether such technology and services are increasing the overall GHG emissions and potentially causing congestion, diverting away from transit, etc. For autonomous and ride-hailing services, it will be useful for charging infrastructure and grid planning purposes to also track the level of automation, make/model of autonomous vehicles, and the number of ride-hailing rides completed in the state.

In order to further increase PEV adoption, existing incentives, such as the now income-capped California Vehicle Rebate Program, utility rebates from the Low Carbon Fuel Standard, and stickers for carpool lane/High Occupancy Vehicle access[120] continue to be important but should sunset in order to transition to stronger regulations. The state could further increase the ZEV mandate for light-duty vehicles and consider introducing a similar mandate for medium-duty and heavy-duty vehicles so that a minimum percentage of vehicles sold to California buyers by each manufacturer are zero emission. This will be simple expansion of the scope of the currently active ZEV regulation that only applies to passenger vehicles. In addition, the state could consider advancing the date of converting the bus fleet to zero emission to 2025 from 2040, given that the price of batteries has fallen more rapidly than previously expected and zero emission buses are now already cost effective on a lifecycle cost basis. For autonomous vehicles, it is worth considering policies (within the limits of state jurisdiction) that require all Level 4 or higher autonomous vehicles be zero-emission in order to negate the emissions impact of VMT rebound. To support this, the CPUC could direct IOUs to deploy more DC fast chargers in urban core areas. SB-1014 (introduced by Nancy Skinner), which would require ride hailing companies to meet a greenhouse gas per passenger mile target that increases in stringency over time, could help in this regard.

The relevant stakeholders for light-duty vehicles are the federal and state Environmental Protection Agency (EPA), the California State Legislature, California energy-related state agencies (CPUC, CARB, CAISO, CEC), local air quality districts, electric utilities, transportation/land-use planning agencies such as Caltrans and local city governments (for ride-hailing related policies). For medium-duty and heavy-duty vehicles, freight/logistics companies and transit agencies are additional relevant stakeholders.

119 Community Air Protection Program AB617. (n.d.). Retrieved May 25, 2018, from https://ww2.arb.ca.gov/our-work/programs/community-air-protection-program-ab617/about

120 Clean Vehicle Rebate Project Income Eligibility. (2016, May 31). Retrieved May 25, 2018, from https://cleanvehiclerebate.org/eng/income-eligibility; LCFS Utility Rebate Programs | Low Carbon Fuel Standard Program. (n.d.). Retrieved May 16, 2018, from https://www.arb.ca.gov/fuels/lcfs/electricity/utilityrebates.htm; California's Clean Air Decals | California Air Resources Board. (n.d.). Retrieved May 25, 2018, from https://ww2.arb.ca.gov/resources/fact-sheets/californias-clean-air-decals

CHARGING INFRASTRUCTURE

Charging infrastructure is the critical link between mobility trends, charging strategies, and grid impacts. In order to advance transportation electrification goals and increase the share of miles traveled with electricity, charging infrastructure needs to be widespread and conveniently accessible for all transportation sectors and use cases. The number, location, utilization, and installation and operating cost of home, multi-family, work, and public chargers by power level should be tracked in a centralized, public database. From these metrics, it would be possible to isolate and address any causes for higher installation costs or under/over utilization. Additionally, more data on the usage and number of PEVs per public charger overall in the state, and in certain geographic areas, can aid planners in siting new chargers and ensuring equitable coverage for existing and new PEV drivers, and possibly in the medium-duty and heavy-duty vehicles sectors.

