STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

DRISI-2011 (REV 10/1998)

1. REPORT NUMBER NCST-UCD-RR-20-15	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE AND SUBTITLE Utilizing Highway Rest Areas for Electric Vehicle Charging: Economics and Impacts on Renewable Energy Penetration in California		5. REPORT DATE April 2020 6. PERFORMING ORGANIZATION CODE UCD-ITS-RR-20-25
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9. PERFORMING ORGANIZATION NAME AND ADDRESS University of California, Davis Institute of Transportation Studies 1605 Tilia Street, Suite #100 Davis, CA 95616		10. WORK UNIT NUMBER 11. CONTRACT OR GRANT NUMBER Caltrans 65A0686 Task Order 011 USDOT Grant 69A3551747114
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation Division of Research, Innovation and System Information, MS-83 1727 30th Street, Sacramento, CA 95816		13. TYPE OF REPORT AND PERIOD COVERED Final Report (December 2018 – October2019) 14. SPONSORING AGENCY CODE USDOT OST-R

15. SUPPLEMENTARY NOTES

DOI: https://doi.org/10.7922/G2N29V6B
Dataset DOI: https://doi.org/10.25338/B8402G

16. ABSTRACT

California policy is incentivizing rapid adoption of zero emission electric vehicles for light-duty and freight applications. This project explored how locating charging facilities at California's highway rest stops might impact electricity demand, grid operation, and integration of renewables like solar and wind into California's energy mix. Assuming a growing population of electric vehicles to meet state goals, state-wide growth of electricity demand was estimated, and the most attractive rest stop locations for siting chargers identified. Using a California-specific electricity dispatch model developed at UC Davis, the project estimated how charging vehicles at these stations would impact renewable energy curtailment in California. It estimated the impacts of charging infrastructures on California's electricity system and how they can be utilized to decrease the duck curve effect resulting from a large amount of solar energy penetration by 2050.

17. KEYWORDS Highway Rest Areas, Electric Vehicle Charging, Energy System, Renewable Energy, Long-distance Travel	18. DISTRIBUTION STATEMENT No restrictions	
19. SECURITY CLASSIFICATION (*of this report*) Unclassified	20. NUMBER OF PAGES 70	21. COST OF REPORT CHARGED N/A

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Title
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Publication Date
2020-04-01

DOI
10.7922/G2N29V6B

Data Availability
The data associated with this publication are available at: https://doi.org/10.25338/B8402G

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April 2020

A Research Report from the National Center for Sustainable Transportation

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National Center for Sustainable Transportation

ITS UCDAVIS INSTITUTE OF TRANSPORTATION STUDIES

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EXECUTIVE SUMMARY

California policy is incentivizing rapid adoption of zero emission electric vehicles for light duty and freight applications. In this project, we explored how locating EV charging facilities at California's highway rest stops, might impact electricity demand, grid operation, and integration of renewables like solar and wind into California's energy mix. Rest areas were the focus of our analysis, because they are situated conveniently at locations alongside highways that facilitate long distance or "intercity" travel. Adding chargers at rest areas might encourage use of light duty BEVs for long distance travel, In addition, Caltrans is presently using rest areas for charger locations for the "30-30" project and is continuing to investigate increased use of rest areas for EV charging infrastructure in coming years (California Department of Transportation, 2019).

To analyze the potential impacts of adding chargers to rest stops, we developed two models (Figure ES-1).

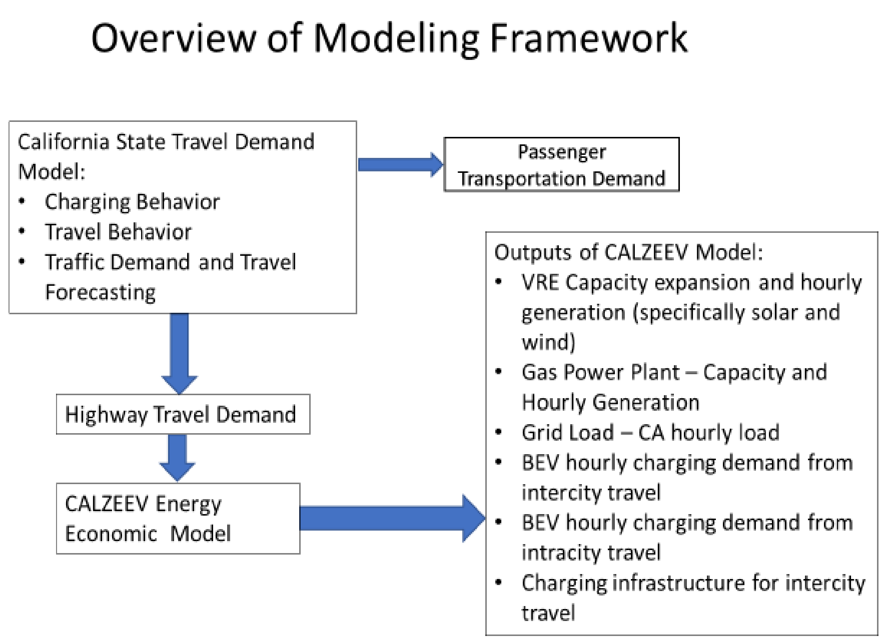

Figure ES-1. Overview of modeling framework with transportation demand model and energy economic model (CALZEEV)

The first "travel demand model" employs travel data from California, to estimate long distance travel demand in the state, and the potential for chargers located at rest stops to serve this demand. Only light-duty personal vehicles (i.e. passenger vehicles with a gross weight less than 8,500 pounds) were considered. Additionally, long-distance travel was defined to be trips of 100 miles or greater. as shorter trips were not likely to necessitate charging at rest areas. Travel was analyzed using

The second model CALZEEV (California Zero Emission Energy and Vehicle Model) is an energy/economic model built on the MESSAGE platform, that incorporates a detailed dispatch model. This allows us to look at how the added demand for charging EVs effects the operation of the overall energy system. Overall charging demand, infrastructure requirements and charging capacity at rest stops are estimated.

Specific research questions addressed in our study are:

- What fraction of light duty travel is for long distance trips ("intercity travel") compared to shorter trips ("intracity travel")?
- How might BEVs intercity travel be enabled by chargers at rest areas?
- What are the hourly operational behavior and demand response effects of intercity ZEVs on the state grid network, if these vehicles are adopted on a massive scale?
- What is the net grid impact of mid-day ZEV charging at rest areas along California's highways? What kind of system would be needed to solve intermittency and duck curve issues state-wide?

Assuming a growing population of electric vehicles to meet state goals, we developed a range of scenarios for 2017, 2030 and 2050. Using models developed at ITS, we estimated state-wide growth of electricity demand, and identified the most attractive rest stop locations for siting chargers to enable long distance travel by light duty BEVs. Using a California-specific electricity dispatch model developed at ITS, we estimated how charging vehicles at these stations might impact renewable energy usage in California. We explored potential advantages if charging stations can utilize renewable energy generation, lowering electricity losses and renewable energy curtailments. We estimated economic impacts of these charging infrastructures on California's electricity system and how they can be utilized to decrease the duck curve effect resulting from a large amount of solar energy penetration by 2050. Beside the grid impact, GHG mitigation effects by increasing EVs and larger penetration of renewable energy by year 2050 were analyzed.

In this work, only light-duty personal vehicles (i.e. passenger vehicles with a gross weight less than 8,500 pounds) were considered. Additionally, long-distance travel was understood to be trips of 100 miles or greater as shorter trips were not likely to necessitate charging at rest areas. Rest areas were categorized into four categories, based on the projected level of charging demand expected. These rest area groupings were used to provide specific policy recommendations based on the results of the study.

In addition, extensive data on the functionality of the energy system in California was gathered and analyzed. This energy data, along with the transportation data, was used to run a multiinteger optimization model in MESSAGE (Model for Energy Supply Strategies and their General Environmental Impacts). MESSAGE is a demand driven model that minimizes the total cost of energy supply system in a multi-period capacity expansion planning. The model carries out an analysis for all hours of the year in 2017, 2030, and 2050. From the results of this model, specific recommendations for the various rest area groupings in terms of total chargers needed as well as the electric infrastructure and generation to supply the needed chargers were determined. The model will ensure that resources, both generation and supporting infrastructure, are optimally allocated to minimize overall cost while maximizing the number of EVs that are able to successfully complete their trip.

In order to quantify the charging demand at the rest areas in California, a sub-model was developed specifically to analyze the flow of long-distance travel in the State. The main source of travel data was publicly available data from the California Statewide Travel Demand Model long-distance component, which details county to county travel of 100 miles or more for an average day. The sub-model took other inputs, such as travel fluctuations over time, BEV penetration, and BEV range. Model results consisted of a charging demand profile for all hours of each model year, in terms of kWh/hour that equated to the amount of charging that would be needed at each rest area, and an hourly total vehicles profile for each rest area in all model years. Both profiles for each rest area were used to group rest areas into four groups for which specific policy recommendations could be made. The travel demand profiles and rest area groupings were further used as MESSAGE model inputs.

Based on four categories of rest areas in California, an electricity grid model was developed incorporating the charging demand and infrastructure needed. The effect of the required load for 8760 hours/year was seen on the electricity supply system, allowing high penetration of renewable energy. The effect of intercity BEV travel on the grid load for different rest areas was analyzed and compared with intracity charging behavior of BEVs for 2050. Optimal electricity demand for each hour and total generation capacity required for 2050 was extracted from the MESSAGE model.

Chargers that are already installed within 25 miles of each rest area are inputs to the model as installed charging capacity. We conclude that depending on the location of the rest area and how many chargers are already available around that area, some rest areas need to be addressed more than the others. Based on the categorization of rest areas we introduced in this project, High Congestion rest areas (totaling 13) and High Congestion & High Demand rest areas (totaling 52) in 2050 are the ones which need higher investment in chargers' infrastructure. Results of this study show that if all vehicles in California are BEVs in 2050, we would need about 730 100kW charging stations installed within a 25 mile distance of "High Congestion Rest Areas" and 1187 100 kW charging stations within 25 mile distance of "High Congestion & High Demand Rest Areas" "High Demand" rest areas each need only 8 charging stations. With this configuration, all long-distance trips which are over 100 miles range could be supported in California. To provide this extra electricity demand, 122 GW solar, 56 GW wind and 67 GW of gas power plants would be required in 2050. Also, regarding load profiles, hourly charging load profiles on the highways are different than charging profiles of intracity stations, but are complementary to adjust the duck-curve as it is spread more in the daytime.

Figure ES-2 shows the electricity required for intercity and intracity LDV charging for 2050 in TWh. This figure represents an all BEV fleet scenario.

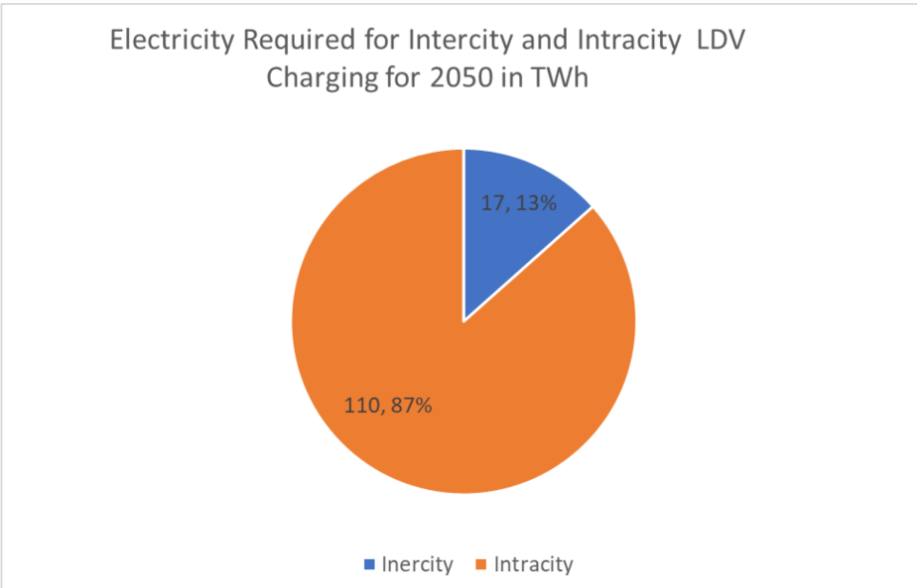

Figure ES-2. Annual Electricity demand required for charging all 28 million BEV LDVs in 2050. Blue section is for intercity travel longer than 100 miles passing rest areas and orange section is for all other intracity travels.

Figure ES-3 shows the installed capacity for gas, wind and solar generation for 2050. We would need 122 GW of solar, 56 GW of wind and 67 GW of gas power plants to supply power statewide for all purposes. This mixture gives us up to 72% variable renewable energy penetration in California's electricity grid. The fraction of generation capacity needed for charging 30 million BEVs in 2050 is shown as a stacked bar. It is seen that capacity required for charging light duty BEVs for intercity travel would be a relatively small fraction of the total installed generation capacity.

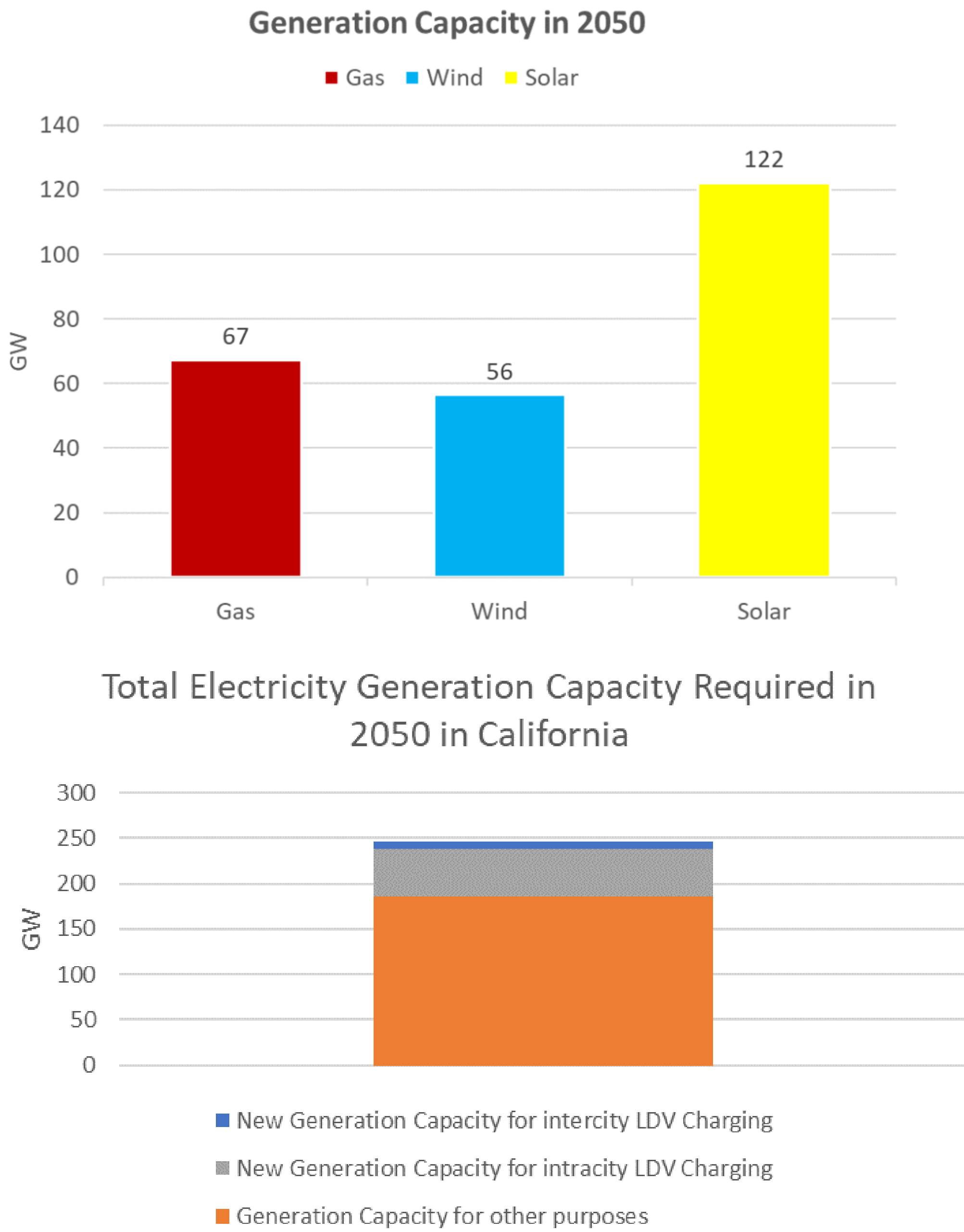

Figure ES-3. Total installed generation capacity in 2050, to serve all electricity needs in California, including 30 million LDV BEVs. The fraction of capacity used for charging BEVs is shown as a stacked bar.

Introduction

Recent legislation in the State of California focuses on reducing greenhouse gas emissions from the transportation sector. One of the main goals of these new policies is to increase the amount of zero emission vehicles (ZEVs) on the road in the coming decades, with refueling infrastructure to support the growing fleet. Executive Order B-48-18, signed into law by former Governor Jerry Brown, calls for 5 million ZEVs, 250,000 electric vehicle (EV) charging stations, and 200 hydrogen refueling stations by 2030 (California Department of Transportation, 2018b). Currently, there are three types of ZEVs commercially available in California: battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV) (when operating in electric mode), and fuel cell electric vehicle (FCEV) (California Department of Transportation, 2017). As of October 2019, there were approximately 655,088 ZEVs and about 21,000 charging stations statewide (Nikolewski, 2019). Additionally, by the end of 2019 there was approximately 52 hydrogen refueling stations in service (California Air Resources Board, 2019). While urban centers have responded well to this shift in vehicle mix by providing numerous EV charging stations and a smaller fraction of hydrogen refueling stations, those desiring to use ZEVs for intercity travel face the challenge of insufficient refueling infrastructure (Nie and Ghamami, 2013; California Energy Commission, 2018; Wang *et al.*, 2019). The California Department of Motor Vehicles (Caltrans) is currently acting to solve this problem by implementing their "30-30" plan. This plan was created to build, at least, 30 DCFC stations in California at rural and underserved locations. Several of these locations include safety roadside rest areas, which will be henceforth known as rest areas. Caltrans' efforts strive to bridge the gap between the public, who are hesitant to buy EVs—mainly BEVs—without widespread charging infrastructure, and the private sector, which does not want to invest in EV charging infrastructure until the fleet size is large enough to make it a worthwhile business venture. In total, 28 highway rest areas were selected under the "30-30" project to close gaps greater than 80 miles in highway charging infrastructure (California Department of Transportation, 2017). Funding for these projects was finalized in December of 2018, with construction to follow in 2019 (California Department of Transportation, 2018b). While this effort is progressing towards supporting a larger fleet of ZEVs, it only aims to serve the presently small share of EVs on the road. In order to appropriately plan for future charging demand for long-distance travel, specific analysis of future travel patterns and the necessary refueling infrastructure is imperative.

A few studies have used transportation data, usually from a survey or vehicle sales, to project the potential demand for EV charging infrastructure (Harris and Webber, 2014; Flores, Shaffer and Brouwer, 2016; Gnann *et al.*, 2018). However, other studies have set out to select convenient locations alongside a highway that would best serve long-distance ZEV travel demand. One such study was conducted in Canada and evaluated the quantity and location of EV chargers needed along a 500 mile stretch of highway, which connects Windsor to Quebec, in order to have a high trip success ratio among EVs and facilitate ease of charging from the driver's perspective. In the end, it was determined that approximately 90% of trips would be completed successfully by installing 11 charging stations along the way (Alhazmi, Mostafa and Salama, 2017). A similar study in Italy investigated where EV charging stations would be needed throughout the country in order to comply with a goal of using zero emission transportation.

This study reported that an optimal configuration included large, urban charging stations which served many vehicles at once and smaller, rural charging stations which served only a few vehicles at a time (Micari *et al.*, 2017). Research completed by Wang et. al set forth a framework for locating EV charging stations along highways in order to encourage intercity EV travel but while also considering the potential wait time for a charging opportunity (Wang *et al.*, 2019). Even battery swapping for light-duty vehicles has been explored (Nie and Ghamami, 2013). Still, siting ZEV refueling stations is only one piece of the puzzle as attention must be given to how the energy for charging will be supplied.

