EXAMINING THE IMPACT OF EVs ON THE CALIFORNIA ELECTRICAL GRID

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Exam Preview:

1. According to the latest available data published by the California Department of Transportation, an average of 64.2 miles are driven daily in Los Angeles County for every vehicle registered in the county.
   a. True
   b. False
2. According to the reference material, assuming extremely fast charging rates (well beyond those possible today) and simultaneous charging, analysts have estimate that as few as _______ EVs in Texas (about 0.25 percent of the cars currently registered in Texas) could equal all of today's peak electricity demand for the region.
   a. 45,000
   b. 50,000
   c. 55,000
   d. 60,000
3. In January 2018, California Governor Edmund G. Brown issued an Executive Order setting a statewide goal of five million zero-emissions vehicles (ZEVs, mostly plug-in electric cars) on the road by 2030.
   a. True
   b. False
4. Using Figure 3 PEV Sales and Market Share in the United States, what year saw the greatest percentage growth in PEV sales?
   a. 2010
   b. 2012
   c. 2014
   d. 2017
5. Using Figure 17, Reserve Margin at Peak under Each Analytic Scenario, which scenario allows the reserve margin to remain greater than 16%?

a. Scenario 1
b. Scenario 2
c. Scenario 3
d. Scenario 4

6. According to the reference material, an early study conducted at Pacific Northwest National Laboratory for the U.S. Department of Energy (DOE) estimated that the existing electric power infrastructure could support electrification of __ percent of the country's cars, trucks and sport utility vehicles, assuming that all charging would be done at off-peak times.
   a. 68
   b. 75
   c. 84
   d. 92
7. According to the reference material, about half of the PEVs sold in the United States have been sold in California. There are approximately 413,568 EVs in California.
   a. True
   b. False
8. Using Figure 12 LADWP's Projected Energy Mix through 2036, by the year 2030, what is the estimated percentage of power to be supplied by renewable resources?
   a. 55%
   b. 29%
   c. 36%
   d. 65%
9. The maximum number of EVs that can charge simultaneously under the combination of assumptions without endangering the reliability of the LADWP grid is 153,194.
   a. True
   b. False
10. Using Figure 8 Evolution of Battery Energy Density and Cost, during what year did battery cost (USD/kWh) fall below 400?
   a. 2012
   b. 2013
   c. 2014
   d. 2015

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LIST OF ACRONYMS AND ABBREVIATIONS

A	amp
BEV	battery electric vehicle
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CEC	California Energy Commission
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EV	electric vehicle
FCEV	fuel cell electric vehicle
FCV	fuel cell vehicle
FERC	Federal Energy Regulatory Commission
GM	General Motors
GWh	gigawatt-hours
HFC	hydrogen fuel cell
IRP	integrated resource plans
kW	kilowatts
kWh	kilowatt hours
LA	Los Angeles
LADWP	Los Angeles Department of Water and Power
LF	load factor
MPGe	miles per gallon equivalent
mph	miles per hour
MW	megawatt
MWh	megawatt hours
NERC	North American Electric Reliability Corporation
NHTSA	National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PEV	plug-in electric vehicle
PG&E	Pacific Gas and Electric

PHEV	plug-in hybrid electric vehicle
POU	publicly owned utilities
SLTRP	Power Strategic Long-term Resource Plan
SONGS	San Onofre Nuclear Generating Station
TOU	time-of-use
TZEV	transitional zero-emissions vehicles
V	volt
V2G	vehicle-to-grid
V2H	vehicle-to-house
V2V	vehicle-to-vehicle
VER	variable energy resources
ZEV	zero-emissions vehicle

EXECUTIVE SUMMARY

How many Teslas will it take to crash the Los Angeles, California, power grid? This thesis conducts a thought experiment to explore whether rapid adoption of electric vehicles (EVs) in Los Angeles (LA) will reduce the reliability of electric power in the Los Angeles Department of Water and Power (LADWP) service territory.

Electric cars, once a novelty, are beginning a sprint into the market. In January 2018, California Governor Edmund G. Brown issued an Executive Order setting a statewide goal of 5 million zero-emissions vehicles (ZEVs, mostly plug-in electric cars) on the road by 2030. This ambitious goal will create additional demand for electricity and test the resilience of California's electric power resources, especially in its major metropolitan areas. In Los Angeles, a leading area for EV adoption, the most recent strategic power plan was based on projections of about half this level of EV market penetration.[1] In this thesis, I will use scenario analysis to look at whether meeting the governor's goal will reduce the reliability of the Los Angeles power grid at times of peak demand.

At first glance, there is plenty of excess capacity in the system. Because electric infrastructure is designed to meet the expected peak demand with a safety margin, at non-peak times (about 95 percent of the time), there is excess, idle generation capacity in the system. However, instead of using idle capacity, uncontrolled charging of EVs could easily add to the peak demand, as consumers would simply plug in their cars on arriving home after work, when power usage is the highest, but after solar energy has begun to decline.

The analysis presented here uses scenarios to explore the question of where a tipping point might exist for grid stability under rapid adoption of fully EVs. California's new Executive Order, the popularity of Tesla's Model 3, and Los Angeles' leading role in EV adoption create ideal conditions for a thought experiment: how many Model 3s, introduced how fast, would it take to endanger the reliability of the electric grid in Los

[1] Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan* (Los Angeles: Los Angeles Department of Water and Power, 2017), ES-10, https://www.ladwp.com/cs/idcplg?IdcService=GET_FILE&dDocName=OPLADWPCCB655007&RevisionSelectionMethod=LatestReleased.

Angeles? To shed light on this, I compared demand for power at the peak hour of the year in 2030 under four scenarios (see Figure 1). I used the generation and demand projections in the LADWP's strategic plan as the basis for constructing four alternative scenarios that combined variations in the EV adoption rate (LADWP assumption versus the Governor's goal) and charging profiles (unconstrained versus constrained charging). Although EV penetration will impact several aspects of electric power networks, this analysis considers only whether sufficient generation resources will be available to ensure grid reliability at the time of peak demand, when the grid is under maximum stress.

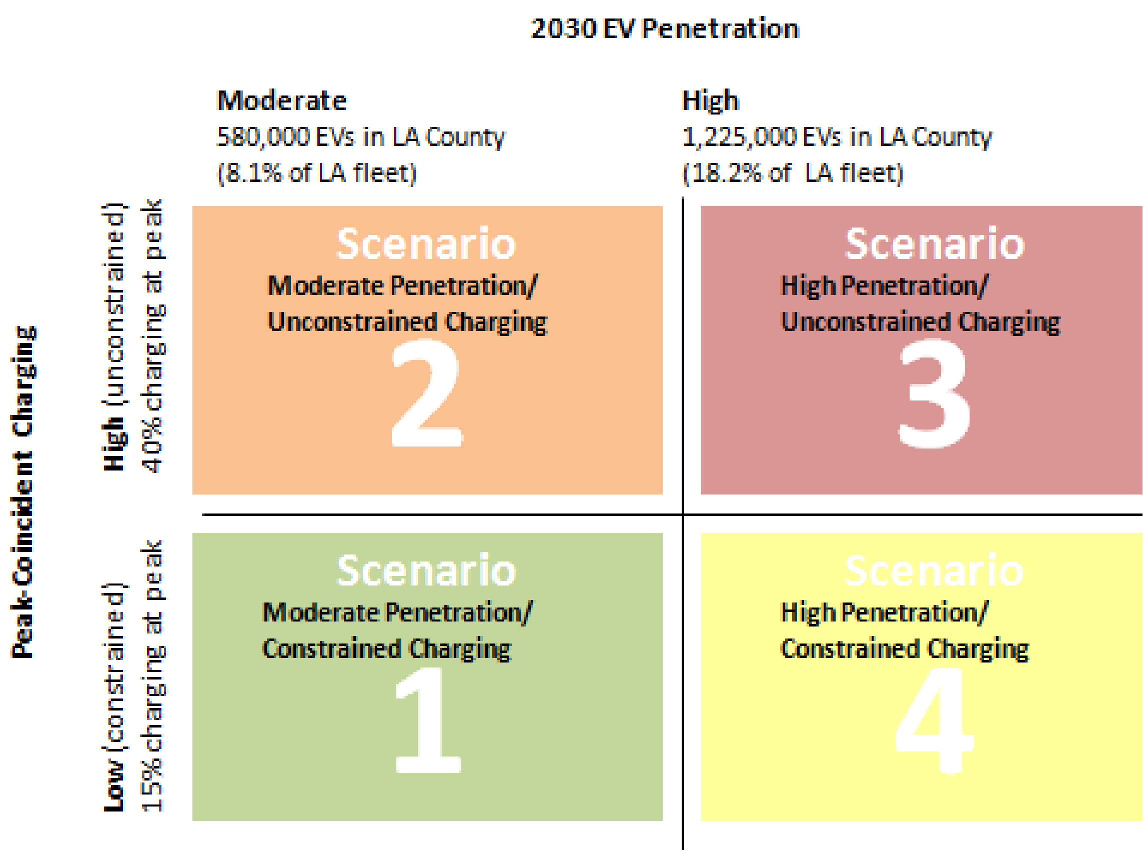

Figure 1. Scenarios Analyzed

Under each scenario, I calculated the projected reserve margin at peak demand and compare it to the planning reserve margin for LADWP. The reserve margin is the portion of the available generation resources left over after the expected demand is met. It is an indicator of system reliability, because the higher the reserve margin, the more resources are available to mitigate any unforeseen generation shortfalls that arise. This calculation is based on LADWP's estimate of how much power will reliably be available at the time of peak demand in 2030.[2] For the LADWP area, which experiences its heaviest demand in summer, the summer planning reserve margin standard is 16 percent. If the reserve margin for a scenario is less than the 16 percent planning reserve margin, I concluded that grid reliability could be compromised.

The principal factors affecting resource adequacy with respect to EV adoption are

- Non-EV supply and demand for electricity in the Los Angeles area
- EV energy requirements
- EV market penetration
- EV driver travel and
- EV charging patterns

I used LADWP's 2017 Power Strategic Long-term Resource Plan and the California Energy Commission's 2017 Integrated Energy Policy Report to project non-EV supply and demand for electricity by time of day in 2030. Based on these data, I selected 6:30 p.m. as the time of instantaneous peak summer demand for the purpose of estimating the contribution of EV charging to demand.

For the purposes of this analysis, I used the Tesla Model 3 with its standard battery pack to represent EV energy requirements. (This is intended as a convenient benchmark for analysis, not a prediction that Tesla will displace all competitors.) The scenarios in this analysis consider two alternative scenarios of EV market penetration. The moderate penetration scenarios use the assumption from LADWP's recommended strategic case, which is that there will be 580,000 EVs on the road in Los Angeles by 2030.[3] The high penetration scenarios assume that California will meet the governor's target of five million ZEVs on the road in California by 2030.

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[2] Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan*, 166.

[3] Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan*, ES-10.

The number of miles driven per day will determine the total amount of electricity used by EVs, and therefore, the total time that each car draws power from the grid each day. According to the latest available data published by the California Department of Transportation, an average of 34.2 miles are driven daily in Los Angeles County for every vehicle registered in the county.[4]

I assume that, absent any constraints or incentives, drivers will tend to plug in their cars when they arrive home from work and begin to draw power immediately. Unfortunately, this means that in the unconstrained scenarios EV power demand would be concentrated in a few hours at the end of the workday, which also coincide with peak demand from other users. I estimate the unconstrained load on the system from the data on energy requirements and EV penetration described above, along with data on time-of-day traffic patterns in Los Angeles from the U.S. Department of Transportation Federal Highway Administration.[5] In the constrained demand scenarios, I assume that time-of-day pricing incentives or direct controls are used to spread demand out more evenly over the night.

The overall results of the analysis are shown in Figure 2. As can be seen, relative to an established reserve margin of 16 percent of capacity, only Scenario 1, with moderate EV penetration and constrained demand, does not fall below the established standard. With even moderate EV penetration, if vehicle charging is unconstrained the load placed on the LADWP grid will exceed the established reserve margin in 2030. Only by adopting some form of incentives for EV drivers to shift their power demands from the normal end-of-day charging routine will LADWP be able to maintain the reliability and resilience of the power grid.

[4] "Vehicle Registrations in Los Angeles County, California," Los Angeles Almanac, 2018, http://www.laalmanac.com/transport/tr02.php.

[5] "Travel Time Reliability: Making It There on Time, All the Time," U.S. Department of Transportation Federal Highway Administration, February 1, 2017, https://ops.fhwa.dot.gov/publications/tt_reliability/long_descriptions/Figure4.htm.

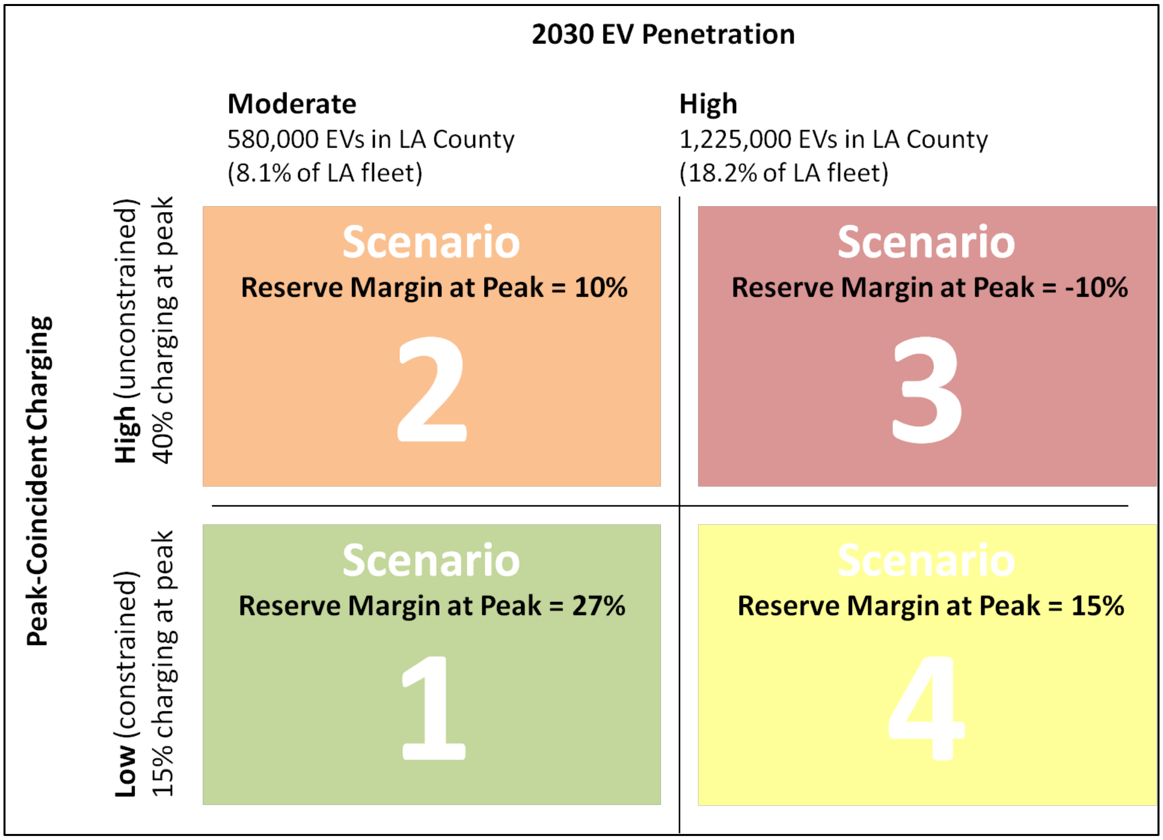

Figure 2. Reserve Margin at Peak under Each Analytic Scenario

Extending this analysis, I calculated the maximum number of EVs that could charge simultaneously at peak without depleting the reserve margin. The tipping point at which grid reliability is compromised (defined as depletion of the reserve margin) occurs when approximately 150,000 EVs charge simultaneously at the time of peak system demand. Los Angeles can absorb much higher EV penetrations, including the governor's new target for 2030, as long as the portion of EVs charging at peak is managed so that the number of vehicles does not exceed this number. This might be done through some combination of time-of-day pricing, partnerships with employers to provide free or reduced price daytime charging, or a system of direct controls in which the utility can control the time of charging to optimize load on the system.

ACKNOWLEDGMENTS

It would be impossible to put into words how grateful I am to my advisors, Professors Rodrigo Nieto-Gomez and Ted Lewis, and to my family for their support and encouragement throughout the writing of this thesis. Conversations with my advisors; my partners, George and Pam; and my father, all helped to move my thinking forward on this topic, and I am grateful for their patience during endless discussions of Teslas and reserve margins. It is perhaps a testament to the pervasiveness of this discussion that my father now drives a Tesla.

I am also grateful for the opportunity to earn my master's degree at the Center for Homeland Defense and Security, which was made possible by funding from the U.S. Department of Homeland Security. The incredible intellectual environment fostered by an amazing faculty renewed my commitment to the mission of advancing homeland security. Professor Christopher Bellavita, in particular, will always be with me as the voice in my head telling me to inquire more deeply into wicked problems.

I. INTRODUCTION

A. THESIS QUESTION

How many Teslas will it take to crash the Los Angeles, California, grid? This thesis conducts a thought experiment to explore whether rapid adoption of electric vehicles (EVs) in Los Angeles (LA) will reduce the reliability of electric power in the Los Angeles Department of Water and Power (LADWP) service territory.

B. CHARGING AHEAD: PROBLEM STATEMENT

Electric cars, once a novelty, are beginning a sprint into the market. In January 2018, California Governor Edmund G. Brown issued an Executive Order setting a statewide goal of five million zero-emissions vehicles (ZEVs, mostly plug-in electric cars) on the road by 2030.[1] This ambitious goal will create additional demand for electricity and test the resilience of California's electric power resources, especially in its major metropolitan areas. In Los Angeles, a leading area for EV adoption, the most recent strategic power plan was based on projections of about half this level of EV market penetration. In this thesis, I will use scenario analysis to look at whether meeting the governor's goal will reduce the reliability of the Los Angeles power grid at times of peak demand.

Federal and state regulations are encouraging the shift to electric transportation, in support of policy priorities that include reducing greenhouse gas emissions and reducing dependence on foreign energy sources. However, high market penetration by EVs will change the patterns of electricity use, especially in urban areas. Under some scenarios, EVs could pose a risk to the reliability and resilience of the electric grid serving these areas. The current electric power system was not designed to handle electric transportation, which will

[1] "Governor Brown Takes Action to Increase Zero-Emission Vehicles, Fund New Climate Investments," Office of the Governor, Governor Edmund G. Brown Jr., January 26, 2018, https://www.ca.gov/archive/gov39/2018/01/26/governor-brown-takes-action-to-increase-zero-emission-vehicles-fund-new-climate-investments/index.html.

reshape where and when consumers use power.[2] Widespread adoption of battery electric vehicles (BEVs) or plug-in hybrid electric vehicles (PHEVs) could negatively affect the electric grid in several ways, including increasing peak power requirements and shortening the life of distribution infrastructure.

Electric power planning takes place at scales ranging from hourly to decadal, but major infrastructure changes occur slowly. Planning for expensive changes to generation or transmission capacity is based on meticulous forecasting and analysis of alternatives, cost-benefit ratios, and impacts. Any changes are carefully considered, since costs will be passed on to utility customers. To ensure that there will be enough electric power generation capacity to meet future demand, regional planners make long-term projections of electricity supply and demand, based on trends in economic growth and development, technological shifts, policy goals, and planned capacity projects, usually including a variety of scenarios for each factor to help account for uncertainty. Despite the sophistication of these plans, conditions may not unfold as the planners anticipate. The long planning cycle and the natural tendency to change forecasts incrementally mean that a rapid rise in EV adoption could overtake planning.

A rapid shift to fully EVs, such as the Tesla Model 3, could expose vulnerabilities in the electric power system. Demand will be mobile—because consumers can charge their vehicles at work, at home, or on the road—and peak charging times may not match the peak supply of renewable energy sources, such as wind and solar.[3] This analysis uses the Tesla Model 3 to assess the capacity of the LA power network to accommodate rapid adoption of plug-in electric vehicle (PEV) technology. It is important to examine the

[2] Ahmed M. A. Haidar, Kashem M. Muttaqi, and Danny Sutanto, "Technical Challenges for Electric Power Industries Due to Grid-Integrated Electric Vehicles in Low Voltage Distributions: A Review," *Energy Conversion and Management* 86 (October 2014): 689–700, https://doi.org/10.1016/j.enconman.2014.06.025.

