CALIFORNIA
ENERGY COMMISSION

Energy Research and Development Division

**FINAL PROJECT REPORT**

# Total Charge Management of Electric Vehicles

**December 2021 | CEC-500-2021-055**

**PREPARED BY**:

**Primary Authors**:
Timothy Lipman, Ph.D.
Institute of Transportation Studies
University of California - Berkeley
2150 Allston Way, Suite 280
Berkeley, CA 94704

Alissa Harrington
BMW NA, LLC
2606 Bayshore Parkway
Mountain View, CA 94043

Adam Langton
BMW NA, LLC
2606 Bayshore Parkway
Mountain View, CA 94043

**Contract Number**: EPC-15-084

**PREPARED FOR**:
California Energy Commission

Matthew Fung
**Project Manager**

Virginia Lew
**Office Manager**
**ENERGY EFFICIENCY RESEARCH OFFICE**

Jonah Steinbuck, Ph.D.
**Deputy Director**
**ENERGY RESEARCH AND DEVELOPMENT DIVISION**

Drew Bohan
**Executive Director**

# ACKNOWLEDGEMENTS

The authors acknowledge the assistance of BMW of North America, LLC (BMW NA), Pacific Gas and Electric Company (PG&E), Olivine, Inc., and Kevala Analytics, Inc. in supporting the development of this report. Specifically, the efforts of Alissa Harrington, Adam Langton, Michelle Bogen, and Tiina Aardemae of BMW NA, Karim Farhat of PG&E; Robert Anderson, Valerie Nibler, and David Siap of Olivine, and Aram Shumavon of Kevala for the input, review, and coordination provided to successfully complete this report. The efforts of Elpiniki Apostolaki-Iosifidou, Soomin Woo, Sierra Spencer, Zhe Fu, and Ankitha Doddonari from UC Berkeley are also gratefully acknowledged.

# PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

*Total Charge Management* is the final report for the Total Charge Management project (Contract Number: EPC-15-084) conducted by BMW North America LLC. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

# ABSTRACT

Managed charging of electric vehicles has the potential to help balance energy demand on the grid and manage intermittent renewables, save costs, and reduce greenhouse gas emissions to support California's strategy to move to full decarbonization by 2045. Electric vehicles can help achieve this goal by acting as a flexible resource for utility grids. They can curtail load when energy demand is high and accept load when energy demand is low and when there is excess generation. Shifting load to lower-cost times can also confer financial benefits to the vehicle owners.

The project examines several use cases for the interaction between driver plug-in/charging and driving behavior from 300 electric vehicle-driving households in the San Francisco Bay Area from 2017 through 2019. These cases range from avoiding electric vehicle home charging during peak evening hours, to shifting charging times and locations, to increasing charging during times of high renewable energy production, to more general goals of increasing the length of time that vehicles are plugged in, a key prerequisite for electric vehicle and grid interaction.

The project demonstrated a strong ability to shift electric vehicle charging loads through the various use cases, with the ability to shift up to about 20 percent of charging in any given hour to other times and the ability to add up to 30 percent of charging in a given hour. Optimization modeling using real-world driving and charging behavior revealed the ability to save about $56 per vehicle per year in reduced grid electricity supply costs by charging at lowest cost times, while meeting driver mobility needs. The modeling also demonstrated the potential to increase about 1,200 kilowatt-hours per vehicle per year in renewable energy use and about 300 kilograms per vehicle per year reduction in greenhouse gas emissions.

**Keywords:** electric vehicle, managed charging, smart charging, load management, grid integration, optimization, demand response, load increase, load decrease, clean energy, energy storage, technology, mobility, transportation, telematics

Please use the following citation for this report:

Lipman, Timothy, Alissa Harrington, and Adam Langton. 2021. *Total Charge Management of Electric Vehicles*. California Energy Commission. Publication Number: CEC-500-2021-055.

# TABLE OF CONTENTS

Page

# LIST OF FIGURES

Page

# LIST OF TABLES

# EXECUTIVE SUMMARY

## Introduction

Vehicle electrification is a key pillar in California's strategy to reduce greenhouse gas emissions as California moves toward full decarbonization by 2045 in response to Senate Bill 100 (De Léon). As electric vehicle (EV) markets continue to develop in California and other regions, the potential for electric vehicles to act as electric grid resources is finally coming to the forefront after years of study. Electric vehicles are unique electricity loads for utility grids because of their flexibility relative to most other loads regarding the timing of electricity use to meet a driver's needs. Electric vehicles can curtail load when grid costs are high, known as demand response, and accept load when grid costs are low and during times when an overgeneration of renewable energy creates excess electricity, an increasing phenomenon in California. This ability to shift load can help to improve grid operations by balancing electricity supply and demand and ultimately reducing costs to ratepayers.

Load flexibility can also potentially provide a host of other ancillary grid services such as spinning reserves (additional power sources available when needed on short notice), frequency response (maintaining the 60 Hertz frequency of the grid), voltage support at the distribution level, and several other larger-scale benefits such as grid upgrade deferral.

## Project Purpose

This project explored real-world opportunities and challenges for electric vehicle-grid integration using a managed charging program that shifts charging loads across time, days, and location within the driver's mobility constraints. A managed charging program can improve the amount of renewable energy on California's electric grid, thereby increasing the capacity factor of renewable resources to help meet state Renewable Portfolio Standard goals. Successful implementation of vehicle-grid integration can also improve grid operations at the distribution level, reduce the cost of providing electricity at the wholesale level, and lower the carbon intensity of electric vehicle charging.

This innovative and groundbreaking total charge management effort, called ChargeForward 2.0, combines the largest real-world electric vehicle and utility grid integration test of its kind. The project encompasses approximately 400 total EV-driving households and 250-300 at a given time in the project, in the San Francisco Bay Area from 2017 through 2019.

ChargeForward 2.0 is a second phase of an initial BMW North America LLC ChargeForward program that examines a series of load shifting and curtailing "use cases" for the interaction of driver plug-in/charging and driving behavior of their electric vehicles in ways to improve grid operations and create value for drivers, grid operators, and California ratepayers. These use cases range from avoiding charging electric vehicles at home during peak evening hours, to shifting charging from nights at home to daytime at locations away from home (typically the workplace), to increasing charging during times of high renewable energy production, to more general goals of simply increasing the period of time that vehicles are plugged in, a key prerequisite for any type of electric vehicle and grid interaction.

The project also addresses several features of this managed charging concept including electric vehicle driver enrollment and participation in the managed charging program, participant response to a range of specific use cases for vehicle-grid integration, and a more theoretical investigation that relaxes constraints on electric vehicle charger availability, particularly at daytime workplace locations.

This project was intended to extend more traditional concepts of building-based demand response to the transportation electrification realm. Most demand response concepts to date involve commercial buildings and their ability to shed load in response to a request from the local utility when the grid becomes strained. This project focused on advancing the understanding of the practical considerations and potential value to demand response of using vehicle-grid integration to inform potential policy development for utilities and regulators to enable demand response and vehicle-grid integration services, and to identify useful next steps to advance these concepts.

The project addressed key research gaps and challenges by conducting an ambitious real-world experiment with hundreds of actual electric vehicle drivers who responded to incentives by changing their vehicle plug-in and charging behavior. The challenges included recruiting and retaining participants throughout the study, developing and implementing an internet-based optimization platform for vehicle charging load control using the telematics systems in the vehicles, understanding participant responses to various types of monetary and non-monetary incentives, examining the performance of vehicles in conjunction with household battery storage systems, and understanding desired participant levels of information and privacy concerns.

Based on the outcomes of pilot projects like this one and subsequent developments, successful future implementation of vehicle-grid integration can achieve objectives important to California electricity ratepayers.

## Project Approach

This project demonstrated vehicle-grid integration with approximately 300 participating households in the San Francisco Bay Area that own or lease one or more BMW plug-in EVs. The project use cases and data collection commenced in 2017 and continued through late 2019.

The project approach involved: (1) recruiting and enrolling customers to participate in the program based on a structure of incentives to reward their participation; (2) conducting a series of use cases with various objectives related to enabling the ability of relatively flexible EV loads to meet grid operational goals; (3) collecting data on household electricity use and vehicle charging patterns; (4) parsing and analyzing data using Python programming language-based scripts; (5) developing a theoretical optimization framework that allows for relaxed constraints around EV charger availability; and (6) developing key project findings and suggestions for next research steps. Using the power of onboard vehicle telematics systems and a sophisticated “back end” optimization platform, the timing of EV charging was altered to enable vehicles to provide a better match to grid operational conditions.

The project also studied household energy use patterns relative to EV load management and explored the potential for further optimization potential with more extensive availability of EV charging infrastructure in the future.

To achieve the project objectives, the effort brought together an extensive team of researchers as well as active involvement of a technical advisory committee. BMW of North America led the project team, with key involvement from Pacific Gas and Electric Company (PG&E) and the University of California, Berkeley. Additional team members included Olivine Inc. and Kevala Analytics Inc. Technical Advisory Committee members provided important advice and feedback that helped to guide the project approach and methods.

In its implementation, the project encountered some non-technical and technical barriers. Non-technical challenges included some difficulties with availability of customer electricity use data, registering households as demand response resources, permitting for home storage installations, and limited access to distribution infrastructure data. An additional issue was the potential effect on customers' bills of certain charging strategies based on local utility rate structures. Technical challenges included some issues with the initial implementation of charging optimization that were resolved with data access improvements. Another issue was delays associated with the interconnection of home energy storage systems, but this was ultimately resolved.

## Project Results

Highlights of the quantitative project findings include the ability to shift charging at home and away locations, the ability to increase the level of participant plug-in behavior, and optimization modeling results showing future potential to shift charge, increase renewable energy use, and reduce greenhouse gas (GHG) emissions.

### Ability to Shift Charging Times

The various use cases demonstrated the ability to shift nearly 20 percent of electric vehicle charging for participating households during individual hours out of times of high wholesale grid prices (typically in the early evening) and into times of lower grid prices, where up to 30 percent of hourly charging could be shifted back in.

### Ability to Increase Participant Behavior

In the Cohort Plug-in Goal use case intended to increase driver plug-in behavior through a group incentive, plug-in time increased by 46 percent compared to the week before across all locations, which is statistically significant at the 99 percent confidence level. This increase in plug-in behavior (even when drivers do not need to charge in that immediate time frame) is a key prerequisite to any type of charge management system.

### Optimization Modeling Results

Using a fixed charging location optimization model with the objective of minimizing grid costs, the project team estimated an average savings of $46 per vehicle per year from shifting charge to the lowest price time periods while still meeting driver mobility needs. A multi-location version of the optimization model increased this estimate to $56 per vehicle per year (on average) by taking advantage of more than one charging location across a longer (multi-day) time period. Inter-locational charging optimizations, when charging at the lowest GHG emission times, suggested an average level of savings of about 300 kilograms per year per vehicle is achievable, albeit requiring a higher level of available future daytime charging infrastructure. When increasing the amount of renewable electricity to charge the electric vehicles (similar to the GHG emission reduction case), an average of about 1,200 additional kilowatt-hours of renewable electricity could be used per vehicle per year through charge shifting within driver mobility constraints, such as drivers' specific plug-out and departure time.

Additional opportunities and future research to further the vehicle-grid integration concept include: (1) better understanding of consumer motivations and information needs to participate in such programs on an ongoing basis; (2) publicly-funded charging investments to bolster workplace charging; (3) more pilots exposing drivers to hourly time-varying rates on a day-ahead basis to encourage plugging in more frequently. Further beneficial technology developments include enhanced abilities for vehicles to provide grid performance information, reliable sub-metering of electricity consumption, and the exchange of local data between vehicles and building operating systems.

## Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

This project expanded the real-world use of electric vehicle charge management from about 90 households to more than 300 households in the San Francisco Bay Area. The project has already been the subject of numerous public presentations, documented in this report; the project team will also make conference presentations and write articles for peer-reviewed journals. BMW will produce a pamphlet of key project results.

BMW worked closely with Pacific Gas and Electric to design the use cases in this pilot. The utility's hourly renewable energy data was used in two use cases and was also integrated into the participant web portal, showing how much of a vehicle's charging came from renewable energy and giving Pacific Gas and Electric customers first-time visibility into their renewable energy use.

To extend the charge management platform developed under this grant agreement across California and beyond, BMW is working with UC Berkeley and the major California investor-owned utilities to develop larger software platforms that integrate commercial as well as residential host sites, multiple types of electrical vehicle supply equipment, and other types of electric vehicles through those additional approaches.