Numerous studies have been conducted with the goal of determining optimal ways to supply needed charging energy for EV charging stations. Solar power was shown to help ease the impacts on the grid associated with EV charging (Khan, Ahmad and Alam, 2019). While renewable resources will help to decrease the impact on the grid in supplying energy for EV charging, they are best paired with battery storage to mitigate the intermittency of renewable resources and minimize overall costs (Dominguez-Navarro *et al.*, 2019). Energy sources, including solar, diesel, and batteries, were tried in various configurations both with and without a grid connection. It was determined that while it was environmentally better to use solar, it was cost prohibitive and it was overall best to use a combination of all three energy sources along with a grid connection (Hafez and Bhattacharya, 2017). Hydrogen, batteries, and a combination of the two paired with grid power were compared and found the combination to be best suited for answering charging demand (Zhao and Burke, 2016). Other work indicates that energy storage used with a smart grid would be effective in providing energy to meet charging demand (Sbordone *et al.*, 2015). Even efforts to quantify the impact of EV charging on grid assets have been conducted (Mao, Gao and Wang, 2019). While these studies aim to answer the question of how charging needs will be met, to the best of the author's knowledge no such study has been conducted specifically for California. Given the State's need to make plans to support a growing fleet of ZEVs in the near future and its diverse energy generation portfolio, an in-depth analysis of the charging demand from long-distance travel and the needed infrastructure and energy to support it is imperative.

The goal of this project is to identify rural locations, specifically highway rest areas, where installing EV charging infrastructure would be most beneficial and to analyze the impact of the increased electricity demand from EV charging on the energy system in California. Rest areas were chosen because they are situated conveniently at locations alongside highways that facilitate intercity travel. In addition, Caltrans is presently using rest areas for charger locations for the "30-30" project and is continuing to investigate increased use of rest areas for EV charging infrastructure in coming years (California Department of Transportation, 2019). Figure 2 shows the locations of the 86 rest areas in California.

Specific research questions addressed in our study are:

- What fraction of light duty travel is for long distance trips ("intercity travel") compared to shorter trips ("intracity travel")?
- How might BEVs intercity travel be enabled by chargers at rest areas?

- What are the hourly operational behavior and demand response effects of intercity ZEVs on the state grid network, if these vehicles are adopted on a massive scale?
- What is the net grid impact of mid-day ZEV charging at rest areas along California's highways? What kind of system would be needed to solve intermittency and duck curve issues state-wide?

Future travel demand was analyzed by building a model to specifically target long-distance charging demand at highway rest areas. In this work, only light-duty personal vehicles (i.e. passenger vehicles with a gross weight less than 8,500 pounds) were considered. Additionally, long-distance travel was understood to be trips of 100 miles or greater as shorter trips were not likely to necessitate charging at rest areas. Rest areas were categorized into four categories, based on the projected level of charging demand expected. These rest area groupings will be used to provide specific policy recommendations based on the results of the study. In addition, extensive data on the functionality of the energy system in California was gathered and analyzed. This energy data, along with the transportation data, was used to run a mixed-integer optimization model in MESSAGE (Model for Energy Supply Strategies and their General Environmental Impacts). MESSAGE is a demand driven model that minimizes the total cost of energy supply system in a multi-period capacity expansion planning. The model will carry out an analysis for all hours of the year in 2017, 2030, and 2050. From the results of this model, specific recommendations for the various rest area groupings in terms of total chargers needed as well as the electric infrastructure and generation to supply the needed chargers will be determined. The model will ensure that resources, both generation and supporting infrastructure, are optimally allocated to minimize overall cost while maximizing the number of EVs that are able to successfully complete their trip.

The "Duck Curve"

California's Renewable Portfolio Standard goals call for significant expansion of renewable electricity (e.g., wind and solar). This means a higher share of variable electricity generation that does not necessarily coincide with time of demand (i.e., is not dispatchable), as illustrated in Figure 1. During midday and early afternoon, the supply of solar energy is high (green curve), but load is relatively low. Then, in the evening, solar energy production is low, but load ramps up. As a result, the net load—the total load in the system minus available solar energy—decreases in the afternoon and rises sharply in the evening. Thus, this net load, which represents electricity produced by nonrenewable sources, follows the duck curve when graphed over a 24-hour cycle (orange curve). The midday dip in the duck curve (brown curve) is deeper in the spring than in the summer or winter, because in the spring the load during the day is lower due to less need for air conditioning or heating. The lower midday load in spring results in a correspondingly lower midday net load (deep duck curve).

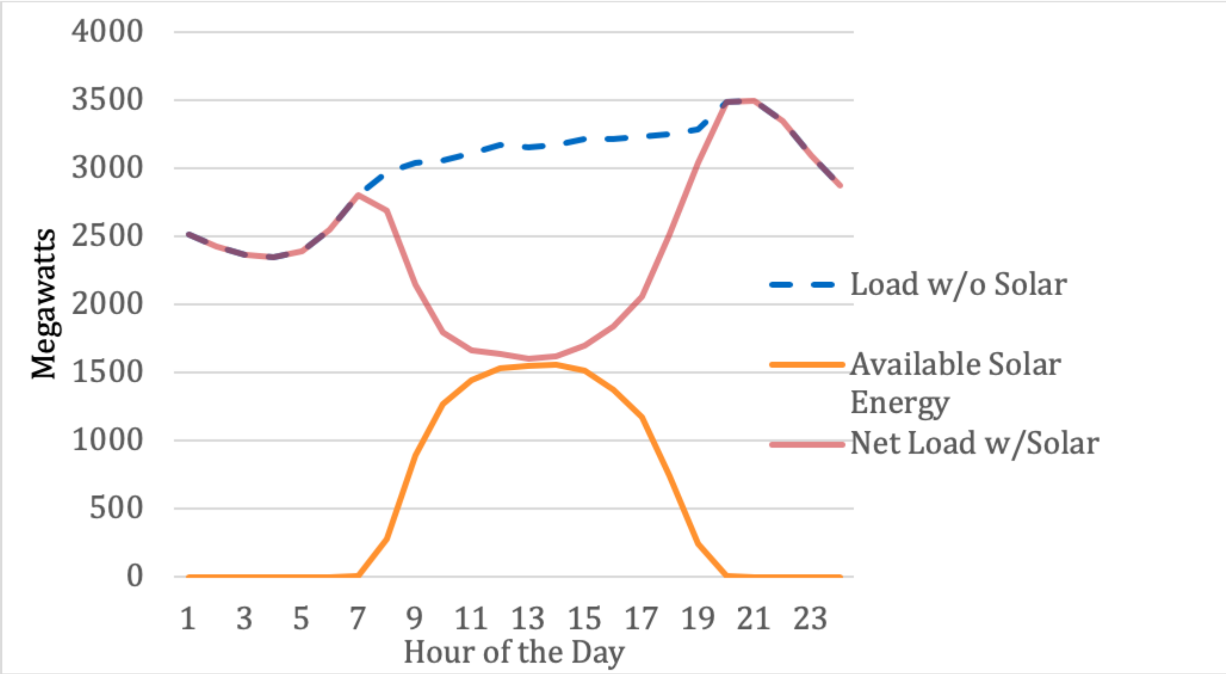

Figure 1. Actual duck curve shown in brown, representing data from March 27, 2017 in Los Angeles Department of Water and Power territory. The net load (brown) represents the load without solar energy (dotted blue) minus the available solar energy (orange).

The duck curve is expected to become more extreme as solar energy harvesting increases in California. Due to limited storage capacity, utility companies must curtail renewable power at its peak productivity in the middle of the day, hindering the ability to reach renewable power goals. EV charging during daytime when solar exceeds the demand can avoid curtailment and flatten the duck curve.

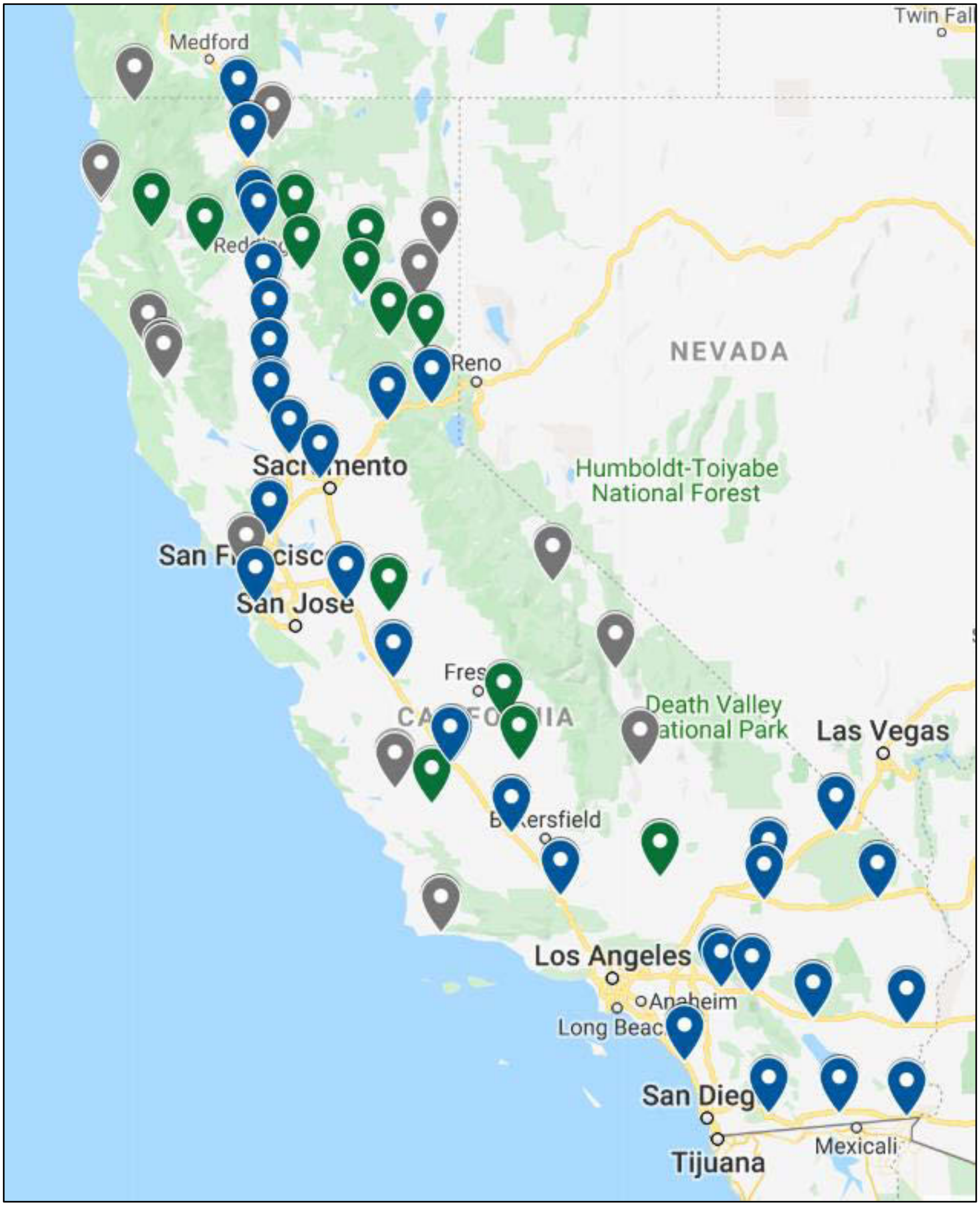

Figure 2. Locations of all rest areas in California. Blue denotes interstates (e.g., I-5), green denotes state routes (e.g., SR-99), and grey denotes US routes (e.g., US-101).

In the following sections, the model inputs and construction will be discussed, followed by the model results and policy recommendations. Finally, we present the conclusion.

Model Inputs and Construction

Two major models are used in this analysis: transportation modeling and energy system modeling. We focused on understanding the role of chargers at rest stops in enabling long distance travel by BEVs, and their effect on the grid and the energy system.

First, we developed a transportation demand model, focusing on long distance BEV travel. This model enables us to estimate the hourly electricity charging demand at particular rest stations throughout California. Scenarios are evaluated for 2017, 2030 and 2050, assuming a growing population of BEVs.

Second, to understand the impact of BEV charging on the operation and economics of California's energy system, we incorporate BEV charging demand into a comprehensive energy system model using the MESSAGE modeling framework. We name the model CALZEEV which was populated with data on California's energy system, as well as locations of rest areas, as described below.

In the following sections, the specific data collection and analysis process for the two main models is indicated as well as the model framework.

Energy System Data

In order to understand the current functionality of California's energy system, extensive electricity data, including installed EV charging capacity, was gathered from several data sources. These data sources include the California Independent System Operator Oasis, the 2016 Emissions and Generation Resource Integrated Database Report, the US EPA, the US Energy Information Administration, the 2018 Annual Baseline Technology Report published by the National Renewable Energy Laboratory, independently owned utility public data and reports, publicly owned utility data from personal interviews, the California Energy Commission, and the Alternative Fueling Station Locator maintained by the US Department of Energy.

These data sources were used to provide an accurate description of the current functionality of the grid in California, including actual electricity demand and generation capacity across the state. In this analysis, California was decomposed into five regions to allow for more granularity in eventual model results and for convenience in processing data to be used as model inputs. The model regions were selected based upon the major utility providers in the state to coincide with the data from these entities. Figure 4 details the breakdown of these regions. Electricity demand was analyzed on the regional and local levels. Regional hourly demand profiles were first developed and then used to create localized estimates for substations serving the rest areas. A total of five regional load profiles were produced, one for each region shown in Figure 3. A substation load profile was created for each rest area in California. Figure 4 shows the annual load profile for the state of California as well as the five model regions. Figure 5–9 show the two substation profiles for each region that are the lowest annual load and highest annual load, highlighting the variation present in the regions. The load profiles represent the substation that serves the larger area around it.

Figure 3. Regions of California used for analyzing grid impacts in California, including all 86 highway rest areas. The five regions include: 1 – California North (CALN), 2 – Southern California Edison (SCE), 3 – Los Angeles Department of Water and Power (LADWP), 4 – San Diego Gas and Electric (SDGE), 5 – Imperial Irrigation District (IID).

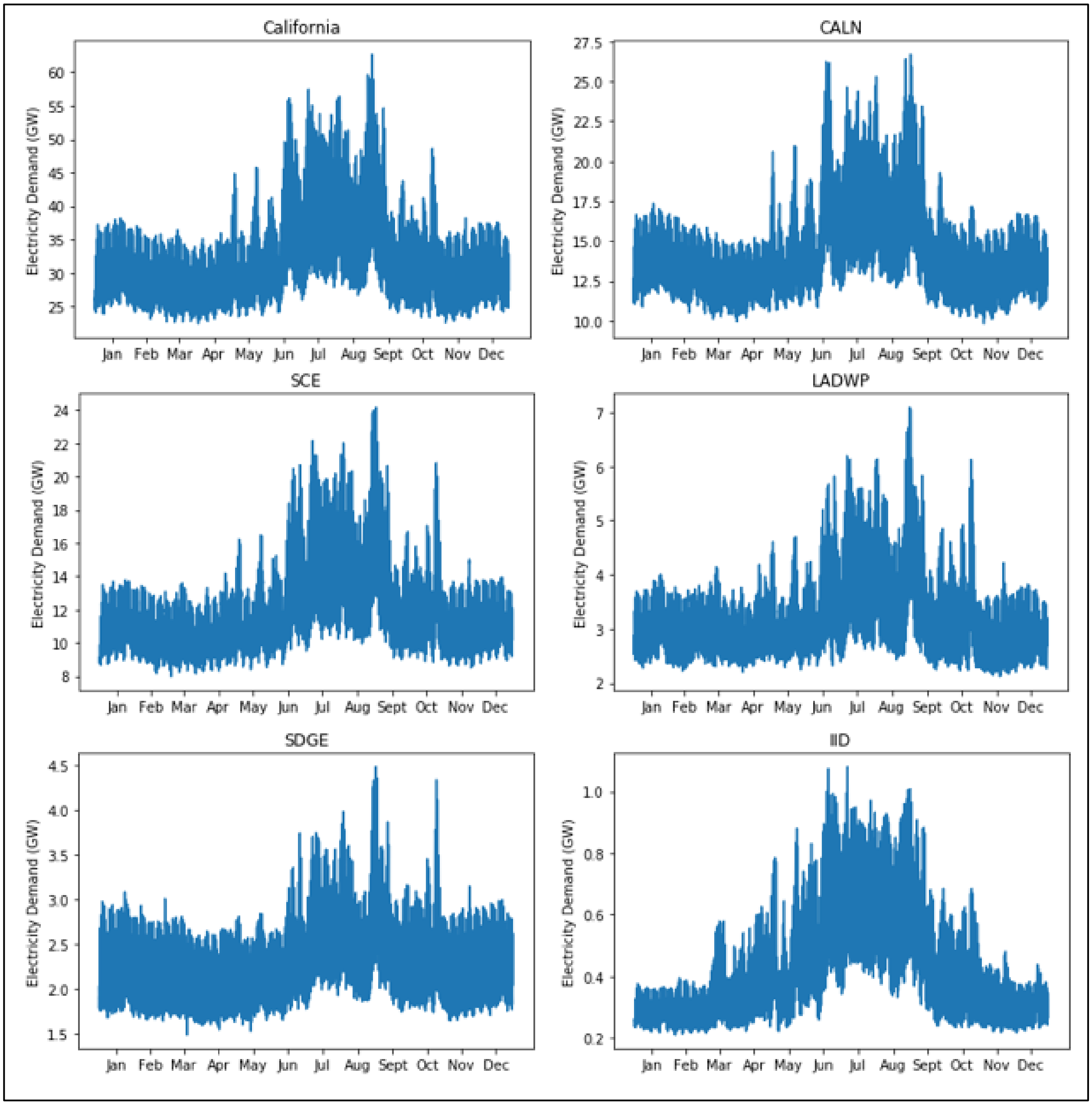

Figure 4. Annual load profile for California and each of the five model regions in 2017. 2030 and 2050 load profiles have been calculated both endogenously by the optimization model based on hourly charging profile of increasing share of BEVs, and for all other sectors of the economy, exogenously based on electricity load forecasts for California.

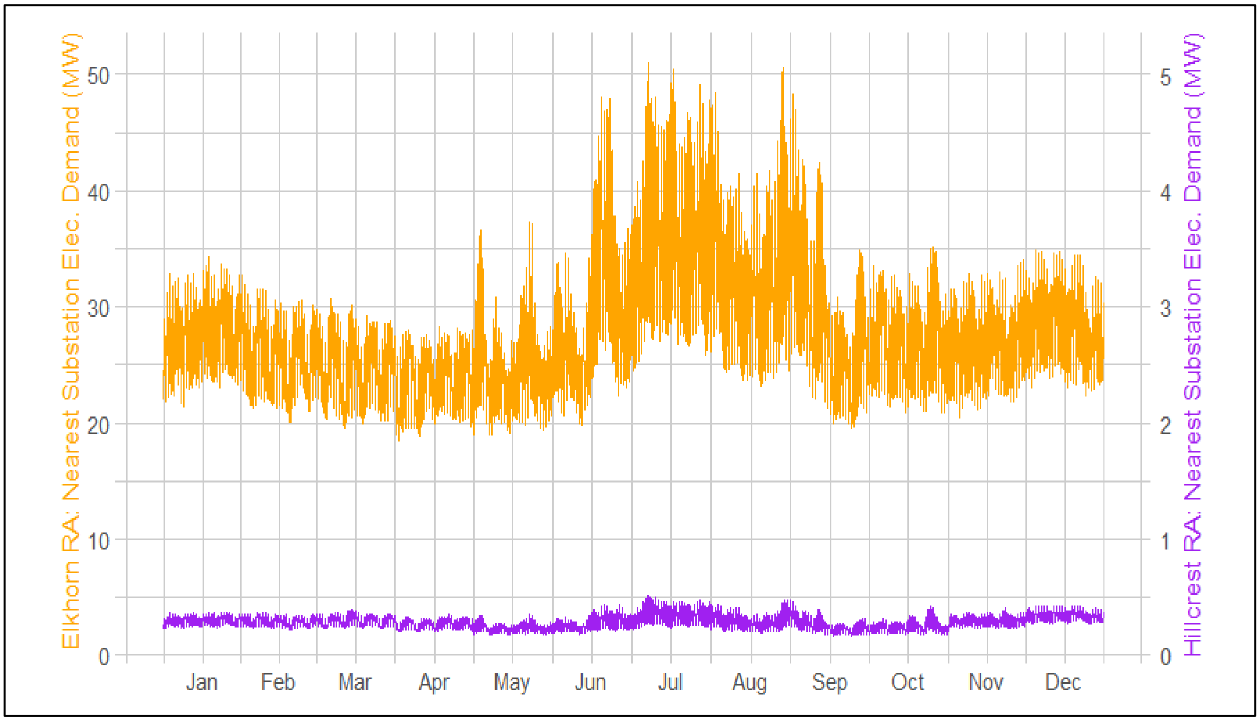

Figure 5. Annual load profile for the substations which serve the highest and lowest annual load in the CALN region.