[3] For many areas, power available from wind peaks at about 5:00 p.m., while power demand peaks at about 7:00 p.m. Sherif F. Abdelsamad, Walid G. Morsi, and Tarlochan S. Sidhu, "Impact of Wind-Based Distributed Generation on Electric Energy in Distribution Systems Embedded with Electric Vehicles," *IEEE Transactions on Sustainable Energy* 6, no. 1 (January 2015): 79–87, https://doi.org/10.1109/TSTE.2014.2356551.

possible impacts of EV adoption on Los Angeles' electric power supplies, because it will likely be one of the first areas to encounter any potential issues.

C. ENOUGH HORSEPOWER: RESOURCE ADEQUACY LITERATURE REVIEW

The fundamental question that concerns us in this analysis is whether existing and planned power generation resources can provide enough power for high rates of EV adoption at times when demand for other uses is peaking. This is the question of resource adequacy. The answer depends on a variety of factors, including how much energy EVs draw (based on travel patterns, charging configurations, and number of vehicles), as well as where and when EV owners charge their vehicles. Secondarily, the charging patterns will determine which power resources are used to supply EV demand, with implications for the amount of emissions produced and the cost of power. For example, if EVs charge in the middle of the day, they will draw power at a time when the grid relies on plentiful solar resources. If most charging is done at night, when solar is unavailable and wind energy is reduced, they will increase demand on more conventional power plants, and the power mix will have higher greenhouse gas emissions overall.[4]

Existing research related to regional resource adequacy for transportation electrification lays out possible concerns. Some of the work described here (especially the older studies) specifically considered PHEVs rather than BEVs. This work is relevant—despite the technological differences between the car types—because in terms of grid impacts, the only difference between the types of PEVs is the amount of power drawn from the grid. Research carried out in other countries is also included because the issues arising from similar grid technology and globally-marketed vehicles can be expected to be similar.

At first glance, there is plenty of excess capacity in the system. Because electric infrastructure is designed to meet the expected peak demand with a safety margin, at non-peak times (about 95 percent of the time), there is excess, idle generation capacity in the

[4] Jae D. Kim and Mansour Rahimi, "Future Energy Loads for a Large-Scale Adoption of Electric Vehicles in the City of Los Angeles: Impacts on Greenhouse Gas (GHG) Emissions," *Energy Policy* 73 (2014): 620–30.

system. For most U.S. systems, including Los Angeles, peak demand occurs in summer, due to the use of air conditioning, and is generally in the late afternoon hours. An early study conducted at Pacific Northwest National Laboratory for the U.S. Department of Energy (DOE) estimated that the existing electric power infrastructure could support electrification of 84 percent of the country's cars, trucks and sport utility vehicles, assuming that all charging would be done at off-peak times. The researchers found that this level of EV penetration would cut U.S. oil imports by more than 50 percent.[5] A companion paper rather optimistically looked at the economic impacts of "downward pressure on [electric utility customer] rates as revenues increase in the absence of new investments for generation, transmission, and distribution."[6]

However, instead of using idle capacity, uncontrolled charging of EVs could easily add to the peak demand, as consumers would simply plug in their cars on arriving home after work, when power usage is the highest, but after solar energy has begun to decline.[7] In the absence of other motivations, this would be the most convenient for drivers, as they are already at the vehicle and they will want to have the vehicle sufficiently charged for any unplanned evening trips.

A study conducted at Oak Ridge National Laboratory (ORNL) looked at resource adequacy for each of the 13 North American Electric Reliability Corporation (NERC) regions. Researchers found that regional impacts for a fleet penetration of 25 percent by 2020 varied; with unconstrained charging, they found that California, Florida, and part of the southwest United States could have generation shortfalls. In addition, the different fuel sources used in different regions (referred to as the region's "energy mix") resulted in different resources being dispatched at peak and off-peak times to serve load, which in

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[5] Michael Kintner-Meyer, Kevin Schneider, and Robert Pratt, *Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids Part 1: Technical Analysis* (Richland, WA: Pacific Northwest National Laboratory, 2007), 1, http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.574.6257.

[6] Kintner-Meyer, Schneider, and Pratt; describing findings from Michael J. Scott et al., *Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids: Part 2: Economic Assessment* (Richland, WA: Pacific Northwest National Laboratory, 2007), 1–39, http://energyenvironment.pnnl.gov/ei/pdf/PHEV_Economic_Analysis_Part2_Final.pdf.

[7] Claire Weiller, "Plug-in Hybrid Electric Vehicle Impacts on Hourly Electricity Demand in the United States," *Energy Policy* 39, no. 6 (June 2011): 3766–78, https://doi.org/10.1016/j.enpol.2011.04.005.

turn, affected costs and emissions.[8] Although the ORNL study did not consider possible utility responses, such as expanding capacity, increasing imports, or implementing programs to manage demand, it clearly demonstrates the importance of regional analysis.

In Australia, researchers used a suite of models to represent EV uptake, travel patterns, household electricity demand and the charging or discharging of EVs in Victoria to generate spatial-temporal profiles for EV energy use. They found that although peak demand increased by less than 10 percent in most places under their scenarios, some areas could face resource constraints on days with particularly high demand.[9]

Assuming extremely fast charging rates (well beyond those possible today) and simultaneous charging, analysts have estimate that as few as 60,000 EVs in Texas (about 0.25 percent of the cars currently registered in Texas) could equal all of today's peak electricity demand for the region. When added to normal demand from other users, this would far exceed today's power supply.[10] This hypothetical case is unrealistic, but illustrates the potential for EV power demand to affect resource adequacy.

D. UNDER THE HOOD: ANALYTIC METHOD

This analysis uses scenarios to explore the question of where a tipping point might exist for grid stability under rapid adoption of fully EVs. California's new Executive Order, the popularity of Tesla's Model 3, and Los Angeles' leading role in EV adoption create ideal conditions for a thought experiment: how many Model 3s, introduced how fast, would it take to endanger the reliability of the electric grid in Los Angeles? To shed light on this, I compared demand for power at the peak hour of the year in 2030 under four scenarios

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[8] Stanton W. Hadley, *Impact of Plug-in Hybrid Vehicles on the Electric Grid* (Oak Ridge, TN: Oak Ridge National Laboratory, 2006), 1, http://web.ornl.gov/info/ornlreview/v40_2_07/2007_plug-in_paper.pdf.

[9] Phillip Paevere et al., "Spatio-Temporal Modelling of Electric Vehicle Charging Demand and Impacts on Peak Household Electrical Load," *Sustainability Science* 9, no. 1 (January 2014): 61–76, https://doi.org/10.1007/s11625-013-0235-3.

[10] Analysis by Wood Mackenzie, "The Rise of the Electric Car: How Will it Impact Oil, Power and Metals?," GreenTech Media, December 2017, https://www.greentechmedia.com/research/report/the-rise-of-the-electric-car-how-will-it-impact-oil-power-and-metals#gs.owJcKBE, as described by Jason Deign, "How Electric Vehicles Could Sink the Texas Grid," GreenTech Media, December 19, 2017, https://www.greentechmedia.com/articles/read/how-electric-cars-could-sink-the-texas-grid.

(Figure 1). I used the generation and demand projections in the LADWP's strategic plan as the basis for constructing four alternative scenarios that combined variations in the adoption rate (LADWP assumption versus the Governor's goal) and charging profiles (unconstrained versus constrained charging). Although EV penetration will impact several aspects of electric power networks, this analysis considers only whether sufficient generation resources will be available to ensure grid reliability at the time of peak demand, when the grid is under maximum stress.

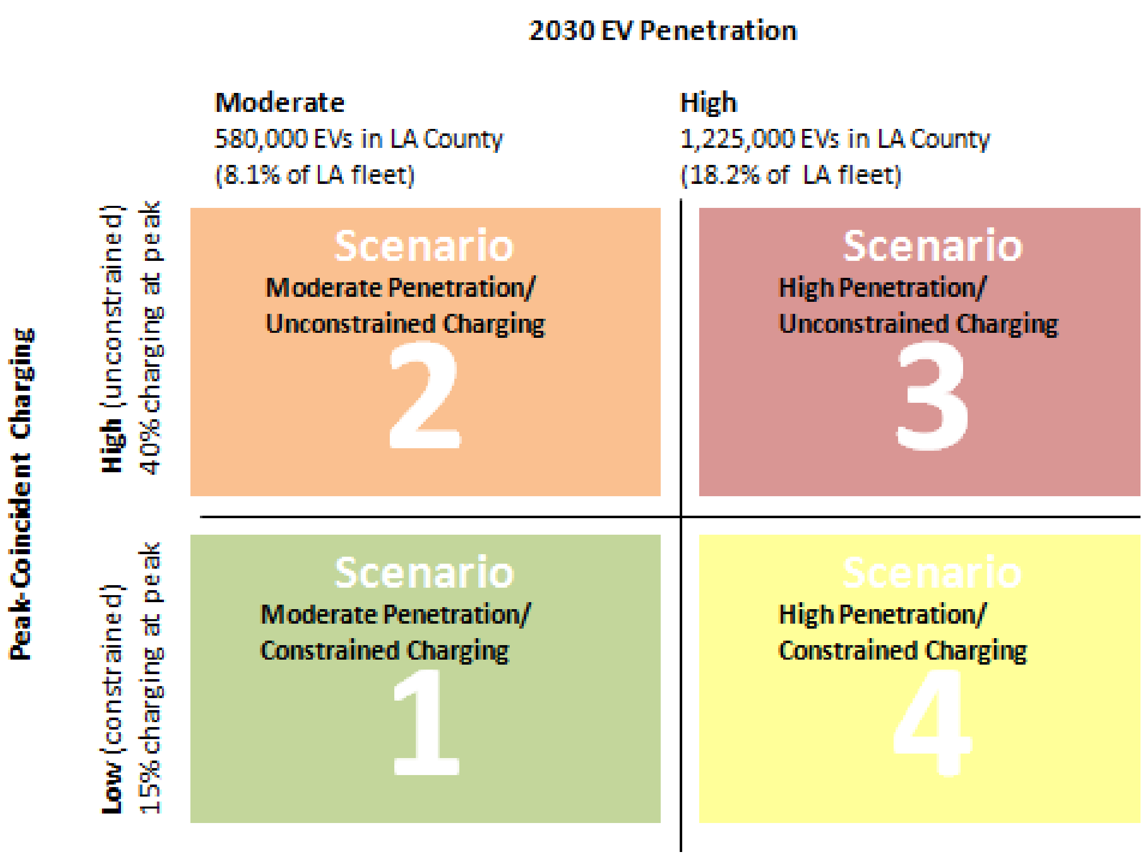

Figure 1. Scenarios Analyzed.

As a simple check to determine whether the estimated demand including the scenario EV contribution would put the grid reliability at risk, I calculated the projected reserve margin at peak demand and compared it to the planning reserve margin for LADWP. The reserve margin is the portion of the available generation resources left over after the expected demand is met. It is an indicator of system reliability, because the higher the reserve margin, the more resources are available to mitigate any unforeseen generation shortfalls that arise. This calculation is based on LADWP's estimate of how much power will reliably be available at the time of peak demand (called dependable resources) in 2030.[11]

The planning reserve margin is the target percentage of resources expected to remain after expected demand is met. Planning reserve margins are designed to help system planners ensure that there will be enough power available to handle unplanned outages or unexpectedly high demand situations (such as a heat wave), while still maintaining power quality. For the LADWP area, which experiences its heaviest demand in summer, the summer planning reserve margin standard is 16.16 percent.[12] If the reserve margin for a scenario is less than the 16 percent planning reserve margin, I conclude that grid reliability could be compromised.

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[11] "Dependable resources" represent only a portion of the generating capacity theoretically available to account for unplanned outages and variability in generation from variable sources, such as solar, wind, and hydroelectric. In 2030, the LADWP forecast for dependable resources includes power imported from other regions, as well as power generated within the area. Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan* (Los Angeles: Los Angeles Department of Water and Power, 2017), 158–159, https://www.ladwp.com/cs/idcplg?IdcService=GET_FILE&dDocName=OPLADWPCCB655007&RevisionSelectionMethod=LatestReleased.

[12] WECC Staff, *2016 Power Supply Assessment* (Salt Lake City, UT: WECC, 2016), 3, https://www.wecc.org/Reliability/2016PSA_Final.pdf.

II. STOP AND GO: HISTORY AND FUTURE OF ELECTRIC VEHICLES

Past and present socio-technological environments provide important context for today's EV development and diffusion. This chapter provides background on EV evolution from the earliest vehicles to the present, including a discussion of the barriers to and drivers of widespread adoption. It concludes with a discussion of the possible future market growth for EVs.

A. IN THE REAR VIEW MIRROR: EARLY EVs

EVs have had more than one false start before gaining traction. Some of the earliest automobiles were electric, and their proponents extolled their quieter performance and lack of exhaust. In fact, the Electric Vehicle Company, founded in 1897 as a holding company for several manufacturers of electric automobiles, pioneered electric taxicabs and charging infrastructure in New York, starting with a fleet of 12 cabs.[13] The company built several hundred cars between 1897 and 1899.[14] By 1900, approximately one-third of the cars on city streets—the only place automobiles were practical before paving was common—were electric.[15]

However, these early EVs were soon displaced. Internal combustion engines began to dominate the market with the advent of the Ford Model T at the start of the 20th century. Compared to an electric car costing $1,750 in 1912, Ford's car was far more economical at $680, and it could travel farther on a single "fill-up."[16] Affordability transformed the automobile from novelty to necessity. Range also became an increasingly important factor,

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[13] David A. Kirsch, "The Electric Car and the Burden of History: Studies in the Automotive Systems Rivalry in America, 1890–1996," *Business and Economic History* 26 (Winter 1997): 304, https://thebhc.org/sites/default/files/beh/BEHprint/v026n2/p0304-p0310.pdf.

[14] Beverly Rae Kimes, *Standard Catalog of American Cars, 1805–1942*, 3rd ed. (Iola, WI: Krause Publications, 1996), 357.

[15] Leandra Poindexter Cooper, "Electric Vehicle Diffusion and Adoption. An Examination of the Major Factors of Influence over Time in the U.S. Market" (master's thesis, University of Iceland, 2014), 13, https://skemman.is/bitstream/1946/17028/1/Cooper_thesis_final.pdf.

[16] Rebecca Matulka, "The History of the Electric Car," U.S. Department of Energy, September 15, 2014, http://energy.gov/articles/history-electric-car.

as more roads suitable for cars were built in the 20th century. The early price edge of internal combustion engines became an entrenched dominance, and gasoline filling stations proliferated along new highways as the century passed.

B. GEARING UP: MODERN EVs

Despite occasional resurgences of interest, the limitations of EVs from the beginning have included cost, battery range, and poor engine performance. Over time, however, increasing concerns about gasoline supply and harmful pollutants from automobile exhaust began to offset the advantages of internal combustion. For this reason, federal, state, and local governments' policies have been important in overcoming the barriers to EV adoption.

In California, where policy makers were particularly concerned about public health impacts from air pollution, legislators passed the first Zero-Emissions Mandate in 1990, requiring major car makers doing business in California to include in their fleets a percentage of vehicles that produce no harmful emissions.[17]

Largely in response to these policy directives, car manufacturers began to revisit electric vehicle technology in the late twentieth century.[18] Some cars were modified from existing gasoline vehicles, but General Motors (GM) produced the first modern purpose-designed, all-electric model, the EV-1, between 1996 and 1999.[19] The EV-1 was available for lease only, and when California relaxed its laws to accommodate so-called transitional zero-emissions vehicles (TZEVs, which operated at least part of the time without emissions), GM scrapped the EV-1. Over the protests of the car's fans, all 1,100 EV-1s were reclaimed and nearly all were destroyed.[20]

[17] "Zero-Emission Vehicle Legal and Regulatory Activities," Air Resources Board, October 27, 2014, https://www.arb.ca.gov/msprog/zevprog/zevregs/zevregs.htm#background.

[18] Matulka, "The History of the Electric Car."

[19] Owen Edwards, "The Death of the EV-1," *Smithsonian Magazine*, June 2006, http://www.smithsonianmag.com/science-nature/the-death-of-the-ev-1-118595941/?no-ist.

[20] Edwards.

Possibly because they are more compatible with the way consumers are used to driving and fueling their cars, TZEV gas-electric hybrid cars, such as the Honda Insight and Toyota Prius have been far more popular than battery electric models to date.[21] In 2016, there were 3.57 million gas-electric hybrids on the road in the United States, making up about 2.9 percent of the total fleet of cars.[22] Gas-electric hybrids still employ internal combustion engines, but are supported by electric drive to improve gas mileage and decrease emissions. Their electric batteries are charged while driving and braking, so there is no need for owners to plug them into the electric grid to charge them. PHEVs extend the all-electric range of the hybrids by adding the ability to charge their batteries through a connection to the grid.

Despite the relaxation for TZEVs, the ZEV requirement in California will continue to become more stringent over time. The federal government, California, other states, and major cities have also implemented policies designed to encourage EV adoption, including providing rebates, offering free or subsidized public charging, permitting individual access to carpool lanes, and building charging infrastructure.[23] For these reasons, auto manufacturers have continued to dedicate some level of effort to the development of ZEVs, including PEVs. There are now more than 40 models of PEVs (including 17 battery-only models) on the market, ranging in base price from $24,000 to well over $100,000.[24] As manufacturers overcome the key barriers to ownership (cost, range, convenience, and image), BEVs are becoming more attractive to the public.

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[21] According to Rogers' Theory of Innovation Diffusion, there are five major factors in successful diffusion of innovation: relative advantage, compatibility with existing practices and norms, complexity, observability, and trialability. Pure electric vehicles and hybrids are similar along most of these dimensions, but EVs require changes in both driver behavior (to accommodate lengthy charging) and supporting infrastructure (charging infrastructure). Rogers' theory was first laid out in Everett M. Rogers, *Diffusion of Innovations*, 1st ed. (New York: Free Press of Glencoe, 1962).

[22] "Annual Energy Outlook 2018: Table 40 Light-Duty Vehicle Stock by Technology Type," U.S. Energy Information Administration, 40, February 6, 2018, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=49-AEO2018&region=0-0&cases=ref2018&start=2016&end=2050&f=A&linechart=ref2018-d121317a.4-49-AEO2018~ref2018-d121317a.6-49-AEO2018&ctype=linechart&sourcekey=0.

[23] J. R. DeShazo et al., *State of the States' Plug-in Electric Vehicle Policies* (Los Angeles, CA: University of California-Los Angeles, Luskin School of Public Affairs, Luskin Center for Innovation, 2015), 1–29, http://innovation.luskin.ucla.edu/sites/default/files/EV_State_Policy.pdf.

[24] "Compare Electric Cars and Plug-in Hybrids—List of Features, Price, Range, Model," PluginCars, 2018, http://www.plugincars.com/cars.

In 2006, the co-founder and chief executive officer of Tesla Motors Elon Musk published his "master plan" for catalyzing the electrification of transportation, which he believes is essential to a sustainable future. As Musk explained it, "The strategy of Tesla is to enter at the high end of the market, where customers are prepared to pay a premium, and then drive down market as fast as possible to higher unit volume and lower prices with each successive model."[25] In other words, where EVs were once out-competed and left behind by more affordable internal combustion engines, Musk plans to use the sale of luxury cars to finance the development of mainstream electric cars, catalyzing the electrification of transportation. Because Tesla is the only automobile manufacturer focusing exclusively on ZEVs, it has been able to sell its excess ZEV credits to supplement its revenue stream.[26]

In contrast to the marketing strategy of other auto manufacturers, who have been content to produce "compliance" vehicles that were the Birkenstocks of the automotive world, Tesla challenged existing assumptions about BEVs with its first stylish, high-performance, luxury Roadsters in 2008. The Roadster had a range of more than 200 miles on its pioneering lithium-ion batteries, as well as highly-acclaimed driving performance.[27] Tesla followed up with a luxury sedan (Model S) and a sport utility/crossover design (Model X). The 2017 Tesla S has a five-star rating from the automotive reviewers at *Car and Driver*, who rated it first in the Luxury Hybrid and Electric Vehicles, above vehicles from BMW and Cadillac. With a top speed of 155 miles per hour (mph) and taking only 2.8 seconds to accelerate from zero to 60 mph, the Model S's performance is impressive for any sedan.[28] Moreover, the National Highway Traffic Safety Administration (NHTSA), which conducts independent safety evaluations of all automobile models, gave the Model

[25] Elon Musk, "The Secret Tesla Motors Master Plan (Just between You and Me)," Tesla, August 2, 2006, https://www.tesla.com/blog/secret-tesla-motors-master-plan-just-between-you-and-me.