In order to encourage increased development of chargers – especially at multi-family homes, workplaces and public locations – government incentives should continue to focus on lowering cost and administrative barriers to installation,[121] through rebates or other financial incentives such as loans and more streamlined permitting processes. To lower the operating cost of chargers at commercial sites – especially DC fast chargers – demand charges should be rationalized, reconsidered, and possibly folded into higher and dynamic (or at least TOU) volumetric rates that capture varying usage and some of the cost of equipment degradation from peak loads. Some of the installation and operating costs of a charging station can also be shared by the charging station developer with other businesses at a site, as the co-benefits of charging stations – such as added retail sales from longer shopping times, "green" branding, and employee perks – may be mutually beneficial.[122] To limit duplicative and inefficient charger development, automakers, utilities and government agency stakeholders should continue to work on alignment with charging plug/communications standards so that charging infrastructure can be shared across PEV types, and more off-the-shelf load management options are available and easier to implement. Lastly, the CPUC should consider authorizing pilot programs for high power Ultra-Fast DC charging stations along freight corridors and bus depots in order to enable electrified medium-duty and heavy-duty vehicles.

A number of stakeholders are relevant for the development of more charging stations, including state agencies (CPUC, CARB, CAISO, CEC), city and regional governments, electric utilities, charging providers, automakers, and land-use planners.

CHARGING STRATEGIES

While PEV loads are still a relatively small presence on both the distribution and transmission grids, at the 5 million scale targeted by Governor's executive order by 2030, managed charging strategies may be needed to limit negative impacts from charging loads and instead leverage the PEVs as a grid resource. One main goal is to increase participation in existing and upcoming load management opportunities such as TOU rates and smart charging programs. Utilities should track enrollment levels and conduct program evaluations to assess change in charging behavior, any program attrition, customer satisfaction, and responses to specific program features such as price, off-peak period length, or DR event overrides, among other key changes. As part of this monitoring process, utilities should also track any customer opt-outs and how load impacts differ for PEV households. In addition, the state should track the number of chargers deployed with smart charging capability, as well as the number of vehicles and their make/model that are capable of V2G charging. Improved monitoring of these programs will help further inform program development, ultimately driving success toward policy goals.

121 Barnes, G. E. (2018). *Electric Vehicle – Grid Integration Pilot Program ("Power Your Drive") Fourth Semi-annual report of San Diego Gas and Electric Company (U902-E)*. Retrieved June 26, 2018 from https://www.sdge.com/sites/default/files/regulatory/FINAL_Power_Your_Drive_Semi_Annual_Rpt.pdf

122 Melaina, M., & Helwig, M. (2014). *California Statewide Plug-In Electric Vehicle Infrastructure Assessment* (No. CEC-600-2014-003). Prepared by National Renewable Energy Laboratory for California Energy Commission.

Continued smart charging pilots and fine-tuning of TOU rate designs that are PEV- and user-friendly will be needed to maximize PEVs as a grid resource. The CPUC should consider mandatory, opt-out TOU rates for PEV drivers. As part of this policy, utilities should monitor the impact TOU rates have on distribution feeders that have a high PEV penetration and should provide PEV drivers with an incentive to use the "charge-by" functionality in their vehicles so as to naturally mitigate artificial second peaks at the beginning of TOU periods. PEV specific TOU rates should have longer off-peak periods, and a larger price differential between peak and off-peak times Utilities may also pilot day-time off-peak TOU rates in the springtime to help avoid RE curtailment. Different smart charging program/business models should be tested with DR aggregators, automakers, and utilities to evaluate which implementer most consistently delivers load-shifting results and is most trusted by customers to adopt. Smart charging at workplaces and with fleet vehicles should be tested because most of the experiences thus far have focused on personal vehicles and home charging. Charging infrastructure developers should also be incentivized to develop smart charging-capable chargers that can be used in the middle of the day. Additionally, further piloting, in coordination with CAISO, is required to evaluate the value and scalability of V2G specifically in California, and whether it is worthwhile to pursue if stationary battery storage costs continue to decline. Lastly, the CAISO and CPUC should coordinate on adjusting regulations to make it easier to count the value of managed charging resources provide to the grid.

To encourage more participation in load management programs, state agencies (CPUC, CARB, CAISO, CEC), utilities, automakers will need to be involved.