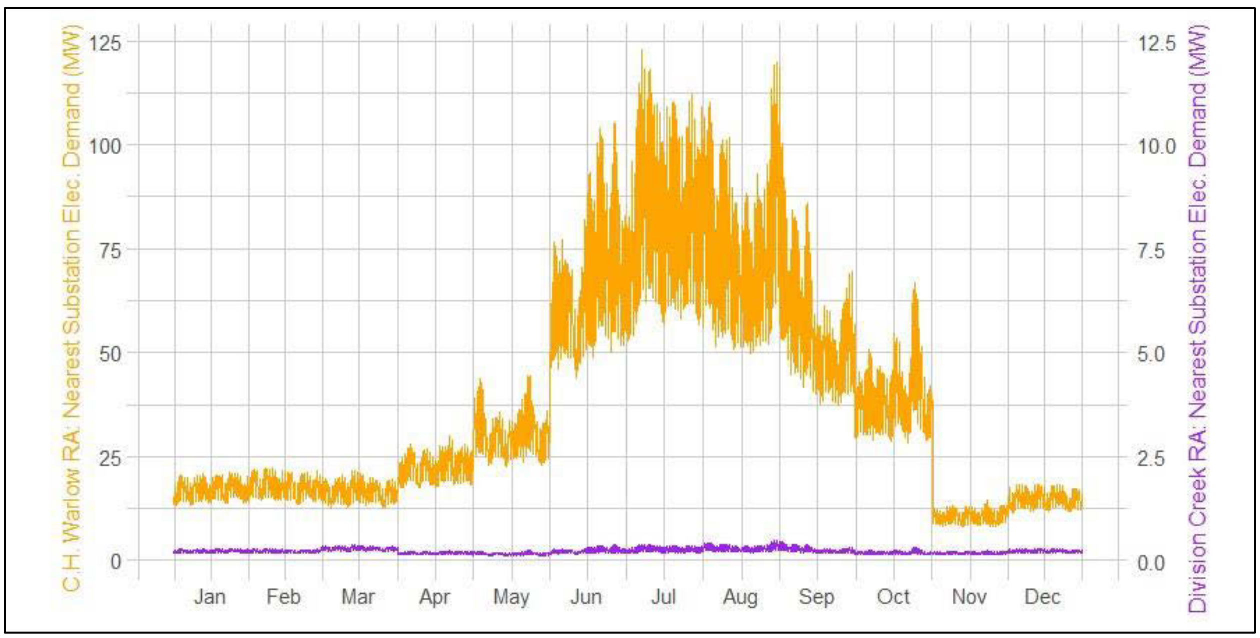

Figure 6. Annual load profile for the substations which serve the highest and lowest annual load in the SCE region.

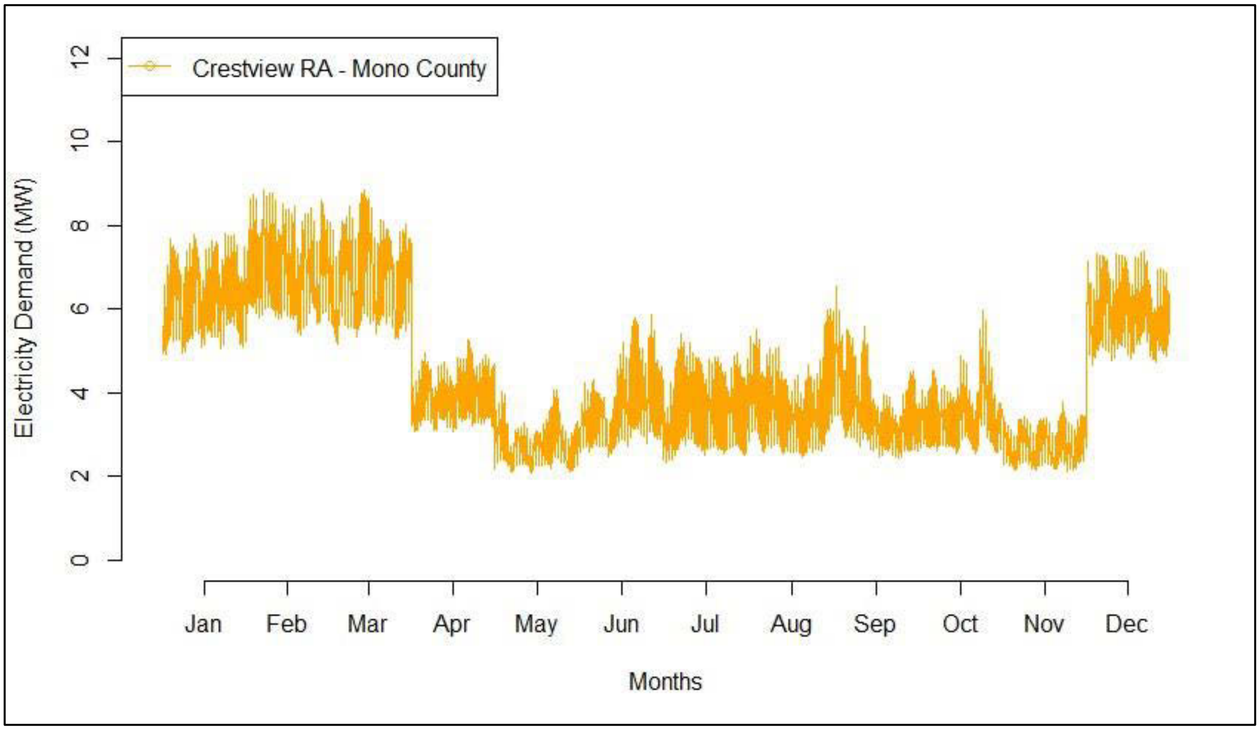

Figure 7. Annual load profile for the substation which serves the annual load in the LADWP region. There is only one rest area in the LADWP Region.

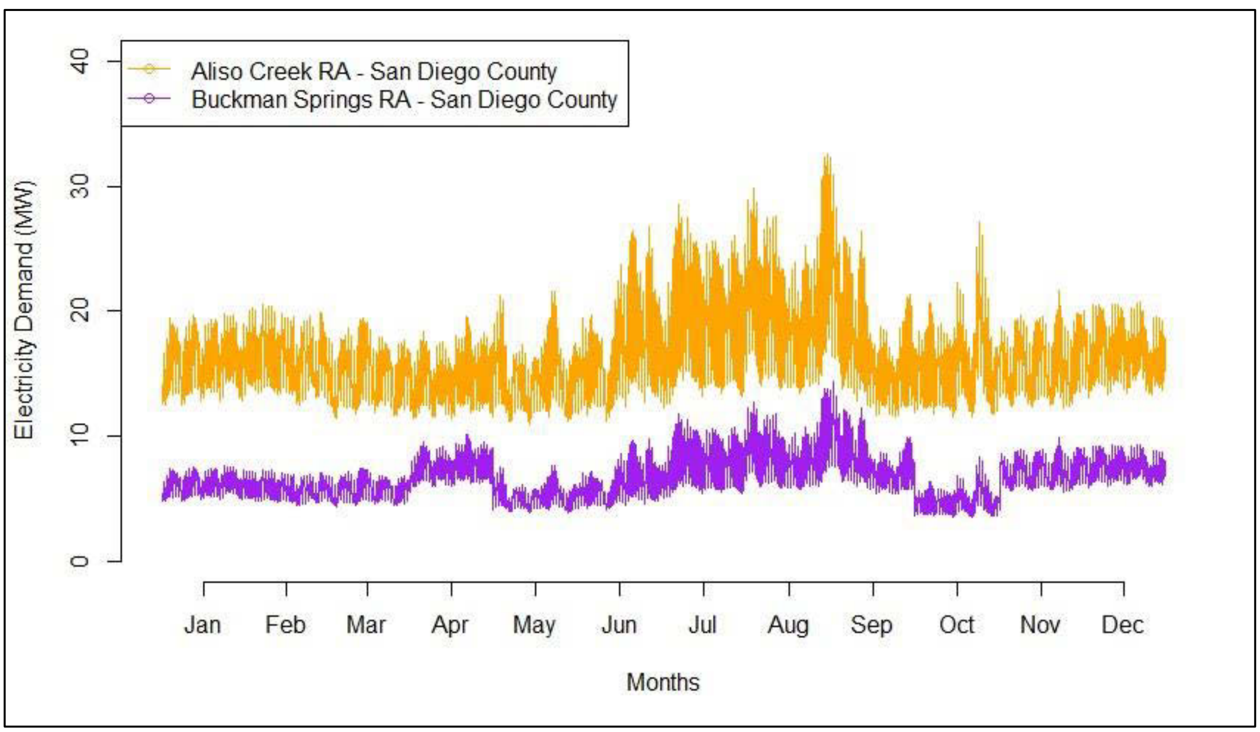

Figure 8. Annual load profile for the substations which serve the highest and lowest annual load in the SDGE region.

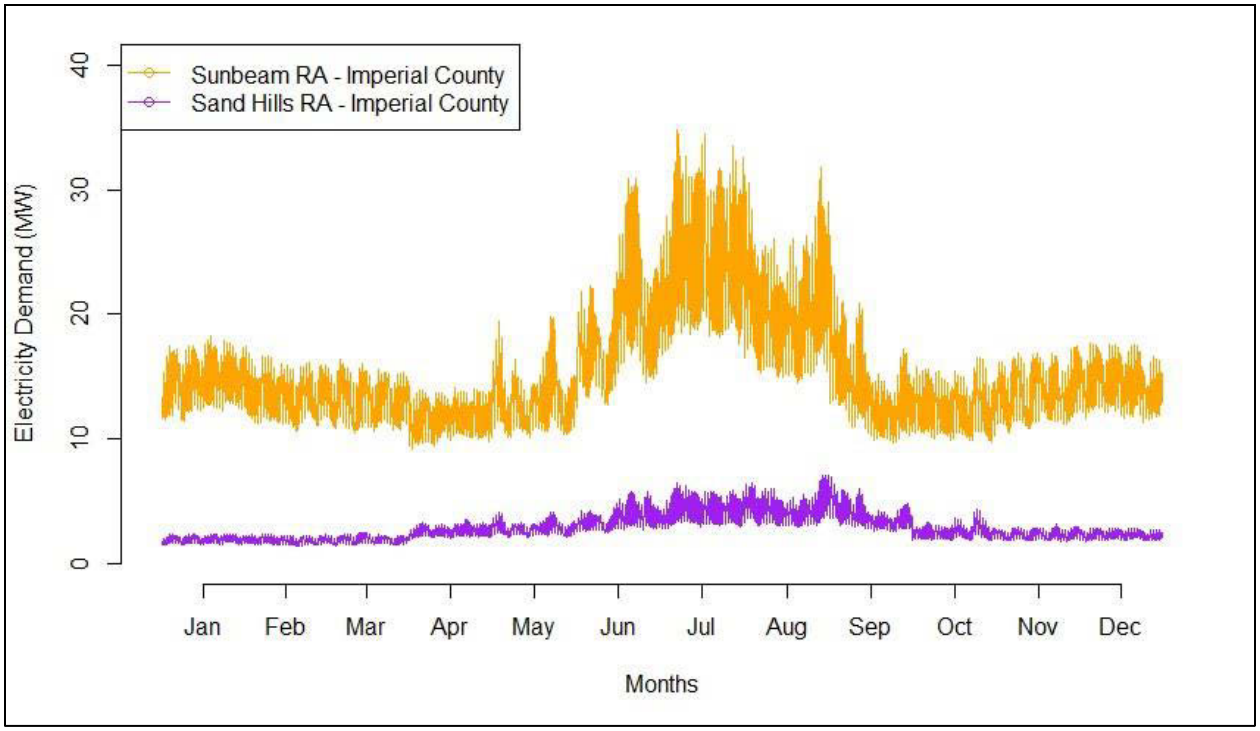

Figure 9. Annual load profile for the substations which serve the highest and lowest annual load in the IID region.

Actual energy generation and generation capacity for power plants in California were aggregated on a state and regional level. 12 categories of major generation technologies (e.g. solar, natural gas, wind, etc.) were used to organize the data. The costs of construction, maintenance, and fuel were also taken from these data sources to be used as a model input. Table 1 shows the generation capacity and actual generation for all of California, organized by generation technology. Table 2 shows the costs associated with each generation type.

Table 1. Annual generation capacity for California for 2017 by generation technology type

Technology	Generation Capacity (MWh)
CA_total_Hydro	9565.6
CA_total_Pumped Hydro	3019.0
CA_total_Solar	8551.1
CA_total_CSP	1286.4
CA_total_Wind	5654.6
CA_total_Nuclear	2323.0
CA_total_Storage	874.5
CA_total_Biopower	1151.0
CA_total_Geothermal	2684.6
CA_total_NG-CC	22381.0
CA_total_NG-CT	20055.4
CA_total_Coal	55.0

Table 2. Cost of major generation technologies in California in US$2017

Technology	Overnight Cap. Cost ($/KW)	Fixed O/M ($/kW-yr)	Variable O/M ($/MWh)	Fuel Cost ($/MWh)
Hydroelectric	3814.08	40.54	0.00	0.00
Pumped Hydroelectric	($/kWh) 615.00	40.54	0.00	0.00
Solar	1130	14.03	0.00	0.00
Concentrated Solar Power	7700.55	66.84	4.05	0.00
Wind	1495.45	51.33	0.00	0.00
Nuclear	5662.50	99.20	2.27	6.62
Battery Storage	($/kWh) 187.00	9.18	2.79	0.00
Biopower	3809.00	110.00	5.00	39.00
Geothermal	5455.40	172.19	0.00	0.00
Natural Gas - Combined Cycle	1032.00	10.00	3.00	18.15
Natural Gas - Combustion Turbine	882.00	12.02	7.03	27.79
Coal	2108	53.63	7.54	18.92

Next, the two main non-dispatchable, or variable, generation technologies used in California were studied explicitly: solar and wind. Because the wind does not always blow and the sun only shines during the day when not cloudy, the annual generation profiles for wind and solar were analyzed for 2017. This will provide a baseline for when these resources might be expected to be available in the future. Figure 10 and 11 show the annual generation profile for solar and wind, respectively, for the State of California and each region in 2017. In addition, imports are an important part of how electricity demand is served in California and will be included as a model input. Figure 12 shows the imports for California for 2017.

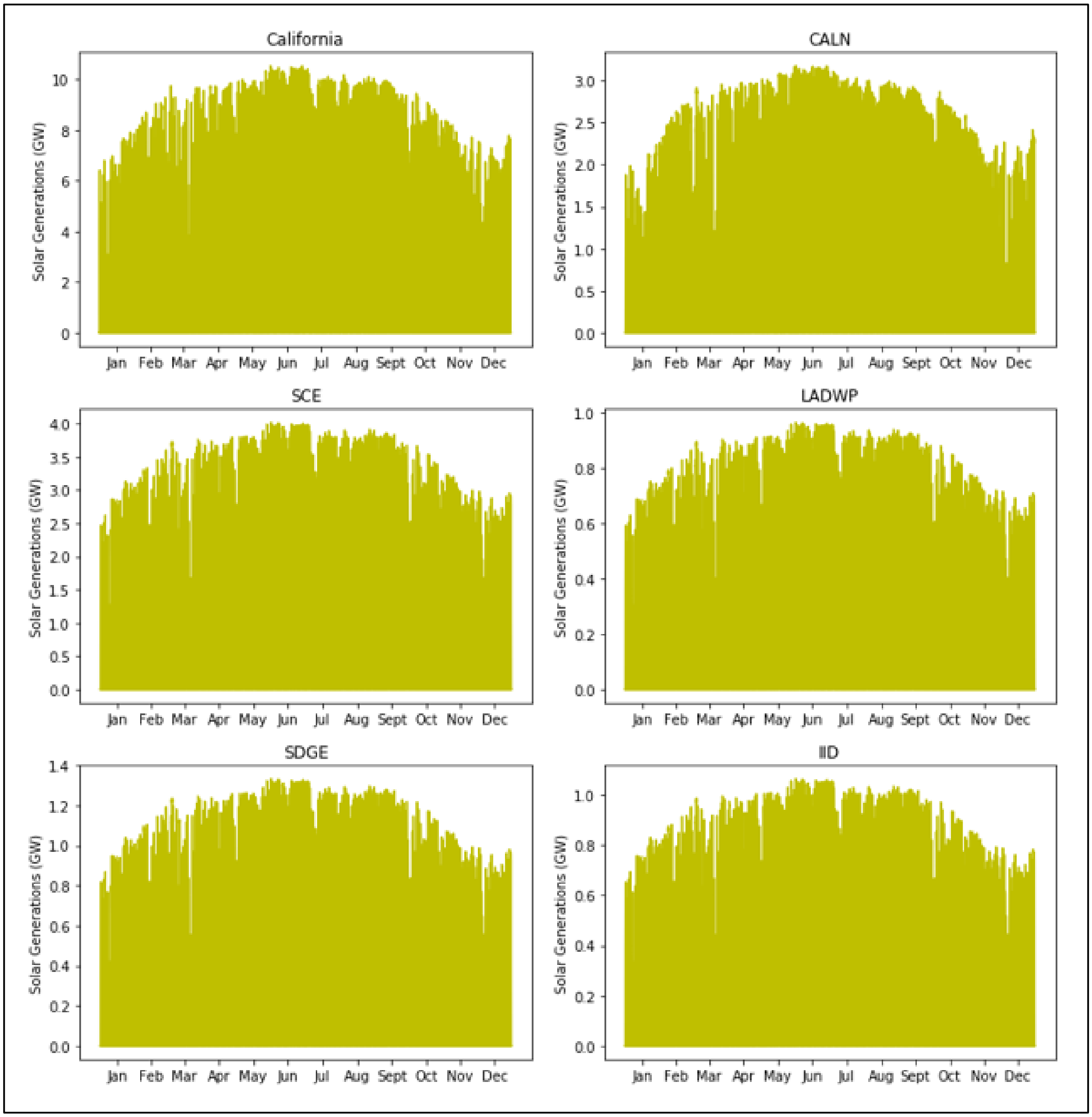

Figure 10. Annual solar generation profiles for California and each region for 2017.

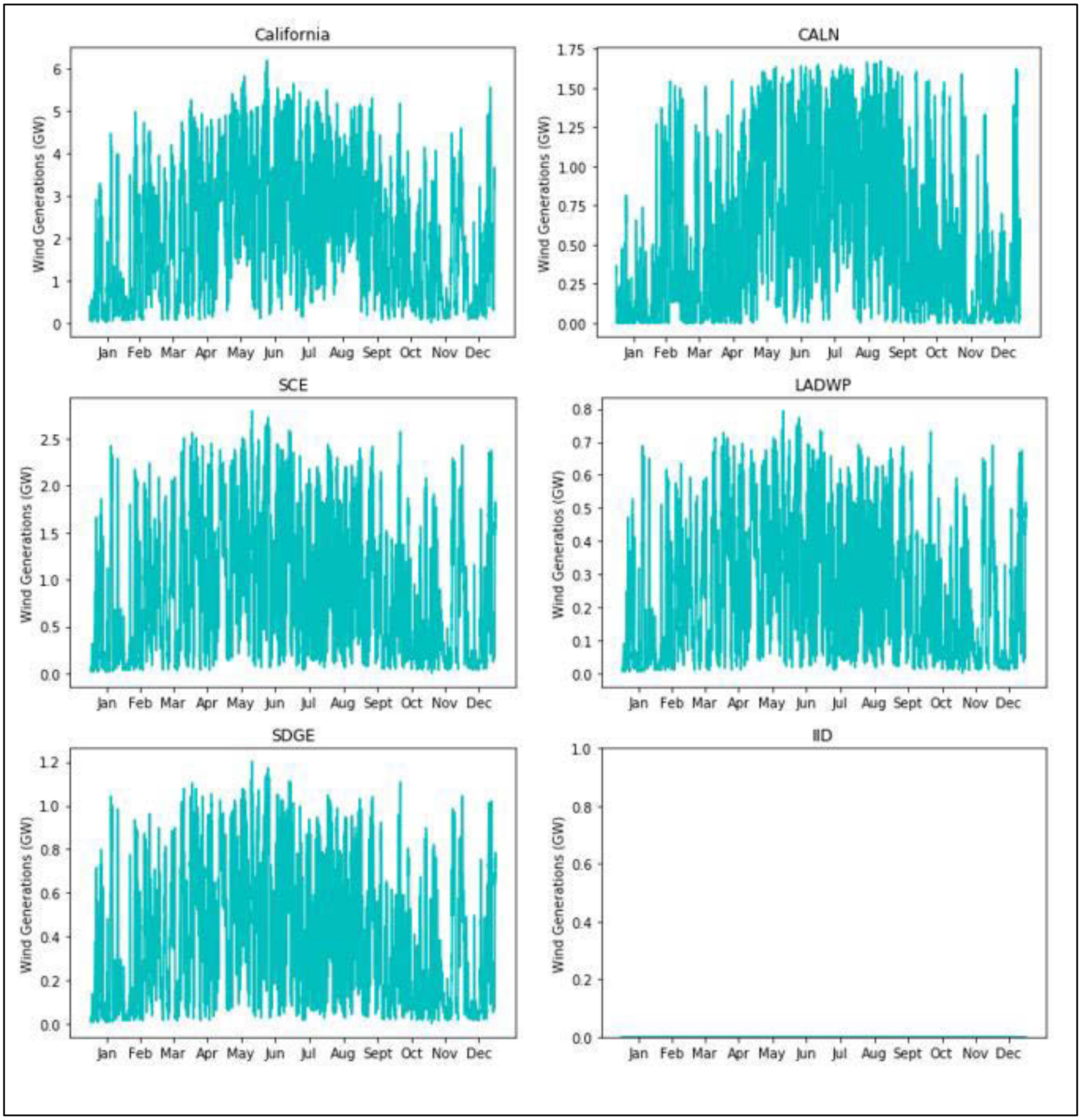

Figure 11. Annual wind generation profiles for California and each region for 2017. For IID, no wind farm generation has been reported.