[26] Matthew DeBord, "Critics Are Wrong—Tesla Should Be Selling ZEV Credits," Business Insider, October 27, 2016, http://www.businessinsider.com/tesla-zev-credits-ok-2016-10.

[27] "Tesla Roadster Review—Research New & Used Tesla Roadster Models," Edmunds, accessed July 24, 2019, http://www.edmunds.com/tesla/roadster/.

[28] Joseph Capparella, "Tesla Model S-Car and Driver," CarandDriver, April 2016, http://www.carand driver.com/tesla/model-s.

S five stars in every testing subcategory, putting it in the top one percent of models tested. The Model S's actual NHTSA safety score was the highest ever issued by the agency.[29]

The announcement of the first mid-priced Tesla in March 2016, the Model 3, generated unprecedented interest, as more than 325,000 customers pre-ordered cars in the first week, even though the cars would not be delivered until July 2017.[30] Belying early skeptics, the company has managed to pull off a steep ramp in production, cutting delivery times for many versions to two to three months after orders are placed.[31] Figure 2 shows Tesla's Model 3 production (cumulative and by week).

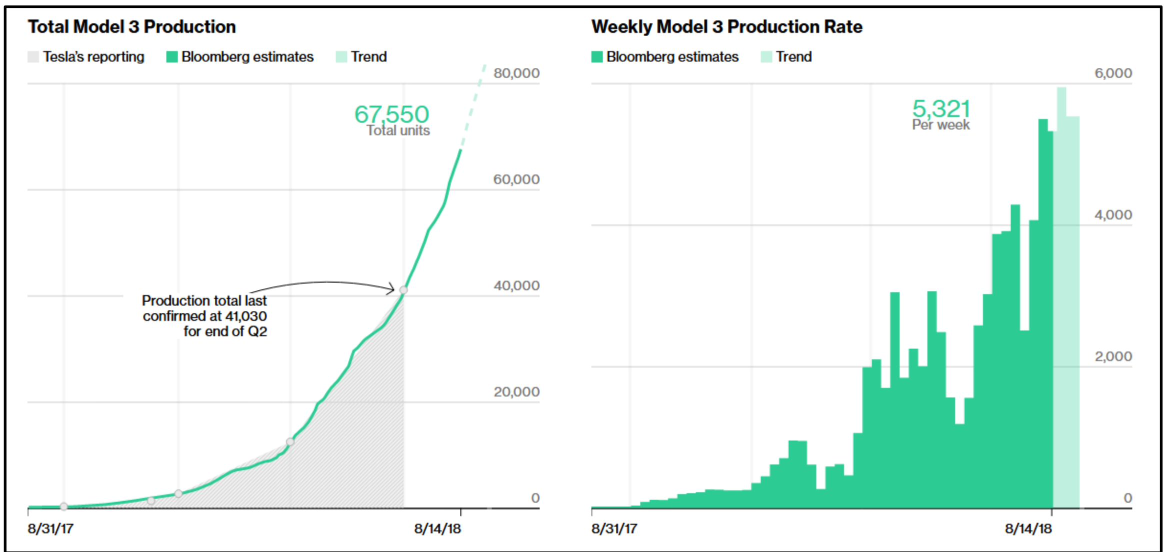

Figure 2. Tesla Model 3 First Year Production Ramp.[32]

[29] "Tesla Model S Achieves Best Safety Rating of Any Car Ever Tested," Tesla, August 19, 2013, https://www.tesla.com/blog/tesla-model-s-achieves-best-safety-rating-any-car-ever-tested?redirect=no.

[30] Brooke Crothers, "With Tesla Model 3 Orders Nearing 400,000, Chevy Bolt Feels Heat of Tesla Brand," Forbes, April 15, 2016, http://www.forbes.com/sites/brookecrothers/2016/04/15/with-tesla-model-3-orders-nearing-400000-chevy-bolt-feels-heat-of-tesla-brand/#66bca5d25349.

[31] Fred Lambert, "Tesla Accelerates Model 3 Delivery Timelines on New Orders," *Electrek* (blog), July 14, 2018, https://electrek.co/2018/07/14/tesla-model-3-delivery-timelines-new-orders/.

[32] Source: Tom Randall and Dean Halford, "We Set Out to Crack Tesla's Biggest Mystery: How Many Model 3s It's Making," Bloomberg, August 14, 2018, https://www.bloomberg.com/graphics/2018-tesla-tracker/.

Tesla expects to produce 10,000 cars per week in 2019.[33] This number of cars alone will not revolutionize transportation, in a nation of over 248 million cars and light-duty trucks, but it has sparked media and cultural interest in EVs; arguably helping EVs more generally turn the corner to mainstream adoption.

C. OUTRACING EXPECTATIONS: ELECTRIC VEHICLE ADOPTION

Just a few years ago, most projections were that EV market growth would be about 20 percent annually.[34] In 2016, one analysis projected 30 percent annual growth; at that rate, by 2040, one-quarter of the vehicles on the road would be electric, and they will consume 11 percent of the total quantity of electricity that was generated worldwide in 2015.[35] Also in 2016, one market research firm increased its estimates of EV and hybrid sales for the year 2020 to 17 million, up from the previous year's estimate of 12 million.[36] Year-over-year sales growth was 36 percent between 2015 and 2016, 27 percent between 2016 and 2017, and is expected to leap 75 percent above 2017 in 2018 (see Figure 3).[37]

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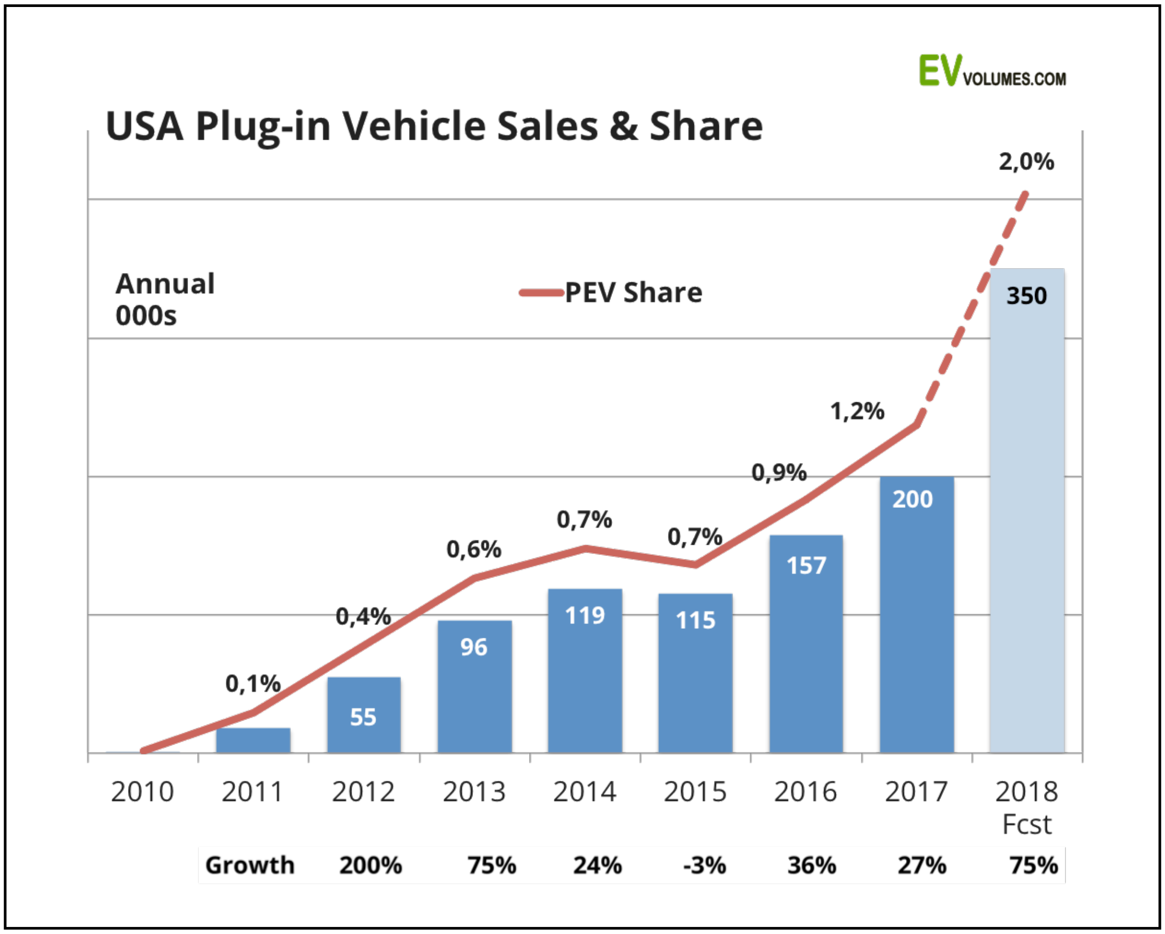
[33] Mark Matousek, "Tesla Expects to Make 6,000 Model 3s per Week by the End of August," Business Insider, August 1, 2018, https://www.businessinsider.com/tesla-model-3-production-to-hit-6000-per-week-by-end-of-august-2018-8.

[34] David Block and John Harrison, *Electric Vehicle Sales and Future Projections* (Cocoa, FL: Electric Vehicle Transportation Center, University of Central Florida, 2014), 7, http://evtc.fsec.ucf.edu/reports/EVTC-RR-01-14.pdf.

[35] "Electric Vehicles to Be 35% of Global New Car Sales by 2040," Bloomberg New Energy Finance, February 25, 2016, http://about.bnef.com/press-releases/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040/.

[36] "Hybrid and Electric Vehicle Sales to Exceed 17 Million by 2020 as 'Range Anxiety' Lessens," Juniper Research, March 8, 2016, https://www.juniperresearch.com/press/press-releases/hybrid-and-electric-vehicle-sales-to-exceed-17m?utm_source=cisionpr&utm_medium=email&utm_campaign=Hybrid_Electric_16_PR1.

[37] "EV-Volumes—The Electric Vehicle World Sales Database," EV Volumes, July 2018, http://www.ev-volumes.com/country/usa/.



Year-over-year growth shown at the bottom axis.

Figure 3. PEV Sales and Market Share in the United States[38]

Currently, EVs make up about 4.5 percent of new car sales in California, and about 1.3 percent of all cars on California roads.[39] In 2018, Governor Brown's original 2012 goal of 1.5 million ZEVs in California by 2025 appears to be easily in reach (see Figure 4).[40]

[38] Source: EV Volumes.

[39] F. Noel Perry et al., T*he Road Ahead for Zero-Emission Vehicles in California: Market Trends and Policy Analysis* (San Francisco: Next 10, 2018), 3–4, http://next10.org/sites/default/files/ca-zev-brief.pdf.

[40] Edmund G. Brown Jr., California Office of the Governor, Executive Order B-16-2012, "Zero Emission Vehicles (ZEVs)," (March 23, 2012), http://gov.ca.gov/news.php?id=17472.

Therefore, in March 2018, the Governor raised the bar: California is now planning to achieve five million ZEVs by 2030.[41]

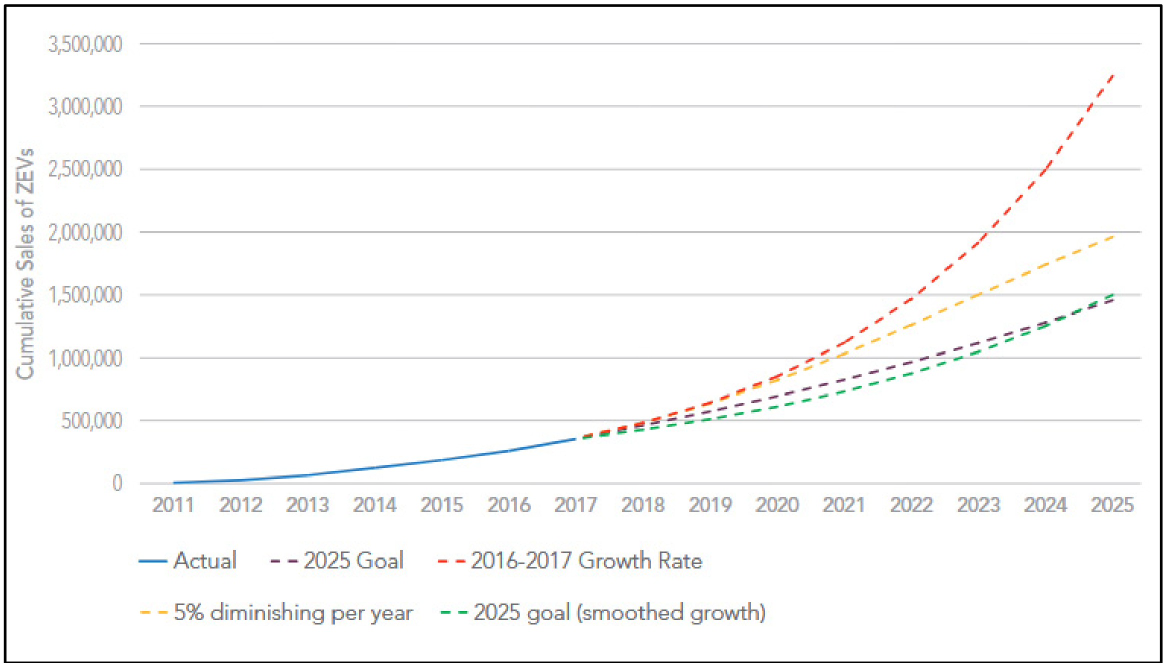


Figure 4. Historical and Projected Cumulative ZEV Sales, Accounting for Vehicle Scrappage Rates for 2025 Goal[42]

D. CURVES AHEAD: TECHNOLOGICAL DIFFUSION

In 2017, global sales of EVs—led by the United States, Europe, and China—accelerated rapidly, increasing 56 percent over 2016 rates (Figure 5).

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[41] Brown, Executive Order B-16-2012.

[42] Source: International Energy Agency, *Global EV Outlook 2018* (Paris, France: International Energy Agency, 2018), 13, https://webstore.iea.org/download/direct/1045?fileName=Global_EV_Outlook_2018.pdf.

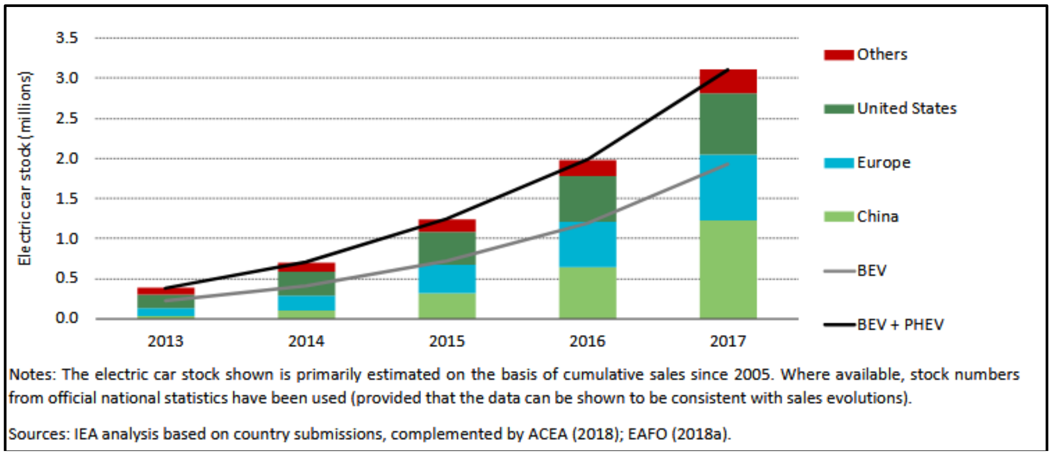

Figure 5. Evolution of Global EV Stock 2013–2017 (All BEVs and PEVs in Service)[43]

The number of EVs in the United States has also increased rapidly over the past few years, despite remaining a small percentage of the automotive fleet overall (Figure 6).

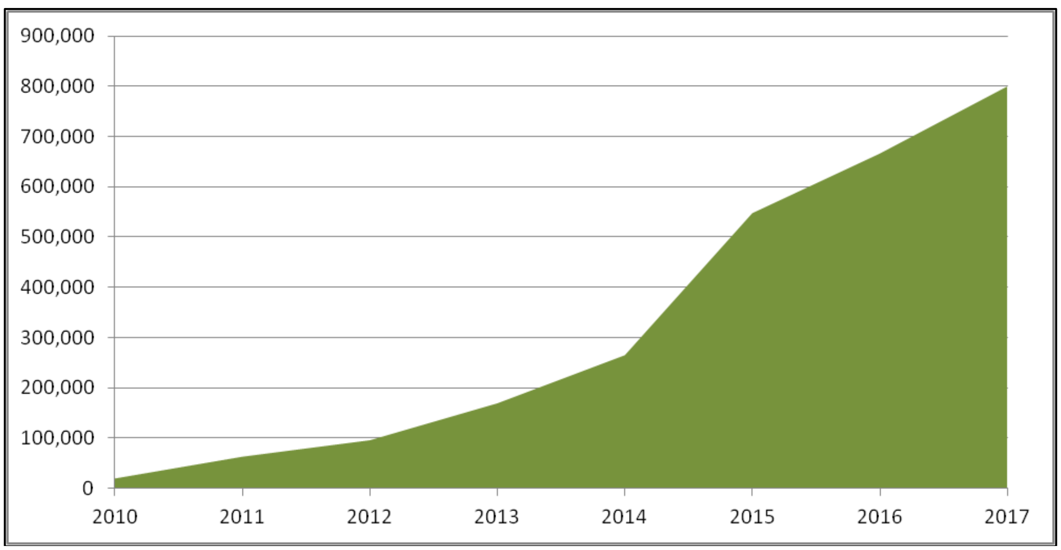

Figure 6. Number of EVs in the United States by Year[44]

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[43] Source: International Energy Agency, 9.

[44] Source: U.S. Energy Information Administration (EIA), "Annual Energy Outlook 2018: Table 40 Light-Duty Vehicle Stock by Technology Type."

In fact, a period of sharp acceleration of adoption rate is a normal feature of technological diffusion. Researchers have shown that many technologies have shared a pattern in which market penetration as a function of time follows an S-shaped (logistic) curve. Frank Bass originally described this model in 1969, demonstrating that it fit the cumulative sales curve for a range of innovations, including steam irons, air conditioners, and power lawnmowers.[45] Bass's equation, commonly called the Bass Diffusion model, yields the curves shown in Figure 7.[46] The specific shape of the curve is determined by two coefficients, p and q, whose values describe the relative strength of internal influences (for example, a friend's recommendation) and external influences (for example, advertising) on a potential first-time buyer. Obviously, it is impossible to directly measure these influences, although they can be inferred *ad hoc* from empirical data. However, there is little agreement in the literature on the correct values of these variables for electric cars, because there are only a few years' worth of data on which to base an estimate. In addition, the model is sensitive to the estimated size of the market (m), which may not be equal to 100% of car-buyers.[47] That said, the cumulative sales curves at the global level and national level (Figures 5 and 6) look remarkably similar, and have not yet reached the inflection point predicted by the Bass Model (shown as time T* in Figure 7).

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[45] Frank M. Bass, "A New Product Growth for Model Consumer Durables," *Management Science* 15, no. 5 (January 1969): 215–27, https://doi.org/10.1287/mnsc.15.5.215.

[46] Vijay Mahajan, Eitan Muller, and Frank M. Bass, "Diffusion of New Products: Empirical Generalizations and Managerial Uses," *Marketing Science* 14, no. 3_supplement (August 1995): G79–88, https://doi.org/10.1287/mksc.14.3.G79.

[47] Jérôme Massiani and Andreas Gohs, "The Choice of Bass Model Coefficients to Forecast Diffusion for Innovative Products: An Empirical Investigation for New Automotive Technologies," *Research in Transportation Economics* 50 (August 2015): 17–28, https://doi.org/10.1016/j.retrec.2015.06.003.