## Benefits to California

Managed charging offers economic and environmental benefits to ratepayers and for utility grid operations. The concept of EV charge management has the potential to provide efficiencies for utility grid operations that can reduce overall costs to utility ratepayers. Customers can also reduce their bills directly by charging during lower priced TOU billing periods. Reducing grid operational costs through reduced wholesale procurement during high cost periods and avoiding the need for distribution-level system capacity expansion can eventually flow back to all ratepayers through avoided future rate increases. Rate design that incentivizes EV drivers to shift their vehicle charging to help. EV charge management can also help with accepting increased levels of renewable energy on the grid by mitigating renewable energy intermittency and overgeneration.

Project participants' increased understanding of their choice to shift to lower-priced time of use billing periods that can reduce their utility bill and may help lower their carbon footprint.

Indirect benefits that reduce grid operational costs through reduced wholesale costs also eventually flow back to ratepayers through avoided costs and future rate design. Electric vehicle charge management can also help with grid acceptance of increased levels of renewable energy, providing environmental and sustainability benefits to California ratepayers.

In terms of grid operations, electric vehicle load shifting can assist in three ways. By encouraging electric vehicle charging during the morning ramp period, load shifting helps to mitigate the morning ramp-down in the net load curve, as solar photovoltaic rapidly comes onto the grid and traditional generators are forced to turn down. As solar photovoltaic comes online in the middle of the day, charging can help fill the midday valley in the net load curve, helping to flatten it and furthering the acceptance of renewable solar generation. Finally, electric vehicle charging can be avoided during the early evening ramp-up period as the solar resource fades away and grid service costs are typically at their peak.

The project proposal identified a goal of establishing potential benefits of $0.50 per vehicle per day in reduced bill costs, as well as 1.8 kilograms of CO2 reduction. Findings from this project show the potential for each EV participating in a charge management project to save up to about $56 per vehicle per year in avoided grid service costs, and a similar amount (about $63 per vehicle per year) in additional distribution system level benefits. An initial estimate of stacked benefits from managed charging suggests that the largest value is from demand response, but that there are additional values from energy arbitrage, grid distribution cost savings, and avoided carbon emissions that could in total be of similar magnitude. Preliminary estimates suggest that these combined values of managed charging could be about $300 per vehicle per year.

Additional benefits possible through optimization modeling include the potential to reduce GHG emissions by about 300 kilograms per vehicle per year on average and absorb about 1,200 kilowatt-hours of additional renewable electricity per vehicle per year. It may be that the possible reductions in GHGs are closer to 1 kilogram per day than the 1.8 kilograms targeted in the initial project proposal. However, these are only a few elements of the potential benefit stack that includes smart charging, using electric vehicles as grid resources—including provision of grid ancillary services such as frequency response and spinning reserves—using electric vehicles for emergency backup resources, and using of electric vehicles as broader grid storage resources through bi-directional vehicle-to-grid power.

# CHAPTER 1: Introduction

As electric vehicle (EV) markets continue to develop in California and other regions, the potential for electric vehicles to act as grid resources is finally coming to the fore after many years of study. EVs are unique electricity loads for utility grids because of their temporal and spatial flexibility. EVs can curtail load when grid costs are high, known as demand response, and accept load when grid costs are low and when electricity is in excess, an increasing phenomenon in California, garnering grid benefits that can be passed on to the vehicle drivers. They can also potentially provide a host of other ancillary grid services such as spinning reserves, frequency response, voltage support, reactive power compensation, and several other larger-scale benefits such as grid upgrade deferral that are beyond the scope of this project.

This innovative and ground-breaking effort, called ChargeForward 2.0, combines the largest real-world test of EV and utility grid integration of its kind. The project was conducted in the greater San Francisco Bay Area between 2017 and 2019. Approximately 400 households participated over the course of the project, with between 250 and 300 participating at any one time. The project examines a series of "use cases" for the interaction of driver plug-in/charging and driving behavior. These include avoiding EV charging at home during peak evening hours, shifting charging from nights at home to daytime at locations away from home (typically a workplace), increasing charging during times of high renewable energy production, and more general actions such as increasing the time periods that vehicles are plugged in—a key prerequisite for any type of EV and grid interaction. The project aims to address several interesting research questions around this topic, with the research questions, project approach and methods, key findings and results, and conclusions and recommendations documented in detail in this final project report.

## Background

The concept of vehicle-grid integration (VGI) has been under research and development for more than 20 years, but is now beginning to move forward as the number of EVs proliferates around the world. VGI pilot projects are occurring in California led by auto companies, electric utilities, utility research groups, EV charging companies, transit agencies using electric buses, and universities and research laboratories. These projects are yielding useful information about VGI market potential and technical and administrative hurdles to near-term development.

### Vehicle-Grid Integration as a Grid Resource

Unlike stationary resources, motor vehicles are intended primarily to provide mobility to their owners. EVs are thus only occasionally at locations where they might be plugged in to charge — typically at home and workplace locations, but sometimes at shopping and recreational locations. Recent analysis of vehicle activity in the United States indicates that on average drivers spend about 51 minutes per day driving about 32 miles (Kim et al. 2019). This means that for approximately 23 hours per day, vehicles are parked. In the case of EVs, they could be plugged in to charge if chargers are available at those locations. Many EV drivers do not currently have dedicated chargers away from their home locations (and some do not have home charging), but in the future the extent of EV charge networks is expected to grow, increasing the opportunities for VGI and smart charging when the vehicles are not being driven.

In the future, it is likely that changes in vehicle operation through growth in transportation network companies (TNCs) may prompt vehicles to be driven more hours per day. It is also possible that automation will lead to more vehicles being owned by managed pools rather than by individual drivers, which will affect the potential availability of EVs as VGI resources. Although these trends are difficult to predict, two aspects are likely to be important for implementation of EV charge management schemes: (1) opportunities for charge management may decrease as the length of time during which EVs are plugged in but not charging may decrease (meaning less charge timing flexibility), and (2) fleet-owned vehicles can be managed in a more coordinated manner than individually owned vehicles, which would increase opportunities for charge management through scheduled periods of charging in prescribed locations. However, it is unclear at this time to what extent TNC evolution will affect personal automobile use, and it is likely that the majority of vehicles will continue to be owned for typical household use for the near future.

## Recent Related Activities in California

The California Public Utilities Commission (CPUC) and the California Energy Commission (CEC) are actively engaged in VGI research, along with the California Independent System Operator (California ISO), large private and public electrical utilities, vehicle automakers and EV charger companies, the Electric Power Research Institute (EPRI), and various other research organizations. A VGI roadmap document, which describes tasks to address VGI policy, economic, and technical barriers, was developed by the California ISO, in coordination with the Governor's Office, the CEC, and the CPUC in 2014 (California ISO 2014). A newer version is in progress and expected in 2021 from the CEC.

There is also a new iteration of the VGI Working Group led by the CPUC, with meetings being held and documents released in 2020. In a related step, Pacific Gas and Electric Company (PG&E) has been developing a comprehensive VGI valuation framework that is being integrated into the CPUC working group process. Finally, there is a growing body of academic literature on various topics related to EVs and grid integration. These documents help to define market opportunities for VGI, the current status of codes and standards, various sets of communication protocols, and remaining obstacles and technology and policy gaps.

## Electric Program Investment Charge Grant 15-084 Project Description

ChargeForward 2.0 is a second phase of the BMW North America LLC ChargeForward program that focuses on enrolling customers in a program to help manage their at-home and away-from-home charging of their EVS in ways to improve grid operations and create value for drivers, grid operators, and California ratepayers. This second phase was enabled by CEC EPIC Program award 15-084 for a project titled Total Charge Management (TCM). The project includes about 400 total households and 250-300 at a given time in the project. It ran through early 2020, exploring a variety of additional use-cases for VGI implementation, including both home-based and work-based charging sessions and shifting charging across different days as well as within a charging session.

### ChargeForward 1.0 Background

Led by PG&E, the BMW ChargeForward pilot project operated from July 2015 to December 2016, and included approximately 90 participating households in the San Francisco Bay Area. VGI use cases included shifting of charge timing at household locations over the course of individual vehicle charge sessions to reduce EV driver recharging costs. The study revealed that electric vehicles can provide viable grid services using vehicle telematics for communicating grid events to vehicles.

The pilot tested Day Ahead and Real Time Energy grid events. Approximately 100 BMW i3 vehicles participated in 209 one-hour demand response events, and additional grid resources were provided by BMW's second-life stationary battery system of used EV batteries. The events totaled 19,500 kilowatt-hours (kWh) of dispatchable load, with approximately 20 percent from the vehicles and 80 percent from the second-life battery system.

The pilot also showed that it was possible to shift vehicle-induced load while minimizing disruption to customers. The final survey results showed that 98 percent of customers were satisfied with the project, and 93 percent were interested in participating in a similar project in the future.

## Project Partners

BMW North America LLC led the EPIC TCM project with additional project partners Pacific Gas and Electric Company (PG&E), the University of California, Berkeley's Transportation Sustainability Research Center (TSRC), Olivine Inc., and Kevala Analytics Inc.

**BMW of North America, LLC (BMW NA)** was established in 1975 as the United States importer of BMW luxury/performance vehicles, including the BMW i sub-brand of BMW founded in 2011 to design and manufacture plug-in electric vehicles. BMW served as the overall project lead and was the grant's prime contractor. The following people from BMW NA Connected eMobility group worked on this project: Adam Langton (Project Lead/Energy Services Manager), Alissa Harrington (Project Manager), Sophia Lu (Customer Engagement Coordinator), and Tiina Aardemae (interim Project Manager).

**Pacific Gas and Electric Company (PG&E)** is one of the largest combined natural gas and electric energy companies in the United States, covering a 70,000-square-mile service area in northern and central California. Dr. Karim Farhat (Vehicle Grid Integration) and Alva Svoboda (Market Design Integration) from PG&E worked on this project. Dr. Farhat collaborated with and advised the BMW team on use-case design, testing, and analysis throughout this project. PG&E also provided renewable energy data that helped support use-case development and implementation.

**University of California, Berkeley Transportation Sustainability Research Center (TSRC)** is a research unit of the Institute of Transportation Studies. TSRC was established in 2006 to conduct research on questions of transportation sustainability, including vehicle electrification, use of biofuels and hydrogen, innovative mobility systems, and advanced freight and goods movement. TSRC was the lead project partner on data analysis and modeling to evaluate project use cases and VGI value propositions and had a leading role in final project reporting. Dr. Timothy Lipman led the TSRC team with additional participants Dr. Elpiniki Apostolaki Iosifidou, Soomin Woo, Sierra Spencer, and Zhe Fu.

**Olivine, Inc.** provides infrastructure and services that enable distributed and aggregated resources to effectively and efficiently offer grid services. The following people from Olivine worked on this project: Robert Anderson (Chief Technology Officer), Valerie Nibler (Project Manager), David Siap (Distributed Energy Resources Technical Analyst), and Lee Schneider (Technical Services and Implementation Lead). Olivine served as the scheduling coordinator for optimization signals sent to enrolled vehicles and provided analytical work to support various technical tasks.

**Kevala Analytics, Inc.** is a data and analytics company focused on electricity infrastructure, the built environment, and the behavior of people and resources. It provides insight and analytics services around non-wires alternatives, hosting capacity, and location net benefits. The following people from Kevala worked on this project: Aram Shumavon (Chief Executive Officer), Emmanuel Levijarvi (Engineering Director), and Laura Wang (Project Manager). Kevala's primary role in this project was providing grid mapping tools and locational marginal price (LMP) analysis.

## Project Objectives

The objectives of this project are to extend the initial ChargeForward project in key additional dimensions including a greater number of participating households, a wider geographical distribution of participating households around the San Francisco Bay Area, and examination of several additional VGI use cases including those that shift EV charging across days and locations as well as within a single charging session at a given location. The project objectives also included extension of the "real world" aspects of the study to additional theoretical modeling analysis that includes consideration of a more extensive away-from-home EV charge network in the future. The project also included the installation of battery energy storage systems at some residential locations to explore the ability of households with both EVs and battery storage to participate in grid support programs with greater storage capacity and flexibility.

The project aims to further define VGI value propositions by understanding the potential grid-side value of EV charge shifting in a California grid context. The study combines participation in a VGI program managed by a major automaker, a large overall set of more than 400 EV-driving households (approximately 250-300 at a given time in the project) participating in a real-world context, data collection using household electricity metering devices and vehicle telematics systems, data interpretation and analysis, and a theoretical optimization modeling analysis that considers a future with a more widespread EV charge network to enable a wider range of potential EV charge shifting opportunities.