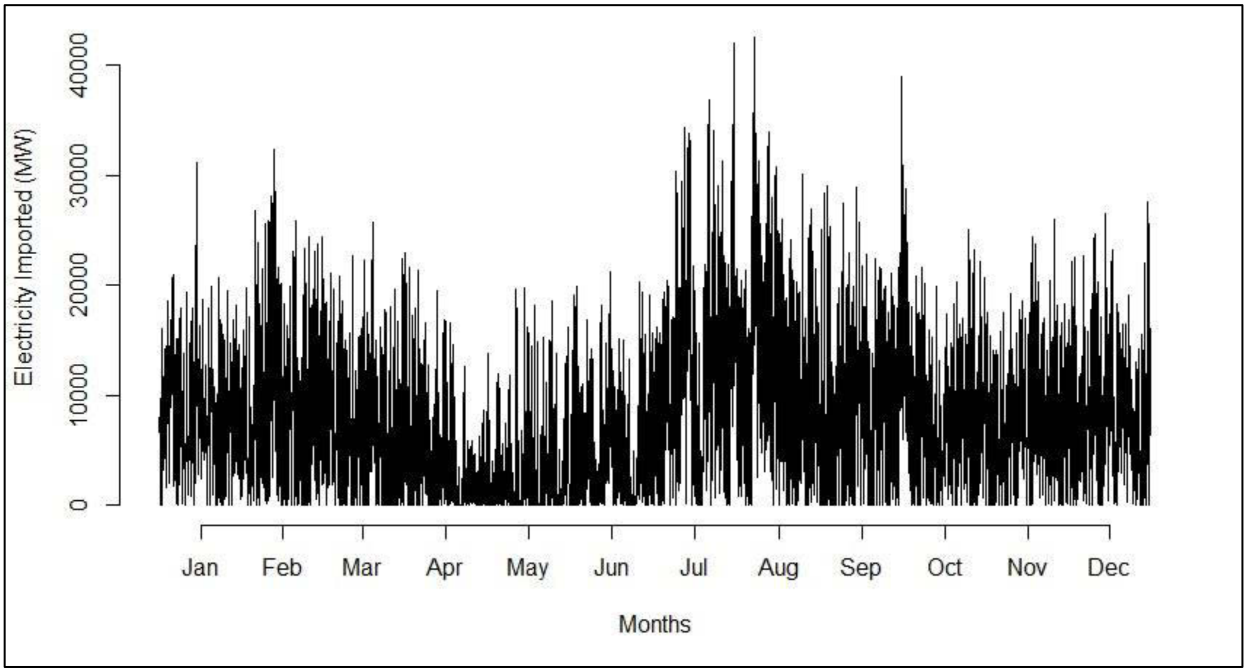

Figure 12. Hourly import profile for 2017 for California.

Because some of California's load is met by imports, transmission capacity between neighboring regions were important to include as a model input. Transmission capacity data between regions in the Western Interconnection was taken from the US EPA's Base Case for their Integrated Planning Model. This data set provides total transmission capacity to and from all regions in California. The data set used regions that correspond with the regions shown in Figure 12, with the exception of San Francisco being a region of itself. San Francisco only has transmission capacities to CALN, which in the context of the analysis at hand, includes San Francisco. Thus, this transmission link has been neglected. The network of transmission connection serving California is detailed in Table 3 in the various parts of the network. Figure 13 further illustrates the transmission network of California.

Table 3. Summary of transmission network in California showing interregional transmission capacities. Key: PNW – Pacific Northwest, AZ – Arizona, SNV – South Nevada, NNV – North Nevada, UT – Utah.

From Region	To Region	Transmission Capacity (MW)
CALN	NNV	100
CALN	PNW	3,675
CALN	SCE	1,275
LADWP	AZ	468
LADWP	PNW	2,858
LADWP	SCE	3,750
LADWP	SNV	3,883
LADWP	UT	1,400
SDGE	AZ	1,168
SDGE	IID	150
SDGE	SCE	2,440
AZ	LADWP	362
AZ	SDGE	1,163
AZ	IID	195
AZ	SCE	1,600
IID	SDGE	150
IID	AZ	163
IID	SCE	600
NNV	CALN	100
PNW	CALN	4,200
PNW	LADWP	2,600
SCE	CALN	3,000
SCE	LADWP	3,750
SCE	SDGE	2,200
SCE	AZ	1,082
SCE	IID	50
SCE	SNV	2,814
SNV	LADWP	2,300
SNV	SCE	1,700
UT	LADWP	1,920

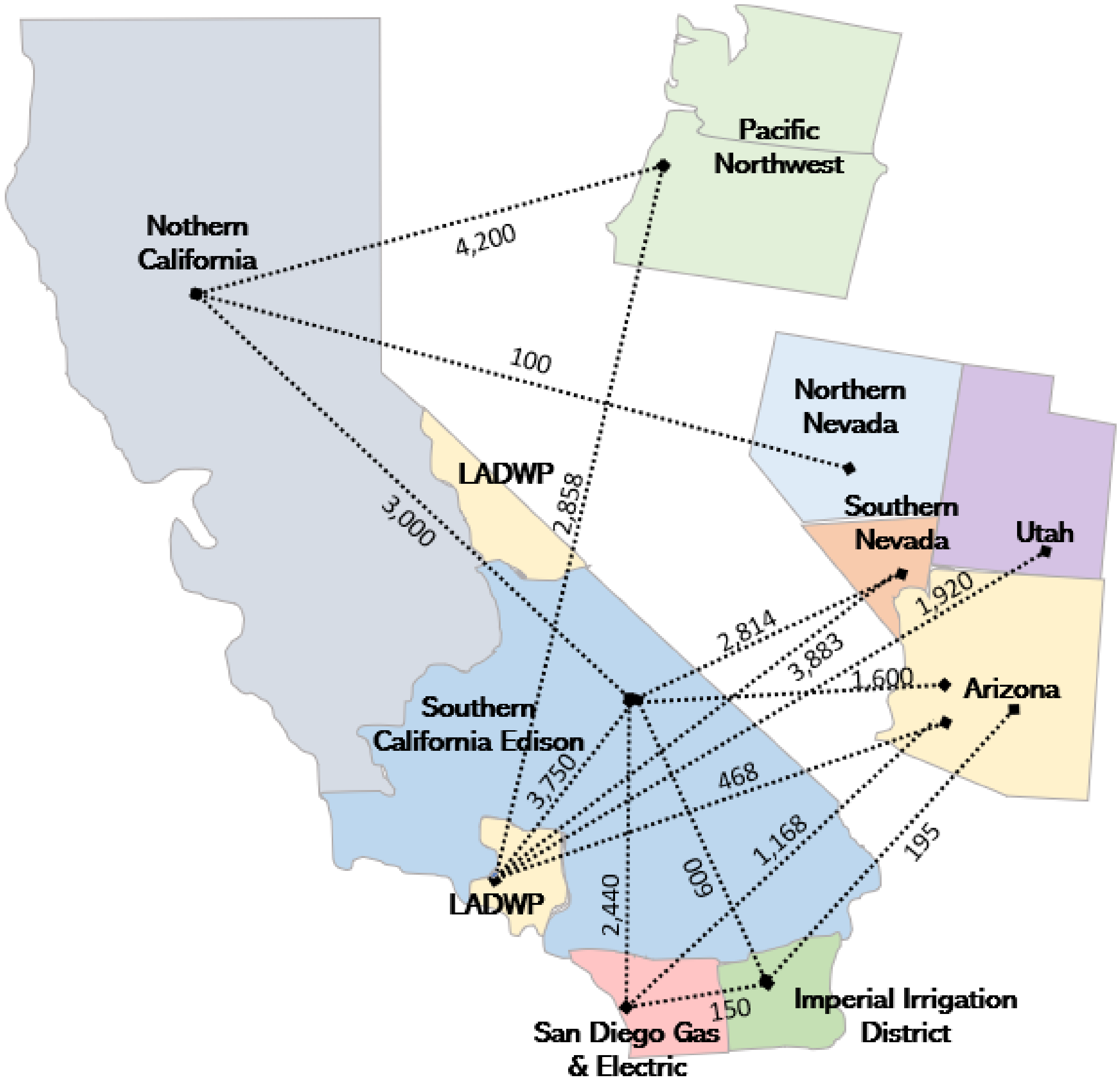

Figure 13. Diagram of California's transmission network.

Model Construction

The transportation and energy system data were used to create a so-called "reference energy system." This reference energy system is used by the MESSAGE to optimize the charging demand associated with the EV penetration scenarios shown in Table 3. Figure 14 shows the various components of the MESSAGE reference energy system.

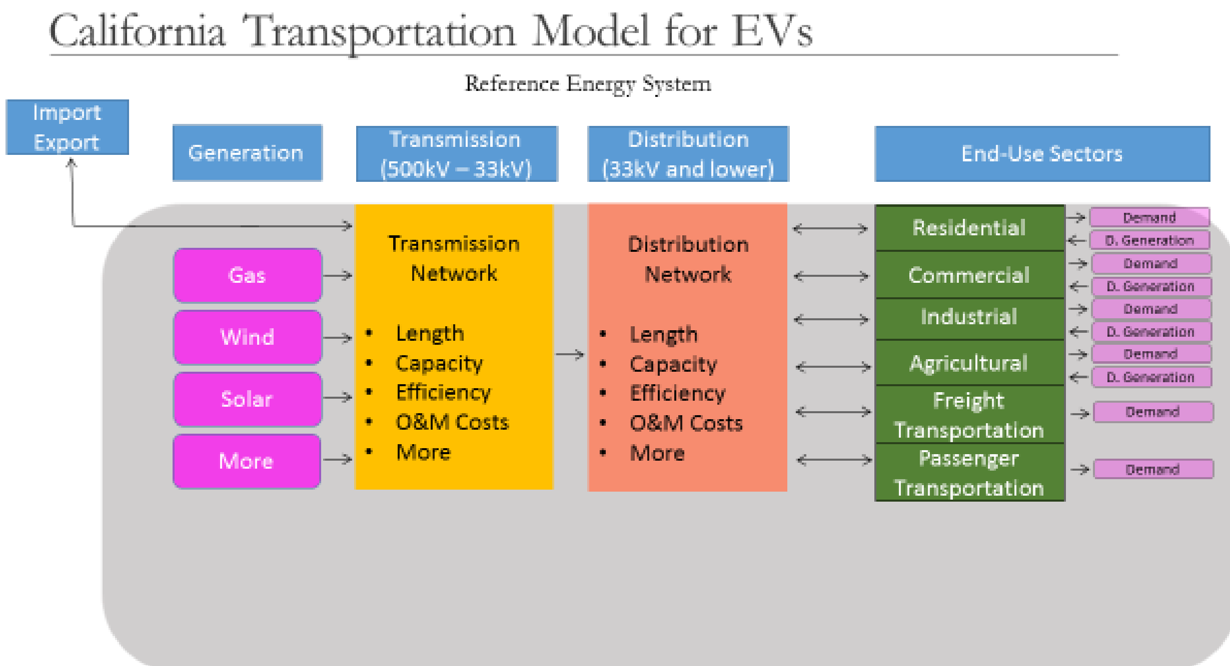

Figure 14. Reference Energy System for California transportation model. ZEVs are incorporated in the transportation end-use sector to provide the energy supply for the actual VMT in the highways.

The constructed model based on MESSAGE platform has the following advantages:

- Flexible, multi-sector model built on MESSAGE platform,
- A 5-region electric sector/EV grid integration model for CA
- 8760 hrs/period for all California Load and VRE during 2017, 2030, 2050, acting as a dispatch model for the grid
- Capacity expansion planning for future periods

Transportation Forecast Analysis

In order to understand future travel patterns that will determine the amount of EV charging infrastructure needed at highway rest areas, a model was specifically created to understand the movement of vehicles across the state of California in terms of long-distance travel demand at highway rest areas. This model is distinct and separate from the CALZEEV model previously mentioned. Travel demand at each station was quantified by charging demand and total vehicles distributions broken down by all hours of the year for 2017, 2030, and 2050. A modified flow capture location model (FCLM) is used as the basis for analysis. This type of model is effective for addressing long-distance travel problems (Nie and Ghamami, 2013). Several studies have employed a FCLM to aid in optimally locating EV charging stations (Kuby and Lim, 2005; Riemann, Wang and Busch, 2015; Wu and Sioshansi, 2017). The model at hand differs from a traditional FCLM in that it only serves to quantify the transportation demand at certain locations and does not seek to perform any optimization.

The California Statewide Travel Demand Model (CSTDM) was selected to provide an aggregated total of long-distance travel in the State. While the CSTDM allows users to build and run specific scenarios for the model to analyze, this approach was time consuming and was not able to provide charging demand or total vehicle distributions at specified locations on an hourly time scale. Caltrans has made publicly available some outputs of this model, including a table of long-distance trips on an average Spring/Fall day. Specifically, this data set consists of a matrix of county to county long-distance travel in the State based on the year 2010 along with a future projection for 2040 (California Department of Transportation, no date). The matrix details the number of peak and off-peak vehicles that travel between two given counties on an average Spring/Fall day. In total, over 2,700 unique trip paths were included in the dataset with over 343,000 vehicle trips described. When data was needed for years other than 2010 and 2040, it was interpolated or extrapolated accordingly.

All travel to and from a given county was assumed to originate or terminate in the most populated city in the county. In addition to in-state travel, the CSTDM trip matrix also included trips that either started in California and ended out-of-state or vice versa. Five out-of-state travel locations were considered. These include Oregon, Nevada North, Nevada South, Arizona, and Mexico and all travel associated with these locations was assumed to be to/from Medford, OR, Reno, NV, Las Vegas, NV, Phoenix, AZ, and Tijuana, Mexico, respectively. The locations assumed for out-of-state origins and destinations were the closest major city to the California border. This ensured that only the VMT that would contribute to the travel demand in California would be included in the analysis.

Python code was developed to automate data acquisition from the Google Directions Application Programming Interface. Google Directions was used for finding the distance and driving time between points. The default route predicted by Google Directions was assumed to be the path that motorists would take from one point to another. All driver preferences were neglected, and no concern was given to possible en route congestion. It was assumed that if stopping at a rest area did not add more than 1.25 miles to the overall trip distance, then the vehicle would pass by the rest area en route to its destination. 1.25 miles was selected as the margin because certain rest areas require vehicles to drive a short distance off the main roadway to utilize the rest area. The miles that a vehicle had driven prior to reaching any given rest area were tracked for further analysis.

The time of day that vehicles arrived at a rest area was determined based on a start time distribution that was developed for the model. While the actual long-distance travel matrix only included peak and off-peak vehicle totals, the accompanying CSTDM report provides the percentage of vehicles beginning their trip in five periods throughout the day, grouped by trip purpose and duration of the trip (Cambridge Systematics, 2014). For the purposes of this study, an average of business/commute and personal trips was used in assigning start times to each trip. All trips 200 miles and under were treated as potential day trips and assigned a start time based on the single day trip distribution. On the other hand, trips over 200 miles were assumed to be multiday trips and were assigned start times as such. As the CSTDM report did not explicitly detail the distribution of start times within a time period, values were estimated to allocate start times within each of the five periods throughout the day. Table 4 shows the distribution used for the five periods for both single and multiday trips. Table 5 shows the assumed distribution for each of the five periods as well as the hour multiplier for single-day and multiday trips. The hour multiplier was determined by multiplying the assumed fraction of travel for each hour in a time period by the corresponding time period fraction shown in Table 4. The hour multipliers were applied directly to vehicle totals presented in the CSTDM trip dataset to estimate the average number of vehicles departing throughout the day. The results of the model indicate the probable number of vehicles utilizing rest areas. It should be noted that the sum of peak and off-peak values in Table 4 both add to one each because both peak and off-peak values are represented separately in the CSTDM dataset.

Table 4. Distribution of peak and off-peak trip start times.

Time Period	Early Off-peak (03:00-05:59)	AM Peak (06:00-09:59)	Midday Off-peak (10:00-14:59)	PM Peak (15:00-18:59)	Late Off-peak (19:00-02:59)
Single-day Trip	0.292	0.480	0.457	0.520	0.251
Multiday Trip	0.030	0.576	0.573	0.424	0.397

Table 5. Hour multipliers for single-day and multiday trips.

Time Period	Hour of Day	Travel Fraction	Single-day Trip Multiplier	Multiday Trip Multiplier
Late Off-peak	0:00	0.100	0.025	0.040
	1:00	0.050	0.013	0.020
	2:00	0.050	0.013	0.020
Early Off-peak	3:00	0.250	0.073	0.007
	4:00	0.250	0.073	0.007
	5:00	0.500	0.146	0.015
AM Peak	6:00	0.300	0.144	0.173
	7:00	0.400	0.192	0.230
	8:00	0.200	0.096	0.115
	9:00	0.100	0.048	0.058

Time Period	Hour of Day	Travel Fraction	Single-day Trip Multiplier	Multiday Trip Multiplier
Midday Off-peak	10:00	0.100	0.046	0.057
	11:00	0.150	0.069	0.086
	12:00	0.250	0.114	0.143
	13:00	0.350	0.160	0.201
	14:00	0.150	0.069	0.086
PM Peak	15:00	0.150	0.078	0.064
	16:00	0.350	0.182	0.148
	17:00	0.350	0.182	0.148
	18:00	0.150	0.078	0.064
Late Off-peak	19:00	0.200	0.050	0.079
	20:00	0.250	0.063	0.099
	21:00	0.150	0.038	0.060
	22:00	0.100	0.025	0.040
	23:00	0.100	0.025	0.040

Scenario Analysis

Additional modifications were still needed as the results up to this point would be representative of all long-distance travel. Presently, not all vehicles traveling long-distance are ZEVs and in coming years not all vehicles traveling long-distance will be ZEVs either. In order to appropriately account for the increasing fleet of ZEVs and to answer the research questions of this work, three scenarios for BEVs were selected and are detailed in Table 6. The total number of light-duty vehicles on the road in 2017 was assumed to be constant for all model years. Ideally, conventional vehicles will be retired in place of ZEVs. The total number of light-duty passenger vehicles in California in 2017 and the corresponding number of BEVs were taken from data published by the California Department of Motor Vehicles (California Department of Transportation, 2018a). The BEV range in 2017 and 2030 was taken from a weighted average of all BEV types in future years presented by the Energy Information Administration (U.S. Energy Information Administration, 2019). In the case of 2050, there is great uncertainty in what BEV ranges might be, so the range was selected to be comparable to a contemporary internal combustion engine vehicle. While the total BEV fleet for 2017 was based on actual data, fleet values for 2030 and 2050 had to be estimated. The 2030 value was assumed to be 5 million as this is the State target for ZEV penetration by 2030. For 2050, 100% BEV penetration was selected as an extreme case. While it is not likely that California's fleet will be exclusively BEVs in future model years, the results of the model scenario will help highlight the magnitude of the change in refueling infrastructure needed to support a mass adoption of BEVs.