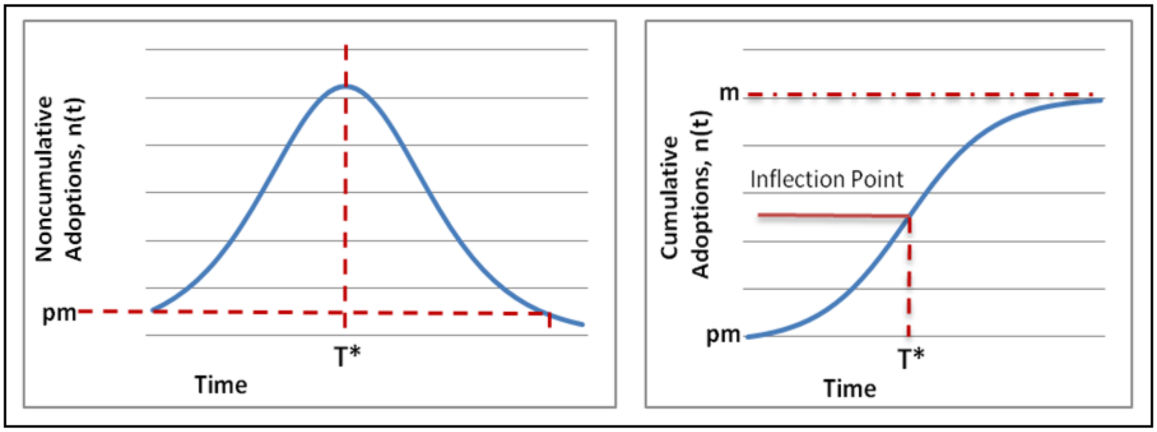

Figure 7. Analytical Structure of the Bass Technology Diffusion Mode.[48]

Several key drivers are behind this acceleration, working to overcome barriers to adoption of EVs that have included high costs, consumer unfamiliarity, and limited range.[49] These factors may be generally categorized as regulatory requirements, consumer incentives, infrastructure development, and technological improvements. A brief description of how each of these drivers is affecting EV adoption follows.

1. Regulatory Requirements

Regulatory requirements aimed at improving fuel efficiency and reducing harmful emissions have helped propel EV growth. Development of alternative fuels vehicles (fuel cell and electric drive) can help manufacturers improve their overall fleet average economy while also reducing greenhouse gas emissions.

The NHTSA Corporate Average Fuel Economy (CAFE) Standards, established by Congress in 1975 and amended several times since, require automobile manufacturers to meet increasingly strict fuel economy standards for their fleets. The NHTSA sets these standards at "the maximum feasible average fuel economy level that it decides the

[48] Adapted from Vijay Mahajan, Eitan Muller, and Frank M. Bass, "New Product Diffusion Models in Marketing: A Review and Directions for Research," *Journal of Marketing* 54, no. 1 (January 1990): 4.

[49] Leandra Poindexter Cooper, "Electric Vehicle Diffusion and Adoption. An Examination of the Major Factors of Influence over Time in the US Market" (master's thesis, University of Iceland, 2014), 5, http://skemman.is/en/item/view/1946/17028.

manufacturers can achieve in each year."[50] Together with the U.S. Environmental Protection Agency (EPA), the NHTSA in 2012 published combined standards for fuel economy and reduction of carbon dioxide emissions that also includes an "incentive multiplier" for PHEVs, BEVs, and FCVs in the model years 2017 to 2025.The current NHTSA standards call for the industry fleet average to reach 40 to 41 mpg fuel efficiency in model year 2021, while the EPA greenhouse gas emission policies call for a reduction in carbon dioxide emissions that would be equivalent to 54.7 mpg if accomplished through fuel economy alone.[51] By comparison, the 2018 Tesla models received EPA fuel economy ratings of 116–130 miles per gallon equivalent (MPGe), depending on model and options.[52]

In addition, California pioneered state-level legislation requiring that car makers who sell cars produce a percentage of alternative fuel vehicles, referred to as ZEVs. Nine other states have adopted similar requirements. These rules are pushing auto manufacturers to develop and market a broader range of EV models, which in turn, raises consumer awareness and meets a wider range of customer requirements.[53]

2. Consumer Incentives

Federal, state, and local policies that provide consumer incentives, such as tax credits, rebates, sales tax exemptions, free parking, subsidized charging, and carpool lane access, are helping to offset the EV price premium.[54] At the federal level, PEV purchasers are eligible for tax credits of up to $7,500 (subject to a 200,000-vehicle cap per

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[50] Interestingly, at least one analysis has shown that there is no statistically significant correlation between gasoline prices and EV sales. Richard Kelly, "Do Gas Prices Correlate with Plug-in Vehicle Sales?," PlugInAmerica, December 15, 2014, https://pluginamerica.org/do-gas-prices-correlate-plug-vehicle-sales/..

[51] "CAFE Public Information Center," U.S. National Highway Traffic Safety Administration, accessed July 24, 2019, http://www.nhtsa.gov/CAFE_PIC/CAFE_PIC_Home.htm.

[52] "Gas Mileage of 2018 Vehicles by Tesla," Fueleconomy, accessed July 24, 2019, https://www.fueleconomy.gov/feg/bymake/Tesla2018.shtml.

[53] "Gas Mileage of 2016 Vehicles by Tesla," Fueleconomy, accessed August 29, 2016, https://www.fueleconomy.gov/feg/bymake/Tesla2016.shtml.

[54] DeShazo et al., *State of the States' Plug-in Electric Vehicle Policies*, 1–29.

manufacturer). A number of states, including California, have additional tax incentives for EV purchase and installation of charging infrastructure.[55]

In California, single-occupant access to carpool lanes for PEVs has proved to be especially important. Researchers at the University of California Los Angeles found that approximately 25 percent of PEV registrations in California between 2010 and 2013 were attributable to this benefit.[56] Carpool-lane access is estimated to be worth about $2,300 over the lifetime of a vehicle for residents of Los Angeles.[57]

3. Infrastructure Development

Policy influences on electric vehicle adoption also include funding for public and private charging infrastructure. The availability of charging infrastructure is an important influence on the uptake of EVs because it reduces customer anxiety about the limited range of EVs. Using funding appropriated under the 2009 American Recovery and Reinvestment Act, DOE has contributed significantly to the development of charging infrastructure in the United States. According to the Alternative Fuels Data Center, there are now more than 22,000 charging stations in the United States, not including private stations, such as the Tesla "Supercharger" stations; California alone now has more than 5,700 public charging stations.[58]

For cities like Los Angeles that include a high proportion of residents living in multi-family housing, installing charging infrastructure in the parking facilities of multi-

[55] Nic Lutsey et al., *Assessment of Leading Electric Vehicle Promotion Activities in United States Cities* (Washington, DC: International Council on Clean Transportation, 2015), 9, http://www.theicct.org/sites/default/files/publications/ICCT_EV-promotion-US-cities_20150729.pdf.

[56] Tamara L. Sheldon and J. R. DeShazo, *How Does the Presence of HOV Lanes Affect Plug-in Electric Vehicle Adoption in California? A Generalized Propensity Score Approach* (Los Angeles: UCLA Luskin School of Public Affairs, Luskin Center for Innovation, 2016), 1.

[57] "Plug-In Electric Drive Vehicle Credit (IRC 30D)," U.S. Internal Revenue Service, February 9, 2016, https://www.irs.gov/businesses/plug-in-electric-vehicle-credit-irc-30-and-irc-30d.

[58] "Alternative Fuels Data Center: Electric Vehicle Charging Station Locations," U.S. Department of Energy, Energy Efficiency and Renewable Energy, accessed July 25, 2019, https://afdc.energy.gov/fuels/electricity_locations.html#/find/nearest?fuel=ELEC&country=US.

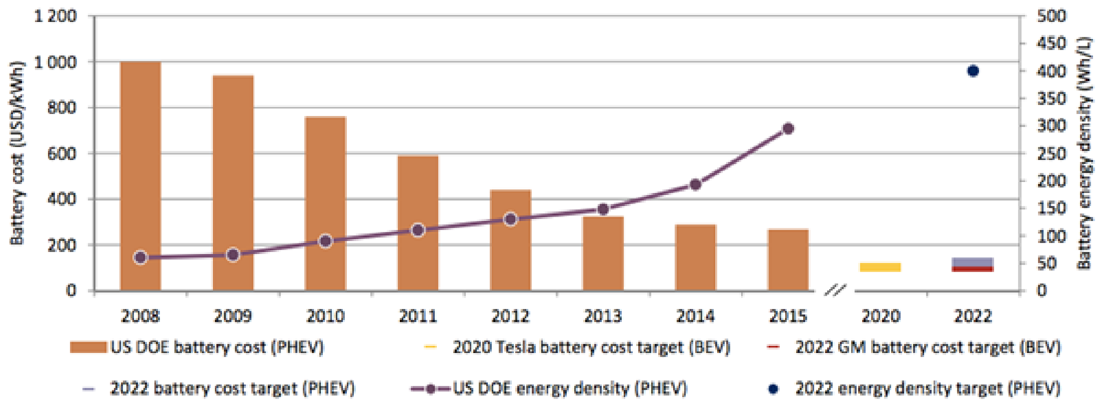
unit dwellings makes EV ownership feasible for and attractive to this population.[59] Workplace charging is also important, as a consumer convenience and because it can help shift EV charging away from the peak demand time in the early evening. Los Angeles has developed partnerships with ten employers to support the deployment of charging infrastructure at workplaces, the most of any major city in the United States. About 80 percent of the workplace installations funded under DOE's Workplace Charging Challenge provide free electricity, creating an additional financial benefit for EV owners.[60]

4. Technological Improvements

Advances in battery technology are improving both vehicle range and affordability. Vehicle range is a function of the amount of energy in kilowatt-hours (kWh) that can be stored in the vehicle's onboard batteries. Because batteries are expensive and heavy, there is a tradeoff between the amount of energy that can be stored and the energy efficiency and cost of the vehicle. However, the amount of power that can be stored (energy density) has been increasing rapidly while the cost of the battery packs has been dropping (see Figure 8). Economies of scale are expected to further reduce the price differential between EVs and conventional internal combustion vehicles.

[59] Recognizing this, California has passes legislation dedicated to removing obstacles to installing charging infrastructure in multi-unit dwellings. Legislative Counsel, *California Senate Bill Number 880, Chapter 6* (Sacramento: CA: Legislative Counsel, 2012), 93, http://www.leginfo.ca.gov/pub/11-12/bill/sen/sb_0851-0900/sb_880_bill_20120229_chaptered.pdf.

[60] Lutsey et al., *Assessment of Leading Electric Vehicle Promotion Activities in United States Cities*, 15.



Notes: USD/kWh = United States dollars per kilowatt-hour; Wh/L = watt-hours per litre. PHEV battery cost and energy density data shown here are based on an observed industry-wide trend, include useful energy only, refer to battery packs and suppose an annual battery production of 100 000 units for each manufacturer.

Sources: US DOE (2015 and 2016) for PHEV battery cost and energy density estimates; EV Obsession (2015); and HybridCARS (2015).

Figure 8. Evolution of Battery Energy Density and Cost[61]

In Los Angeles, all of these factors (policy, consumer incentives, infrastructure, and technology) align and seem to be pushing the EV adoption curve into overdrive.

[61] Source: International Energy Agency, *Global EV Outlook 2016: Beyond One Million Electric Cars* (Paris, France: International Energy Agency, 2016), 13, https://www.iea.org/publications/freepublications/publication/Global_EV_Outlook_2016.pdf.

III. WHERE THE RUBBER MEETS THE ROAD: EVs IN LOS ANGELES

While other cities will certainly grapple with the integration of EVs into their electric grid, Los Angeles is a pioneer. A unique combination of characteristics makes Los Angeles a particularly interesting bellwether for the future. First, California is a world leader in embracing EVs, with Los Angeles among the cities leading California.[62] Second, the LADWP grid is undergoing unprecedented changes, as Los Angeles transitions to a smart grid and follows the California mandate to increase the portion of its electricity provided by renewable energy sources. Third, the electric power system serving Los Angeles is tightly constrained by state and local geo-physical and policy considerations, reducing its grid's resilience to disruption. Fourth, the fact that the Balancing Region for the area approximately matches the city's footprint makes it possible to match electrical grid data with metropolitan data from other sources, allowing us to bring the metropolitan area into sharp focus in the analysis. This chapter gives a brief overview of each of these factors.

A. OUT IN FRONT: EV ADOPTION

California is in the vanguard of EV adoption, due to the combination of its state-sponsored EV ownership incentives, emissions policies, and its environmentally conscious, technologically savvy population. In fact, Tesla is headquartered in Silicon Valley, and clearly identifies itself as a Silicon Valley company.

California has required auto manufacturers doing business in California to produce a certain percentage of ZEVs since 1990, helping to foster their development and acceptance.[63] Because California is such an important automotive market, automobile manufacturers have aimed much of their EV development at complying with these requirements. As shown in Figure 9, about half of the PEVs sold in the United States have

[62] Stephen Edelstein, "What Cities Have Most Electric Cars in the U.S.?," Green Car Reports, accessed July 19, 2016, http://www.greencarreports.com/news/1099636_what-cities-have-most-electric-cars-in-the-u-s; International Energy Agency, *Global EV Outlook 2018*.

[63] Matthew N. Eisler, "A Tesla in Every Garage?," *IEEE Spectrum* 53, no. 2 (2016): 34–55.

been sold in California.[64] EVs could account for as much as 7.5 percent of its light-duty vehicle sales for 2018.[65]

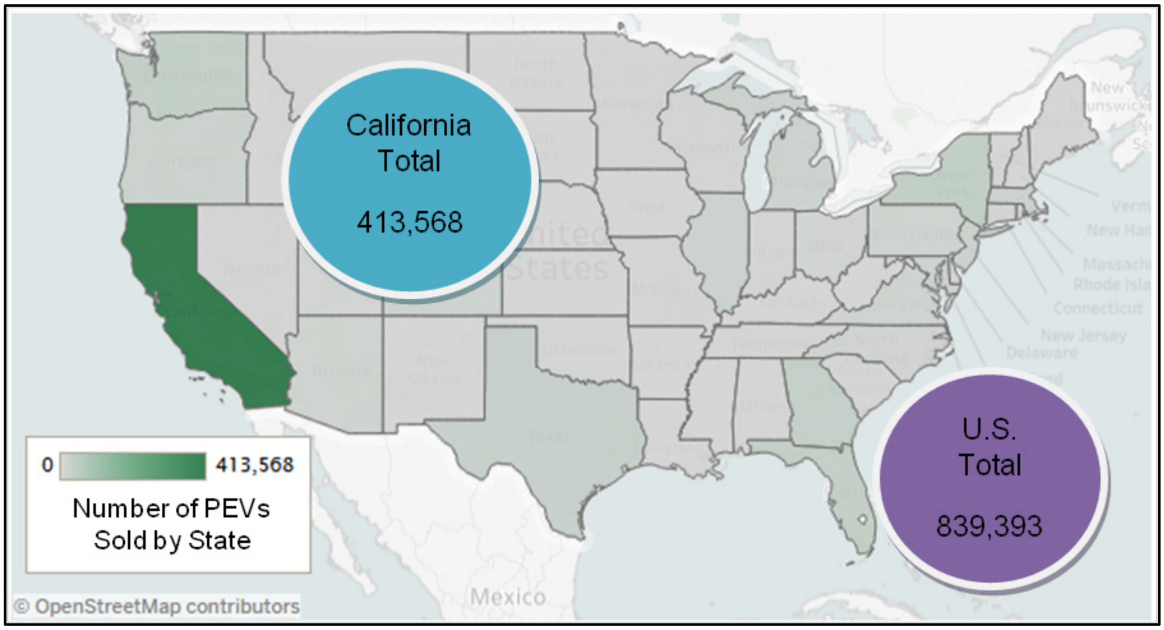


Figure 9. PEV Sales by State (January 2011–June 2018)[66]

In large part, this is because California's policies have consistently encouraged EV adoption. A 2005 Executive Order signed by then California Governor Arnold Schwarzenegger directed California to reduce its greenhouse gas emissions to 80 percent below 1990 levels by 2050.[67] In order to meet this target, Governor Jerry Brown established the goal of 1.5 million ZEVs (including BEVs, PHEVs, and fuel cell electric vehicles

[64] "Advanced Technology Vehicle Sales Dashboard," Auto Alliance, 2018, https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard/.

[65] Loren McDonald, "Please Stop Saying 'EVs Are Only 1% of Auto Sales in the US," CleanTechnica, July 1, 2018, https://cleantechnica.com/2018/07/01/please-stop-saying-evs-are-only-1-of-auto-sales-in-the-us/.

[66] Adapted from Auto Alliance, "Advanced Technology Vehicle Sales Dashboard." Data compiled by the Alliance of Automobile Manufacturers using information provided by HIS Markit. Data last updated August 23, 2018.

[67] Arnold Schwarzenegger, Executive Order S-3-05 (June 2005), http://gov.ca.gov/news.php?id=1861.

[FCEVs]) by 2025 by Executive Order issued in 2012.[68] The Charge Ahead California Initiative, passed by the California legislature in September 2014, added an interim goal of 1 million ZEVs in service by 2023.[69] According to an analysis carried out by the National Renewable Energy Laboratory (NREL) for the California Energy Commission (CEC), this goal translates into approximately 420,000 BEVs (such as the Tesla models) in California by 2025.[70] Most recently, Governor Jerry Brown increased the target for ZEVs in service to five million by 2030.[71] As Figure 10 illustrates, California is expected to continue to account for a large portion of the growing EV market.

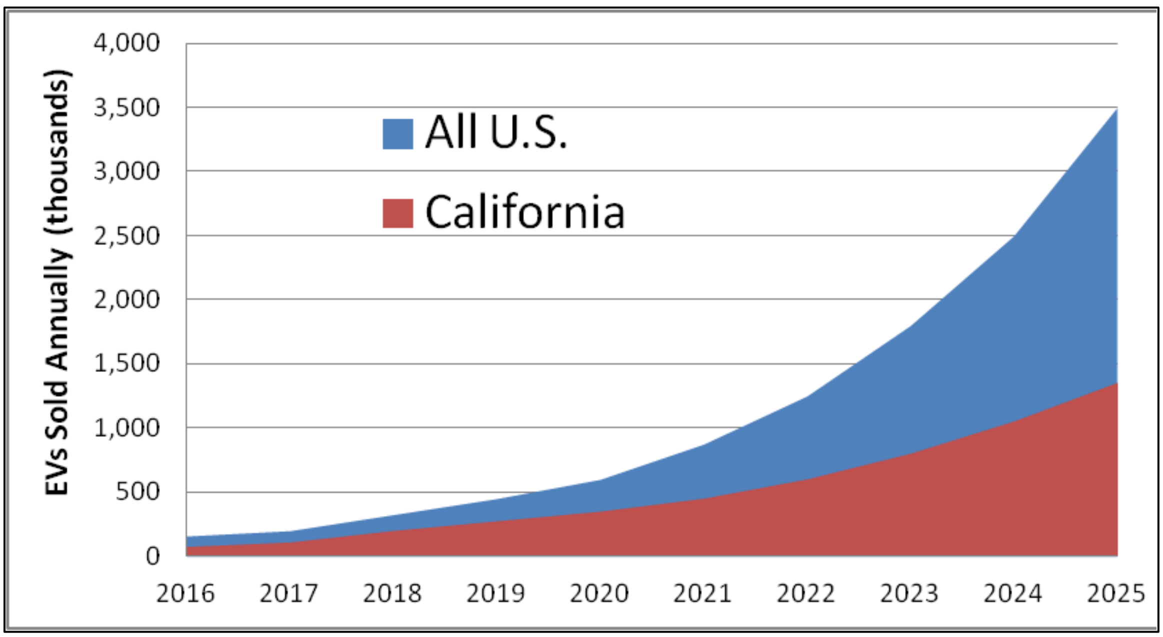


Figure 10. PEV Sales (2016–2017) and Projections (2018–2025)[72]

[68] Brown, Executive Order B-16-2012.

[69] "SB-1275 Charge Ahead California Initiative," California Legislature, 2014, http://leginfo.legislature.ca.gov/faces/billCompareClient.xhtml?bill_id=201320140SB1275.

[70] Marc Melaina and Michael S. Helwig, *California Statewide Plug-In Electric Vehicle Infrastructure Assessment* (Golden, CO: Iowa State University, 2014), 17, https://works.bepress.com/michael_helwig/2/.

[71] Edmund G. Brown Jr., California Office of the Governor, Executive Order B-48-18, "Zero Emission Vehicles" (January 26, 2018), http://gov.ca.gov/news.php?id=17472.

[72] Source: Projections from EVAdoption. "EV Sales Forecasts," EVAdoption, 2018, http://evadoption.com/ev-sales/ev-sales-forecasts/.