## Key Research Objectives

The main research areas addressed in this study include the following elements:

- Customer experience

    - Explore the driver engagement and incentives needed to fully optimize charging events
    - Observe level of participation in a real-world VGI program among a set of EV driving households
    - Identify participating households' motivations and concerns for inclusion in VGI programs
- System operations
    - Evaluate the use of vehicle-based telematics charging data to measure vehicle grid performance away from home
    - Enable optimization of charging across wholesale (California ISO) and retail (utility) programs, such as demand response and distributed resource planning procurement opportunities
    - Identify how the use of vehicle-based telematics charging data can be used to measure vehicle grid performance away from home
    - Capture technical and operational issues revealed by VGI experiments in the real world and how can they be overcome (for example, participant failure to indicate a departure time, issues with obtaining vehicle telematics data, and other details)
- Identifying grid and customer value
    - Identify VGI use cases that offer the greatest opportunities for flexible charging and the greatest potential grid benefits
    - Understand the optimization opportunities within drivers' home electrical load relative to their residential tariff and power usage patterns
    - Evaluate parking and charging events away from home to determine if the time and location of these events lend themselves to realizing grid benefits beyond what is achieved with nighttime charging
    - Evaluate the use of locational marginal prices and other transaction energy signals as tools to improve grid efficiency

The outcomes of the evaluation of these research objectives are described in this report, following a description of the research approaches used to address them.

# CHAPTER 2: Project Approach

The following sections describe the approaches used for the various elements of the project. These include how EV driver participants were enrolled and retained in the study, concepts related to using EVs as grid resources, the analysis methods used to evaluate the project use cases, and the mathematical approach used to perform the more theoretical optimization modeling exercise.

## Customer Enrollment

### Vehicle Enrollment Goal

BMW committed to enroll at a minimum 250 electric vehicles for participation in the optimization use cases featured in this phase of the pilot, which at the time was one of the largest electric vehicle smart charging pilots in the United States. The maximum enrollment target was set at 500, and the actual maximum observed was 399 customers. The average number of participants between 2017 and 2020 was around 250.

### Customer Engagement Strategy

The ChargeForward customer engagement strategy focused on providing transparency around participation and the benefits of smart charging, rewarding participants for smart charging, and gathering feedback on the program and use cases.

During the on-boarding phase, new participants were provided a customer handbook and access to the program website. The website details participation guidelines, vehicle and fleet performance, and sustainability metrics such as renewable miles driven.

To retain existing customers, various tools were used to keep customers engaged. These included, but were not limited to: an interactive phone app and website, financial incentives and special awards, participant performance comparison against the full fleet, education on how to improve vehicle performance, and education on vehicle-grid interactions.

Participant feedback on the program and its use cases was captured primarily through emails and surveys. Select interviews also captured in-depth behavioral insights. For a small group of participants, a professional photo and/or video shoot was also conducted to highlight interesting user stories around smart charging.

### Customer Enrollment Tools

The program relied on various modes of communication to engage and enroll participants. The main tools used include:

- *Ad hoc* targeted email correspondence
- Mass email notifications on upcoming events or program communications
- Push notifications through the ChargeForward phone app
- Content made available through the ChargeForward phone app

- Content made available through the newly updated participant web portal
- Surveys to gather participant feedback

Appendix I, Customer Communication Tools Report #1, offers more details on these tools, including sample outreach, enrollment, and website launch emails and a sample survey from one of the use cases.

### Enrollment Process

The 2017 enrollment process for this pilot had seven steps:

1. Generate potential project participants through awareness activities
2. Ask interested applicants to submit enrollment forms to BMW
3. Process participant household meter data Customer Information Service Request (CISR) forms
4. Set up customer profiles
5. Set up home area network (HAN) devices
6. Ask enrollees to install ChargeForward phone app
7. Distribute enrollment incentives

Appendix A, Customer Enrollment Lessons Learned, describes details of these steps.

The initial enrollment period lasted about 10 months and was the first time that BMW used PG&E's CISR process and moved the entire enrollment process online. Because this pilot involved a partnership with PG&E, the enrollment process also incorporated setting up HAN devices as part of a PG&E HAN study.

Enrollment opened for customers again in the fall of 2018, to maintain a minimum of 250 enrollees.

### Enrollment Participation

During the enrollment processes, 55 percent of those who started the process ended up participating, showing how utilities can benefit from partnering with automakers to identify and recruit program participants. However, the CISR form proved cumbersome for some applicants and required additional customer engagement to determine whether an applicant was eligible to enroll.

Current utility regulations do not allow households to be enrolled in more than one device-specific program (for example, an electric vehicle program and an air conditioning program). To maintain a more stable level of enrollment, utilities may want to consider the feasibility of introducing programs that allow multiple device enrollments, as well as provide more awareness on which programs a household is eligible to participate in.

## Vehicles As an Aggregated Grid Resource

EVs are becoming interesting as grid resources because they are proliferating in numbers that are starting to become significant, coupled with the inclusion of battery pack sizes that, when aggregated, can represent sizable overall loads. However, taking advantage of this in practical ways may require sophisticated approaches to metering and control, as well as systems to aggregate vehicles into blocks of resources in given regions that are relevant for grid operations. Several features of these challenges are discussed, followed by approaches used for analysis in this EPIC project.

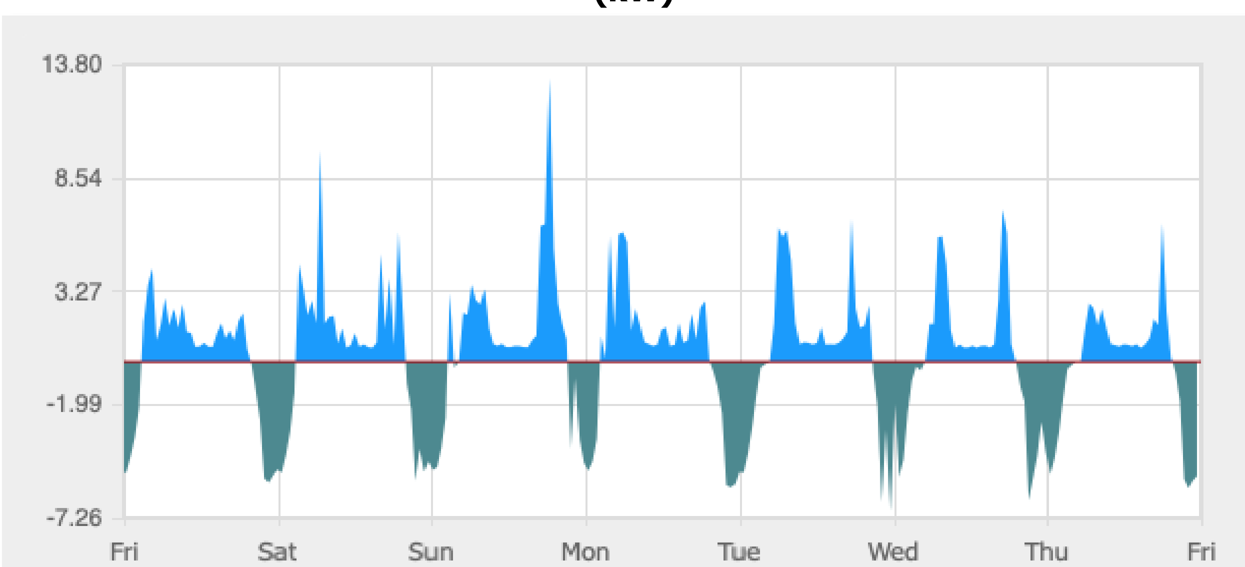
### Metering

Energy-use metering related to EV charge management is relevant in two key areas: (1) metering local building loads to understand the effect of EV charge management on customer utility bills; and (2) metering the charging behavior of individual vehicles to assess the effect of load shifting for utility grid operations. These two concepts may be important depending on the desired effects of charge management programs. For example, utilities may wish to better understand and control EV charging along individual grid feeder lines to help maintain system voltage; individual host sites that are subject to utility demand charges (for example, commercial and industrial sites) may wish to control EV charging to reduce the impacts of demand charges on utility bills; and individual households may wish to shift EV charging to times of lower prices under TOU billing rate schedules.

#### HAN/PG&E Data

At the household level, utility meters are increasingly becoming "smart" devices that can remotely relay data to the host utility through mesh networks. These data are typically reported at 15-minute intervals, meaning that some finer grained variations in local loads can be missed. Also, there is typically a few days of delay in obtaining meter data through the utility process. A higher resolution of local energy use can be obtained using "home area network" devices that can be connected to the utility meter that can extract power level data at 15-second intervals for much higher resolution. An example is shown in Figure 1, where the dynamics of household loads become apparent. Note that this is for a household with onsite solar power, where net additions to the grid from the solar system are shown as negative loads.

**Figure 1: Example Weekly Home Area Network Meter Data for a Solar Household (kW)**




Source: UC Berkeley

These HAN devices can be useful for understanding the effects of EV charging on overall household loads. Efforts in this project also used PG&E meter and HAN data to attempt to discern EV charging events, but discerning EV charging from the rest of the household load proved to be difficult, especially for households with Level 1 chargers. Using HAN data was more useful in this regard than the coarser 15-minute meter data, and Level 2 (approximately 7 kW) charging events are much easier to detect than Level 1 (approximately 1.5 kW) events because the latter are similar in magnitude to several other types of common household loads such as washing machines and dishwashers. Details of these household load analyses are presented in Appendix E, Customer Home Load Report.

### Vehicle Telematics

Modern vehicles are equipped with increasing levels of sophistication regarding the ability to remotely monitor and understand vehicle operations. For EVs, this means that important aspects of charge management can be monitored and controlled remotely with "telematics" systems onboard the vehicles. Telematics systems can detect when a vehicle is plugged into a charger, when it is charging, the battery state of charge, and vehicle location — all critical elements of vehicle charge management strategies. Furthermore, vehicle telematics systems can allow EV drivers to set desired levels of target state of charge and their departure times and remotely control charging around those times, critically needed to ensure that drivers have the needed vehicle driving range to meet their mobility needs. The vehicle telematics systems used in the project were designed to turn charging on or off in a binary fashion, but in the future charging power could be ramped up and down through amperage level control (at a fixed voltage) in a more gradual fashion depending on grid needs.

## Resource Categorization

EVs represent a unique and growing type of load for electric utilities. Because of their use for mobility and ability to charge in different locations, EVs are challenging loads to forecast because of their relative unpredictability compared with stationary building power demands. Predictions are further challenged because the market for EVs is growing but with geographical variations.

### Resource Size

More than 600,000 EVs of various types have been sold in California over the past several years (Veloz 2019). Of the vehicles receiving state purchase incentives (somewhat more than 300,000) approximately 61 percent are identified as battery EVs and about 37 percent are identified as plug-in hybrid EVs (Clean Vehicle Rebate Project 2019), with a small percentage being fuel cell vehicles. Meanwhile, the state has ambitious goals to rapidly expand the zero-emission vehicle fleet with a goal of 5 million zero-emission vehicles on the roads by 2030, or almost 10 times the current number (Governor Executive Order, B-48-18, 2018).

Applying an approximate 60/40 percent split for battery EVs and plug-in hybrids and assuming current "usable capacity" battery pack size of 30 kWh and 10 kWh respectively, a California fleet of 600,000 EVs would have a total electricity storage capacity of more than 13,200 megawatt-hours (MWh). A fleet of 5 million EVs in 2030 would have a corresponding storage capacity of about 110,000 MWh, with the same assumptions and more than 200,000 MWh if average battery pack size is double by that time, a possibility given expected industry trends and declining battery pack costs. To put this into context, California currently has a plan to connect 1,300 MW of storage to the California grid by 2024 through a “storage mandate” to help support the growth of renewable power on the state grid. If these are sized to be four-hour battery discharges, that would represent about 5,200 MWh of storage, or significantly less than even the current California EV fleet. Of course, unlike dedicated stationary devices, EVs are mobile devices that are not always able to provide grid services.

### Location

The location of this project was the San Francisco Bay Area with some participants in the Sacramento area. This included the counties of Alameda, Contra Costa, Marin, Napa, Sacramento, San Francisco, San Mateo, Santa Clara, Solano, Sonoma, and Yolo. This area was expanded from the initial ChargeForward 1.0 project that focused only on the San Jose/Mountain View area, generally known as Silicon Valley.