Table 6. BEV Scenario details.

Model Year	Total BEVs on Road	%BEV Penetration into the fleet	BEV Range (miles)
2017	225, 240	0.75	154
2030	5,000,000	16.6	241
2050	30,087,116	100	350

Using the percent of BEV penetration shown in Table 6, results reflecting all long-distance travel for model years were scaled accordingly. Still, additional analysis was needed to find out which rest areas were likely to be utilized for charging. Figure 15 shows the logic used by the model in deciding if a vehicle would utilize a rest area it passes en route to its destination. It was assumed that a vehicle would use at the most, 80% of its total range before recharging. Due to range anxiety, BEV drivers will be more comfortable recharging with more than single digit range remaining. In addition, it is assumed that DCFCs will be employed in recharging and will provide at least 80% of the vehicle's battery capacity in 30 minutes. As vehicles are not completely out of charge before charging, then during a 30-minute charging event they will be able to gain greater than 80% charge to use the excess as a safety cushion to avoid range anxiety when using 80% of their full battery capacity. All vehicles are assumed to begin a trip with a full charge and be able to charge at their destination.

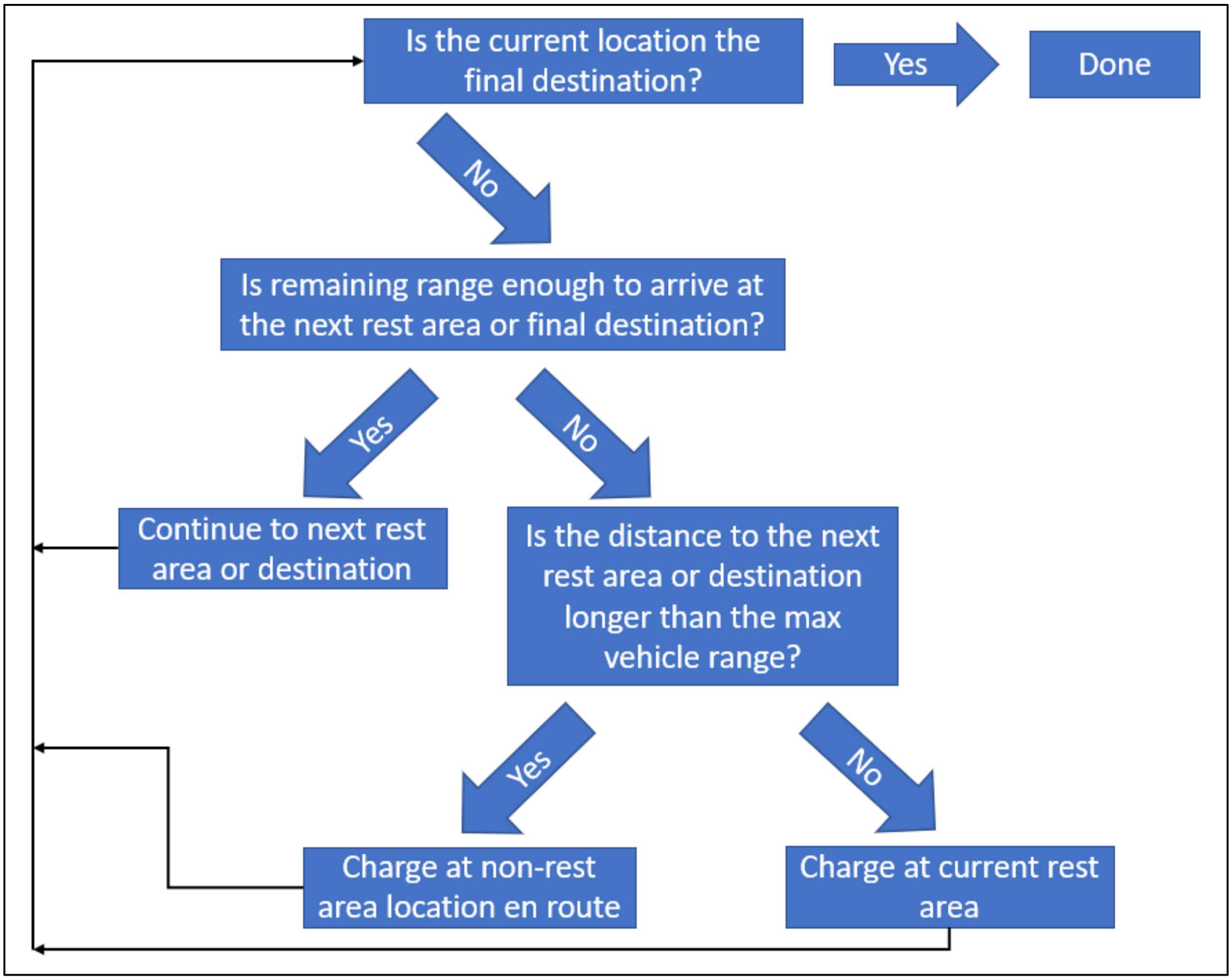

Figure 15. Model logic employed in determining if rest areas passed en route to a destination will be utilized for recharging.

Finally, using the peak and off-peak totals from the CSTDM dataset, the distribution of start times shown in Table 4, and which rest areas are utilized for en route charging, travel demand profiles were developed for an average Spring/Fall day for each rest area. Data from the 2012 California Household Travel Survey Report was used to estimate weekly travel distributions (Nustats Research Solutions, 2013) while data from the Federal Highway Administration was used to estimate travel demand throughout the year (Federal Highway Administration, 2018). The results of the model are two profiles for each rest area. The first is a charging demand per hour distribution, reflecting only the VMT that contributes directly to charging demand at a given rest area. The second is a total vehicles distribution, or in other words, the total number of vehicles in an hour that would need to utilize the rest area for recharging. These two distributions were created for each rest area in the State.

Modeling Results and Policy Recommendations

Not surprisingly, we found that the charging demand at rest areas increased moderately between 2017 and 2030 and then significantly increased between 2030 and 2050. Figure 16 shows the charging demand, in terms of MWh/hour for all model years in California for an average Spring/Fall day. The energy requirement for VMT, and the range of the battery determine the need for charging at each rest area. Figure 17 shows the start times and quantities for all BEV long-distance travel in California for an average Spring/Fall day. Based on electricity required for driving and each BEV battery capacity, the model optimizes charging demand and the required charging stations necessary to meet this demand. The electricity could be provided through distribution and transmission capacity expansion resulting in installing more renewable or thermal electricity generation plants.

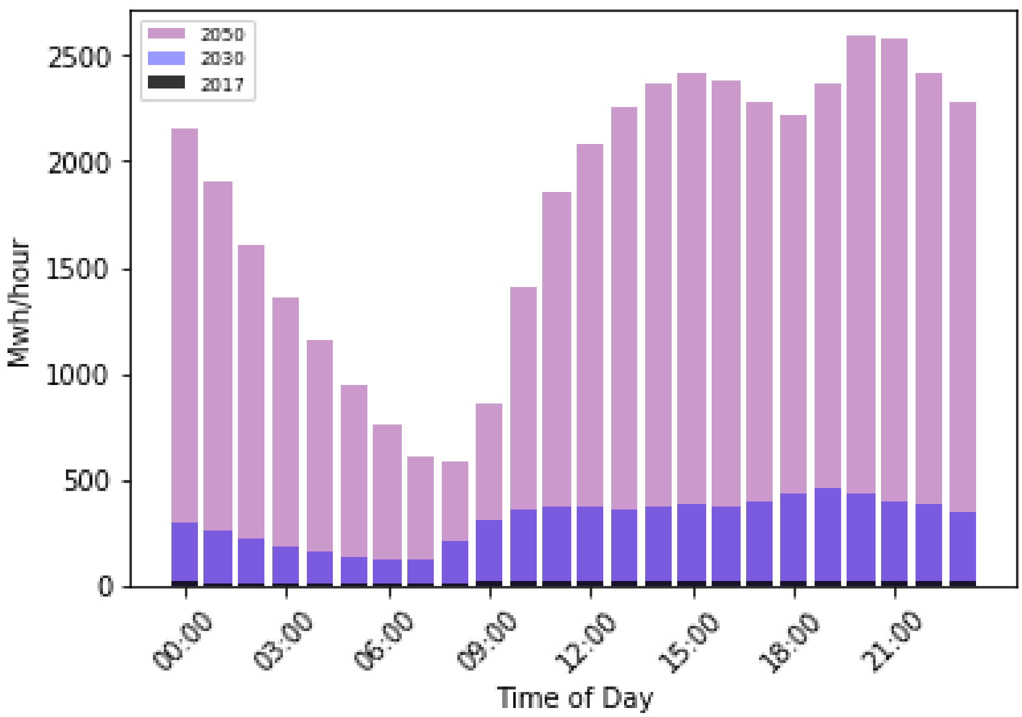

Figure 16. Statewide aggregated charging demand at rest areas during an average Spring/Fall day, in terms of megawatt-hour/hour for all BEV long-distance travel in California for all model years.

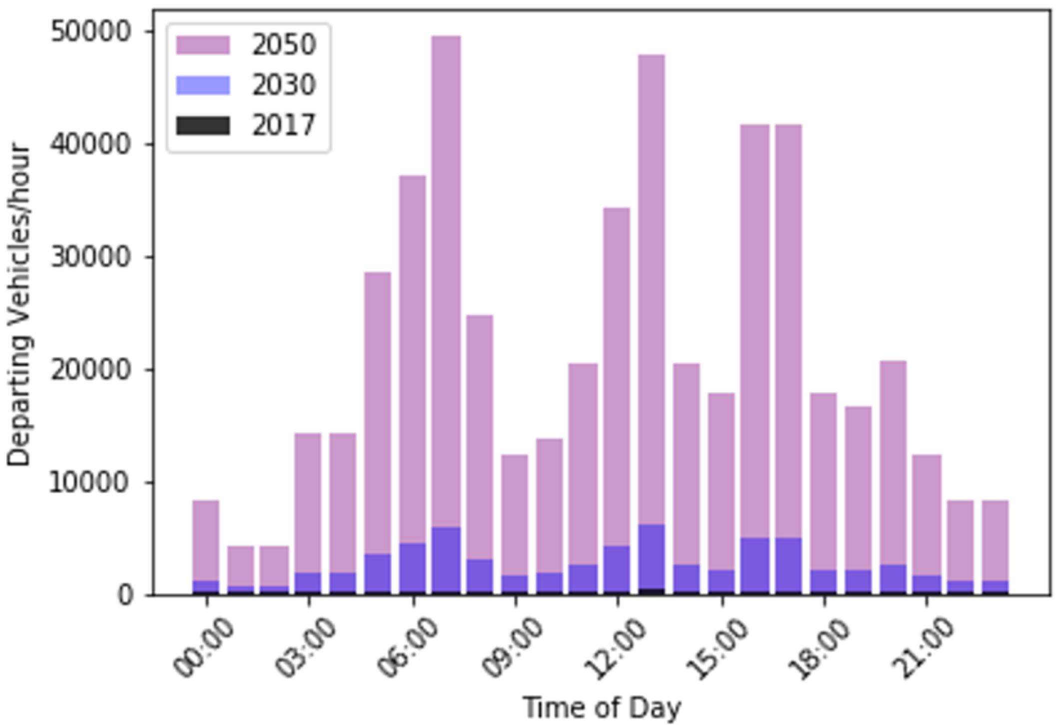

Figure 17. Start times and quantities for all BEV long-distance travel in California for all model years.

Figure 16 shows that a significant portion of travel is during daylight hours, especially during the summer. This trend is promising for the utilization of solar power to facilitate roadside charging at rest areas, which may help mitigate impacts associated with the duck curve.

The duck curve refers to the shape of the energy net load curve (i.e., real time demand minus variable energy resources). When electricity demand is lowest (during the daytime hours), solar production is at its highest, which causes the "duck shaped" discrepancy between demand and resource availability. The problem with this phenomenon is that occasionally solar power must be curtailed in favor of non-renewable generation sources (mainly natural gas) to help with the steep evening ramp up in electricity demand as people return home in the evening. Using excess solar energy for BEV charging is one of the solutions proposed by California Independent System Operator (CAISO) to increase renewable energy penetration in the state and ensure reliability of the electric grid (California Independent System Operator, 2016). Furthermore, Figure 17 shows three high-peak times for starting long-distance travel. In the case of the latter two peaks, occurring around 1:00 PM and 4:00-5:00 PM, solar power could be used to provide these vehicles with a full charge prior to departing.

Figure 16 shows that by 2050, charging demand (based on projected hourly VMT) will peak in the evening hours. This anticipated timeframe for charging demand, coupled with the existing duck curve in California, could add stress to the grid and increase California's reliance on non-renewable generation sources. In order to mitigate the effects of high charging demand during already high demand time for the grid, policies can be implemented to promote EV charging earlier in the day. While this can take many forms, one idea could be to incentivize roadside charging during the morning, when solar energy is widely available. Some studies have even explored the possibility of BEV batteries sending electricity back to the grid during the evening ramp up hours (Hu et al., 2019; Krzywda, Jurasz, & Mikulik, 2018; Richardson, 2013). As charging station networks expand, it becomes increasingly crucial that electricity infrastructure is able to support increased demand. If such planning is successful, renewable curtailment can instead be used to charge the growing fleet of ZEVs in California.

Figure 18 and 19 show the charging demand, in terms of MWh/hour, and the total vehicles profiles, respectively, for the Wiley's Well Rest Area for the 2030 scenario. Consistent with the input data, and as shown in Figure 16-17, VMT values peak during weekends, the summer, and December. The results of the transportation model do not account for previously installed charging infrastructure that drivers may utilize, but rather illustrate the charging demand at rest areas. This data will be used as an input to the MESSAGE model, which will optimally meet the charging demand using all available charging resources and installing additional resources as needed both in rest areas and within 25 mile of the rest areas.

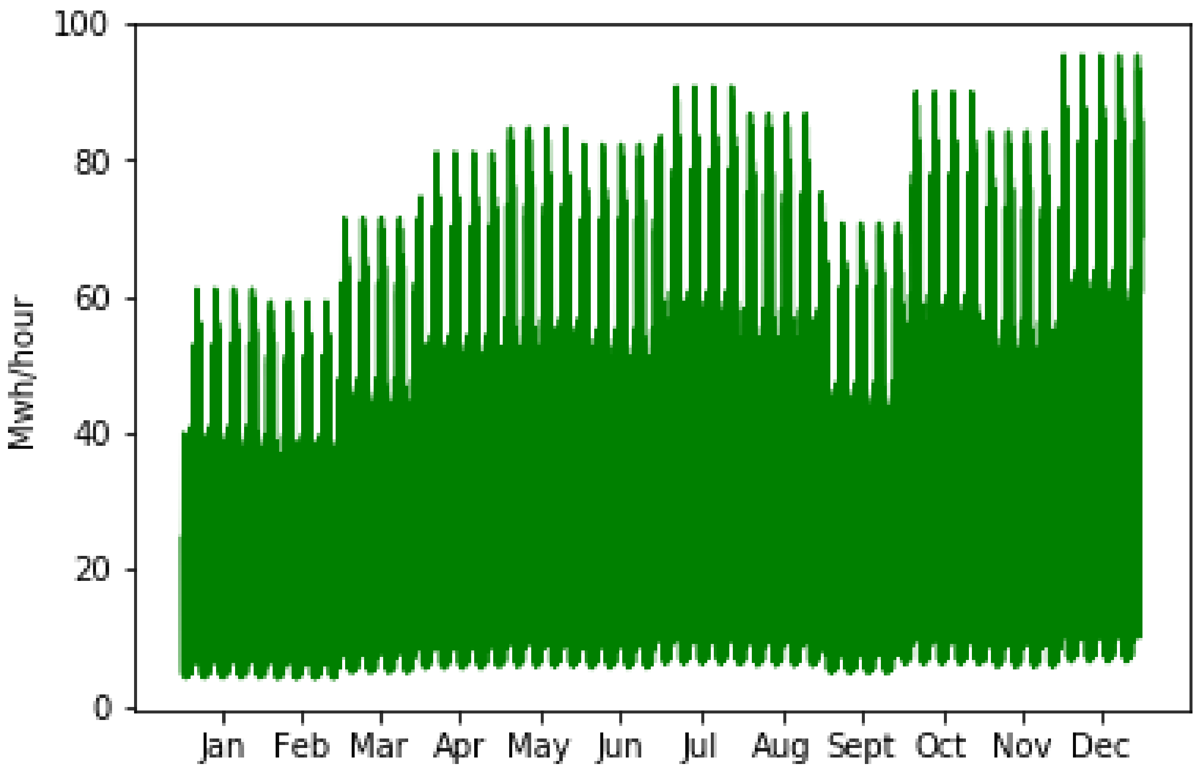

Figure 18. Annual charging demand profile for the Wiley's Well Rest Area for the 2030 model year.

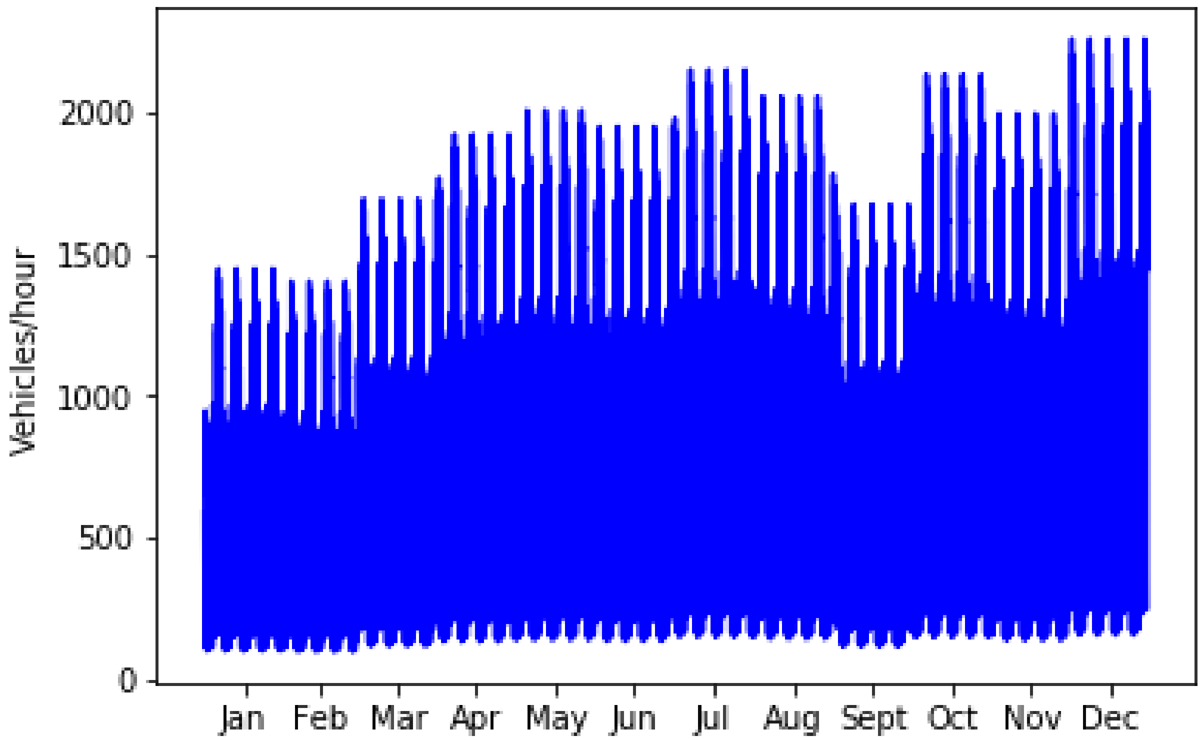

Figure 19. Hourly total vehicles profile for the Wiley's Well Rest Area for the 2030 model year.

The MWh/hour and vehicles/hour for each rest area was computed and then used to categorize rest areas based on the amount of energy and total charging stations that would be needed at each location. A vehicle was considered to be in need of significant charging if it has expended more than two thirds of its SOC (State of Charge). So, if the average MWh/hour for a rest area was greater than two thirds the useable range for the given scenario year, a large amount of energy would be needed for recharging. In order to evaluate the potential for a queue to form and the need for additional charging stations, a normal rest area was assumed to have two charging stations in our base year 2017. With each charge taking approximately 30 minutes, a normal rest area today would serve on average four vehicles per hour with no queue. In the case that a queue would form due to a high number of vehicles using the rest area in question, then the rest area would need additional charging stations. Combining the measure of VMT/hour and vehicles/hour, four categories were developed and include Normal, Congestion, HighDemand, Congestion/HighDemand. Table 7 further details the specific parameters for each grouping for our base year 2017. We assume that in 2017, two charging stations were installed in each rest area. The numbers of charging stations will increase to 10 by 2030 and 30 by 2050.