At a finer scale, the major cities in California are driving electric vehicle adoption by providing additional incentives, such as access to restricted commuting lanes, and by fostering charging infrastructure development. Among these, the San Francisco and Los Angeles metropolitan areas are at the forefront of electric vehicle adoption. In 2015, Los Angeles accounted for nine percent of all EV sales (second only to San Francisco for total sales).[73] Los Angeles is ranked as one of the most conducive cities in the United States for EVs, suggesting that the EV market in Los Angeles will continue to grow.[74]

LADWP is actively promoting the shift to EVs, in order to build its revenue stream and help it manage the integration of more renewable energy sources. In addition to the federal and state incentives to EV owners, LADWP is offering rebates of up to $4,000 per installed charger to large and small businesses and multi-family residences. It has already installed more than 400 public charging stations in Los Angeles, and it is piloting a program to deploy additional chargers on utility poles.[75] It also has a multi-tiered and time-of-use (TOU) rate structure designed to encourage users to conserve energy and shift energy use away from peak times (1:00 p.m. to 5:00 p.m. Monday through Friday).[76]

B. SHIFTING GEARS: CHANGING ELECTRIC POWER SYSTEMS

In addition to its leadership in EV adoption, California, like other electric power systems across the United States, is in the throes of organizational and technological changes, collectively referred to as "grid modernization." At the heart of this modernization

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[73] "The Future Is Electric—The World Is on the Verge of an Automotive Revolution: CURRENT Is Helping Los Angeles Customers Find the Right EV for Their Lifestyle," *CURRENT* (blog), January 19, 2016, http://currentev.com/blog/future-electric-%E2%80%93-world-verge-automotive-revolution-current-helping-los-angeles-customers.

[74] Kyle Clark-Sutton et al., "Plug-in Electric Vehicle Readiness: Rating Cities in the United States," *The Electricity Journal* 29, no. 1 (January 2016): 30–40, https://doi.org/10.1016/j.tej.2015.12.006.

[75] Los Angeles Department of Water and Power, *Los Angeles Department of Water and Power Briefing Book 2017–2018* (Los Angeles: Los Angeles Department of Water and Power, 2017), 21, https://s3-us-west-2.amazonaws.com/ladwp-jtti/wp-content/uploads/sites/3/2017/09/08143247/Briefing-Book-Rolling-PDF.pdf.

[76] "Electric Rates," Los Angeles Department of Water and Power, accessed August 5, 2019, https://www.ladwp.com/ladwp/faces/ladwp/residential/r-customerservices/r-cs-understandingyourrates/r-cs-ur-electricrates?_afrLoop=551686086234012&_afrWindowMode=0&_afrWindowId=18f8hpkcrz_1#%40%3F_afrWindowId%3D18f8hpkcrz_1%26_afrLoop%3D551686086234012%26_afrWindowMode%3D0%26_adf.ctrl-state%3D6jxwheeb9_4.

is the implementation of two-way communication between electricity producers and consumers, enabled by sophisticated monitoring, control, and communications technology. The new "smart grid" is intended to allow greater integration of renewable resources and distributed energy resources, such as rooftop solar and smart appliances; improve resilience; reduce costs of grid operation; and help manage peak demands.[77] Higher degrees of interconnection and greater reliance on communication and information technology will also increase the complexity of the electric grid, already one of our greatest engineering achievements and an enormously complex socio-technical system.[78] In general, increasing complexity in such a tightly coupled system decreases the system's resilience.[79]

California's energy profile is further complicated by the fact that it is leading the country in the incorporation of renewable resources, such as wind and solar energy, into its electric generation mix (shown in Figure 11). About 32 percent of the state's electricity in 2017 came from renewable resources, including wind, solar, geothermal, and small hydropower generators, a far larger contribution than the national average of 17 percent.[80] California is aggressively pursuing a statewide goal of producing 50 percent of its electricity from renewable sources by 2030.[81]

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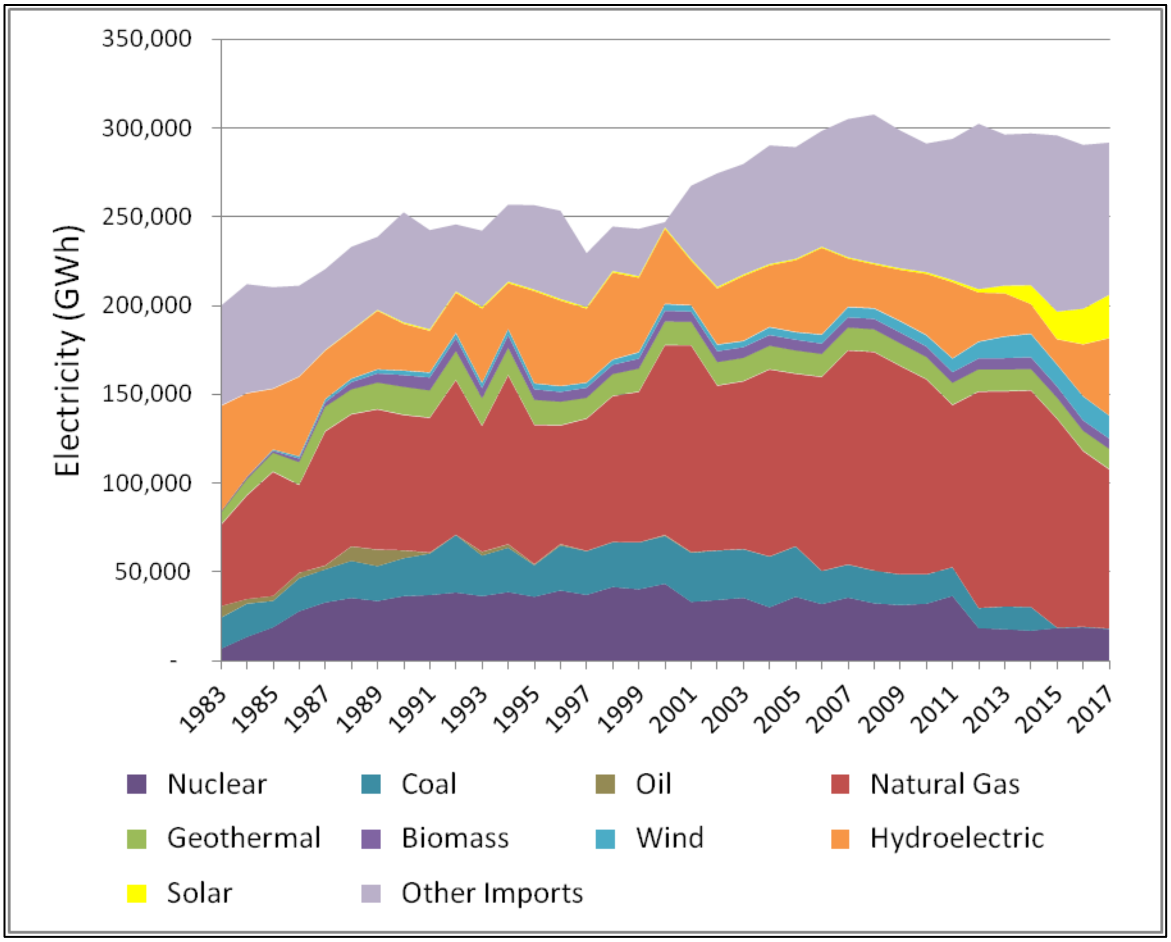
[77] "What Is the Smart Grid?," SmartGrid, accessed October 17, 2015, https://www.smartgrid.gov/the_smart_grid/smart_grid.html.

[78] "Electrification—Greatest Engineering Achievements of the Twentieth Century," National Academy of Engineering, 2003, http://www.greatachievements.org/?id=2949.

[79] Charles Perrow, *Normal Accidents: Living with High Risk Technologies* (Princeton, NJ: Princeton University Press, 2011). Updated edition with a new afterword and a new postscript by the author edition.

[80] California Energy Commission, *Tracking Progress: Renewable Energy* (Sacramento, CA: California Energy Commission, 2018), 3, https://www.energy.ca.gov/sites/default/files/2019-05/renewable.pdf, "Electricity in the United States—Energy Explained, Your Guide to Understanding Energy," Energy Information Administration, April 20, 2018, https://www.eia.gov/energyexplained/index.php?page=electricity_in_the_united_states.

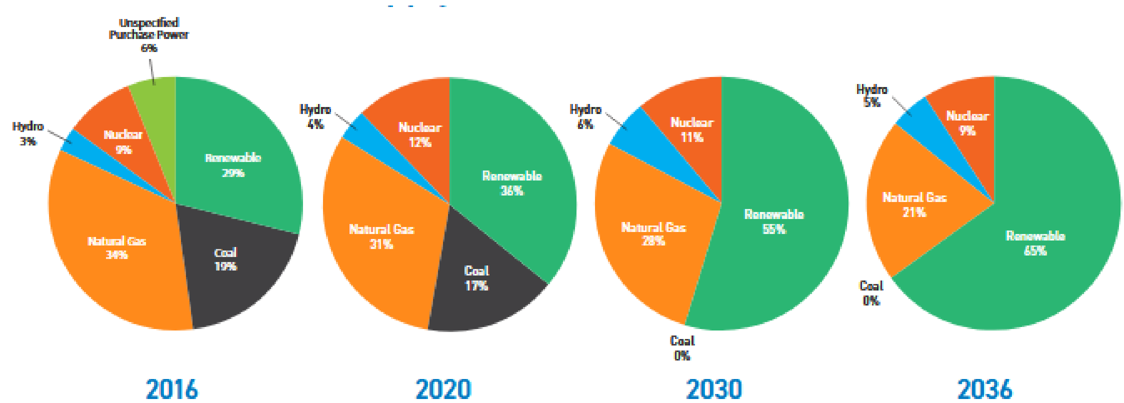
[81] California Energy Commission, *Tracking Progress*, 1.



Note the decreased reliance on traditional coal and nuclear generation and increased solar and wind. Decreased hydro from 2010 on can be attributed to persistent drought.

Figure 11. California's Energy Mix by Source, 1983–2017

LADWP is specifically focused on reducing its carbon footprint by eliminating coal from its energy mix, improving energy efficiency, and increasing the portion of its electricity provided by renewable sources. Figure 12 shows the evolution of its anticipated energy mix through 2036.



Power supply was reduced by 8 percent through energy efficiency savings in 2016. The 2016 percentages are estimates and may differ from final reporting to the CEC.

Energy efficiency is expected to account for 15 percent of power needs in 2020 and beyond.

LADWP plans to eliminate coal from its generation mix, replacing it with increased reliance on renewable energy.

Figure 12. LADWP's Projected Energy Mix through 2036[82]

However, some of these resources (notably, wind and solar) cannot be called up or increased by system operators to follow load (meet variations in demand). Such energy sources are referred to as variable energy resources (VERs). The challenge of managing higher levels of VER integration is spurring innovations in grid management, including the development of energy storage technology and "smart market"-based solutions to help ensure reliable operations.[83]

C. NO SHOULDER: CONSTRAINTS ON POWER IN THE LAWP AREA

California imports a significant proportion of its electricity from outside the state, to support its large population and bustling economy, the fifth largest in the world.[84] The electric power transmission network is especially constrained in the LADWP area. The

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[82] Source: Los Angeles Department of Water and Power, *Los Angeles Department of Water and Power Briefing Book 2017–2018*, 9.

[83] See for example Executive Office of the President of the United States, *Incorporating Renewables into the Electric Grid: Expanding Opportunities for Smart Markets and Energy Storage* (Washington, DC: Executive Office of the President of the United, 2016), 1–140, https://obamawhitehouse.archives.gov/sites/default/files/page/files/20160616_cea_renewables_electricgrid.pdf.

[84] Benjy Egel, "California Now World's Fifth-Largest Economy, Bigger than Britain," *The Sacramento Bee*, May 4, 2018, https://www.sacbee.com/news/business/article210466514.html.

unexpected but permanent closure of the San Onofre Nuclear Generating Station (SONGS, located between Los Angeles and San Diego) in 2012, exacerbated an already-tight generation situation in Southern California. SONGS supplied about eight percent of the electricity generated in California; its closure shifted that load to other in-state generation sources, principally those burning natural gas.[85] Pacific Gas and Electric (PG&E) plans to phase out California's remaining nuclear power station, Diablo Canyon, near San Luis Obispo, by 2025. PG&E plans to replace Diablo Canyon's energy output with energy from renewable sources.[86] LADWP imports power from outside the state via a few high-voltage, direct-current ties, creating a potential transmission bottleneck (see Figure 13).

[85] Lucas Davis and Catherine Hausman, "Market Impacts of a Nuclear Power Plant Closure," *American Economic Journal: Applied Economics* 8, no. 2 (April 2016): 92–122, https://doi.org/10.1257/app.20140473.

[86] "In Step With California's Evolving Energy Policy, PG&E, Labor and Environmental Groups Announce Proposal to Increase Energy Efficiency, Renewables and Storage While Phasing Out Nuclear Power over the Next Decade," Pacific Gas and Electric, June 21, 2016, http://www.pge.com/en/about/newsroom/newsdetails/index.page?title=20160621_in_step_with_californias_evolving_energy_policy_pge_labor_and_environmental_groups_announce_proposal_to_increase_energy_efficiency_renewables_and_storage_while_phasing_out_nuclear_power_over_the_next_decade.

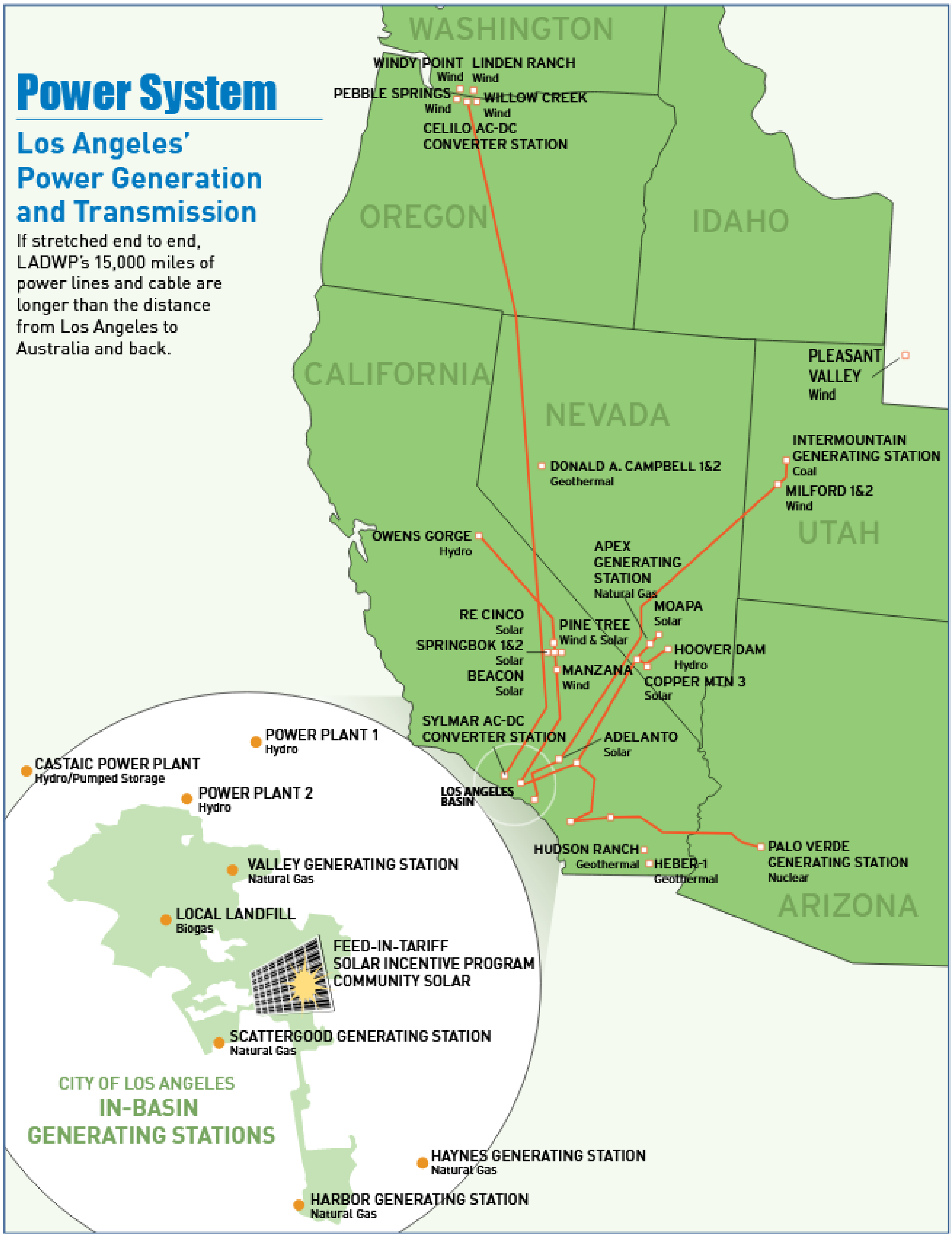

Figure 13. Overview of the LADWP Power System[87]

[87] Source: Los Angeles Department of Water and Power, *Los Angeles Department of Water and Power Briefing Book 2017–2018*, 6.

The fragility of the LA area electric power system was made abundantly clear by two recent examples: First, the major natural gas leak that occurred outside of LA at the Aliso Canyon Natural Gas Storage Facility on October 23, 2015, reducing LADWP's ability to rely on natural gas generators. Analysis in the spring of 2016 suggested that the additional stress could result in up to 14 days of blackouts in Los Angeles during the summer of 2016.[88] Although no load shedding (blackouts) occurred in 2016 or 2017, LADWP received a variance during a heat wave in June 2016 allowing it to burn diesel fuel in several generation plants that normally use natural gas, expressly in order to avoid load shedding.[89]

Second, on July 6, 2018, record temperatures caused electricity demand in Los Angeles to reach an hourly peak of 6,979 megawatt hours (MWh). LADPW called on additional gas-fired generation plants and imports from outside the region, but in this instance was unable to meet the demand. Thousands of customers experienced power outages.[90]

D. BALANCING ACT: LOS ANGELES IN FOCUS

LADWP manages and supplies the third largest California electric market, consuming more than 27,000 gigawatt-hours (GWh) of electricity in 2015. LADWP is a municipal utility, part of the city government of Los Angeles, and is responsible for meeting the electric and water needs of approximately 1.5 million customers (about four million people) in Los Angeles. Its service area (shown in Figure 14) covers most of the greater Los Angeles metropolitan area.

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[88] Staff of the California Public Utilities Commission, *Aliso Canyon Action Plan to Preserve Gas and Electric Reliability for the Los Angeles Basin* (Sacramento, CA: California Energy Commission, the California Independent System Operator, and the Los Angeles Department of Water and Power, 2016), 3, http://www.energy.ca.gov/2016_energypolicy/documents/2016-04-08_joint_agency_workshop/Aliso_Canyon_Action_Plan_to_Preserve_Gas_and_Electric_Reliability_for_the_Los_Angeles_Basin.pdf.

[89] Dana Bartholemew, "Heat Wave Could Bring More Diesel Pollution from SoCal Power Plants," *Los Angeles Daily News*, June 17, 2016.

[90] "Southern California Daily Energy Report: Record Daily-High Temperatures in Southern California Lead to High Electricity Demand and Power Outages," Energy Information Administration, July 13, 2018, https://www.eia.gov/special/disruptions/socal/summer/#commentary.

LADWP service area in light blue; the LADWP balancing area also includes a discontinuous area in Inyo County, California.

Figure 14. LADWP Balancing Area.[91]

LADWP does not fall under the jurisdiction of the CEC. However, LADWP does coordinate its forecasts with the CEC and submits system information to FERC as a transmission system operator. As with any complex analysis, assumptions are necessary, but given the close correlation of the service territory with Los Angeles County, there is sufficient data to analyze and draw conclusions regarding the impact of EVs in Los Angeles. The physical and policy constraints on the system make it an ideal case study for the impacts of EV adoption on grid reliability.

As the largest publicly-owned utility in California, LADWP is also an ideal test bed for policy and technological solutions to potential issues related to EV adoption. Publicly-owned utilities are not regulated by the California Public Utility Commission; the utility is

[91] Source: California Energy Commission, *California Electric Utility Service Areas* (Sacramento, CA: California Energy Commission, 2015), 1, http://www.energy.ca.gov/maps/serviceareas/Electric_Service_Areas_Detail.pdf.

instead managed by the local government, which sets customer rates and utility policy.[92] LADWP is governed by the Mayor and City Council of Los Angeles, through a board of five commissioners appointed by the Mayor.[93] This relatively flat management structure means that the city can more easily implement energy management policies tailored to its specific situation.

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[92] "Differences between Publicly and Investor-Owned Utilities," California Energy Commission, 2019, https://www.energy.ca.gov/pou_reporting/background/difference_pou_iou.html.