For purposes of project analysis, the project location was disaggregated into key functional units for utility grid management. These include the utility sub-load aggregation point or “SubLAP” regions, of which there are several in the project study area, and also the more finely grained “p-node” zones for purposes of application of locational marginal pricing. The application of these sub-regions to the various types of analysis are described in the narrative sections in the relevant report chapters, along with a discussion of general study participant travel patterns in the section below.

### Vehicle Types

Table 1 shows the vehicle types that participated in this pilot, as well as their battery capacities in kilowatt-hours and rated operational efficiency.

**Table 1: ChargeForward Participating Vehicle Types**

| Vehicle | Battery Size (kWh) | USEPA Efficiency (kWh.100 mi) | Vehicle Type |
|---|---|---|---|
| 330EIPERFORMANCE | 7.6 | 47 | Plug-in electric hybrid |
| 530EIPERFORMANCE | 12 | 47.5 | Plug-in electric hybrid |
| 530EXDRIVE IPERFORMANCE | 12 | 47.5 | Plug-in electric hybrid |
| X5 XDRIVE 40E IPERFORMANCE | 9.2 | 59 | Plug-in electric hybrid |
| I3 (+REX) | 33 | 30 | Battery electric vehicle with range extender |
| I3 94 (+REX) | 33 | 30 | Battery electric vehicle with range extender |
| I3S 94 REX | 33 | 30 | Battery electric vehicle with range extender |
| I3 120 REX | 42.2 | 32 | Battery electric vehicle with range extender |
| I3S 120 REX | 42.2 | 32 | Battery electric vehicle with range extender |

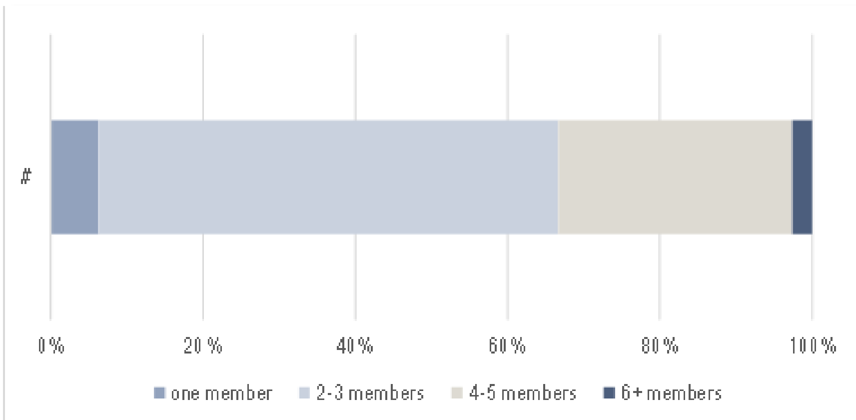
| Vehicle | Battery Size (kWh) | USEPA Efficiency (kWh.100 mi) | Vehicle Type |
|---|---|---|---|
| I8 | 11.6 | 49 | Battery electric vehicle |
| I3 | 22 | 27 | Battery electric vehicle |
| I3 94 | 33 | 29 | Battery electric vehicle |
| I3S 94 | 33 | 29 | Battery electric vehicle |
| I3 120 | 42.2 | 30 | Battery electric vehicle |
| I3S 120 | 42.2 | 30 | Battery electric vehicle |

Source: BMW of North America, LLC

### Household Characteristics

More than 500 vehicles have participated in the ChargeForward pilot across more than 400 households. Figure 2 and Table 2 summarize participant household characteristics.

**Figure 2: Distribution of Project Participant Household Size**




Source: BMW of North America, LLC

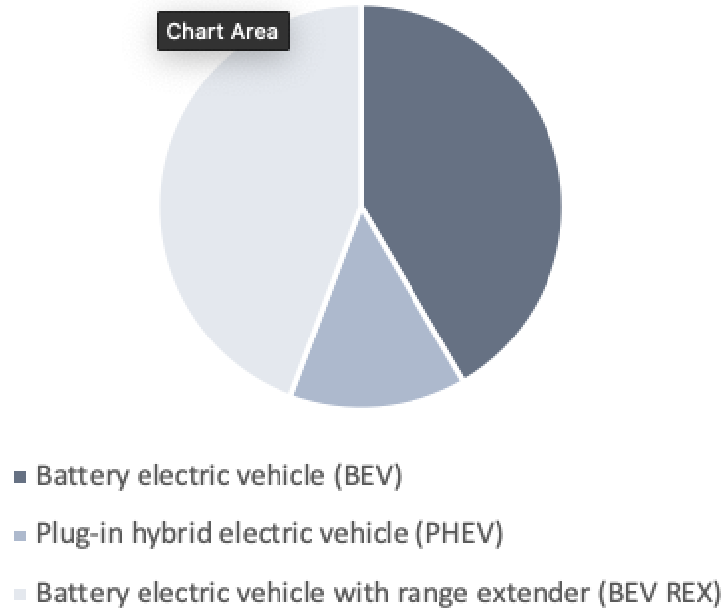
**Table 2: ChargeForward Household Characteristics**

| Value | Household Characteristic Description |
|---|---|
| 3.0 | Average household size |
| 52 percent | Households with at least one member under 19 years |
| 15 percent | Households with at least one member aged 65 or over |
| 4 percent | Households with at least one member under 19 and one over 65 |

Source: BMW of North America, LLC

**Error! Reference source not found.** shows the share of PEV types in the project participant group of households. As shown the split between BEVs and PHEVs was about even and constituted most of the vehicles, with a small share of about 15 percent consisting of the BEV with range extender model of the i3.

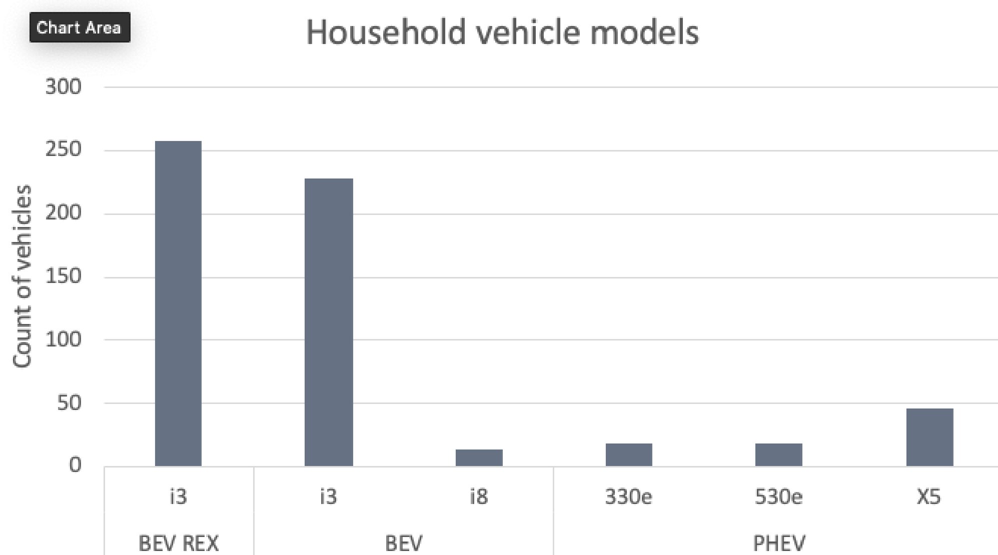
**Figure 3: Share of PEV Types in ChargeForward**




Source: BMW of North America, LLC

**Error! Reference source not found.** 4 shows the specific vehicle models included in the study. As shown the sample was dominated by versions of the i3, roughly split between BEV and range-extender models. There were also a few luxury i8 models and three different models of PEVs but that together made up a minority of the sample.

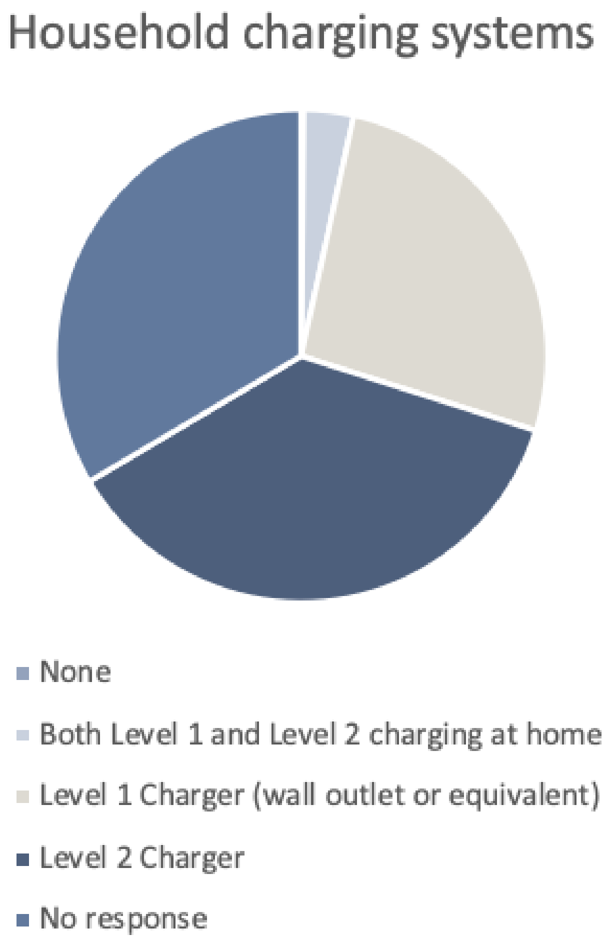
**Figure 4: Types and Models of ChargeForward Household Vehicles**




Source: BMW of North America, LLC

Shown in Figure 5 are the types of household charging systems (Level 1, Level 2, both, or none) included in the study. About 40 percent of the households had Level 2 chargers installed, about 25 percent had Level 1 chargers, a small percentage had both, and about 40 percent did not respond to the survey question.

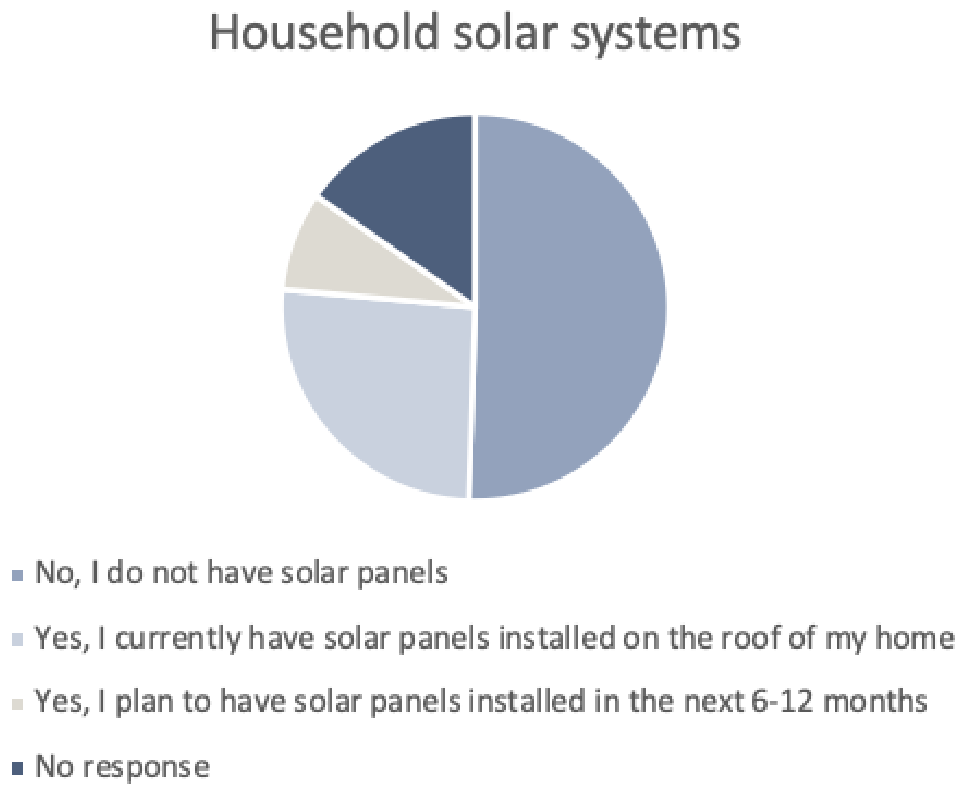
**Figure 5: Types of PEV Charging Systems in ChargeForward Households**




Source: BMW of North America, LLC

Finally, Figure 6 shows that about half of the households did not have solar panels installed or near-term intent to install them, about one-quarter did have solar panels installed, and about 10 percent have plans to install solar panels in the next year.