GRID

Depending on when, where and how fast they charge, PEVs can have vastly different impacts on the distribution system and the bulk power system. Stakeholders should aim to limit the negative impacts on the grid and maximize the grid service benefits that PEVs can provide. To track the grid impacts PEVs are and will likely have, utilities should develop standardized ways to track the number of PEVs connected to each feeder, the level of charger they have at home, any problems caused by the addition of PEVs such as transformer overloads or voltage excursions and resulting distribution system upgrade costs. Currently, the IOUs do not have a streamlined, way they are notified when and where a customer starts driving a PEV, which makes distribution system planning difficult.[123] Together with utilities, the CAISO also should track any changes in peak loads and subsequent added ramping requirements due to unmanaged PEV loads, as well as change in renewable curtailment attributable to load management programs.

Utilities should work with dealerships, the Department of Motor Vehicles and other relevant agencies to enforce an easy and standardized reporting requirement when a customer adds a PEV to their home utility service.[124] For existing smart charging programs, and the single V2G pilot, much of the challenge is the process and cost of CAISO market participation, particularly in the ancillary services market. More education by the CAISO on market participation steps, and a more simplified process for participation for smaller resources such as aggregated PEV loads would enable them to more readily contribute grid services. Smart charging DR pilots should be considered especially with electrified medium-duty and heavy-duty vehicles fleets that have bigger loads. The CAISO could also develop a more streamlined way for fleet operators of electric vehicles to access real-time power market prices to enable easier integration of renewables

The state's energy related agencies and regulators, (CPUC, CARB, CAISO, CEC), utilities, automakers, aggregators/DR providers, and scheduling coordinators will need to work together to enable PEV grid services.

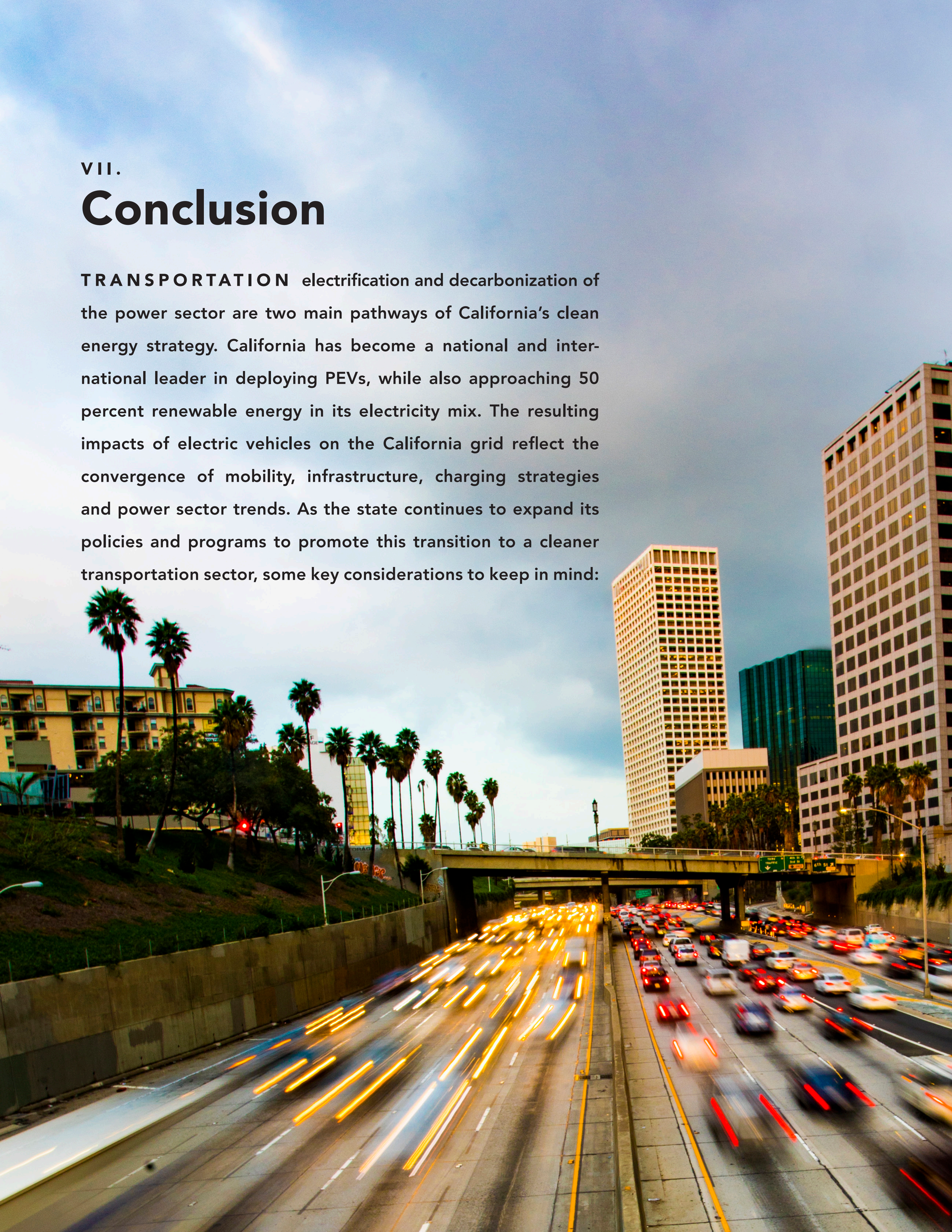
123 California Public Utilities Commission. (2017). *Load Research Report Compliance Filing of San Diego Gas & Electric Company (U 902-M), Southern California Edison Company (U 338 - E), and Pacific Gas and Electric Company (U 39E) Pursuant to Ordering Paragraph 2 of D.16-06-011*. Retrieved from http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442455828