Table 7. Descriptions of rest area groupings to be used for formulating eventual policy recommendations for highway rest areas in California. This table presents assumptions for our base year 2017 with 2 charging stations for each rest area, serving 4 BEVs per hour. We assume that the number of charging stations for each rest area increases to 10 in 2030 and 30 in 2050, serving 20 cars per hour in 2030 and 60 cars per hour in 2050.

Rest Area Grouping	EV Battery State of Charge Limits in terms of remaining range (Low to High)		Vehicle/Hour Limits (Low to High)		Description
Normal	>=0	<=(2/3)* range	>=0	<=4	The normal condition is when charging demand can be met with two EV charging stations. The risk for a queue or excess electricity demand is low.
Congestion	>=0	<=(2/3)* range	>=5	n/a	The congestion condition indicates that while the same average charging demand per vehicle as the normal case is likely, more charging stations will be needed to efficiently serve total demand.
High Demand	>(2/3)* range	<=range	>=0	<=4	The demand condition means that higher capacity charging infrastructure will be needed to serve charging demand.
Congestion/ High Demand	>(2/3)* range	<=range	>=5	n/a	The congestion/demand condition necessitates additional charging stations with higher charging capacity.

Table 8 shows the categorization of rest areas based on congestion and charging demand. This information was obtained from 2017 traffic statistics.

Table 8. Categorization of rest areas based on congestion and charging demand they need based on 2017 statistics.

Normal Rest Areas	High Congestion Rest Areas	High Demand Rest Areas		High Congestion & High Demand
CALN	**CALN**	**CALN**		**CALN**
Weed Airport Southbound- Siskiyou County	Gold Run Westbound - Placer County	Collier Tunnel - Del Norte County	Herbert S. Miles Northbound - Tehama County	Westley Southbound - Stanislaus County
Donner Summit Westbound - Nevada County	Westley Northbound - Stanislaus County	Randolph E. Collier - Siskiyou County	Herbert S. Miles Southbound- Tehama County	Enoch Christoffersen Northbound - Stanislaus County
Lake Almanor - Plumas County	John "Chuck" Erreca Northbound - Merced County	Grass Lake - Siskiyou County	Lt. John C. Helmick Northbound - Tehama County	Enoch Christoffersen Southbound - Stanislaus County
Honey Lake - Lassen County	Coalinga/Avenal Southbound - Fresno County	Weed Airport Northbound - Siskiyou County	Lt. John C. Helmick Southbound - Tehama County	John "Chuck" Erreca Southbound - Merced County
Empire Camp - Mendocino County	Camp Roberts Northbound - Monterey County	Trinidad Northbound - Humboldt County	Willows Southbound- Glenn County	Coalinga/Avenal Northbound - Fresno County
Lester.T. Davis - Plumas County	**SCE**	Lakehead Rest Area - Shasta County	Willows Northbound - Glenn County	Shandon - San Luis Obispo County
Trinidad Southbound - Humboldt County	C. H. Warlow - Tulare County	Francis B. Mathews - Trinity County	Irvine Lodge - Mendocino County	**SCE**
Dunnigan Southbound - Yolo County	Philip S. Raine Southbound - Tulare County	Hillcrest Safety Roadside Rest Area	Moss Cove - Mendocino County	Philip S. Raine Northbound - Tulare County
Elkhorn - Sacramento County	Valley Wells Northbound- San Bernardino County	Camp Roberts Southbound - Monterey County	Donner Summit Eastbound - Nevada County	Clyde V. Kane Southbound - San Bernardino County
H. Dana Bowers - Marin County	Wiley's Well - Riverside County	Moon Lim Lee - Trinity County	Maxwell Southbound - Colusa County	Clyde V. Kane Northbound - San Bernardino County
SCE	**SDGE**	Secret Valley - Lassen County	Maxwell Northbound - Colusa County	Tejon Pass Southbound - Kern County
Buttonwillow Northbound - Kern County	Aliso Creek Northbound - San Diego County	Bogard - Lassen County	Gold Run Eastbound - Placer County	Tejon Pass Northbound - Kern County
John Wilkie Eastbound - San Bernardino County	**IID**	Shingletown - Shasta County	Dunnigan Northbound - Yolo County	Gaviota Southbound - Santa Barbara County
Brookside - Riverside County	Sand Hills - Imperial County	Hunter Hill - Solano County	O'Brien Rest Area - Shasta County	Gaviota Northbound - Santa Barbara County
LADWP		Crystal Springs - San Mateo County		Cactus City Eastbound - Riverside County
Crestview - Mono County		**SCE**		Cactus City Westbound - Riverside County

Normal Rest Areas	High Congestion Rest Areas	High Demand Rest Areas		High Congestion & High Demand
CALN	**CALN**	**CALN**		**CALN**
		Division Creek - Inyo County	Desert Oasis Eastbound - San Bernardino County	**SDGE**
		Coso Junction - Inyo County	Desert Oasis Westbound - San Bernardino County	Buckman Springs - San Diego County
		Buttonwillow Southbound- Kern County	Wildwood - San Bernardino County	
		Boron Westbound - Kern County	Whitewater Eastbound - Riverside County	
		Boron Eastbound - Kern County	Whitewater Westbound - Riverside County	
		SDGE	**IID**	
		Aliso Creek Southbound - San Diego County	Sunbeam Eastbound - Imperial County	

The categorization was done for the 2050 100% BEV scenario. This is based on average battery capacity of 100kWh for each BEV, and an assumed range of 350 miles.

Installed EV charging infrastructure within a 25-mile radius of each rest area was estimated and was used as installed charging infrastructure for the energy model. This will help ensure that an optimal number of chargers at rest areas will be estimated. Table 9 shows how rest area grouping changes when all the fleet changes to BEVs in 2050. It also shows total existing installed capacity of charging stations within 25 miles of each rest area. Our model projects that additional charging infrastructure would be required to serve the intercity travel charging needs by 2050.

Table 9. Rest areas characteristic projections for 2050. More rest areas move from the normal to high congestion/ high demand category in the 2050 all BEV scenario. The third column shows total existing installed capacity of EV charging stations within a 25-mile radius of each rest area.

Rest Area Characteristic Projections for 2050	Region	Existing Charging Capacity in 2017 (KW)
Normal Rest Areas		
Weed Airport Southbound- Siskiyou County	CALN	1208
Normal Total		1208
High Congestion Rest Areas		
Lake Almanor - Plumas County	CALN	0
Honey Lake - Lassen County	CALN	24
Moss Cove - Mendocino County	CALN	78
Donner Summit Westbound - Nevada County	CALN	1328
Gold Run Westbound - Placer County	CALN	1460
Crestview - Mono County	LADWP	478
Enoch Christoffersen Northbound - Stanislaus County	CALN	608
Coso Junction - Inyo County	SCE	0
Clyde V. Kane Southbound - San Bernardino County	SCE	900
Brookside - Riverside County	SCE	2212
Wiley's Well - Riverside County	SCE	74
Aliso Creek Northbound - San Diego County	SDGE	1070
Sand Hills - Imperial County	IID	406
High Congestion Installed Charging Total		8638
High Demand Rest Areas		
Grass Lake - Siskiyou County	CALN	1072
Trinidad Southbound - Humboldt County	CALN	198
Moon Lim Lee - Trinity County	CALN	12
Lt. John C. Helmick Northbound - Tehama County	CALN	466
Lester.T. Davis - Plumas County	CALN	24
Philip S. Raine Northbound - Tulare County	SCE	522
Boron Eastbound - Kern County	SCE	30
Wildwood - San Bernardino County	SCE	1314
High Demand Installed Charging Total		3638
High Congestion & High Demand Rest Areas		
Randolph E. Collier - Siskiyou County	CALN	310
Weed Airport Northbound - Siskiyou County	CALN	1208
Trinidad Northbound - Humboldt County	CALN	198
Francis B. Mathews - Trinity County	CALN	42
Hillcrest Safety Roadside Rest Area	CALN	12
O'Brien Rest Area - Shasta County	CALN	198
Secret Valley - Lassen County	CALN	0

Rest Area Characteristic Projections for 2050	Region	Existing Charging Capacity in 2017 (KW)
Herbert S. Miles Northbound/Southbound - Tehama County	CALN	560
Lt. John C. Helmick Southbound - Tehama County	CALN	466
Empire Camp - Mendocino County	CALN	18
Willows Northbound - Glenn County	CALN	658
Irvine Lodge - Mendocino County	CALN	66
Donner Summit Eastbound - Nevada County	CALN	1328
Maxwell Southbound - Colusa County	CALN	50
Maxwell Northbound - Colusa County	CALN	50
Gold Run Eastbound - Placer County	CALN	1460
Dunnigan Northbound - Yolo County	CALN	460
Dunnigan Southbound - Yolo County	CALN	460
Elkhorn - Sacramento County	CALN	1026
Hunter Hill - Solano County	CALN	1176
Westley Northbound/Southbnd - Stanislaus County	CALN	1860
Crystal Springs - San Mateo County	CALN	614
Enoch Christoffersen Southbound - Stanislaus County	CALN	608
Division Creek - Inyo County	SCE	0
John "Chuck" Erreca Northbnd/Southbnd - Merced County	CALN	782
C. H. Warlow - Tulare County	SCE	392
Philip S. Raine Southbound - Tulare County	SCE	522
Coalinga/Avenal Southbound - Fresno County	CALN	3176
Coalinga/Avenal Northbound - Fresno County	CALN	3176
Camp Roberts Northbnd/Southbnd - Monterey County	CALN	240
Shandon - San Luis Obispo County	CALN	278
Valley Wells Northbound- San Bernardino County	SCE	2712
Buttonwillow Northbound/ Southbound- Kern County	SCE	1788
Clyde V. Kane Northbound - San Bernardino County	SCE	900
Boron Westbound - Kern County	SCE	30
Tejon Pass Northbound/ Southbound - Kern County	SCE	1250
John Wilkie Eastbound - San Bernardino County	SCE	0
Desert Oasis Eastbnd/Westbnd - San Bernardino County	SCE	900
Gaviota Southbound - Santa Barbara County	SCE	806
Gaviota Northbound - Santa Barbara County	SCE	806
Whitewater Eastbound/Westbnd - Riverside County	SCE	1524
Cactus City Eastbound - Riverside County	SCE	974
Aliso Creek Southbound - San Diego County	SDGE	1070
Sunbeam Westbound - Imperial County	IID	400
High Congestion & High Demand Installed Charging Total		28,160

Table 11 and 12 show results for 2030 and 2050 categorization of the rest areas based on the four categories we defined in this project (normal, congestion, high demand and high congestion/high demand). The categorization of rest areas changed between model years because as EV penetration and range increased, the total number of vehicles needing charging and the amount of energy needed increased as well. Additionally, with increasing range, charging was needed in different amounts at each rest area in each model year.

Table 10 shows which rest areas have no charging demand for each model year, while Figure 20 shows their location on a map. As BEV range increases, the number of rest areas with charging demand decreases. The rest areas that do not have charging demand stay relatively constant over the three model years, which provides more certainty as to where resources should be allocated long term. The geographical context of the rest areas where no charging is needed is important to consider. For example, the Valley Wells Southbound Rest Area is about 70 miles southwest of Las Vegas and 50 miles northeast of the Clyde V. Cane Southbound Rest Area. Thus, there is little need for charging at the intermediate distance where the Valley Wells Southbound Rest area is located. While not included in this model as an input, it is important to consider the demographic context of zero-demand rest areas. More affluent cities are likely to have a higher BEV penetration (relevant for the 2017 and 2030 model years) than less affluent cities and could affect the mix of vehicles traveling to and from certain locations. Additionally, charging locations aside from rest areas are not directly considered by the model, except as shown in Figure 3 where gaps in rest areas are greater than vehicle range. Taking the example of the Valley Wells Southbound Rest Area again, it is located close to Baker, CA in addition to Las Vegas, NV. These cities are probable locations for drivers to charge their vehicles. Further work is needed to expand the model to include both demographic context and account for alternative charging locations.

Table 10. Summary of rest areas with zero charging demand in each model year. Note: SB=Southbound, WB=Westbound, and EB=Eastbound.

Model Year	Rest Areas with No Charging Demand	Rest Area Location
2017	John Wilkie WB	I-40, San Bernardino County
	Massack	CA-70 E, Plumas County
	Sunbeam WB	I-8, Imperial County
	Valley Wells SB	I-15, San Bernardino County
2030	John Wilkie WB	I-40, San Bernardino County
	Massack	CA-70 E, Plumas County
	Sunbeam WB	I-8, Imperial County
	Valley Wells SB	I-15, San Bernardino County
	Cactus City WB	I-10, Riverside County
	Desert Oasis WB	I-40, San Bernardino County
	Lakehead	I-5, Shasta County
	Whitewater WB	I-10, Riverside County
2050	Bogard	CA-44, Lassen County
	Buckman Springs	I-8, San Diego County
	Cactus City WB	I-10, Riverside County
	H. Dana Bowers	US-101, Marin County
	John Wilkie WB	I-40, San Bernardino County
	Lakehead	I-5, Shasta County
	Massack	CA-70 E, Plumas County
	Shingletown	SR-44, Shasta County
	Sunbeam EB	I-8, Imperial County
	Valley Wells SB	I-15, San Bernardino County
	Willows SB	I-5, Glenn County

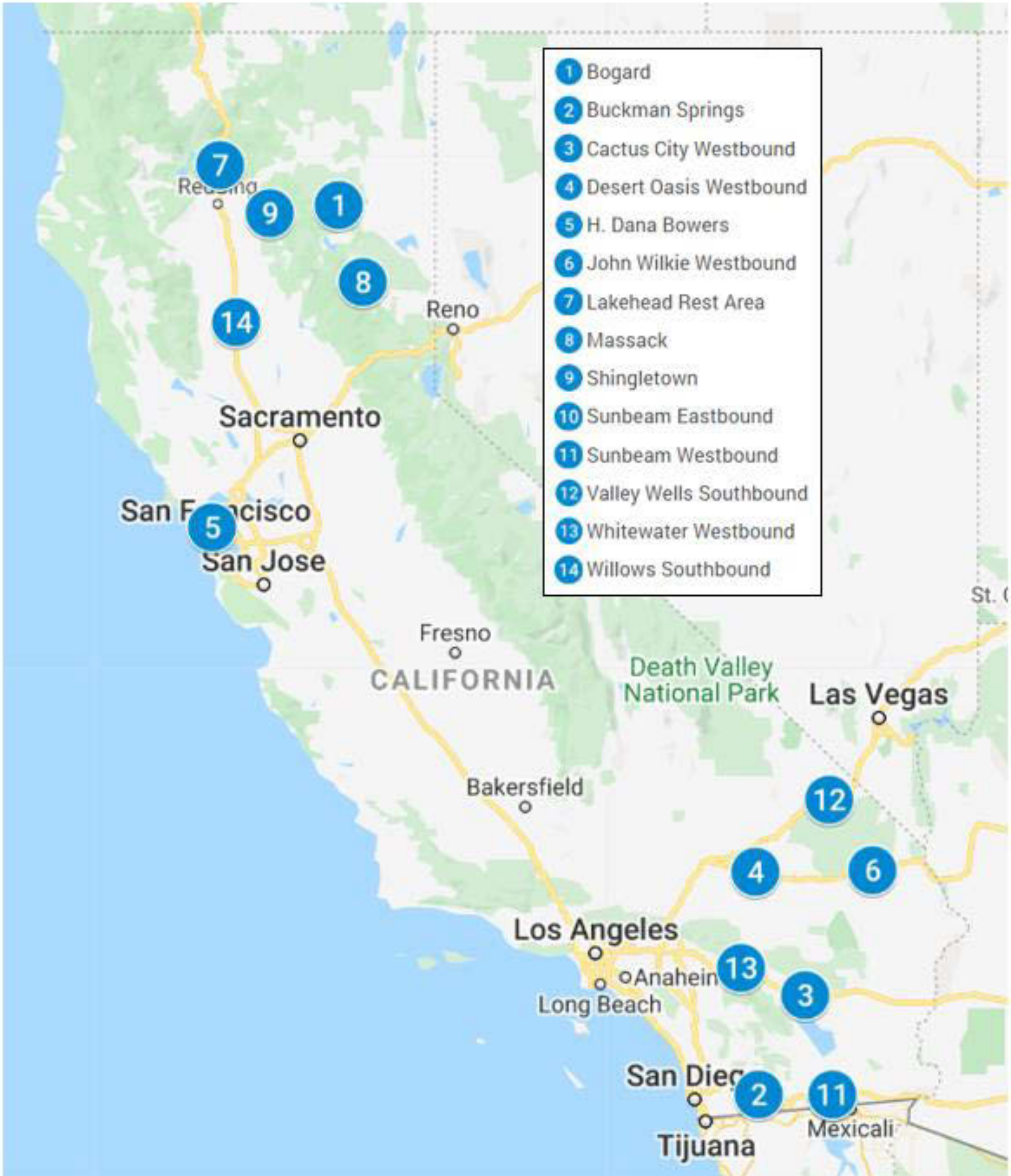

Figure 20. Map showing locations of rest areas where zero charging demand is projected for at least one model year. Google Maps was used to create this image.

Table 11. Categorization of rest areas base on congestion and the charging demand they need in 2030.

Normal Rest Areas	High Congestion Rest Areas	High Demand Rest Areas	High Congestion & High Demand Rest Areas	
CALN	**CALN**	**CALN**	**CALN**	
Lake Almanor - Plumas County	Collier Tunnel - Del Norte County	Grass Lake - Siskiyou County	Donner Summit Eastbound - Nevada County	Camp Roberts Southbound - Monterey County
Honey Lake - Lassen County	Moss Cove - Mendocino County	Weed Airport Southbound- Siskiyou County	Trinidad Southbound - Humboldt County	Shandon - San Luis Obispo County
Lester.T. Davis - Plumas County	Gold Run Westbound - Placer County	Weed Airport Northbound - Siskiyou County	Herbert S. Miles Southbound-Tehama County	Coalinga/Avenal Southbound - Fresno County
Donner Summit West - Nevada County	Dunnigan Southbound - Yolo County	Trinidad Northbound - Humboldt County	Herbert S. Miles Northbound-Tehama County	Coalinga/Avenal Northbound - Fresno County
H. Dana Bowers - Marin County	Camp Roberts Northbound - Monterey County	Francis B. Mathews - Trinity County	O'Brien Rest Area - Shasta County	Coso Junction - Inyo County
SCE	**SCE**	Hillcrest Safety Roadside Rest Area	Lt. John C. Helmick Northbound - Tehama County	John "Chuck" Erreca Northbound - Merced County
Desert Oasis Eastbound -San Bernardino County	Clyde V. Kane Southbound - San Bernardino County	Moon Lim Lee - Trinity County	Lt. John C. Helmick Southbound - Tehama County	John "Chuck" Erreca Southbound - Merced County
Boron Westbound - Kern County	Whitewater Eastbound - Riverside County	Secret Valley - Lassen County	Enoch Christoffersen Northbound - Stanislaus County	Enoch Christoffersen Southbound - Stanislaus County
	IID	Bogard - Lassen County	Willows Northbound - Glenn County	Empire Camp - Mendocino County
	Sand Hills - Imperial County	Shingletown - Shasta County	Randolph E. Collier - Siskiyou County	Westley Southbound - Stanislaus County
	LADWP	Willows Southbound- Glenn County	Maxwell Southbound - Colusa County	Crystal Springs - San Mateo County
	Crestview - Mono County	Irvine Lodge - Mendocino County	Gold Run Eastbound - Placer County	Hunter Hill - Solano County
	SDGE	Maxwell Northbound - Colusa County	Dunnigan Northbound - Yolo County	Westley Northbound - Stanislaus County
	Aliso Creek Northbound - San Diego County	**SCE**	Elkhorn - Sacramento County	
		Boron Eastbound - Kern County	**SCE**	
		Wildwood - San Bernardino County	Gaviota Southbound - Santa Barbara County	Gaviota Northbound - Santa Barbara County
		Division Creek - Inyo County	Tejon Pass Southbound - Kern County	Brookside - Riverside County
			Tejon Pass Northbound - Kern County	Cactus City Eastbound - Riverside County

Normal Rest Areas	High Congestion Rest Areas	High Demand Rest Areas	High Congestion & High Demand Rest Areas	
			Buttonwillow Southbound- Kern County	Clyde V. Kane Northbound - San Bernardino County
			Wiley's Well - Riverside County	John Wilkie Eastbound - San Bernardino County
			Valley Wells Northbound- San Bernardino County	Buttonwillow Northbound - Kern County
			Philip S. Raine Southbound - Tulare County	Philip S. Raine Northbound - Tulare County
			C. H. Warlow - Tulare County	
			SDGE	**IID**
			Aliso Creek Southbound - San Diego County	Sunbeam Eastbound - Imperial County
			Buckman Springs - San Diego County	

Table 12. Categorization of rest areas base on congestion and charging demand they need in 2050.