**Figure 6: Participant Household Vehicle and Charging System Information**



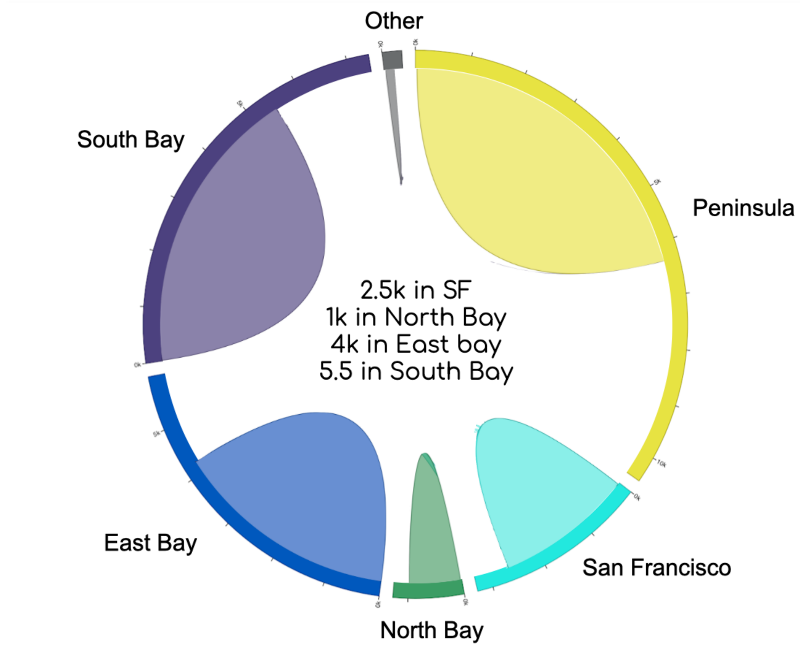

Source: BMW of North America, LLC

### Travel Behavior

Program participants are located around the San Francisco Bay Area, in five general regions: South Bay, East Bay, North Bay, the Peninsula, and San Francisco. These regions correspond to PG&E sub-load aggregation points or "SubLAP" regions. These are defined as zones that are used for load aggregation for participation in utility programs such as demand response.

In studying the travel patterns of these participants, a majority typically travel within rather than between these broad SubLAP regions, in what could be called "intra-regional" travel. Figure 7 presents the trips on an annual basis for project year 2017, where the arcs shown represent trips that start and end in the same region. Particularly for regions other than the Peninsula, most trips are intra-regional. These patterns have implications for potential aggregation of EV-based grid services, where aggregation will typically need to occur within SubLAP zones.

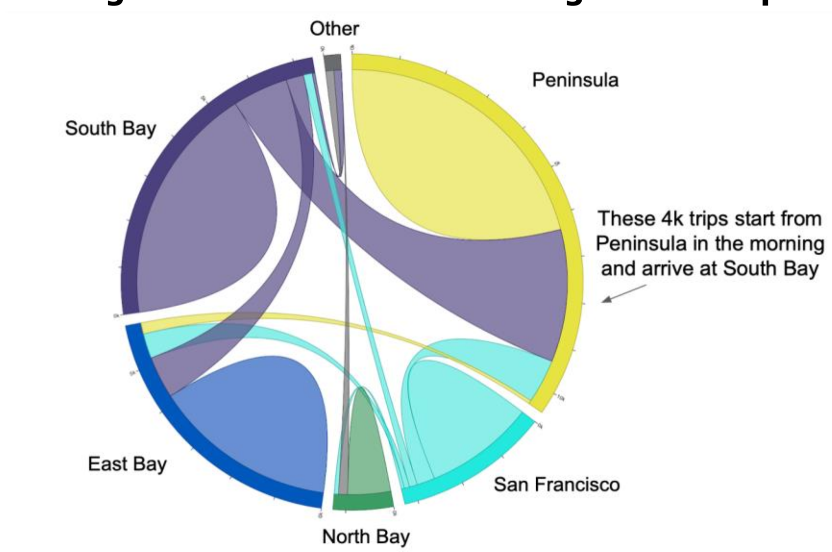
**Figure 7: Intra-Regional Travel Patterns of Program Participants (# of trips)**




Source: UC Berkeley

However, a significant amount of travel among study participants crosses between SubLAP zones, creating potentially greater challenges for aggregation of VGI services as more than one SubLAP zone may need to be considered for individual drivers who, for example, live in one SubLAP zone and work in a different one. Figure 8 shows the inter-regional travel as well as the intra-regional travel. As can be seen, a relatively large number of trips originate on the Peninsula and end on the South Bay, as well as the San Francisco zone. Additional patterns of inter-regional travel for the other SubLAP regions can be seen in the figure.

**Figure 8: Inter-Regional Travel Patterns of Program Participants (# of trips)**




Source: UC Berkeley

These data are presented quantitatively in Table 3, where trips to-from and from-to the various SubLAPs are closely in balance, represented by squares of the same color. Also shown are the various inter-regional trips between different SubLAP regions.

**Table 3: Trip Counts of Inter-Regional Travel Patterns Among ChargeForward Program Participants**

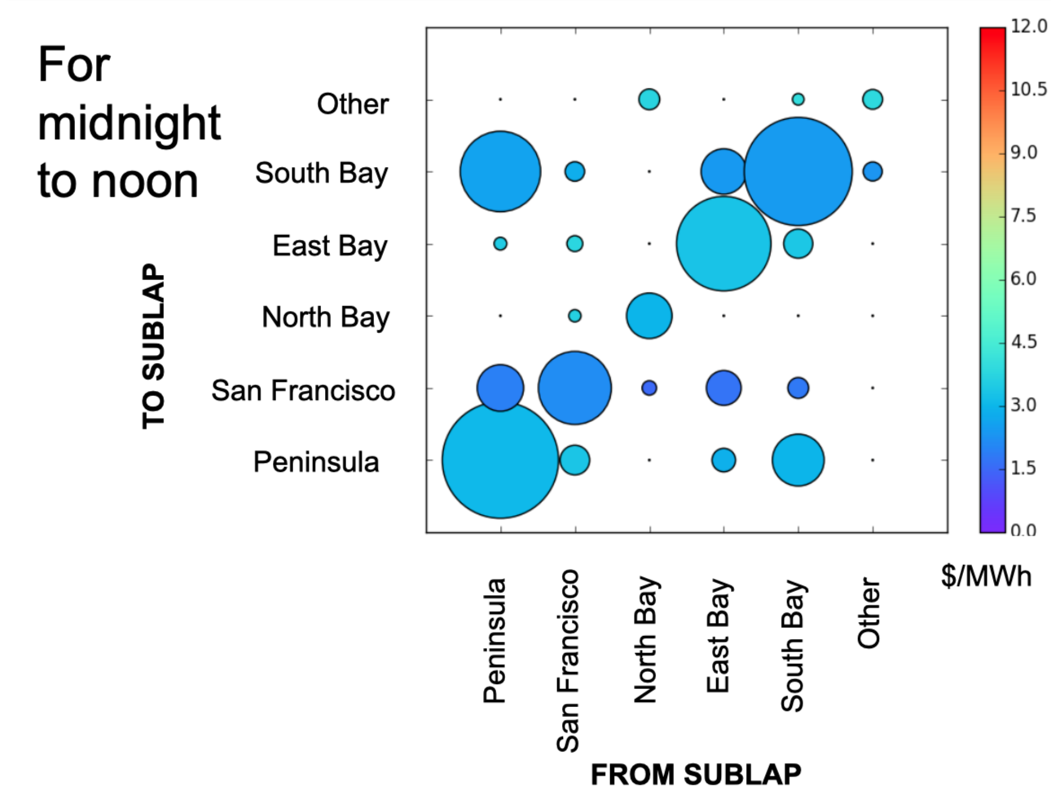
| | To | | | | | | |
|---|---|---|---|---|---|---|---|
| **From** | **PGPW** | **PGSF** | **PGNB** | **PGEB** | **PGSB** | **Other** | **Total (from)** |
| **PGP2** | 33,099 | 2,669 | 0 | 516 | 8,320 | 101 | 44,705 |
| **PGSF** | 2,685 | 15,052 | 379 | 1,079 | 598 | 0 | 19,793 |
| **PGNB** | 0 | 376 | 5,404 | 192 | 0 | 86 | 6,058 |
| **PGEB** | 514 | 1,095 | 191 | 24,374 | 2,127 | 0 | 28,301 |
| **PGSB** | 8,321 | 591 | 0 | 2,155 | 28,843 | 440 | 40,350 |
| **Other** | 99 | 0 | 91 | 0 | 139 | 13,660 | 13,989 |
| **Total** | | | | | | | 153,196 |

**PGP2 is the Peninsula zone, PGSF is San Francisco, PGNB is the North Bay, PGEB is the East Bay, and PGSB is the South Bay.**

Source: UC Berkeley

Figure 9 shows trips occurring in the first part of the day from midnight until noon and includes the average LMP levels in each SubLAP zone. The size of the circles represents the volume of trips, including both intra- and inter-zone travel. As can be seen, the early day period tends to have fairly low grid LMP across the SubLAP zones, typically in the range of a few dollars per MWh. Later in the day the LMP levels are considerably higher, in the vicinity of $10/MWh versus $2-3/MWh in the early day period. Also, the colors in the plots are relatively homogenous, suggesting there is relatively little opportunity for saving costs at the grid level during the same time period but in different LMP zones, but a significant opportunity to save costs during different time periods. This can be done by shifting charging from evening times to early day periods, where LMP levels are uniformly lower, and to some extent by finding the lowest price nodes, to the extent possible, during those low-price periods.

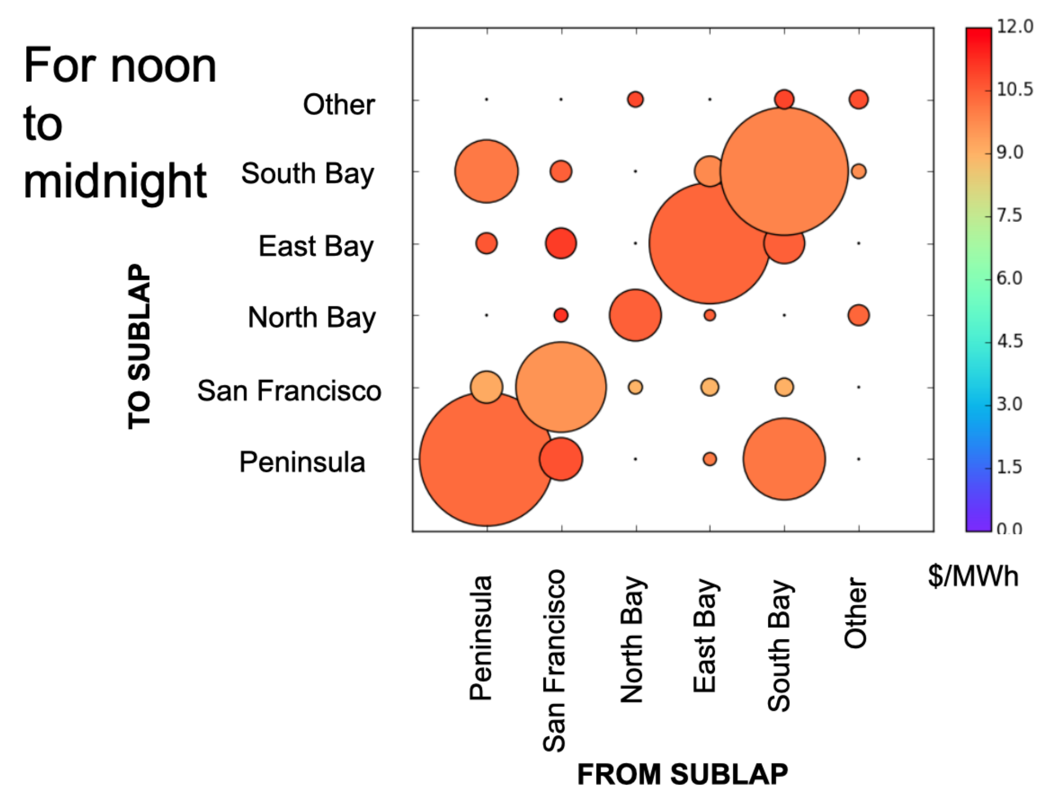
**Figure 9: Early-Day Travel Behavior and Average LMP in SubLAP Zones**




Source: UC Berkeley

For travel during the second part of the day from noon until midnight, average LMP is considerably higher as shown in Figure 10. Prices during this period average approximately $9 – $10 per MWh, considerably higher than in the early day periods. The daily variations in LMP are discussed in more detail, but this generally highlights the potential for shifting load away from evening periods when nodal grid-level prices are higher, to overnight periods when prices are lower.