124 Baumhefner, M., Hwang, R., & Bull, P. (n.d.). *Driving Out Pollution: How Utilities Can Accelerate the Market for Electric Vehicles* (No. R:16-05-B). Natural Resources Defense Council

VII.

Conclusion

TRANSPORTATION electrification and decarbonization of the power sector are two main pathways of California's clean energy strategy. California has become a national and international leader in deploying PEVs, while also approaching 50 percent renewable energy in its electricity mix. The resulting impacts of electric vehicles on the California grid reflect the convergence of mobility, infrastructure, charging strategies and power sector trends. As the state continues to expand its policies and programs to promote this transition to a cleaner transportation sector, some key considerations to keep in mind:



PEVs have historically been sold as privately owned and operated vehicles, but with improved technology driving automation of transport, fleets of electric automated PEVs that provide mobility-on-demand are on the horizon. Lower battery costs also make electric medium-duty and heavy-duty vehicles more feasible. These trends could have significant implications on driving (increased VMT) and charging patterns (higher energy demand), and subsequently on the grid (added loads).

- The charging infrastructure is the connector between all of these areas, but is lagging compared to the deployment of PEVs, and compared to charger density in the rest of the US and globally. Part of the reason for lagging charging infrastructure development is that it has thus far been primarily built by private actors, but under current electricity rates and costs, the business model is not financially viable. Other barriers include cost, competing standards and multiple use cases. Existing utility, government and other private sector investments are underway to boost charging infrastructure, but additional expansion of infrastructure will be necessary.

- Depending on the type available charger, mobility needs and other factors, PEVs either charge in an unmanaged way (drivers plug in whenever they want) or can participate in managed charging strategies such as TOU rates, smart charging or (eventually) V2G. These managed charging strategies can limit the possible negative impacts that PEVs can have on the grid and instead provide grid services such as distribution system support, load-shifting, and ancillary services. Thus far TOU programs have been effective, but uptake has been low. Smart charging and V2G strategies have only be tried at the pilot stage. How these programs continue to be shaped and promoted could have significant impacts for grid management.

- With a relatively smaller share of PEVs on the road, the distribution system impact has been minimal. Even with clustering of PEVs on certain feeders, some studies still estimate the cost for upgrades to be nominal. At the bulk power system scale, which is already coping with challenges of intermittent renewable energy, managed PEV loads are expected to help limit curtailment and save on grid operating cost by lowering peak load. However, the role of PEVs in providing such grid services remains to be seen if stationary battery storage and other distributed energy resources continue to increase, and if a large share of the transportation sector is also automated.