Normal Rest Areas	High Congestion Rest Areas	High Demand Rest Areas	High Congestion & High Demand Rest Areas	
CALN	**CALN**	**CALN**	**CALN**	
Weed Airport South - Siskiyou County	Lake Almanor - Plumas County	Grass Lake - Siskiyou County	Randolph E. Collier - Siskiyou County	Gold Run Eastbound - Placer County
	Honey Lake - Lassen County	Trinidad Southbound - Humboldt County	Weed Airport Northbound - Siskiyou County	Trinidad Northbound - Humboldt County
	Moss Cove - Mendocino County	Boron Eastbound - Kern County	John "Chuck" Erreca Southbound- Merced County	John "Chuck" Erreca Northbound-Merced County
	Donner Summit Westbound - Nevada County	Lt. John C. Helmick Northbound - Tehama County	Francis B. Mathews - Trinity County	Dunnigan Northbound - Yolo County
	Gold Run Westbound - Placer County	Lester.T. Davis - Plumas County	Hillcrest Safety Roadside Rest Area	Dunnigan Southbound - Yolo County
	Enoch Christoffersen Northbound - Stanislaus County	Philip S. Raine Northbound - Tulare County	Enoch Christoffersen Southbound - Stanislaus County	Lt. John C. Helmick Southbound - Tehama County
	SCE	Moon Lim Lee - Trinity County	Secret Valley - Lassen County	Hunter Hill - Solano County
	Coso Junction - Inyo County	Wildwood - San Bernardino County	Herbert S. Miles Northbound - Tehama County	Camp Roberts Southbound - Monterey County
	Clyde V. Kane Southbound - San Bernardino County		Herbert S. Miles Southbound- Tehama County	Camp Roberts Northbound - Monterey County

Normal Rest Areas	High Congestion Rest Areas	High Demand Rest Areas	High Congestion & High Demand Rest Areas	
	Brookside - Riverside County		Coalinga/Avenal Southbound - Fresno County	Shandon - San Luis Obispo County
	Wiley's Well - Riverside County		Empire Camp - Mendocino County	Elkhorn - Sacramento County
	IID		Willows Northbound - Glenn County	Coalinga/Avenal Northbound - Fresno County
	Sand Hills - Imperial County		Irvine Lodge - Mendocino County	Westley Northbound - Stanislaus County
	SDGE		Donner Summit Eastbound - Nevada County	Westley Southbound - Stanislaus County
	Aliso Creek Northbound - San Diego County		Maxwell Southbound - Colusa County	Crystal Springs - San Mateo County
	LADWP		Maxwell Northbound - Colusa County	O'Brien Rest Area - Shasta County
	Crestview - Mono County		**SCE**	
			Tejon Pass Northbound - Kern County	John Wilkie Eastbound - San Bernardino County
			Gaviota Southbound - Santa Barbara County	Desert Oasis Eastbound - San Bernardino County
			Cactus City Eastbound - Riverside County	Desert Oasis Westbound - San Bernardino County
			Division Creek - Inyo County	C. H. Warlow- Tulare County
			Valley Wells Northbound- San Bernardino County	Gaviota Northbound - Santa Barbara County
			Buttonwillow Southbound- Kern County	Whitewater Eastbound - Riverside County
			Buttonwillow Northbound - Kern County	Whitewater Westbound - Riverside County
			Clyde V. Kane Northbound - San Bernardino County	Philip S. Raine Southbound - Tulare County
			Boron Westbound - Kern County	Tejon Pass Southbound - Kern County
			SDGE	**IID**
			Aliso Creek Southbound - San Diego County	Sunbeam Westbound - Imperial County

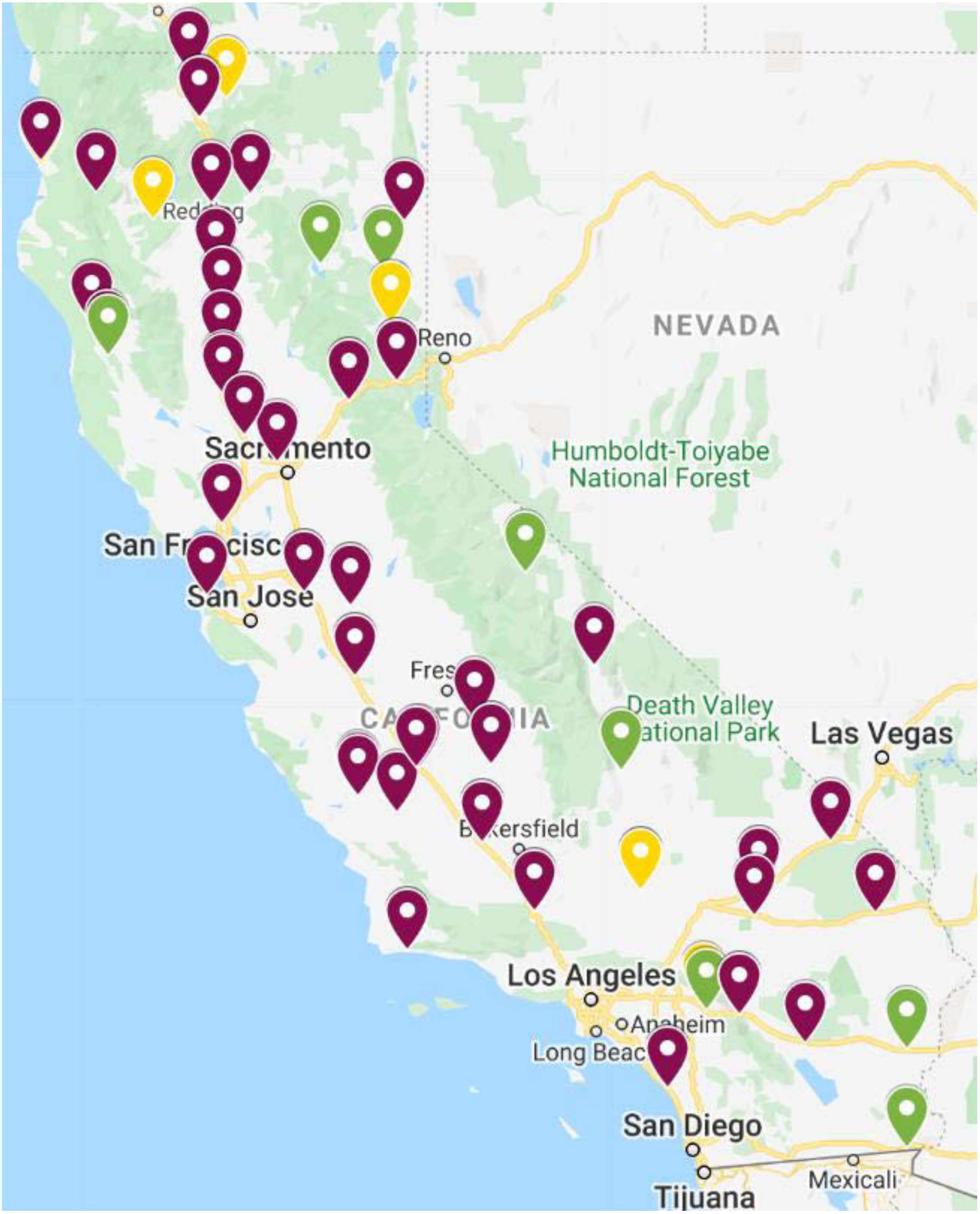

Figure 21. Map of 2050 rest area groupings based on congestion and demand. It excludes rest areas that were found to have zero charging demand in 2050. Note: Yellow markers: High Demand Rest Areas, Green markers: High Congestion Rest Areas, Red markers: High Congestion and High Demand Rest Areas

Optimal result of hourly managed charging for 8760 hours in 2050 intracity and intercity BEVs were obtained through optimization work. Figure 22 and 23 present two typical days, one in summer and one in winter to show the effect of managed charging which happens more during intracity trips and also vehicles that are traveling 100 miles or more and would need charging during different times of day within 25 miles of the rest areas.

It is seen that intracity managed charging has the highest effect on the duck curve, but highway charging is spread throughout the day and so has also positive effect on load management. However, the effect is much less than other vehicles who are mostly parked either at home or work location and their charging could be managed by a smart grid.

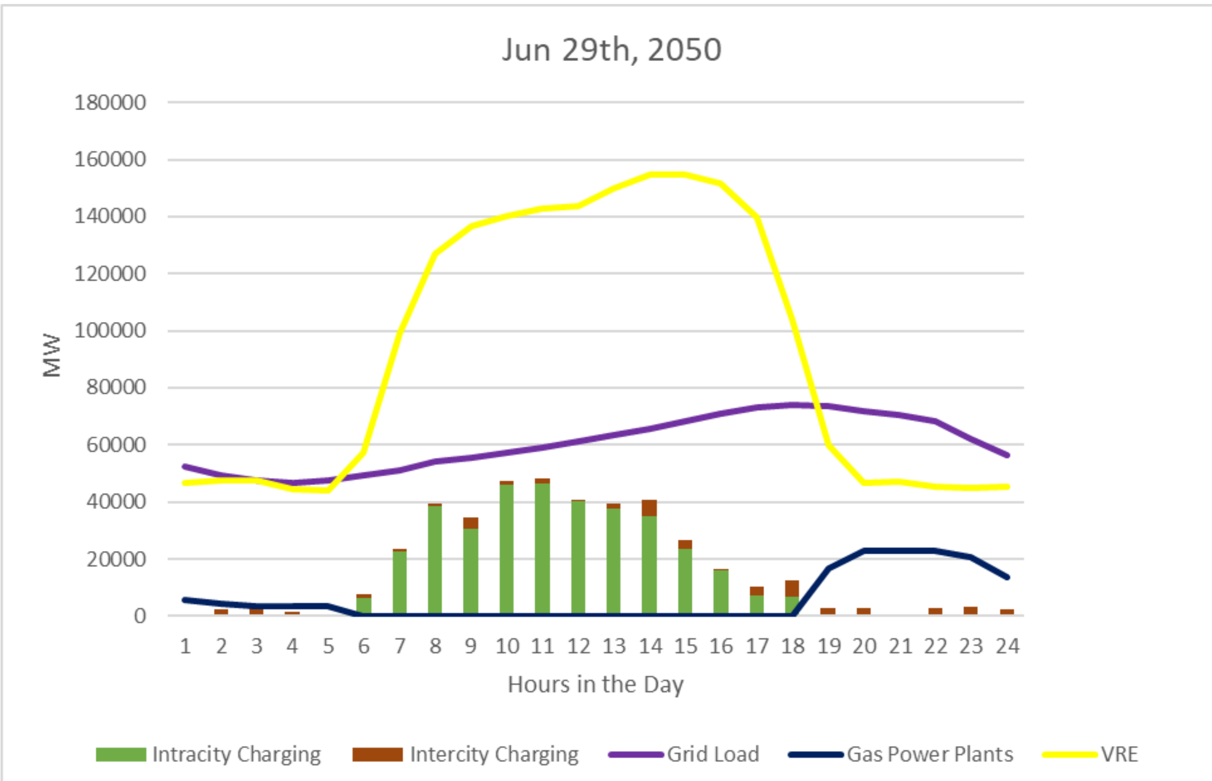

Figure 22. Effect of charging on grid load in 2050 for a typical summer day. Brown bars show charging load for vehicles passing rest areas with trips longer than 100 miles range. Green bars show charging load from other vehicles mostly having intracity trips. The lower line shows electricity generated by gas power plants that has been flattened. Green and brown bars are stacked bars.

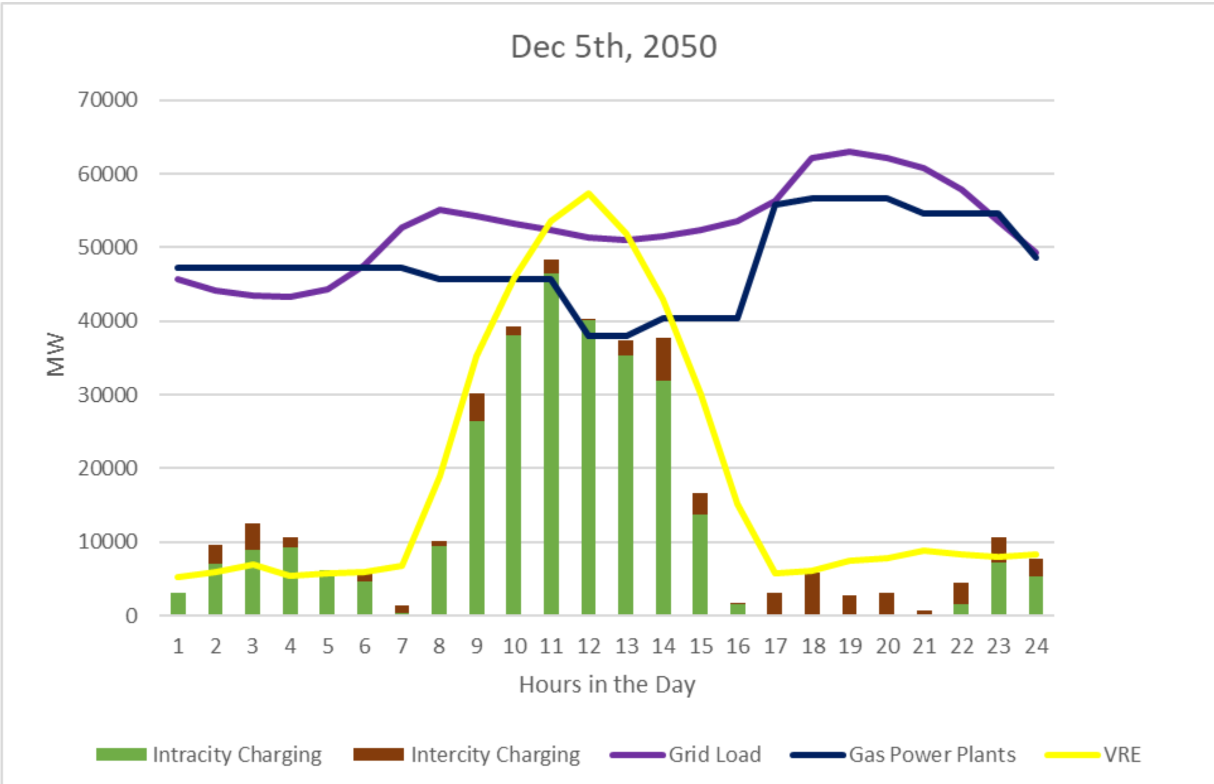

Figure 23. Effect of charging on grid load in 2050 for a typical winter day. Brown bars show charging load for vehicles passing rest areas with trips longer than 100 miles range. Green bars show charging load from other vehicles mostly having intracity trips. The lowest line shows VRE, variable renewable energy (namely solar), the middle line Gas PP shows electricity production from natural gas, and the upper line shows the overall grid load.

Based on the hourly VMT distribution of vehicles with longer than 100 mile trips, the optimal location of chargers are obtained. The locations have been divided into four main categories that we defined for our rest areas. Depending on the location of the rest areas and how many chargers are already available within a 25 mile range of that area, some rest areas need to be addressed more than the others. Based on the categorization of rest areas we introduced in this project, High Congestion rest areas (totaling 13) and High Congestion & High Demand rest areas (totaling 52) in 2050 are the ones which need higher investment on charger infrastructures. Results of this study show that if all vehicles in California are BEVs in 2050, we would need about 730 charging stations with 100kW charging rate installed within a 25 mile range of “High Congestion Rest Areas” and 1187 similar charging stations within a 25 mile distance of “High Congestion & High Demand Rest Areas”. “High Demand” rest areas each need only 8 charging stations. With this configuration, all long-distance BEV trips which are over 100 miles range could be supported in California.

It is important to note that, as Table 9 shows, the current number of charging stations (and the stations’ charging capacity) within a 25-mile radius of a rest area differs greatly between each rest area. For instance, Cactus City and Whitewater rest areas are both in Riverside county and they are both projected to have high congestion rates and high demand rates by 2050, however Cactus City rest area currently has 974 KW of installed charging within a 25 mile radius, while Whitewater rest area has over 1500 KW installed, almost twice as much. This means that their level of need is different in the coming years, and it may be beneficial to prioritize installing DCFCs at the rest areas which are anticipated to have high demand needs, and which are currently lacking any installed charging whatsoever. These 'at risk' rest areas, all of which currently have less than 50 KW or less of charging within a 25-mile radius of the rest area, include John Wilkie rest area (I-40), Boron rest area (CA-58), Maxwell rest area (I-5), Secret Valley and Division Creek rest areas (US-395), Empire Camp and Irvine Lodge rest areas (US-101), and Francis B. Matthews and Hillcrest Safety Roadside rest areas (CA-299). The Caltrans "30-30" project does plan to install a DCFC charger at many of these locations, namely the at rest areas along US-395, CA-299, and I-5, but additional chargers should be considered (California Department of Transportation, 2017).

Table 13. Charging infrastructure required by 2050 for each defined rest area category.

Rest Areas Grouping	No. of Rest Areas in Each group	Installed Charging Capacity within 25 miles of each rest area in 2017 (MW)	Total Charging Infrastructure Required within each category (MW) in 2050	New Charging Capacity required per rest area (MW)	No. of chargers with 100kW rating required within 25 miles of each rest area
Normal Rest Areas	1	1.2	0.14	0	0
High Congestion Rest Areas	13	8.64	958.33	73	730
High Demand Rest Areas	8	3.64	10.21	0.82	8
High Congestion & High Demand Rest Areas	52	28.85	6204.15	118	1187

Results of optimization for new charging infrastructure that will be needed in 2050 within 25 miles of each rest area is shown in Table 13. As seen in the last column of the table, in two ret area groups, High Congestion Rest Areas and High Congestion/High Demand Rest areas, the number of chargers required per each rest area would be much higher than the physical capacity they might have. Additional chargers should be installed within 25 miles range of each rest area (in commercial areas for example) so intercity travel of all these BEVs would be possible. Figure 24 shows the total charging infrastructure needed for these two main categories of rest areas in 2050. This figure shows that about 6 GW of charging stations should be added around High Congestion/High Demand rest areas and only 1 GW for High Congestion category.

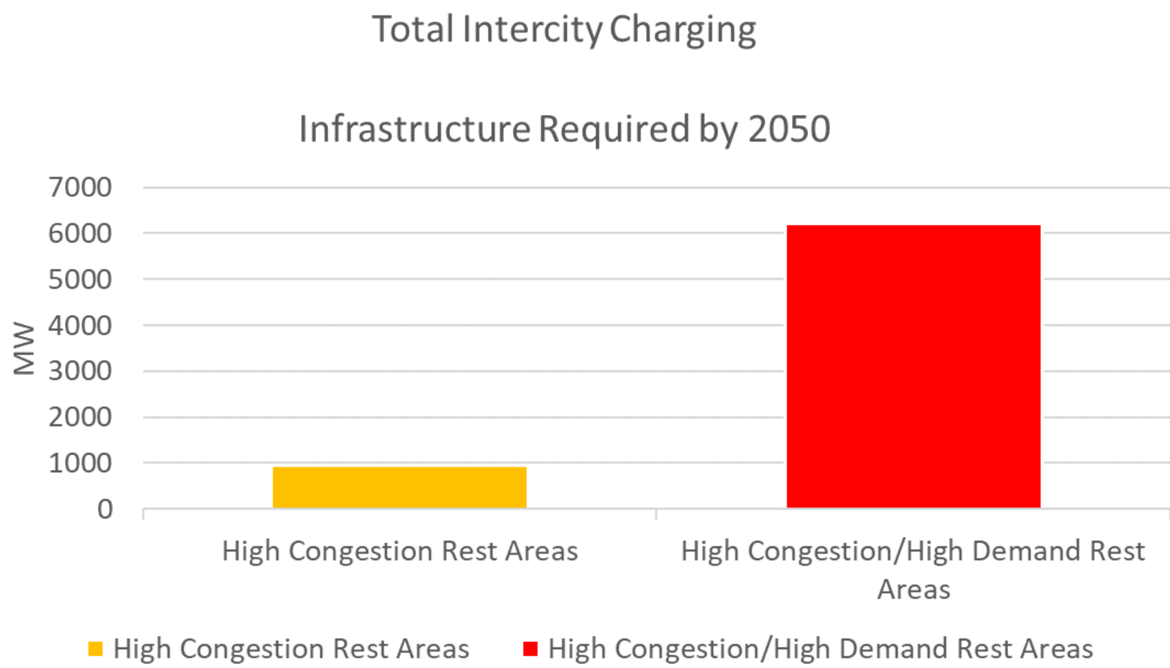

Figure 24. Total charging infrastructure needed for two main categories of rest areas for 2050

Figure 25 shows the model result of the amount of electricity required for LDVs passing by the rest areas in California and whose trip are longer than 100 miles. These vehicles would require about 13% of LDV transportation electricity demand in 2050. The rest will be utilized by intracity trips.