[93] "Who We Are," Los Angeles Department of Water and Power, 2013, https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-whoweare;jsessionid=LxsqcdcBR85TXzhvR3qRmwSx3rTSWcKWX0ncynPpX70f1yMQ0d5v!-674362223?_afrLoop=147074180102173&_afrWindowMode=0&_afrWindowId=null#%40%3F_afrWindowId%3Dnull%26_afrLoop%3D147074180102173%26_afrWindowMode%3D0%26_adf.ctrl-state%3D47a02xjjm_4.

IV. MOVING PARTS: ASSUMPTIONS AND ANALYSIS

As described in Chapter I, Introduction, in order to examine the impacts to resource adequacy of various levels of EV penetration combined with different charging paradigms, I constructed four scenarios (Figure 15). I calculated the power demand at peak time due to EV charging in each scenario and evaluated the total demand against the LADWP dependable capacity at peak to determine whether LADWP would be able to maintain an adequate reserve margin. If the reserve margin fell below the standard planning reserve margin of 16 percent, I conclude that the scenario would reduce grid reliability.

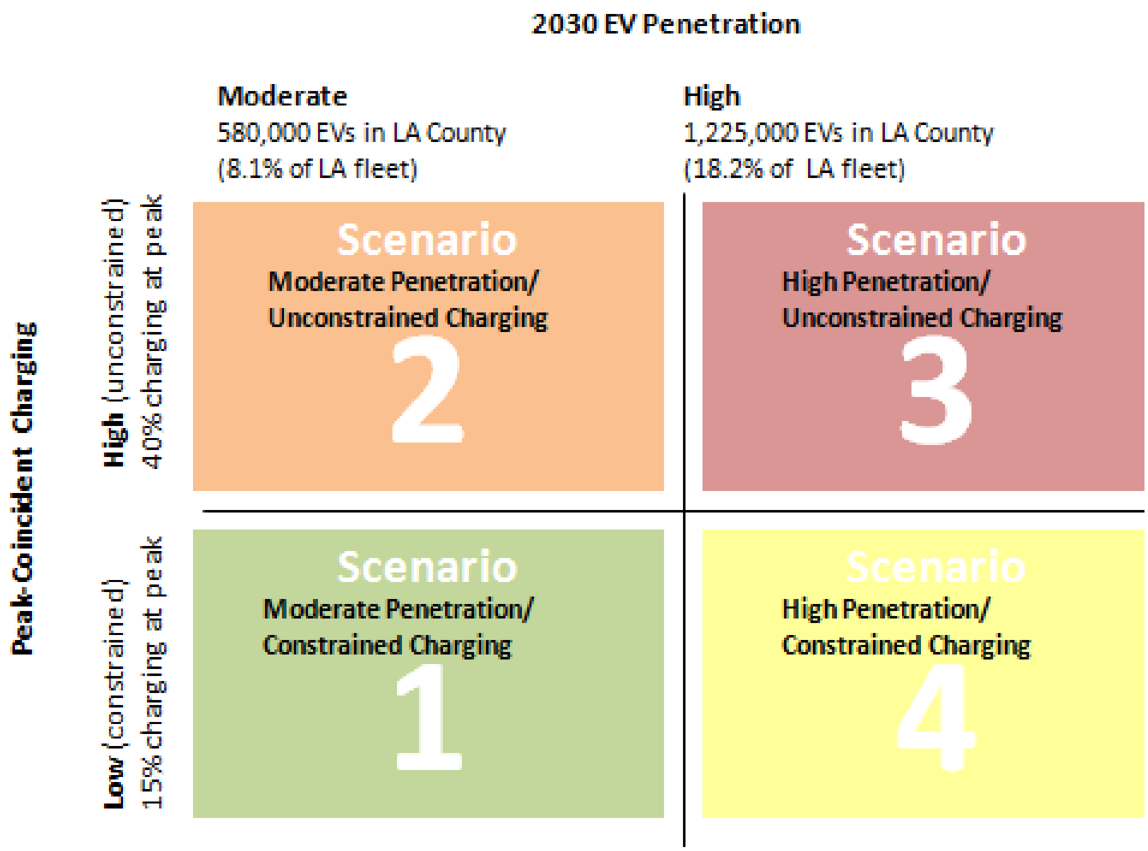

Figure 15. Scenario Combinations of EV Penetration and Charging Behavior for 2030

A. SCENARIO CONSTRUCTION

The scenarios are the combinations of Moderate and High degrees of EV penetration with Low and High Levels of Peak-Coincident Charging (as shown in Figure 15). The following sections provide more detail on the data and assumptions used to construct the scenarios and describe the analytic method.

The principal factors affecting resource adequacy with respect to EV adoption are:

- Supply and demand for electricity in the Los Angeles area
- EV energy requirements
- EV market penetration
- EV driver travel
- EV charging patterns

The following subsections describe the data, methods, and assumptions used to address each of these factors.

1. Supply and Demand of Electricity in Los Angeles

In addition to being at the leading edge of EV adoption and therefore the likely destination for many Tesla Model 3s, the Los Angeles area is unique in California in that the electric power service area managed by LADWP roughly conforms to the metropolitan statistical area, so data from LADWP reports, projections, and filings with the Federal Energy Regulatory Commission (FERC) can be used to understand the current electric power situation in the city.[94] The LADWP's 2017 Power Strategic Long-term Resource Plan (SLTRP) and the California Energy Commission's 2017 Integrated Energy Policy Report are the most important sources for this information.

[94] The LADWP balancing area also includes a non-contiguous portion of California's Inyo County, the site of the Owens River Valley (an important water impoundment for LADWP) and Death Valley National Park. Inyo County has a total population of 18,546 according to the 2010 census. Therefore, this portion of the county is assumed to have negligible contribution to total demand within the LADWP region. "United States QuickFacts from the United States Census Bureau," United States Census Bureau, 2010, http://www.census.gov/quickfacts/.

The SLTRP provides long-term projections of electricity supply and demand, based on trends in economic growth and development, technological shifts, policy goals, and planned capacity projects, usually including a variety of scenarios for each factor to help account for uncertainty. It meets the California requirement for publicly owned utilities (POUs) to submit integrated resource plans (IRP) to the CEC every five years. According to the CEC, "IRPs are electricity system planning documents intended to ensure that POUs lay out the resource needs, policy goals, physical and operational constraints, and general priorities or proposed resource choices of an electric utility, including customer-side preferred resources. These plans will provide a framework to evaluate how utilities have chosen to align with greenhouse gas emission reduction targets as well as energy and other policy goals."[95]

a. Supply

Notably, the LADWP SLTRP projects a generation shortfall starting in 2024 under its recommended strategy. This means that—despite LADWP's policy that it has an obligation to "be self-sufficient in supplying native load and not rely on external energy markets"[96]—meeting the peak demand for the system will require buying power from outside the balancing area, from sources outside of LADWP's control. Buying power on the market like this is common, and a reasonable solution compared to building new power plants that might only be used a few hours per year. However, because there are only a few transmission pathways into the LADWP grid, there are limits on how much power can be imported.

b. Demand

In addition to publishing its resource plans, LADWP must file an Electric Balancing Area and Planning Area Report (FERC Form 714) annually, and these forms are publicly

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[95] "Publicly Owned Utility Integrated Resource Plans," California Energy Commission, 2019, https://ww2.energy.ca.gov/sb350/IRPs/.

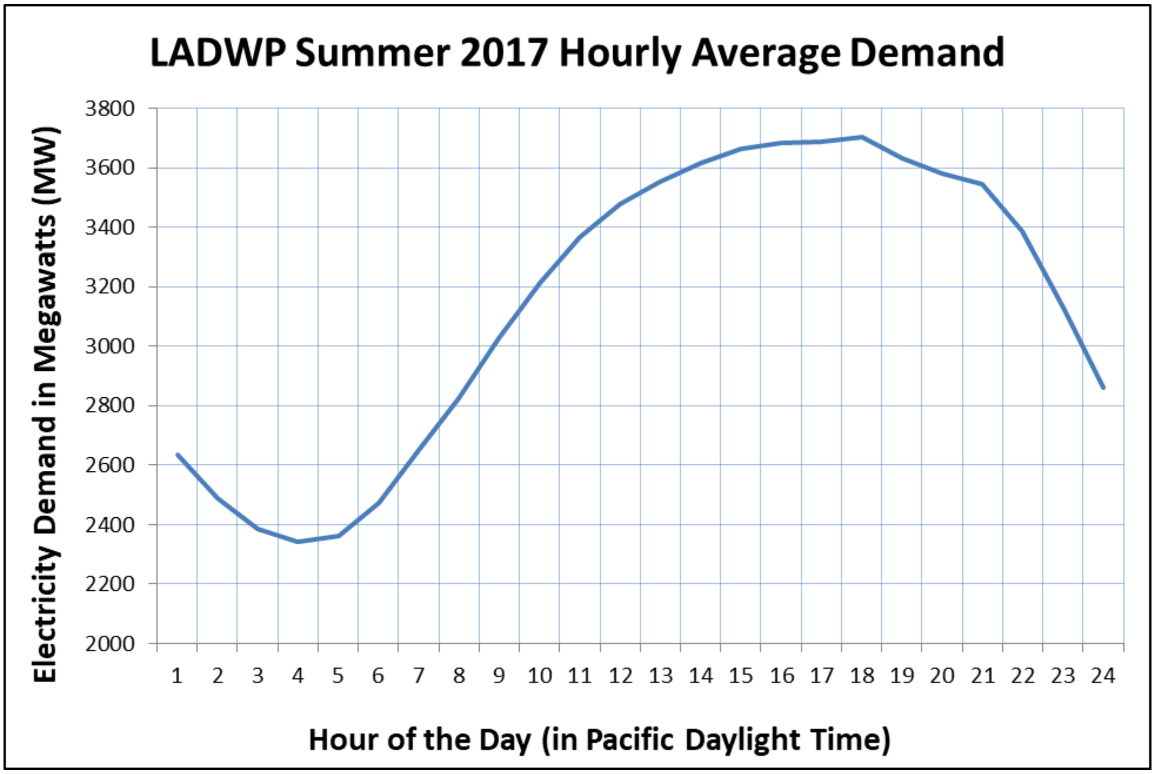
[96] Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource*, A–4.

available.[97] The Form 714 includes hourly performance data for the system for the entire year, which provide information on the timing and amount of historic peak demand on the system, which is important for estimating how much overlap there is likely to be between EV charging demand and other sources of demand at different times of day.

LADWP serves its heaviest loads in the summer, as commercial and residential air conditioning drives up demand, especially in the late afternoons. For June through August 2017, the average peak occurred between 5:00 p.m. and 6:00 pm (Figure 16). In its planning cases, LADWP assumes that the peak load will occur on the fourth Thursday in August.[98]

[97] "FERC: Documents & Filing—Forms—Form 714—Annual Electric Balancing Authority Area and Planning Area Report—Data Downloads, Part 3 Schedule 2—Planning Area Hourly Demand," Federal Energy Regulatory Commission, July 31, 2018, https://www.ferc.gov/docs-filing/forms/form-714/data.asp?csrt=8307667189022913311.

[98] Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource*, A–5.



Note that for summer 2017, the average peak is in the 5:00 p.m. hour.

Figure 16. LADWP Average Hourly Demand for Summer (June 1–August 31)[99]

However, LADWP observed in its SLTRP that while its system has typically peaked in the 5:00 hour in the past, it is increasingly experiencing peaks in the 6:00 hour.[100] Based on this trend, I assume that by 2030, peak power demand will be consistently occurring in the 6:00 hour. I therefore selected 6:30 p.m. as the time of instantaneous peak demand for the purpose of estimating the contribution of EV charging to demand.

[99] Source: Federal Energy Regulatory Commission, "FERC: Documents & Filing—Forms—Form 714."

[100] Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan*, 7.

2. EV Energy Requirements

Different electric car models have somewhat different energy requirements, but for the purposes of this analysis, I used the Tesla Model 3 with its standard battery pack to represent a typical BEV. I selected the Model 3 as a representative unit because its sales have surged past its competition, and its charging configuration is the current state of the art.[101] (This is a convenient starting place for analysis, not a prediction that Tesla will displace all competitors.) I expect the results to be generally applicable to a broad range of EVs, although differences in model characteristics and fleet makeup could have minor effects.

The standard battery pack in the base Model 3 has a capacity of approximately 50 kWh, which gives it a range of about 220 miles between charges.[102] Using a 240-volt (V) charger on a home 30-amp (A) circuit (called Level 2 charging apparatus), each EV will draw 7.2 kilowatts (kW) (instantaneous demand) from the grid. A variety of additional factors affect how quickly the battery will charge, including the age of the battery and whether it is relatively full or depleted; estimates in the literature range from nine to 52 miles of range per hour of charging time.[103] For the purposes of this analysis, I will assume that owners get an average of 15 miles of range per hour of charging time.[104]

3. EV Market Penetration

The scenarios in this analysis include two possible levels of EV market penetration. The moderate penetration scenarios use the assumption from LADWP's recommended

[101] Bruce Brown, "Tesla Model 3 Sales Rev up in First Quarter, Outpace Other Electric Cars in U.S.," Digital Trends, April 7, 2018, https://www.digitaltrends.com/cars/tesla-model-3-best-selling-electric-car/.

[102] "Tesla Model 3," Tesla, accessed April 13, 2018, https://www.tesla.com/model3.

[103] See, for example, Vanja Kljaic, "Charging Your Tesla Model 3 with Just A Wall Outlet—Is It Possible?," InsideEVs, June 26, 2018, https://insideevs.com/charging-your-tesla-model-3-with-just-a-wall-outlet-is-it-possible/; "Electric Vehicle Charging: Types, Time, Cost and Savings," Union of Concerned Scientists, March 9, 2018, https://www.ucsusa.org/clean-vehicles/electric-vehicles/car-charging-time-type-cost; Fred Lambert, "A Look at Tesla Model 3 Charging Options," *Electrek* (blog), August 2, 2017, https://electrek.co/2017/08/02/tesla-model-3-charging-options/.

[104] This is consistent with Lambert, "A Look at Tesla Model 3 Charging Options."

strategic case, which is that there will be 580,000 EVs on the road in Los Angeles by 2030.[105]

The high penetration scenarios assume that California will meet the governor's target of five million ZEVs on the road in California by 2030. To determine how many of these will be EVs registered in Los Angeles, I assumed that the current proportion of California cars registered in Los Angeles County (25 percent) will remain constant, resulting in a total of 1.25 million ZEVs registered in Los Angeles County in 2030.[106] ZEVs include both EVs and FCVs. Although today FCVs are a negligible proportion of the ZEV population, their share is expected to grow. In order to estimate the contribution of FCVs to the total ZEV count, I used projections developed by the California Air Resources Board (CARB) based on its survey of auto manufacturers, along with the CARB data on Los Angeles share of the total FCVs fleet (32 percent).[107] Since the CARB projections only extend through 2023, I fit a polynomial curve to the points provided and extrapolated to 2030, giving an expected total of 78,000 FCVs on the road in California in 2030.[108] The net number of EVs in Los Angeles, then, would be 1,225,040 (1.25 million minus 32 percent of 78,000) under the high penetration scenarios.

4. EV Driver Travel

The number of miles driven per day will determine the total amount of electricity used by EVs. It will also determine the total time that each car draws power from the grid,

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[105] This is actually the "high transportation electrification" assumption for LADWP. As evidence of how quickly EV uptake projections are accelerating, it is double the projection from the California Energy Commission. California Energy Commission, *2013 Integrated Energy Policy Report*, CEC-100-2013-001-CM (Sacramento, CA: California Energy Commission, 201), 21–27, https://ww2.energy.ca.gov/2013publications/CEC-100-2013-001/CEC-100-2013-001-CMF.pdf; Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan*, 139.

[106] Number of automobiles in California from California Department of Motor Vehicles. "State of California Department of Motor Vehicles Statistics for Publication January through December 2017," California Department of Motor Vehicles, March 2018, https://www.dmv.ca.gov/portal/wcm/connect/5aa16cd3-39a5-402f-9453-0d353706cc9a/official.pdf?MOD=AJPERES; "Vehicle Registrations in Los Angeles County, California," Los Angeles Almanac, 2018, http://www.laalmanac.com/transport/tr02.php.

[107] California Air Resources Board, *2017 Annual Evaluation Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development* (Sacramento, CA: California Air Resources Board, 2017), 24, 67, https://www.arb.ca.gov/msprog/zevprog/ab8/ab8_report_2017.pdf.

[108] Polynomial fit with $R^2 = 0.99$.

because cars will stop drawing power once the battery is full, even though they may remain plugged in until driven again. The time of day that most trips are made will also affect when vehicles draw charge from the grid, because most charging will immediately follow the return home or to a public charging site (such as while parked at work), unless drivers explicitly program their cars to charge later, in order to take advantage of any power pricing incentives.

As the range and driving characteristics of EVs increasingly resemble those of conventional automobiles, this analysis assumes that the travel patterns of EV drivers are, and will continue to be, similar to the travel patterns of the general population for the Los Angeles area. Further, it assumes that the same general travel patterns (trip timing and average miles per day by car) that are observed in the present will continue in 2030. According to statistical information derived from the Highway Performance Monitoring System in 2016 (latest available data, published by the California Department of Transportation (Caltrans)), an average of 34.2 miles are driven daily in Los Angeles County for every vehicle registered in the county.[109] Of course, some vehicles from outside the county will drive into LA and some LA drivers will travel outside the county, but I assume there is a negligible net difference. This assumption is supported by other sources of information on driving patterns, which give similar estimates of average daily vehicle miles traveled.[110] Based on the Tesla 3 charging characteristics, this translates to approximately two hours of charge used per day if the vehicle is charged at home using 240 V charging equipment (see EV Energy Requirements section for Tesla Model 3 charging specifications). To simplify this analysis, I assume that all EVs will charge at this rate and for this period on the day relevant to the analysis, the peak energy demand day for LADWP.

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[109] Los Angeles Almanac, "Vehicle Registrations in Los Angeles County, California"; California Department of Transportation, *California Public Road Data 2016* (Sacramento, CA: California Department of Transportation, 2018), 54, table 6, https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/california-public-road-data/prd20161-a11y.pdf.

[110] Although there is not necessarily a one-to-one relationship between drivers and vehicles, the national average is 29 miles per day per driver, according to studies by the U.S. Department of Transportation and AAA. "National Household Travel Survey Daily Travel Quick Facts," Bureau of Transportation Statistics, May 2017, https://www.bts.gov/statistical-products/surveys/national-household-travel-survey-daily-travel-quick-facts; Tamra Johnson, "New Study Reveals When, Where and How Much Motorists Drive," AAA NewsRoom, April 16, 2015, https://newsroom.aaa.com/2015/04/new-study-reveals-much-motorists-drive/.

Obviously, in the real world, some vehicles will use more or less energy, charge more slowly using 120 V home chargers, or use faster non-residential charging options. (Faster charging will not reduce the total amount of energy used by EVs, but extremely fast rates—beyond what is currently possible—could exacerbate the problems with managing grid resources in real time.[111])

5. EV Charging Patterns

a. The Open Road: Unconstrained Charging

Utility analysis, government reports, and academic studies of early EV adopters support the assumption that in the absence of any external incentives, EV owners are most likely to start charging their vehicles when they arrive home after work.[112] Therefore, for the "unconstrained charging" scenarios in this analysis, I used the evening peak traffic congestion times for Los Angeles to indicate when drivers would arrive at home and start charging their EVs. Evening rush hour traffic in Los Angeles peaks at approximately 6:00 p.m. (Figure 17).[113]

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[111] Deign, "How Electric Vehicles Could Sink the Texas Grid."

[112] For example, Florida Public Service Commission, *Report on Electric Vehicle Charging* (Tallahassee, FL: Florida Public Service Commission, 2012), 15–16, http://www.psc.state.fl.us/Files/PDF/Publications/Reports/Electricgas/Electric_Vehicle_Charging_Report.pdf; Stephen Schey, Don Scoffield, and John Smart, "A First Look at the Impact of Electric Vehicle Charging on the Electric Grid in the EV Project," *World Electric Vehicle Journal* 5, no. 3 (September 28, 2012): 667–78, https://doi.org/10.3390/wevj5030667; Mohd Redzuan Ahmad et al., "PHEV Charging Strategy via User Preferences and Its Impacts on Power System Network," in *Energy Conversion (CENCON), 2014 IEEE Conference On* (2014 IEEE Conference on Energy Conversion (CENCON), Johor Bahru, Malaysia: IEEE, 2014), 19–24, https://doi.org/10.1109/CENCON.2014.6967470; Weiller, "Plug-in Hybrid Electric Vehicle Impacts on Hourly Electricity Demand in the United States," 3767.