**Figure 10: Late-Day Travel Behavior and Average LMP in SubLAP Zones**




Source: UC Berkeley

## Overview of Smart Charging

Smart, or managed, charging is only one of several potential aspects of VGI that includes both load shifting and reverse flow or vehicle to grid (V2G) concepts, as well as a multitude of ways in which EVs can support the operation of utility grids through the provision of ancillary services such as grid frequency response and regulation, spinning reserves, voltage support, reactive power support, and others.

The focus of this project is one of the most basic but powerful concepts: enabling EV drivers to allow charge management for shifting load from periods of high grid demand to periods of lower demand, from periods of high locational marginal prices to periods of lower marginal prices, and from periods of more carbon-intense power generation to periods with lower carbon emissions, typically associated with the level of renewable electricity being provided. These concepts are explored in both direct ways, with real world experiments defined by use cases, as well by more theoretical optimization analyses that assume, for example, more ubiquitous access to daytime charging in the future.

### Use Case Overview

During the project, several distinct use cases were tested during periods of varying lengths. The use case descriptions and time periods are as follows:

- Earth Week Renewable Energy Use Case (April 22– 28, 2018): EV charging was optimized against day-ahead signals of renewable energy availability. Given California's usual correlation of high midday solar output and low midday demand, participants were especially encouraged to charge in the middle of the day to use excess solar energy that was generated. An incentive was offered to participants to charge between 10:00 a.m. and 2:00 p.m., when solar overgeneration is highest. BMW only optimized vehicles that were at home. Given that many participants are at work during midday when solar overgeneration is highest, use of excess solar was often not paired with an optimization designation, but still represented optimal charging behavior.

- Home Overnight Use Case (April 29 – July 10, 2018): Charging was optimized against the day-ahead LMP signal. LMP signals represent the real wholesale price of providing electricity to a given area, defined by the electricity transmission system. Optimizations took place only at home and overnight (between 4:00 p.m. and 4:00 a.m.).
- Home 24-Hour Use Case (July 11 – October 14, 2018): Charging was again optimized against LMP price, but included all hours of the day. Optimizations still only occurred at home.
- Cohort Goal Use Case (September 26 – October 10, 2018): Drivers were asked to participate in a group goal to plug in more during this use case timeframe. The Home 24-Hour Use Case continued in the background, but analysis was done to see if an incentive would increase the optimization potential for charging. Optimizations took place at home during all hours of the day.
- Overgeneration Away from Home Use Case (October 15 – November 9, 2018): Charging was again optimized against the day ahead LMP price signal, but optimizations could now occur for away from home charging in addition to home charging.
- Transactive Energy Signal Use Case (December 3 – 10, 2018): Charging was optimized against the EPRI transmission signal. Optimizations took place at home during all hours of the day.
- Sub Lap Decrease (January 31 – February 28, 2019): Hour-long load decrease signals were chosen based on day-ahead LMP pricing. The optimization signals were for home-only locations and included both weekends and weekdays, during which vehicle charging was shifted outside of the event hour.
- Excess Supply Pilot (XSP) (April 1 – 30, 2019): Hour-long load increase signals were selected based on the highest forecasted probability of renewable overgeneration (excess supply) on the grid; this data was provided by PG&E. The optimization signals included both weekends and weekdays, during which vehicle charging was shifted into the event hour. This use case followed the same process for calling events as PG&E's current XSP program.
- Home Energy Storage System (HESS) (March 4 – July 31, 2019): The ChargeForward Plus pilot (a subset of HESS and ChargeForward pilots) conducted four use cases with its four households. The four use cases included: load increase/XSP, load decrease/demand response, frequency regulation (matching battery demand to grid frequency (60 Hertz) maintenance signals), and optimizations/energy arbitrage based on TOU or LMP. Each use case was broken into two sub-cases testing grid and customer benefits.

A description of how the use case analysis was addressed follows.

## Analysis Methodology

The overall method of this primary aspect of the study was to conduct a series of use cases with the participating households, with different objectives and timeframes. The study then examined vehicle plug-in and charging behavior both before and after the experimentation periods to assess the effect of the project use cases. Based on the timing of the charging behavior, economic analysis was conducted regarding the potential grid-side benefits of shifting load from higher to lower pricing periods, on both a participant fleet and per-vehicle basis.

In addition to the various real-world use case experiments, additional analysis in the form of a theoretical model, was also conducted to examine the broader possibilities for charge management in the future where more charge flexibility is possible with a more extensive and available EV charge network. This more comprehensive modeling assessment was then used to produce estimates of annual grid-level (that is, wholesale) values from smart charging of individual EVs.

### Analysis Methods and Models

To conduct this analysis, a series of existing and new models and methods were employed. These included: (1) python language scripts to process large amounts of project data into useful analysis segments; (2) economic analysis algorithms and scripts to assess grid-level savings in electricity costs through charge management; (3) optimization modeling to further define economic possibilities from VGI that are less constrained by current infrastructure availability; and (4) additional grid-level analysis tools available through the Olivine Inc. VGI valuation matrix capability. The application of these methods is described in detail in the report sections to follow, with further details available in the report appendices.

## Approach to Optimizations

BMW collected data from each vehicle and driver to estimate the time required to charge the vehicle. BMW passed this information to the optimization engine, provided by Olivine, along with information about the vehicle location and charger power level. Olivine then paired the information from BMW with information from one of the following hourly data sets, depending on use case:

- Day-ahead LMP provided by California ISO via Kevala
- Renewable energy estimate provided by PG&E
- Transactive energy (TE) price provided by EPRI

Ultimately, the objective of the optimization is to minimize price (LMP or TE) or maximize renewable energy, depending on the use case for each individual charge.

The Olivine optimization engine determined which hours the vehicle should charge and then passed a charging schedule back to BMW. BMW then implemented the optimized charging schedule in the vehicle. The number of times a vehicle stopped or started charging was not limited. Once the vehicle received the charging schedule, the vehicle was considered optimized and the driver was notified via push notification in the ChargeForward App.

See Appendix H, Distribution Analysis #2, for analysis on using day-ahead versus hour-ahead locational marginal pricing signals.

## Approach to Total Charge Management

BMW designed and implemented a series of use cases to meet the overall program goals and objectives to:

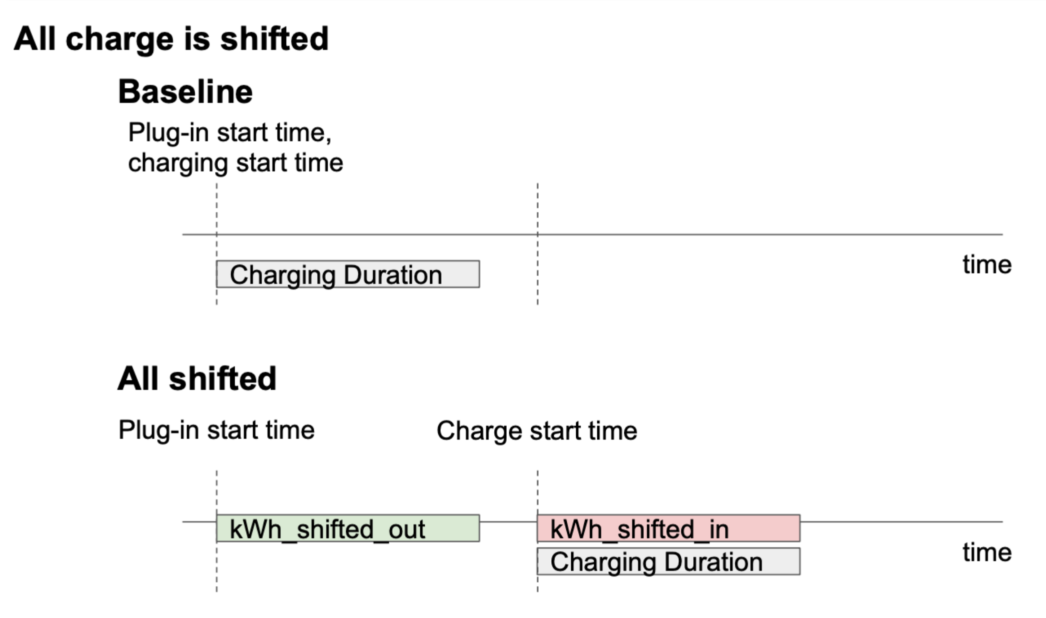
- Evaluate the use of vehicle-based telematics charging controls for charge management at home and away from home.
- Understand optimization opportunities within a participant’s residential TOU tariff constraint, if any, as well as opportunities away from home.
- Understand the role electric vehicles can play in wholesale and retail electricity programs such as demand response and distributed resource planning.
- Understand the effect on grid efficiency of optimizing against locational marginal prices, renewable energy, excess supply, and other transaction energy signals.
- Explore incentives to drive customer engagement and participation.
- Understand the interplay among tariffs, electricity programs, and optimizations and their effects on the grid.

The effects of the various use-case optimizations were determined on an hourly basis. Optimized schedules were compared to default charge-immediately profiles. For example, if a vehicle plugged in at 6:00 p.m. and required two hours of charge, the non-optimized charging was assumed to take place from 6:00 p.m. to 8:00 p.m. Charge shifted out of one hour was considered a negative charging effect for that hour. If the optimization determined the best two hours to charge were 3:00 a.m. to 5:00 a.m., that charge shifted into an hour was considered a positive charging effect. Note that all hours can potentially have a positive and negative charging effect in example weeks of months of analysis (on different example days, where grid conditions vary) except for the best and worst hours of the day. That is, the best hour of the day to charge should have only positive charging effect as no charge would be shifted away from that hour and the worst hour of the day to charge should only have negative charging effect as charge would not be shifted into the hour. Any charging taking place in the worst hour would be charge that could not be shifted due to mobility requirements of the driver.

## Approach to Use Case Analysis

The general approach to analyzing the use cases is to examine differences in plug-in behavior and the timing and nature of charging behavior in response to the incentives offered to drivers and the results of the BMW optimizations. Regarding the load shifting aspects, two primary concepts were applicable. In the simpler set of the cases, all the charging in a given charge session was shifted to a different time within a charging event period. This shift is depicted in Figure 11.

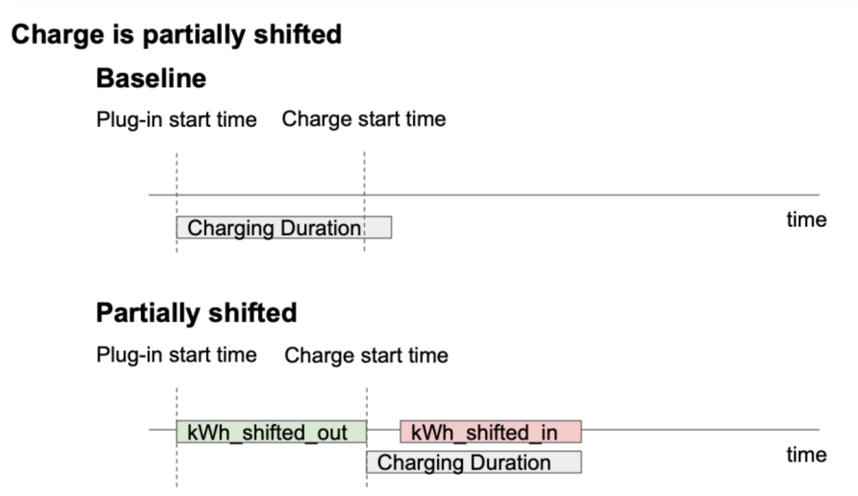
**Figure 11: Simple Concept of Electric Vehicle Charge Load Shifting**




Source: UC Berkeley

In a second more complex set of scenarios, some charge was shifted out of a charging session, but some charge remains un-shifted and then the shifted-out charge energy is replaced later. In Figure 12, this scenario is shown in two discrete steps, but in fact there could be several periods in a charging session where charge is interrupted or shifted out and then shifted back in either a single time period or multiple periods.

**Figure 12: Complex Concept of Electric Vehicle Charge Load Shifting**




Source: UC Berkeley

### Study Challenges and Limitations

Operating a data-intensive study in a real-world context is not without challenge. TCM's primary challenge was data access and limitations in the data. Data access relied on customer vehicle settings that were changed each time the user performed car maintenance. System outages during use cases meant that data could not be used fully or that there were fewer vehicles optimized.