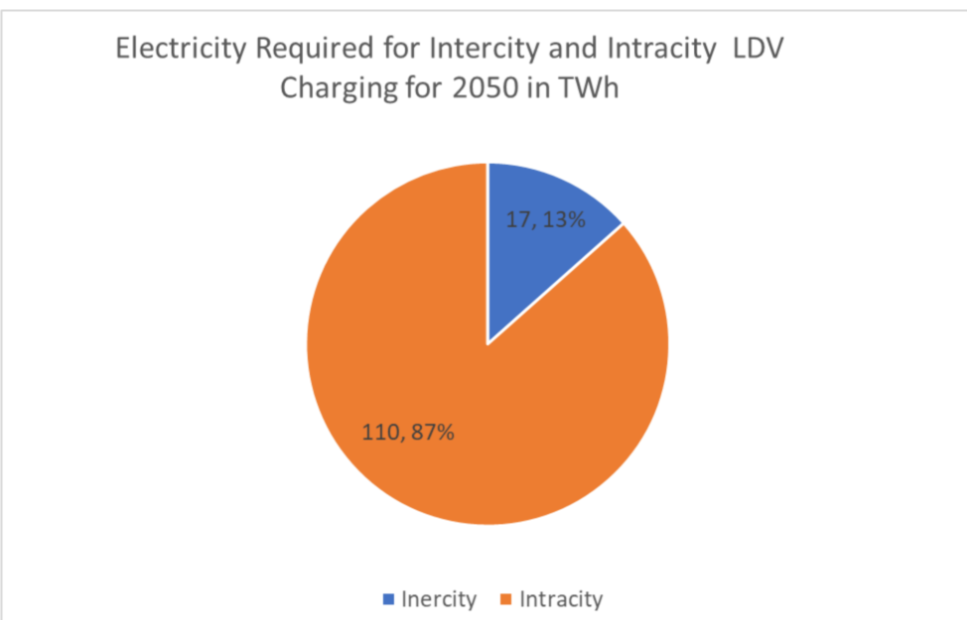

Figure 25. Electricity demand required for charging all 28M BEV LDVs in 2050. Blue section is for intercity travels longer than 100 miles passing the rest areas and orange section is for all other intracity travels.

Figure 26 and 27 show the installed capacity for gas, wind and solar generation for 2050. We would need 122 GW of solar, 56 GW of wind and 67 GW of gas power plants to be able to have 30M BEVs driving in California. This mixture gives us up to 72% variable renewable energy penetration in California's electricity grid.

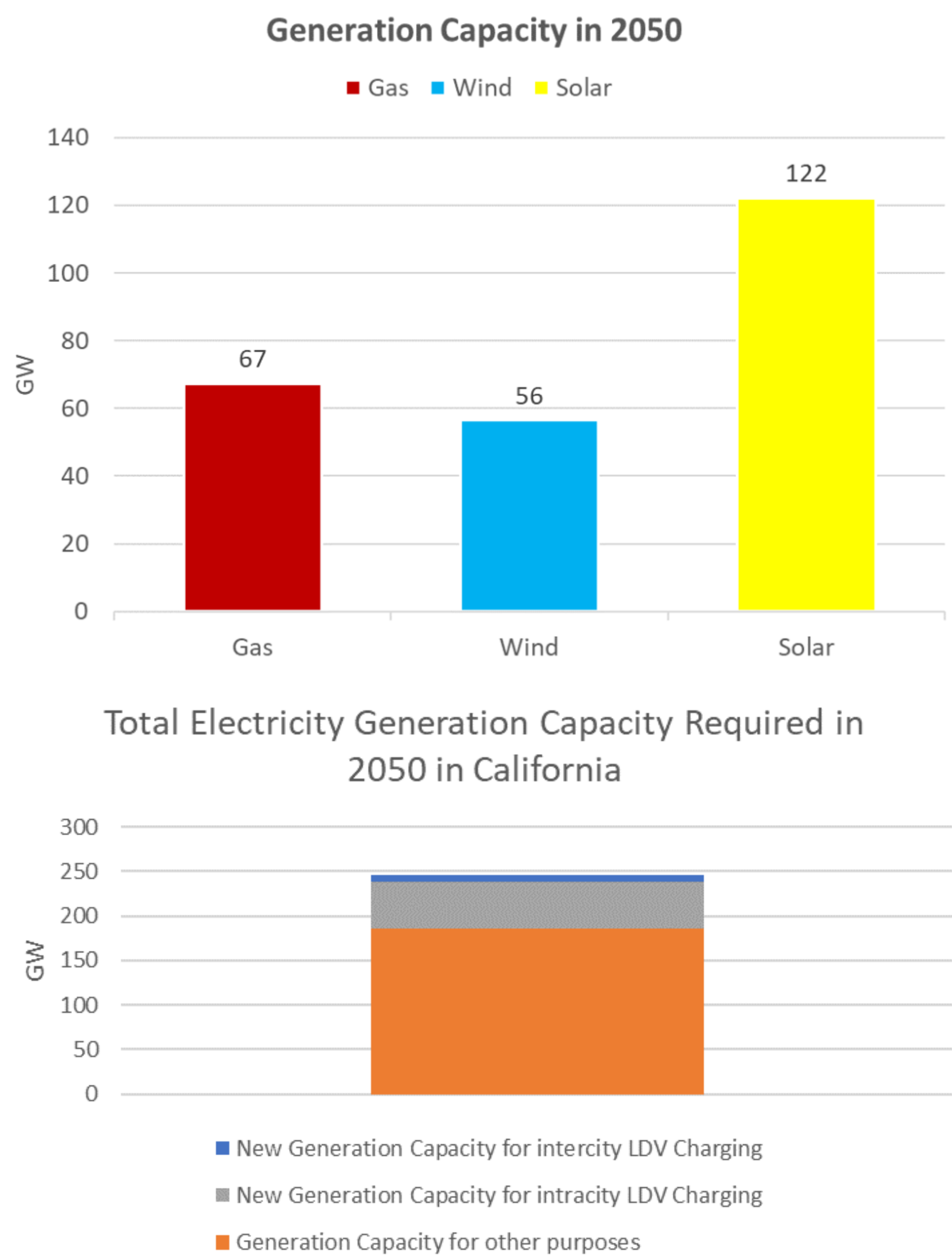

Figure 26. Total installed generation capacity in 2050, to serve all electricity needs in California, including 30 million LDV BEVs. The fraction of capacity used for charging BEVs is shown as a stacked bar.

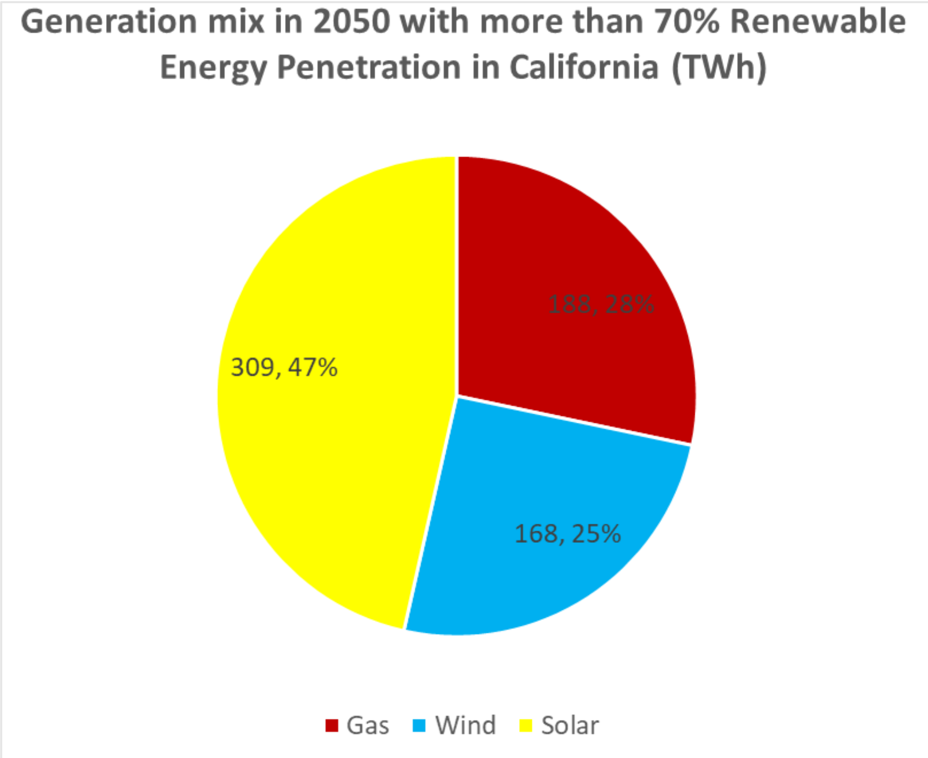

Figure 27. California generation mix in 2050 with 72% renewable energy penetration into the grid.

Limitations of the Model and Future Work

There are federal regulations which limit commercial sale of goods within federal highways defined areas. Some rest areas in California which have areas outside the federal property were able to install charging stations. These limitations should be removed so other rest areas can sell electricity to BEV owners as well.

There were also challenges in getting specific cost information from utilities and other stakeholders which limited the access to detailed financial information and we had to make assumptions to complete this project.

Due to time limit and lack of travel data, this study was limited to light duty electric vehicles. Heavy duty intercity travel would have large impact on the charging infrastructure and energy system and is strongly suggested for future study.

Conclusion

It is concluded that depending on the location of the rest area and how many chargers are already available around that area, some rest areas need to be addressed more than the others. Based on the categorization of rest areas we introduced in this project, High Congestion rest areas (totaling 13) and High Congestion & High Demand rest areas (totaling 52) in 2050 are the ones which need higher investment in chargers' infrastructure. Results of this study show that if all vehicles in California are BEVs in 2050, we would need about 730 100kW rate charging stations installed within 25 miles of range of "High Congestion Rest Areas" and 1187 of similar charging stations within 25 mile distance of "High Congestion & High Demand Rest Areas". "High Demand" rest areas each need only 8 charging stations. With this configuration, all long-distance trips which are over 100 miles range could be supported in California. In all model years, travel peaks on the weekends, during the summer, and December.

To provide the extra electricity demanded by an 100% BEV fleet, 122 GW solar, 56 GW wind and 67 GW of gas power plants would be required in 2050. This mixture gives California up to 72% variable renewable energy penetration in the electricity grid, which is a substantial improvement from the 32% renewable energy penetration in the grid today, but still falls short of the SB-100 goal for California to supply 100% renewable electricity by the end of 2045.

In summary, we return to the initial research questions addressed in this study (see page 2).

1. What fraction of light duty travel is for long distance trips ("intercity travel") compared to shorter trips ("intracity travel")?

We find that a large majority of the travel demand and BEV charging energy is associated with relatively short distance or intracity trips (of 100 miles or less), As shown in Figure 25, intracity trips require 87% of BEV charging energy, and intercity trips (greater than 100 miles) only about 13%. The added electric capacity for charging an all-BEV fleet would be required mostly for intracity travel. Chargers to enable intercity travel are a small fraction of the total (see Figure 26).

2. How might BEVs intercity travel be enabled by chargers at rest areas?

We find that to be able to serve the charging demand for an all BEV fleet by 2050, we would need to install totally about 7GW of charging infrastructures on our roads. From this, 6GW of chargers should be installed up to the limitations of 52 High Congestion/High Demand rest areas and within 25 miles of each as defined in this study. About another 1 GW of chargers should be installed up to the limitations of 13 High Congestion rest areas and within 25 miles of each.

3. What are the hourly operational behavior and demand response effects of intercity ZEVs on the state grid network, if these vehicles are adopted on a massive scale?

We find that although intercity charging effect on the load is a small portion of load on the state grid network compared to intracity and other sectors, they wouldn't have a negative effect on flattening the duck curve, if not positive.

4. What is the net grid impact of mid-day ZEV charging at rest areas along California's highways? What kind of system would be needed to solve intermittency and duck curve issues state-wide?

This study also shows that although intracity charging has more flexibility for demand response and intracity charging is less flexible, the total demand response of intracity plus intercity hourly charging on the grid helps in flattening the duck curve (see Figure 22 and 23).

Hourly charging load profiles on the highways are different than charging profiles of intracity stations but are still able to help adjust the duck-curve, as its spread covers more daytime hours compared to intracity charging. It is concluded that if all light duty vehicles are BEVs, then about 87% of charging would be required for intracity travel and 13% of charging would take place for intercity travel (trips that are 100 miles or longer).

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Data Management

Products of Research

No new data was collected by the authors for this study; all inputs used for the model in this work were created using the publicly available datasets as indicated in this report. All inputs created for the model, including travel demand and electricity system data, are considered products of this research. The specific products are detailed below.

Data Format and Content

1. *VMT_Profiles_20XX.xlsx* and *Vehicles_Profiles_20XX.xlsx* where XX=17, 30, and 50: The main products of research for this study include hourly charging demand (in terms of VMT/hr that would contribute to charging demand at a rest area) and total vehicles profiles for each of the 86 rest areas in California. For each rest area these two profiles were evaluated on an hourly basis for 2017, 2030, and 2050.
2. *Transmission_Capacity.xlsx*: The transmission capacity into and out of California was calculated and is presented in net transmission capacities between specific points in the Western Interconnection.
3. *Net_Imports.xlsx*: An hourly net electricity import profile for California was created for the base year (2017).
4. *Renewable_Generation.xlsx*: Hourly renewable energy generation profiles (wind and solar) were created for the base year (2017).
5. *Generation_Capacity_Cost.xlsx*: Generations capacity and cost by generation types was calculated for California for the base year (2017).
6. *Rest_Area_Substation_Loads.xlsx*: Hourly baseline electricity demand profile for the substation serving each of the 86 rest areas in California was created for the base year (2017).
7. *Region_Loads.xlsx*: Hourly baseline electricity demand for each of the 5 model regions used in the study for the base year (2017).
8. *Installed_Charging_Capacity.xlsx*: Installed charging capacity, including Level 2 and Direct Current Fast Charging, withing 25 miles a rest area was aggregated for each of the 86 rest areas in California.

Data Access and Sharing

Data is archived with Dryad, the University of California's sponsored data archive platform at https://doi.org/10.25338/B8402G. This platform meets the requirements for the Public Access Plan created by the US Department of Transportation.

Reuse and Redistribution

There is no restriction on how the data can be used, however it must be properly cited when used in other work. For citation, please use any recognized citation method and the file name(s) of the data used:

> Kiani, Behdad; Ogden, Joan; Sheldon, F. Alex; Cordano, Lauren (2020), Utilizing Highway Rest Areas for Electric Vehicle Charging: Economics and Impacts of Renewable Energy Penetration in California, v2, UC Davis, Dataset, https://doi.org/10.25338/B8402G

Appendix

Table 14. Existing charging capacities in 2017. Level 2 and DCFC numbers and their total Installed Charging Capacity (in KW) within 25 miles of each Rest Area based on 2017 analysis. None of these are installed in rest areas.

Rest Areas by Region	Level 2 Chargers	Level 2 Capacity (KW)	DCFC	DCFC Capacity (KW)	Total Installed Charging Capacity (KW)
CALN Rest Areas					
Collier Tunnel - Del Norte County	2	12	0	0	12
Randolph E. Collier - Siskiyou County	35	210	2	100	310
Grass Lake - Siskiyou County	12	72	20	1000	1072
Weed Airport South/Northbound-Siskiyou County	18	108	22	1100	1208
Trinidad South/Northbound - Humboldt County	33	198	0	0	198
Lakehead Rest Area - Shasta County	14	84	4	200	284
Francis B. Mathews - Trinity County	7	42	0	0	42
Hillcrest Safety Roadside Rest Area	2	12	0	0	12
O'Brien Rest Area - Shasta County	8	48	3	150	198
Moon Lim Lee - Trinity County	2	12	0	0	12
Secret Valley - Lassen County	0	0	0	0	0
Bogard - Lassen County	0	0	0	0	0
Shingletown - Shasta County	2	12	0	0	12
Lake Almanor - Plumas County	0	0	0	0	0
Herbert S. Miles South/Northbound - Tehama County	10	60	10	500	560
Honey Lake - Lassen County	4	24	0	0	24
Lt. John C. Helmick South/Northbound - Tehama County	11	66	8	400	466
Massack - Plumas County	4	24	0	0	24
Empire Camp - Mendocino County	3	18	0	0	18
Lester.T. Davis - Plumas County	4	24	0	0	24
Willows South/Northbound- Glenn County	18	108	11	550	658
Irvine Lodge - Mendocino County	11	66	0	0	66
Moss Cove - Mendocino County	13	78	0	0	78
Donner Summit West/Eastbound- Nevada County	38	228	22	1100	1328
Alpha Omega - Nevada County	15	90	21	1050	1140
Maxwell South/Northbound - Colusa County	0	0	1	50	50
Gold Run West/Eastbound - Placer County	35	210	25	1250	1460
Dunnigan South/Northbound - Yolo County	35	210	5	250	460
Elkhorn - Sacramento County	46	276	15	750	1026
Hunter Hill - Solano County	71	426	15	750	1176
H. Dana Bowers - Marin County	44	264	0	0	264
Westley South/Northbound - Stanislaus County	35	210	33	1650	1860

Rest Areas by Region	Level 2 Chargers	Level 2 Capacity (KW)	DCFC	DCFC Capacity (KW)	Total Installed Charging Capacity (KW)
Crystal Springs - San Mateo County	69	414	4	200	614
Enoch Christoffersen South/Northbound - Stanislaus County	43	258	7	350	608
John "Chuck" Erreca South/Northbound - Merced County	22	132	13	650	782
Coalinga/Avenal South/Northbound - Fresno County	21	126	61	3050	3176
Camp Roberts South/Northbound - Monterey County	40	240	0	0	240
Shandon - San Luis Obispo County	38	228	1	50	278
IID Rest Areas					
Sunbeam West/Eastbound - Imperial County	0	0	8	400	400
Sand Hills - Imperial County	1	6	8	400	406
LADWP Rest Areas					
Crestview - Mono County	13	78	8	400	478
SCE Rest Areas					
Division Creek - Inyo County	0	0	0	0	0
C. H. Warlow - Tulare County	32	192	4	200	392
Philip S. Raine South/Northbound - Tulare County	37	222	6	300	522
Coso Junction - Inyo County	0	0	0	0	0
Valley Wells South/Northbound - San Bernardino County	2	12	54	2700	2712
Buttonwillow South/Northbound- Kern County	23	138	33	1650	1788
Clyde V. Kane South/Northbound - San Bernardino County	0	0	18	900	900
Boron West/Eastbound - Kern County	5	30	0	0	30
Tejon Pass South/Northbound - Kern County	0	0	25	1250	1250
John Wilkie West/Eastbound- San Bernardino County	0	0	0	0	0
Desert Oasis West/Eastbound - San Bernardino County	0	0	18	900	900
Gaviota South/Northbound-Santa Barbara County	26	156	13	650	806
Wildwood - San Bernardino County	69	414	18	900	1314
Brookside - Riverside County	52	312	38	1900	2212
Whitewater West/Eastbound - Riverside County	54	324	24	1200	1524
Cactus City West/Eastbound - Riverside County	54	324	13	650	974
Wiley's Well - Riverside County	4	24	1	50	74
SDGE Rest Areas					
Aliso Creek South/Northbound- San Diego County	45	270	16	800	1070
Buckman Springs - San Diego County	17	102	0	0	102