As California looks to bring millions more electric vehicles onto its roadways in the years ahead, it will be critical for industry and policy leaders to develop management strategies, policies and incentives that will help optimize impacts and services that the newly added EV demand could provide to the grid.

VIII.

Appendix

TABLE A1 Vehicle-Grid Communications Standards (1 of 2)

	Open ADR	IEEE 2030.5	OCPP	Telematics	SAE Suite	IEEE 2030.1.1	ISO 15118
Standards and Sponsoring Organization:							
	Open Automated Demand Response standard (Open ADR Alliance)	Smart Energy Profile 2.0 Application Protocol Standard (IEEE)	Open Charge Point Protocol (Open Charge Alliance)	Data monitoring and communications system onboard the vehicle (Automaker's proprietary or through IEEE)	Charging Network Management Protocol (or IEEE 2690)	CHAdeMO Standard (IEEE)	Vehicle to grid communication interface (International Organization for Standardization)
Use Cases and Supporting Standards:							
V2G: Send information needed to interconnect to the grid (discharge controls with start time and duration)	○	●	○	◐	◐	◐	○
Pricing: Communication of different electricity pricing/tariffs	●	●	◐	◐	◐	◐	◐
Load Control: Send info needed to respond to DR signals for specific events (increase or reduce charge with start time and duration)	●	●	○/◐	◐	◐	◐	◐
Smart Charging: Communicate info for optimal charging or discharging based upon driver or site preferences	○/◐	●	○/◐	◐	◐	◐	◐

○ **Not Supported** ○/◐ **Supported in Combination** ● **Supported**

TABLE A1 Vehicle-Grid Communications Standards (2 of 2)

	Open ADR	IEEE 2030.5	OCPP	Telematics	SAE Suite	IEEE 2030.1.1	ISO 15118
Standards and Sponsoring Organization:							
	Open Automated Demand Response standard (Open ADR Alliance)	Smart Energy Profile 2.0 Application Protocol Standard (IEEE)	Open Charge Point Protocol (Open Charge Alliance)	Data monitoring and communications system onboard the vehicle (Automaker's proprietary or through IEEE)	Charging Network Management Protocol (or IEEE 2690)	CHAdeMO Standard (IEEE)	Vehicle to grid communication interface (International Organization for Standardization)
Use Cases and Supporting Standards:							
Monitoring: Collect charging event data for M&V, billing, and monitoring	○/◐	●	○/◐	◐	◐	◐	◐
Restart: Communicate info to restore power if interrupted	◐	●	◐	◐	◐	◐	◐

Source: California Public Utilities Commission[125]

○ **Not Supported** ○/◐ **Supported in Combination** ● **Supported**

A Vehicle Grid Integration Communications working group of stakeholders from "state and federal agencies, academia, utilities, ratepayer, advocates, EVSE equipment and component manufacturers/providers, EV service providers, automakers, standards experts, nonprofits, and other software and technology providers" convened over nine months to discuss vehicle-grid use cases (such as smart charging or V2G), the required communications components to achieve the use cases, and combinations of existing communications standards that could support the requirements.[126] A summary table above shows the seven currently available communications standards that were discussed and the use cases they each support. Many of the use cases could not be achieved by a single communications protocol, but were possible through a combination of several of the more specialized protocols. The working group determined that there was no universally best communications path between the grid and the PEV, and the CPUC decided not to recommend a specific set of protocols to the utilities developing EVSE.

The figure below from the working group final report shows the various combinations of communications standards that can be used between the various actors that can be involved in a vehicle-grid interaction.

125 Table adapted from Requirements and Use Case Summaries Spreadsheets from: Vehicle-Grid Integration Communications Protocol Working Group. (n.d.). from http://www.cpuc.ca.gov/vgi/

126 Sisto, C., & Mesrobian, A. (2018). *Final Report on VGI Communication Protocol Working Group*. Energy Division, California Public Utilities Commission.

FIG A1 Diagram of Vehicle-Grid Communications Pathways from VGI Working Group