The study limitations included the sample of participants that were included. All participants in this study were BMW drivers that owned or leased a BMW plug-in hybrid electric vehicle (PHEV) or battery electric vehicle (BEV) during the study period. The equipment tested in this study was also limited by the types and sizes of batteries of the respective vehicles, as well as the charging power of the chargers to which the vehicles were connected. All study drivers lived in or around the San Francisco Bay Area.

## Optimization Modeling Approach

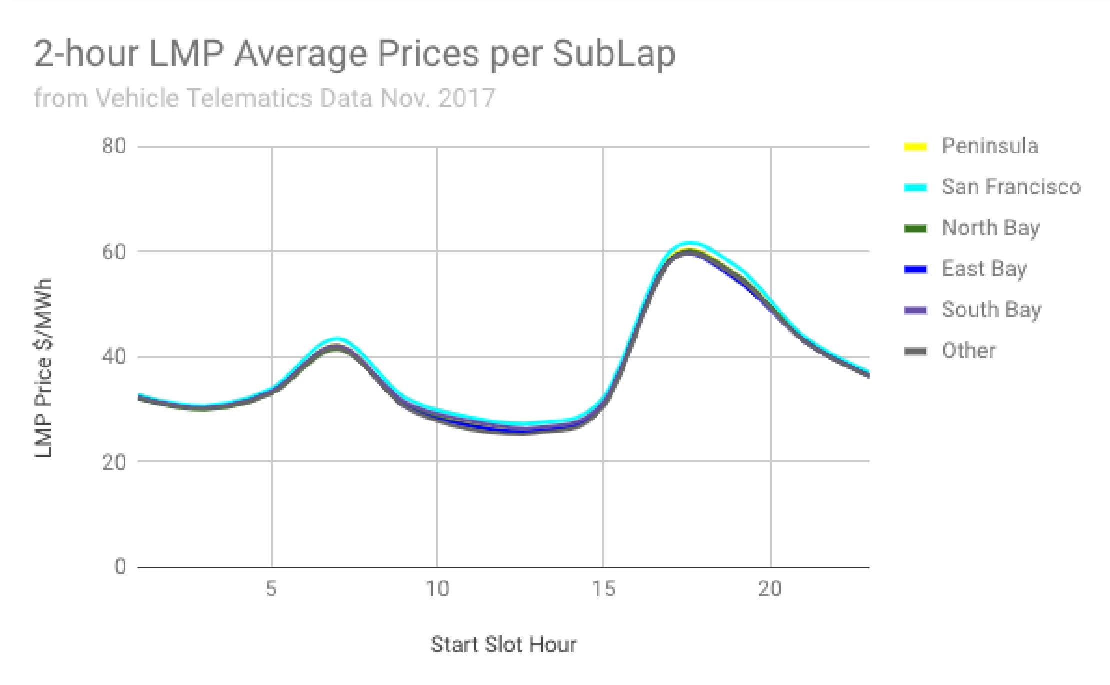
In addition to applying the TCM use cases in a real-world context, the project team also performed a more theoretical optimization exercise. The goal of this aspect of the project was to examine a more extensive opportunity for EV load shifting that is unconstrained by driver plug-in behavior and the availability of away-from-home charging.

For this analysis, two optimization models were proposed and implemented to plan the time and location of charging for electric vehicles, based on two different approaches. The first model relates to "fixed-location scheduling," where charging timing is optimized at home locations, and the second one is "inter-location scheduling," where charging timing can be optimized across locations and into the following day.

Both strategies optimized charging based on wholesale electricity prices. More specifically, the transmission system operator of California (California ISO) uses wholesale electricity prices, known as LMPs, to control systemwide electricity grid congestion and optimize power flow. LMP at a grid location and at any time interval is the marginal cost of delivering the power at that node and at that time ($/MW) (Singh et al. 2010). The LMP behavior shows spatiotemporal variations based on power losses and grid congestion (Singh et al. 2010). An example of LMP variation is shown in Figure  for the month of November 2017, and for six SubLAP zones in the study area.

Figure 3 shows that there is an increase of the pricing in the morning before work hours and then a higher increase in the afternoon and early evening when people return home. The proposed optimization approaches used these LMP-based spatiotemporal variations to minimize the electricity costs both within and in some cases across SubLAP regions.

**Figure 4: Example Location Marginal Price Patterns for SubLAP Areas ($/MW)**




Source: UC Berkeley

In this analysis, the event-based vehicle data consisted of the parking and charging timestamp, state of charge of the battery, the connection status of the vehicle to a charger, location of the vehicle, odometer reading, and the vehicle model. These data were from approximately 300 BMW electric and hybrid vehicles during certain time periods in 2018 – 2019, using representative weeks of analysis data to characterize months, seasons, and a year-long period. Additionally, the battery capacity and charging power of the vehicle model and anonymized location of the vehicle owners' homes were supplemented by BMW.

In addition to LMP optimization, the team also examined renewables percentage and marginal GHG emissions intensity data as additional optimization criteria. The results of these analyses for the different objective function criteria are presented in the following chapter, with additional details in Appendix F.

# CHAPTER 3: Project Results

The TCM project resulted in a series of findings across several dimensions of the project. These included results related to engaging and retaining participants in the program, results from the various use case trials, results from distribution and grid effects modeling, and results from further optimization modeling based on more unconstrained future cases to be considered. These results are described with overall project conclusions presented in Chapter 5.

## Evaluating the Customer Experience

One of the main project goals for ChargeForward was to understand how customer engagement techniques can affect customer participation (for example, increasing charging flexibility opportunities). Growing a customer base is critical for future large-scale smart charging programs looking to provide grid flexibility services. The various engagement methods used were described in Chapter 2. A summary of the customer feedback received from this aspect of the project and lessons learned follow.

### Customer Feedback Methods

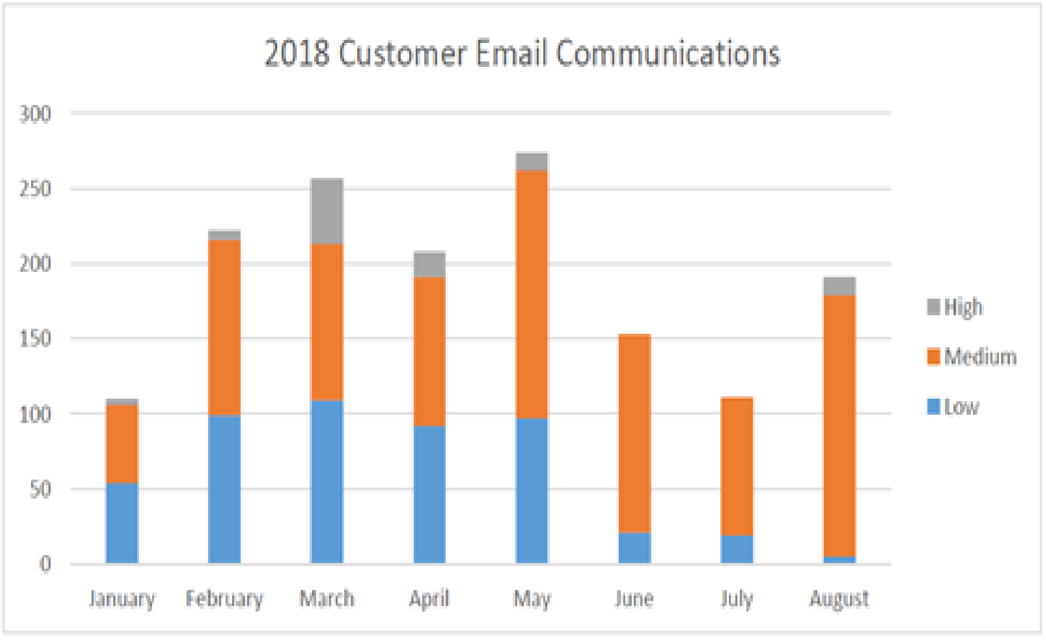
Customers provided feedback throughout the project through a variety of methods.

#### Customer Email

Three types of email correspondence were used in this project to engage customers: ad hoc targeted emails, mass emails on program communication and events, and general responses to customer inquiries. Examples of emails are provided in Appendix I, Customer Communication Tools Report #1.

The largest number of email inquiries from customers were received in 2018, which is when most use cases were conducted. Figure 4 highlights a sample period from 2018, where High/Medium/Low indicate the level of effort required to resolve the inquiry. Appendix I provides more details.

**Figure 5: 2018 Customer Email Communications**




Source: BMW of North America, LLC

## Driver Surveys

The ChargeForward program surveyed participants periodically to gather feedback on their experience in the program. The surveys were conducted through an online service, and the participants could provide open response feedback in addition to choosing pre-set answers. The surveys generally took place either after ChargeForward had completed a use case, after a new feature launch, or after new program participation criteria was implemented. Table 4 presents the dates of the participant surveys, the number of questions in each survey, and the total number of responses.

**Table 4: 2018 Participant Surveys**

| Survey Name | Survey Date | # of Questions | Total Responses |
|---|---|---|---|
| BMW ChargeForward Participant Survey | January 2018 | 44 | 278 |
| Earth Week | May 2018 | 24 | 210 |
| BMW ChargeForward Participant Survey | December 2018 | 44 | 231 |

Source: BMW of North America, LLC

## Focus Groups

BMW worked with UC Berkeley’s TSRC to conduct a three-day, five-session series of focus groups in March 2017 in a related study (see Lipman et al. 2020 for details). The focus groups covered 28 ChargeForward participants, who were BMW i3 94 drivers. Each participant received a $100 Amazon gift card for participation and filled out a 15-minute survey prior to the focus group, which assessed driving and charging behavior, environmental attitudes, vehicle purchase motivation, technology adoption, trust in managed charging programs, and demographics.

The key themes and findings from the focus groups are summarized in Table 5.

**Table 5: 2017 Focus Group Findings**

| 2017 Focus Group Findings |
|---|
| **PEV driving and charging patterns and habits**<br>• Most participants found home charging more convenient than away charging.<br>• Workplace charging was not realistic for most, due to lack of enough infrastructure.<br>• Public charging was inconvenient to most, because public chargers were found to be either out of order, in use, expensive, inaccurately indicated on phone apps, or incompatible between different charging networks.<br>• Vehicle electric range was sufficient for most needs, but out-of-routine trips caused range anxiety due to the issues related to away charging listed above.<br>• Many participants own a second car for non-routine or destination trips. |
| **PEV adoption motivations and environmental attitudes**<br>• The most common reasons for purchasing an EV were related to the environment, having access to the carpool lane, and trying a new technology.<br>• Even though participants placed a high value on emissions, environmental benefits, and climate change, providing grid benefits to balance renewable energy was among the lowest ranked reason for purchasing an electric vehicle.<br>• Most participants also had solar panels on their roofs.<br>• Most participants were more interested in helping contribute to local renewable generation than using their PEV to balance intermittent wholesale renewables. |
| **Experience and concerns with managed charging**<br>• Drivers didn't mind participating in managed charging as long as they had full charge when needed, and as long as there is an opt-out feature. |
| **Home automation and managed charging**<br>• Drivers expressed privacy and security concerns around linking charging with home energy management systems. |

Source: BMW of North America, LLC

## Customer Feedback Results and Conclusions

While surveys were found to be the most effective method for gathering feedback, one-on-one conversations (interviews, ad hoc emails, and phone calls) yielded more in-depth responses, especially when it came to better understanding behavior. Since conducting interviews requires significant resources, interviewees were carefully selected based on their participation history, household attributes, and survey responses that were specific to the topic of discussion.

Some main takeaways from feedback received were that participants with predictable schedules found the program easy to participate in, since they only needed to set their departure time(s) once. The most common complaint received was from customers not understanding why they did not receive an incentive, which was often due either to the departure time not being set at all or being inaccurate.

Participants largely preferred at-home charging, where they could control how long the vehicle is plugged in. Many expressed concerns with participating in away charging optimizations (at the workplace or other public places), since many public chargers are priced by the amount of time plugged in and not by the energy consumed. This defeats the principles of smart charging, which require vehicles to be plugged in as long as possible to allow for shifting of charge. Some workplace chargers are also constrained by valet services that unplug vehicles after a certain amount of time to allow for other vehicles to charge, making it impossible to effectively participate in smart charging involving shifted charge.