[113] "Travel Time Reliability: Making It There on Time, All the Time," U.S. Department of Transportation Federal Highway Administration, February 1, 2017, https://ops.fhwa.dot.gov/publications/tt_reliability/long_descriptions/Figure4.htm; Blanca Barragan, "The Absolute Worst Times to Drive on Every Freeway in LA," Curbed Los Angeles, March 5, 2014, https://la.curbed.com/2014/3/5/10136008/the-absolute-worst-times-to-drive-on-every-freeway-in-la.

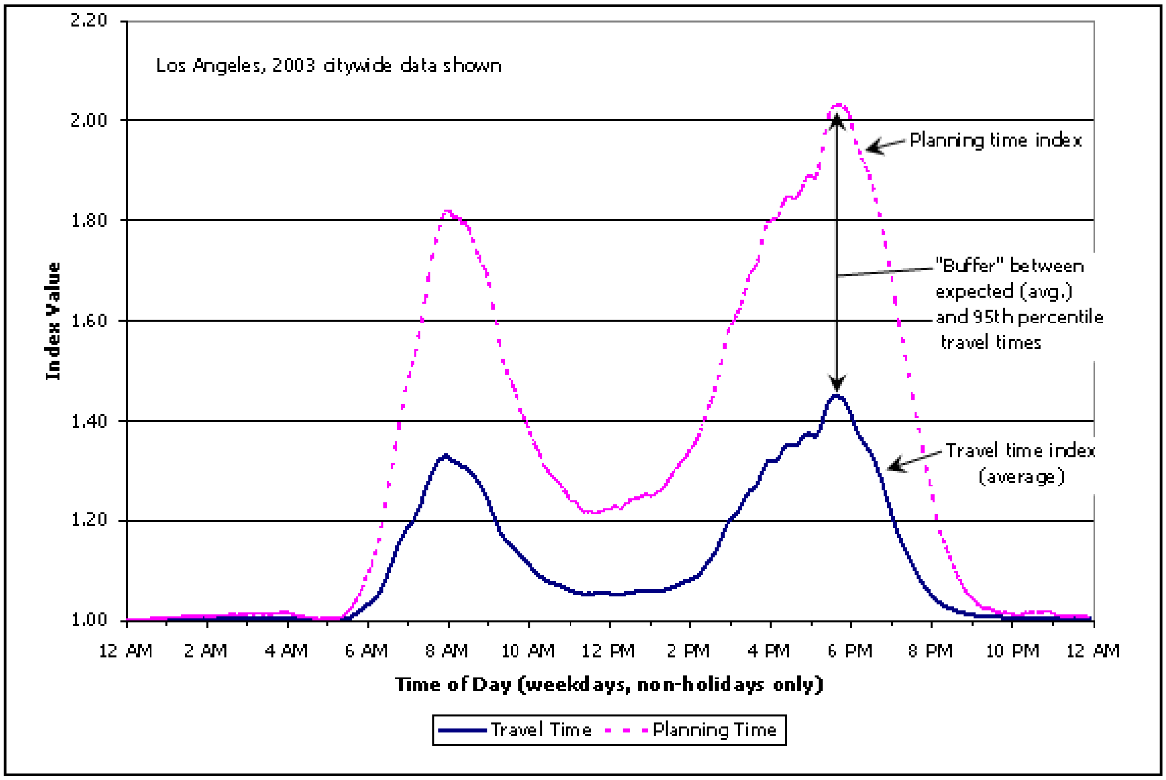

Figure 17. Travel Time Variability, an Indication of Traffic Congestion, for Los Angeles[114]

If the individual driver trips are independent events, the exact timing of arrivals and departures should follow the law of large numbers, resulting in a normal distribution of trip departures and arrival times around the mean times. Assuming a normal distribution around the 6:00 p.m. mean with a standard deviation of 1.5 hours yields a curve that approximates the actual evening rush hour profile shown in Figure 17. One way to understand this curve is that before 6:00 p.m. more people are entering traffic than leaving it, while after 6:00 p.m., more people are arriving home than are leaving work; at 6:00 p.m. the rates are roughly balanced. The average time that people in Los Angeles commute (one-way) to work is 30.4 minutes.[115] In order to simplify the analysis, I assume that all drivers have a half-hour commute, if they all plug in on arriving home, the number of vehicles plugging

[114] Adapted from U.S. Department of Transportation Federal Highway Administration, "Travel Time Reliability: Making It There On Time, All the Time," Figure 4.

[115] "Mean Commuting Time for Workers in Los Angeles County, CA," Federal Reserve Bank of St. Louis, September 16, 2018, https://fred.stlouisfed.org/series/B080ACS006037.

at any given moment will form a second normal distribution that lags the traffic pattern by 30 minutes, peaking at 6:30 p.m. and tapering off afterwards. A third distribution, the number of vehicles that complete their two-hour charging time, would peak at 8:30 p.m. These three curves are shown conceptually in Figure 18.

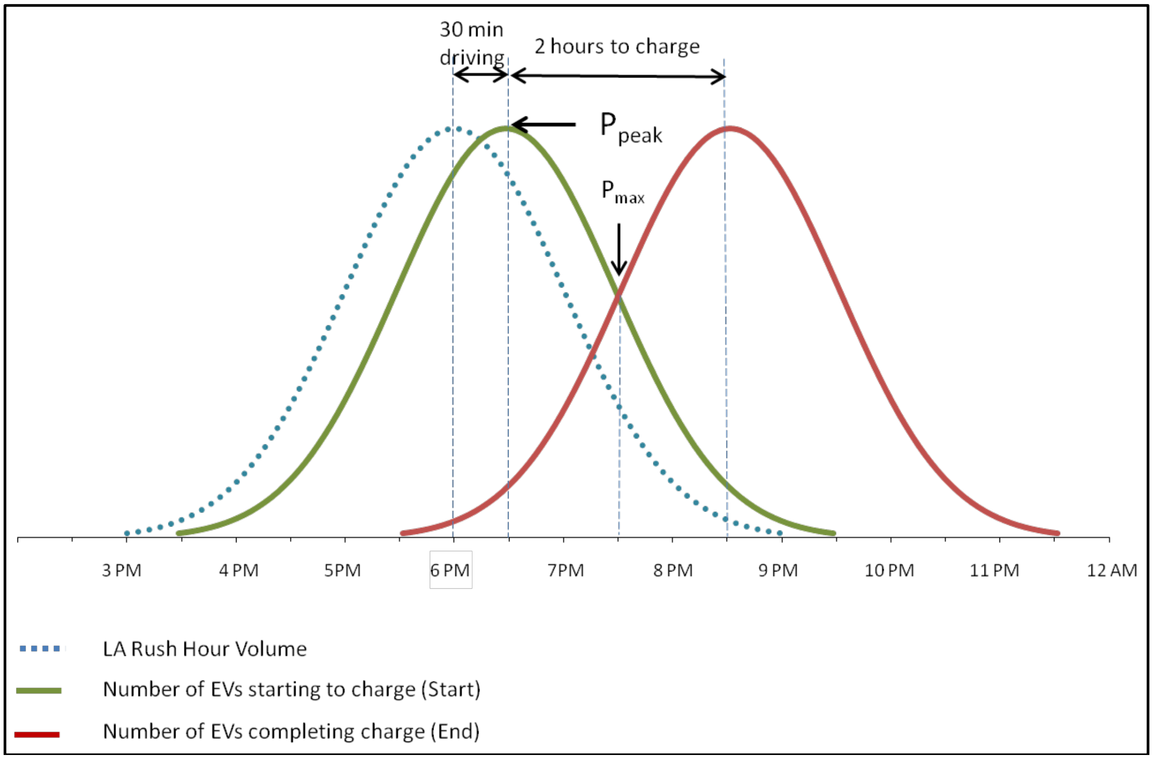

Figure 18. Conceptual Diagram of Sequential Driving, Starting, and Ending Charging Time Distributions

The net proportion of vehicles charging at a given time, P_t, is the difference between the proportion of vehicles that have plugged in and started charging (P_S) and the proportion that have completed charging and ceased to draw power (P_E), $P_t = P_s - P_E$. Each of these curves has a standard deviation of 1.5 hours (in order to approximate the six-hour span observed in rush hour traffic), so the peak-to-peak distance between the Start and End curves is 1.333 standard deviations (σ) from the mean. The point at which they intersect (0.667σ from each peak) is the time that the maximum proportion of EVs ($P_{\max}$) is drawing current from the grid.[116] I can solve for $P_{\max}$ at this time (7:30 p.m.) as follows using standard error tables for the normal curve:[117]

$$P_{\max} = P_{S(0.67\sigma)} - P_{E(-0.67\sigma)} = 0.748 - 0.252 = 0.496.$$

The maximum percentage of the total EV fleet that would draw current simultaneously under this scenario is thus 49.6 percent, at 7:30 p.m.

However, the focus of this analysis is on the contribution of EVs to electric demand at the time of peak demand from other users. As described in the previous section Supply and Demand of Electricity in Los Angeles, I assume that the peak demand hour for the LADWP system in 2030 will be 6:00 p.m. to 7:00 p.m., and I selected 6:30 p.m. as the time of interest. This time is indicated on the Start curve in Figure 18 as P_{peak}. Using the approach outlined above, the proportion of the EV fleet charging at the time of peak demand on the LADWP system (P_{peak}) is 40.1 percent:

$$P_{peak} = P_{S(0\sigma)} - P_{E(-0.67\sigma)} = 0.5000 - 0.0918 = 0.4082.$$

b. Speed Limits: Constrained Charging

Utilities have strong incentives to find ways to manage how drivers charge their EVs. In a utility-ideal scenario, no EVs would be charging at the peak hour; they would instead be charging in the mid-day to absorb over-generation from solar power sources and at night to fill the "valley" in demand, thereby maximizing the utilization of generation resources.[118] However, it is highly unlikely that all consumers will cooperate with a regime

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[116] This can be easily understood with the following logic: before the point of intersection, more drivers are starting to charge than are ending their charge, so the number charging is rising; after this point, more drivers are ending their charge than starting, so the number charging is falling. Therefore, the maximum charging must be at the point of intersection.

[117] Charles D. Hodgman, ed., *C.R.C. Standard Mathematical Tables*, 11th ed. (Cleveland, OH: Chemical Rubber Publishing Company, 1957), 238, "Normal Curve of Error Table."

[118] Such an ideal scenario is presented in Kintner-Meyer, Schneider, and Pratt, *Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids Part 1: Technical Analysis*.

that causes them inconvenience or anxiety about whether their EV will have sufficient charge when they need it, even in the face of economic incentives or altruistic appeals. LADWP has found, for example, that while consumers are willing to curtail overall energy use in exchange for favorable rates, this only works up to a point. In extremely hot weather, consumers still prioritize their health and comfort above the available incentives.[119]

Therefore, while the ideal distribution of charging—from LADWP's perspective—would include no charging during periods of high demand (valley-filling only), this seems unrealistic. It is difficult to predict, based solely on the few limited studies of early adopters, how well various pricing structures and other strategies will work to shift demand, given the variations between locations and the fact that early adopters are likely to have different demographic characteristics and motivations from those who come later.[120] This is an area of active research for utilities and municipalities, but their approaches to managing the problem (and perhaps their results) will probably vary widely. If EV charging were evenly distributed across the day as a constant demand, about eight percent of the total fleet would be charging at one time (each EV charging for two of the 24 hours). For this analysis, I have chosen 15 percent of the fleet as a plausible level for the constrained-charging scenarios.

6. EV Penetration

In its 2017 SLTRP, LADWP used EV adoption forecasts from the California Energy Commission's 2013 Integrated Energy Policy Report.[121] In the base analysis case, the CEC forecast that Los Angeles will have 290,000 PEVs by 2030; the LADWP SLTRP recommends providing incentives to reach 580,000 PEVs by 2030. In this analysis, I use the LADWP recommendation as the "moderate EV penetration" case.

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[119] Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan*, 7.

[120] According to the theory proposed by Everett Rogers, there are five distinct categories of adopter, each with unique priorities and interests. These groups drive technological diffusion at different stages of the diffusion process. Rogers, *Diffusion of Innovations*. It is also logical that as EVs evolve and the price barrier is reduced, customers who waited for a more affordable car will also be willing to defer charging by a few hours in order to save money on their electric bill.

[121] Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan*, 70.

However, the governor's 2018 Zero-Emission Vehicle Executive Order (EO-B-48-18) set a goal for California to have five million ZEVs by 2030.[122] Currently, 25 percent of California's registered vehicles are in Los Angeles County.[123] Assuming this percentage remains unchanged and that the ZEVs are evenly distributed throughout the state, meeting this goal would mean that 1,250,000 ZEVs would be in Los Angeles County; almost twice the number expected under the LADWP recommended case. Given LA's leadership in EV adoption, its aggressive incentive programs, and its entrenched car-centric culture, a higher percentage of EVs will probably be focused in LA in reality, so this assumption is conservative.

ZEVs include both PEVs and hydrogen fuel cell (HFC) cars. PEVs make up 99 percent of the current ZEV stock in Los Angeles, but the HFC share is projected to grow.[124] The CARB has projected growth for HFC cars through 2023.[125] Extrapolating the CARB projections out to 2030, I estimate there would be 78,000 HFC cars in Los Angeles County.[126] This projection may be low, given that the CARB forecasts were prepared before the ZEV Executive Order increased the total ZEV target, and they therefore do not account for any additional policy incentives for adoption. In the absence of better information, subtracting 78,000 HFC cars from the total 1,250,000 ZEVs gives us 1,117,000 PEVs in Los Angeles in 2030. This a reasonable upper bound for the PEV component of the total ZEV inventory in Los Angeles, and therefore this number of vehicles provides the "high EV penetration" case.

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[122] Brown, Executive Order B-48-18.

[123] California Department of Motor Vehicles, "State of California Department of Motor Vehicles Statistics for Publication January through December 2017."

[124] "Fuel Type by County as of 1/1/2018," California Department of Motor Vehicles, accessed August 7, 2018, https://www.dmv.ca.gov/portal/wcm/connect/2156a052-c137-4fad-9d4f-db658c11c5c9/MotorVehicleFuelTypes_County.pdf?MOD=AJPERES&CVID=.

[125] California Air Resources Board, *2017 Annual Evaluation Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development*, 27.

[126] Extrapolation via best-fit polynomial curve (r^2=.996).

B. ASSESSING EV CONTRIBUTION TO PEAK DEMAND

Simply multiplying the proportion of EVs charging at peak (P_{peak}) by the number of EVs assumed and the instantaneous demand per EV $(240\text{V} * 30\text{A} = 7.2\text{kW})$ gives us the amount of power needed by EVs for each scenario. To get the adjusted peak demand, before adding our estimated demand for EVs, the LADWP projected demand must be reduced by the amount of EV charging that it (implicitly) includes, to avoid double-counting some EVs. Unfortunately, the LADWP SLTRP does not spell out the contribution of EVs to its peak demand, because it models peak demand based on probabilistic weather scenarios, rather than adding up demand from various market segments. Efforts to discuss this with LADWP load forecasters were unsuccessful.

However, the SLTRP also includes projected annual sales by market segment, including the amount of power expected to be used by EVs. In order to translate the annual sales projections into demand at peak hour, I made two separate assumptions. First, I assumed that EV demand would be evenly distributed over the year, so I divided the projected annual sales for EVs by 8,760 hours per year to get the average hourly amount of electricity LADWP expects EVs to draw each day.[127] Then, in order to determine how much of that would be needed at the peak hour, I assumed that LADWP's projected EV demand would be distributed in the same way that the general load is distributed; as a constant proportion of demand, rather than a constant quantity. Therefore, the EV demand at peak would have the same relationship to the average demand that is seen in the total power market. The ratio of the average load (A) on the system to the peak load (P) over the same period (T) is called the load factor (LF):

$$\frac{A * T}{P * T} = LF.$$

[127] EV Sales for 2029–30 (the year that includes summer 2030) from Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan*, 14.

Under these assumptions, the EV load will have the same load factor as the entire system load. LADWP has provided the data for the total sales and EV sales, as well as the total peak demand data for 2030, so all that remains is to solve for P_{EV} in the following:

$$\frac{A_{EV}}{P_{EV}} = \frac{A_S}{P_S} .$$

By substituting LF for $\frac{A}{P}$, this can also be stated as:

$$P_{EV} = \frac{A_{EV}}{LF_S} .$$

Carrying out the calculation yields an estimated contribution from EVs implicit in the LADWP forecast of 253 megawatt (MW), so the adjusted peak demand is the LADWP forecast (6,727 MW) minus 253 MW, or 6,474 MW.[128] (It is worth pointing out that LADWP's load factor is trending downward, indicating sharper peaks on the system, although the forecasts in the SLTRP show a constant load factor through 2030.[129] Sharper peaks require the operators to ramp up generation more quickly and create additional stress on the system.)

A new peak demand can then be calculated for each scenario, using the assumptions that define each scenario. Subtracting the scenario peak demand from LADWP's estimated dependable capacity at peak (9,000 MW) gives the number of MW remaining to act as a reserve margin. If the reserve margin is greater than or equal to 16 percent of the total peak demand, LADWP will meet its planning reserve margin standard. If the reserve margin is less than 16 percent, I conclude that the scenario poses a risk to grid stability.

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[128] Peak demand total for 2029–30 (the year that includes summer 2030) from Los Angeles Department of Water and Power, *2017 Power Strategic Long-Term Resource Plan*, 14.

[129] Los Angeles Department of Water and Power, 7; load factor calculated for future years from data on page 14.

C. RESULTS

The overall results of the analysis are shown in Figure 19.

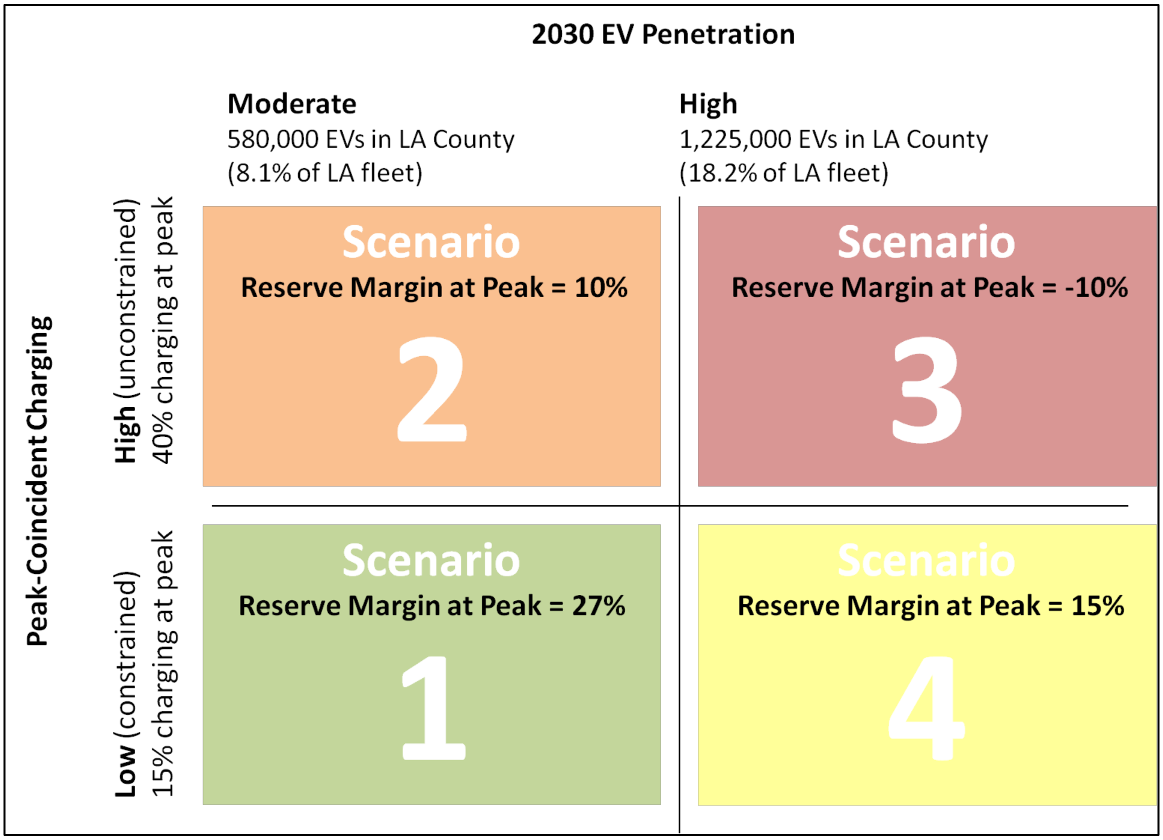

Figure 19. Reserve Margin at Peak under Each Analytic Scenario

(1) Scenario 1 (Moderate EV Penetration with Constrained Charging)

This is the case that comes closest to LADWP's forecast and assumptions because the EV penetration is taken directly from the LADWP "high transportation electrification" case. However, the calculated contribution from 15 percent of the EV fleet charging at peak for this scenario is 626 MW, more than double the amount derived using the load factor to estimate the contribution of EVs in LADWP's forecast. This suggests that LADWP is (at least implicitly) assuming that EV load will be successfully shifted away from the peak demand hours. The remaining reserve margin in this case is 27 percent, well above the 16 percent planning reserve margin.

(2) Scenario 2 (Moderate EV Penetration with Unconstrained Charging)

This case uses the moderate EV penetration level taken from the LADPW "high transportation electrification" case with 40 percent of the EV fleet charging at the time of peak demand (unconstrained charging). The remaining reserve margin in this case is 10 percent, less than the 16 percent planning reserve margin.

(3) Scenario 3 (High EV Penetration with Unconstrained Charging)

This case combines the number of EVs in Los Angeles in 2030 if the governor's goal is met (high EV penetration) with assumed 40 percent of the EV fleet charging at the time of peak demand (unconstrained charging). In this case, dependable capacity estimated by LADWP will fall short of demand by 10 percent. There is no remaining reserve margin.

(4) Scenario 4 (High EV Penetration with Constrained Charging)

This case combines the number of EVs in Los Angeles in 2030 if the governor's goal is met (high EV penetration) with an assumed 15 percent of the EV fleet charging at peak (constrained charging). The remaining reserve margin in this case is 15 percent, near the 16 percent planning reserve margin.

(5) Maximum Number of Cars that Can Charge at Peak

Extending this analysis, I calculated the maximum number of EVs that could charge simultaneously at peak without exceeding 87 percent of the dependable capacity. The maximum amount of available electricity available for EVs at peak that is consistent with a 16 percent reserve margin would be 87 percent of the dependable capacity, minus the quantity needed for other demand:

$$(0.87 * 9{,}000\text{MW}) - 6{,}727\text{MW} = 1{,}103\text{MW}.$$

Dividing this amount by the instantaneous demand per EV gives:

$$\frac{1{,}500\text{MW}}{0.0072\text{MW / EV}} = 153{,}194\text{EVs}.$$

Thus, the maximum number of EVs that can charge simultaneously under the combination of assumptions without endangering the reliability of the LADWP grid is 153,194. This number of cars would be about 2.2 percent of the entire automotive fleet expected in Los Angeles in 2030.[130]

[130] Based on the current number of automobiles per capita in Los Angeles and the projected population of Los Angeles in 2030. "Demographic Projections," State of California Department of Finance, 2016, http://www.dof.ca.gov/Forecasting/Demographics/Projections/; California Department of Motor Vehicles, "State of California Department of Motor Vehicles Statistics for Publication January through December 2017."

V. NAVIGATING THE FUTURE: CONCLUSIONS AND IMPLICATIONS

The results of this analysis demonstrate how crucial it will be for LADWP to manage the hourly load from EV charging in order to ensure reliable power at peak times. As larger numbers of EVs depend on the LADWP grid, LADWP should avail itself of as many as possible of the available tools to manage charging. If successfully managed, EVs have the potential to provide benefits to the grid without compromising reliability. Research gaps remain, especially around the comparative effectiveness and general applicability of strategies for influencing consumer behavior. This chapter discusses the implications of the analytic results and alternative policy options to manage any mismatch between demand and capacity; describes some potential futures for vehicle-to-grid interactions; and points out areas that might benefit from additional modeling and analysis.

A. READING THE MAP: IMPLICATIONS OF THE RESULTS

The tipping point at which grid reliability is compromised (defined as depletion of the reserve margin) occurs when approximately 150,000 EVs charge simultaneously at the time of peak system demand. Los Angeles can absorb much higher EV penetrations, including the governor's new target for 2030, as long as the portion of EVs charging at peak is managed so that the number of vehicles does not exceed this number.

Of the four scenarios analyzed, two result in little to no risk to reliability to the grid. Scenario 1 (Moderate EV Penetration with Constrained Charging) results in a comfortable reserve margin and Scenario 4 (High EV Penetration with Constrained Charging) is just below the planning reserve margin. Scenario 1 clearly presents no risk to the grid reliability, and Scenario 4 is probably acceptable, given the uncertainties built into all planning assumptions.

On the other hand, the two scenarios with unconstrained charging result in unacceptable reserve margins, with Scenario 3 actually exceeding the dependable capacity by 10 percent. Scenario 2 (Moderate EV Penetration with Unconstrained Charging) presents a clear risk to grid stability, while Scenario 3 (High EV Penetration with

Unconstrained Charging) would certainly result in unmet power demand, either through load curtailment (turning off power to customers whose contracts specifically allow the utility to curtail their power to reduce demand) or load shedding (blackouts).

B. ALTERNATIVE ROUTES: OPTIONS FOR MANAGING EV CHARGING

In theory, the risk to resource adequacy could be addressed either by adding additional generation capacity (for example, by building additional power plants) or by reducing the use of power when demand is at its greatest. In practice, it is prohibitively expensive to build capacity that would only be used a few hours per year, so utilities seek to manage potential shortfalls by shifting charging to off-peak times.[131] When the extra demand from EVs is shifted to off-peak times, it can be met using more efficient generation resources, because the most expensive generation sources are dispatched last, entering the mix only at peak times. Reducing the nighttime drop in demand (valley-filling) would also ensure more consistent utilization of these resources. Admittedly, pushing EV loads to the lowest-demand hours (nighttime) does tend to offset some of the reductions in greenhouse gas emissions that have been a driver of EV policy. This is because at night, power is provided by a different mix of generation sources; solar power is not an option, so (depending on the specific generation mix for the local grid) more energy may be provided by conventional natural gas and coal-fired generation, which emits more greenhouse gases.[132]

[131] C. Farmer et al., "Modeling the Impact of Increasing PHEV Loads on the Distribution Infrastructure," in *2010 43rd Hawaii International Conference on System Sciences*, 2010, 1–10, https://doi.org/10.1109/HICSS.2010.277; Stanton W. Hadley, "Evaluating the Impact of Plug-in Hybrid Electric Vehicles on Regional Electricity Supplies," in *2007 IREP Symposium—Bulk Power System Dynamics and Control—VII. Revitalizing Operational Reliability* (Charleston, SC: IEEE, 2007), 1–12, https://doi.org/10.1109/IREP.2007.4410538; Anamika Dubey and Surya Santoso, "Electric Vehicle Charging on Residential Distribution Systems: Impacts and Mitigations," *IEEE Access* 3 (2015): 1871–93, https://doi.org/10.1109/ACCESS.2015.2476996.

[132] Kim and Rahimi, "Future Energy Loads for a Large-Scale Adoption of Electric Vehicles in the City of Los Angeles"; Brian Tarroja et al., "The Effectiveness of Plug-in Hybrid Electric Vehicles and Renewable Power in Support of Holistic Environmental Goals: Part 2—Design and Operation Implications for Load-Balancing Resources on the Electric Grid," *Journal of Power Sources* 278 (March 2015): 782–93, https://doi.org/10.1016/j.jpowsour.2014.06.169; Hadley, "Evaluating the Impact of Plug-in Hybrid Electric Vehicles on Regional Electricity Supplies."

A number of researchers have studied ways to optimize the coordination of charging.[133] Some of the options for managing demand depend on technological solutions, while others seek to influence consumer behavior through pricing incentives (leveraging automated metering infrastructure). Technological solutions may be described as direct (in which charging is centrally controlled by the utility or a third-party aggregator) or decentralized, in which the vehicles "negotiate" an optimal solution.[134]

Each type of solution has some drawbacks, since technological solutions increase the complexity of the system and may fail to satisfy consumer needs, while pricing incentives may not be effective for the comparatively well-off consumers expected to be the early adopters of EVs.[135] Direct optimization by the utility seems unlikely to be accepted by consumers unless it fully accounts for the convenience of the customers. Customers' concern that their vehicles may not be charged and available when they need them is essentially a variation on range anxiety; it will tend to dampen enthusiasm for EVs.

LADWP is a municipal utility, part of the city government of Los Angeles. Publicly owned utilities are not regulated by the California Public Utility Commission; the utility is instead managed by the local government, which sets customer rates and utility policy. Therefore, the City of Los Angeles, through the LAPWD, has broad discretion to set rates and rules intended to manage the peak load generated by EVs.

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[133] See for example Zahra Darabi and Mehdi Ferdowsi, "Aggregated Impact of Plug-in Hybrid Electric Vehicles on Electricity Demand Profile," *IEEE Transactions on Sustainable Energy* 2, no. 4 (October 2011): 501–8, https://doi.org/10.1109/TSTE.2011.2158123; Moayed Moghbel, Mohammad A. S. Masoum, and Alireza Fereidouni, "Decentralize Coordinated Charging of Plug-In Electric Vehicles in Unbalanced Residential Networks to Control Distribution Transformer Loading, Voltage Profile and Current Unbalance," *Intelligent Industrial Systems* 1, no. 2 (August 2015): 141–51, https://doi.org/10.1007/s40903-015-0008-7; Li Zhang et al., "Coordinating Plug-in Electric Vehicle Charging with Electric Grid: Valley Filling and Target Load Following," *Journal of Power Sources* 267 (December 2014): 584–97, https://doi.org/10.1016/j.jpowsour.2014.04.078.

[134] For an example of a direct strategy, see Mahnoosh Alizadeh, Anna Scaglione, and Robert J. Thomas, "Direct Load Management of Electric Vehicles," in *2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 5964–67, 2011, https://doi.org/10.1109/ICASSP.2011.5947720; Moghbel, Masoum, and Fereidouni, "Decentralize Coordinated Charging of Plug-In Electric Vehicles in Unbalanced Residential Networks to Control Distribution Transformer Loading, Voltage Profile and Current Unbalance"; Zhang et al., "Coordinating Plug-in Electric Vehicle Charging with Electric Grid."

[135] Jim Gorzelany, "Electric-Car Buyers Younger and Richer than Hybrid Owners," *Forbes*, April 22, 2014, http://www.forbes.com/sites/jimgorzelany/2014/04/22/electric-car-buyers-younger-and-richer-than-hybrid-owners/#3887ee05ad32.

LADWP began its exploration of TOU pricing in 1975, with a five-year experiment that demonstrated the value of peak-pricing in reducing peak power use.[136] At this writing, customers can choose between two pricing structures, selecting either TOU rates or a tiered pricing schedule that encourages overall energy conservation.[137] Customers who elect TOU pricing for EV charging and install a separate meter for their EV chargers receive an additional EV discount.[138] LADWP also offers its customers rebates on the purchase of residential charging equipment. In addition to continuing these proven strategies, Los Angeles should continue to expand its downtown charging infrastructure in public parking and workplace garages, in order to encourage charging during the day and accelerate EV adoption.[139]

In the future, LADWP may also wish to explore cooperative scheduling of EV charging facilitated by a third party. Such an arrangement might follow the pattern established to manage residential rooftop solar electric generation, in which an "aggregator" serves as a third party that provides the software and services necessary to monitor rooftop generation and manage its bulk sale to the utility. Such an arrangement would offer customers options among vendors and facilitate utility grid management.[140]

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[136] Bridger M. Mitchell and Jan Paul Acton, *The Effect of Time-of-Use Rates in the Los Angeles Electricity Study* (Santa, Monica, CA: RAND Corporation for the Los Angeles Department of Power and Water and the John A. Hartford Foundation, 1980), 1–29, http://www.rand.org/content/dam/rand/pubs/notes/2007/N1533.pdf.

[137] Los Angeles Department of Water and Power, "Electric Rates."

[138] "Electric Vehicle Incentives," Los Angeles Department of Water and Power, 2013, https://www.ladwp.com/ladwp/faces/ladwp/residential/r-gogreen/r-gg-driveelectric/r-gg-de-evncentives?_afrWindowId=null&_afrLoop=168072590378703&_afrWindowMode=0&_adf.ctrl-state=bj6j0m1nd_4#%40%3F_afrWindowId%3Dnull%26_afrLoop%3D168072590378703%26_afrWindowMode%3D0%26_adf.ctrl-state%3Dqrjejscgp_4.

[139] James Di Filippo et al., *Prioritizing Workplace EV Charging Stations Investments in Los Angeles County* (Los Angeles: UCLA Luskin School of Public Affairs, Luskin Center for Innovation, 2017), 34–35, https://innovation.luskin.ucla.edu/wp-content/uploads/2019/03/Prioritizing_Workplace_EV_Charging_Stations_Investments_in_LA.pdf.

[140] Fereidoon Sioshansi, "How Aggregators Will Alter Fundamentals of Electricity Business," *Energy Post* (blog), April 9, 2018, https://energypost.eu/how-aggregators-will-alter-fundamentals-of-electricity-business/.

C. DOWN THE ROAD: VEHICLE TO GRID INTEGRATION

Moving EV charging away from the peak times when the grid is under the greatest stress has other benefits. By charging at off-peak times, EVs would help with valley-filling, smoothing out load curves and reducing the problems associated with rapid ramping of generation resources to meet steep increases in load. At some point in the future, they may also be able to improve grid functioning in more subtle ways.

In 1997, when EVs were mounting their second wave with the ill-fated GM EV-1, Willett Kempton and Steven Letendre made the then-novel proposal that BEVs could be used to store power for the electric grid. Kempton and Letendre went so far as to suggest that vehicles with alternative fuel sources, such as hydrogen cells, could actually supply power to the grid, noting that the U.S. vehicle fleet has 10 times the mechanical power of all the generation plants and is unused 95 percent of the time. Their paper expressed the view that utilities would benefit from subsidizing BEVs or at least the batteries for the vehicles, in return for the right to control the charging and discharging of the batteries, within parameters set by the drivers.[141]

A specific application of vehicle-to-grid (V2G) integration is the use of EV batteries to help grid operators manage the variability of generation when a high proportion of power is provided by VERs, such as wind and solar power. Excess power generated by these resources could be stored in EV batteries and withdrawn at peak use times. Several researchers have looked at the potential to use EVs in this way.[142]

The benefits identified by Kempton and Letendre, and other researchers since, fall into the category of "ancillary services" to utilities. The FERC defines ancillary services as "Those services necessary to support the transmission of electric power from seller to purchaser… to maintain reliable operations of the interconnected transmission system.

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[141] Willett Kempton and Steven E. Letendre, "Electric Vehicles as a New Power Source for Electric Utilities," *Transportation Research Part D: Transport and Environment* 2, no. 3 (September 1997): 157–75, https://doi.org/10.1016/S1361-9209(97)00001-1.

[142] Jianhui Wang et al., "Impact of Plug-in Hybrid Electric Vehicles on Power Systems with Demand Response and Wind Power," *Energy Policy* 39, no. 7 (July 2011): 4016–21, https://doi.org/10.1016/j.enpol.2011.01.042; Abdelsamad, Morsi, and Sidhu, "Impact of Wind-Based Distributed Generation on Electric Energy in Distribution Systems Embedded with Electric Vehicles."

Ancillary services supplied with generation include load following, reactive power-voltage regulation, system protective services, loss compensation service, system control, load dispatch services, and energy imbalance services."[143] In other words, they are the services that help ensure power quality and reliability, as well as system efficiency. Under normal grid operations, EV batteries can in theory reduce peak demand (a service called peak-shaving) either by discharging to the grid or by curtailing charging to reduce demand. For example, an Australian team found that EVs could potentially shave about five percent from peak loads.[144] EVs could also provide the more subtle benefits of grid regulation and reactive power compensation. In emergencies, they could act as spinning reserves for the grid or backup generators for homes and facilities, power supplies that can be brought online quickly to replace unexpected losses.[145]

The idea that EVs can provide value when interconnected and integrated into grid operations is now expressed in several shorthand abbreviations for different types of integrations, depending on the linkages: V2G, vehicle-to-house (V2H), and vehicle-to-vehicle (V2V). All of these forms of integration require that the EVs and grid operators can communicate; some (such as curtailing EV charging at peak times) would require only one-way control, by grid operators sending commands to EVs, but others (such as coordinating charging to smoothly fill demand valleys) will require two-way communications to optimize. Therefore, the deployment of V2G technology will dovetail with the grid modernization initiatives that are incorporating sensors and communications technology to improve grid operations.

Analysis performed by Kempton et al. for the CARB and LADWP concluded that selling ancillary services to the grid would be more valuable for EV owners in the California electric power market (specifically, grid regulation and spinning reserves) than

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[143] "FERC: Guide to Market Oversight—Glossary," Federal Energy Regulatory Commission, March 15, 2016, https://www.ferc.gov/market-oversight/guide/glossary.asp.

[144] Paevere et al., "Spatio-Temporal Modelling of Electric Vehicle Charging Demand and Impacts on Peak Household Electrical Load."

[145] Kang Miao Tan, Vigna K. Ramachandaramurthy, and Jia Ying Yong, "Integration of Electric Vehicles in Smart Grid: A Review on Vehicle to Grid Technologies and Optimization Techniques," *Renewable and Sustainable Energy Reviews* 53 (January 2016): 720–32, https://doi.org/10.1016/j.rser.2015.09.012.

to discharge power and sell it at peak times. Grid regulation services in particular are valuable to utilities because using EVs would give grid operators an improved ability to fine-tune power management. For EV owners, selling this service is attractive because the charge/discharge cycles would be very shallow, creating less potential inconvenience and wear and tear on the battery pack.[146]

In the future, it may even be possible to wirelessly charge EVs while driving on specially-designed electrified roads. Electrifying roads would remove range restrictions of EVs and potentially add to the fuel savings possible with EVs and PHEVs, if implemented on a large scale. Researchers estimate that 25 percent of all miles traveled are on one percent of the nation's roads, so electrifying these high-volume roadways could displace up to 25 percent of the fuel used by a fleet of appropriately equipped vehicles.[147]

D. ONE FOR THE ROAD: RESEARCH GAPS AND FINAL THOUGHTS

This analysis contained a number of necessary simplifying assumptions, and a more nuanced picture could be developed using more sophisticated techniques to model the scenario space. However, the results make it clear that managing the resource adequacy issues related to EV charging will be primarily a matter of effectively influencing EV owner behavior. With options ranging from providing free public charging near workplaces to encourage midday charging to direct charge/discharge control of EVs by utilities, the most urgent policy need is to understand the tradeoffs and effectiveness associated with the various strategies. This problem is complicated by the fact that governments tend to employ combinations of strategies, making the results of any single strategy difficult to quantify, and the fact that different areas have unique policy, cultural, geographical, and demographic characteristics that may mean that a successful solution in one area is not applicable to another. Large-scale, randomized trials across multiple markets would be the

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[146] Willett Kempton et al., *Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California* (Davis, CA: Institution of Transportation Studies, University of California-Davis, 2001), 166–167, http://www1.udel.edu/V2G/docs/V2G-Cal-2001.pdf.

[147] Eric Burton et al., *Fuel Savings from Future In-Motion Wireless Power Transfer (WPT)* (Park City, UT: Conference on Electric Roads & Vehicles, 2015), slide 2, http://www.nrel.gov/docs/fy15osti/63758.pdf.

ideal approach to evaluate the merits of various policy approaches. Policies that could be tested in this way include alternative time-of-day pricing regimes for consumers, utility-employer partnerships to provide free or reduced price daytime charging, and/or direct control of EV charging, either by the utility or by a third-party "aggregator" serving as an intermediary between the consumer and the utility.

In the longer term, an agenda of technological research needs to be pursued, if futuristic ideas like electrified roads are to become a reality. Along with solving the technical problems of such innovations, careful attention must be given to their likely costs and benefits.

Introducing EVs into Los Angeles' complex and fragile power system brings both risks and opportunities. Demand from EVs is a welcome revenue stream for utilities like LADWP that have been actively promoting energy efficiency and coping with trends that tend to reduce electric demand, including rooftop solar installations and "green buildings." In addition, utilities, including LADWP, see the potential for incentivizing EV charging in order to smooth out their load profiles, solving problems ranging from mid-day over-generation from solar plants to nighttime idling of conventional plants. Integration of EVs into the grid through sophisticated communications and management could even improve power quality for other customers. Whether these advantages will be realized in spite of the risks remains to be seen, but it is clear that Los Angeles is at an important turning point--at the intersection of transportation and electrification.

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