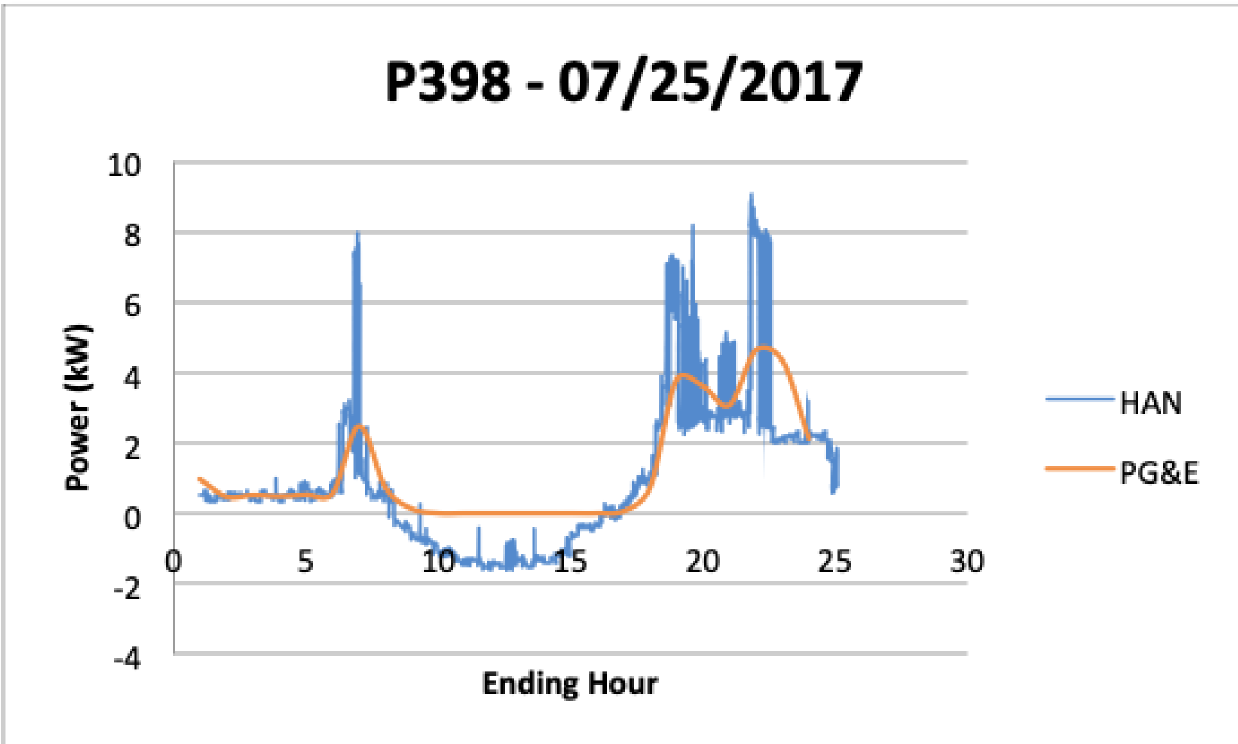
Feedback such as this can be taken into consideration when improving ChargeForward program design and designing future larger-scale workplace charging programs in California.

## Household Electricity and Charging Load Profiles

To understand baseline charging behavior and the overall effects of the project optimizations, the project team analyzed EV charging loads for households with both time-of-use (TOU) and more typical "tiered" by usage household utility rate structures. Also examined were overall household electricity use patterns, using both PG&E meter and more highly resolved HAN data as described in Chapter 2.

An example household electricity use plot is shown in Figure 5. This household is a solar power customer, hence the negative power usage shown in the HAN data. The HAN devices show much higher data resolution than the 15-minute interval data from the PG&E meter, which masks the sub-15-minute power usage spikes. The PG&E meter data shown in the figure do not indicate the negative power usage when the solar system was producing electricity in the middle of the day, but these are reflected in the HAN data. The PG&E data also show the net power exported to the grid, not accounting for usage in the household, but these are again depicted in the more detailed HAN data.

**Figure 6: Electricity Usage Pattern for One Household and One Example Day**




Source: UC Berkeley

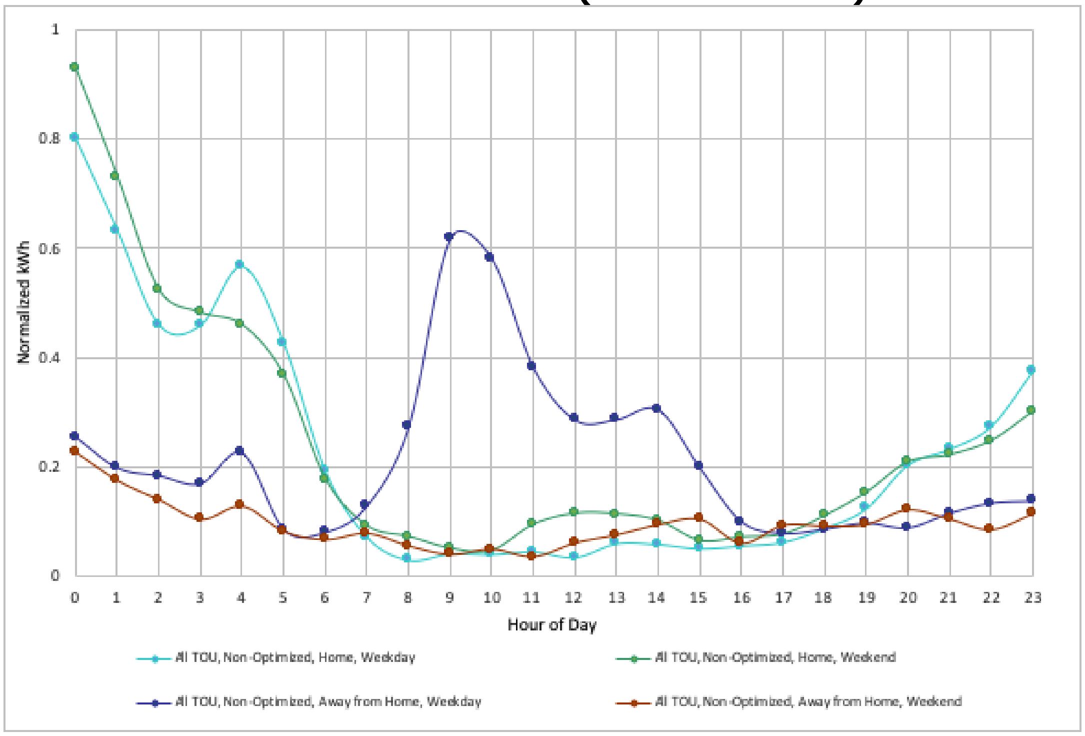
These overall household electricity use patterns were used to determine if EV charging events can be reliably detected using a few different proposed algorithms to analyze the data and considering both the PG&E and HAN data sets. The results suggest that it is somewhat more reliable to detect Level 2 (around 7 kW) charging events in data sets of households that are known to have Level 2 charging capabilities, especially with the HAN data set. However, it is much harder to detect Level 1 (around 1.5 kW) charging events as they are much more typical of other types of household loads. Further description of this household load analysis can be found in Appendix E, Customer Home Load Report.

## Vehicle Charging Load Profiles and Utility Rate Schedules

Figure 6 and Figure 7 compare the results for EV charging both at home and away from home, weekdays and weekends, and for households that had EV charge optimization and those that did not. These are the electrical loads specific to EV charging events; whereas, the plot in Figure 15 represents all the electricity use in the household. Because the various cases involve different numbers of vehicles, the charging loads have been normalized to the minimum and near-maximum values for each plot. This was done so that the charging patterns could be more reasonably compared, regardless of the number of vehicles in each case. Further details including the actual charging power in each case are presented in Appendix E, Customer Home Load Report.

Figure  shows the results for households on TOU rates, where charging was not optimized. As shown in the figure, charging patterns during weekdays and weekends were similar, except for away-from-home charging during weekdays where there was a large volume of charging from around 8:00 a.m. until the early afternoon. Also, as expected, there was less weekday charging during the day than there was on weekends. A somewhat curious feature of the data is the increase in charging during the night at around 4:00 a.m., especially on weekdays, even in the non-optimized cases, suspected to be due to drivers setting charge timing to top-off their vehicles before the morning commute.

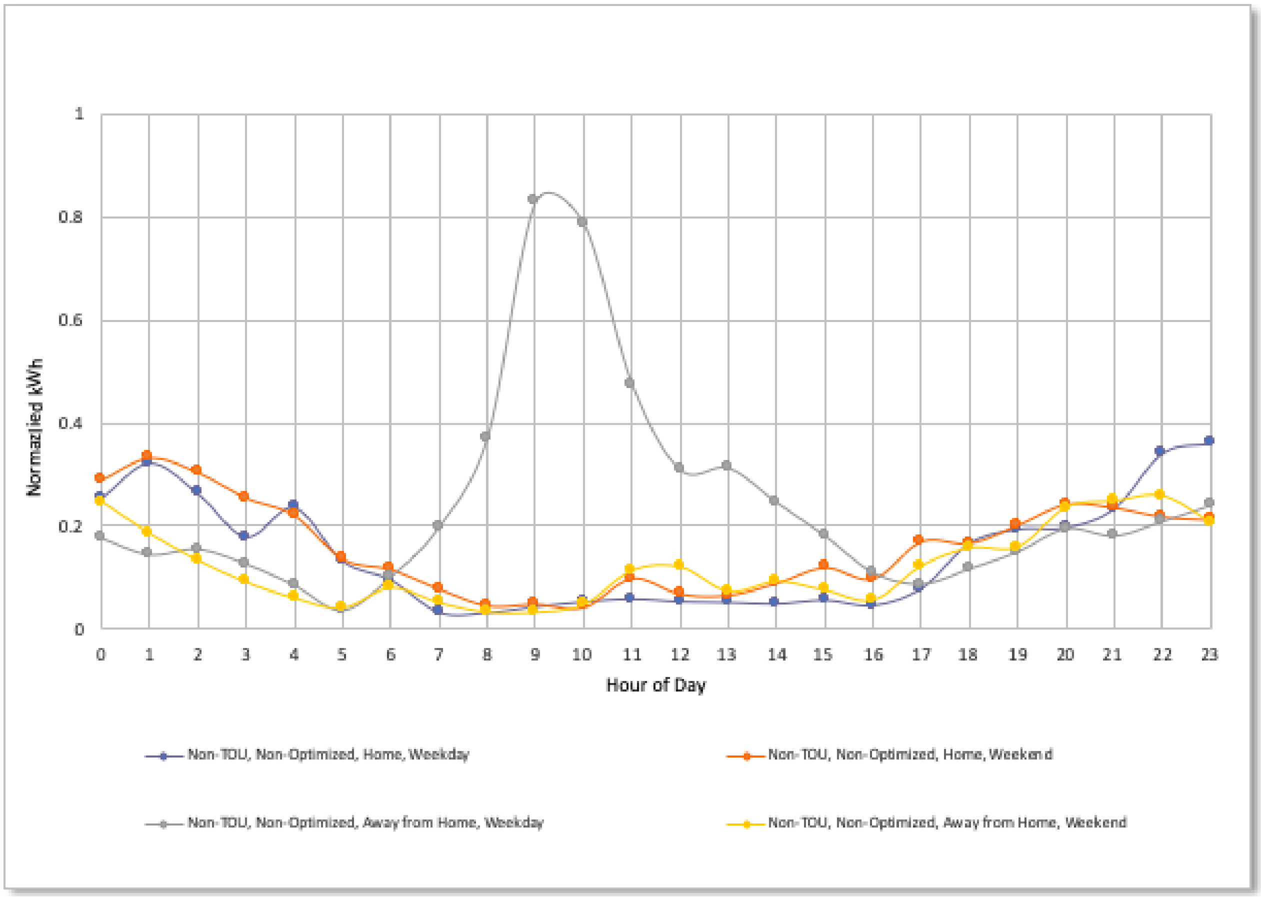
**Figure 7: Daily Average EV Charging Load Profiles for Non-Optimized Households on Time-of-Use Rates (normalized kWh)**




Source: UC Berkeley

Figure 7 shows the EV charging patterns for the households not on TOU rate schedules, also where EV charging was not optimized. Similar patterns are seen for away-from-home charging during weekdays, but the other patterns are quite different than in the TOU households. For the non-TOU households, charging loads were flatter and more consistent, with more charging occurring in the overnight hours but in a less pronounced way than in the TOU rate households. It seems that households on TOU rates were responsive to avoiding the peak during late-afternoon and early-evening periods, as would be expected.

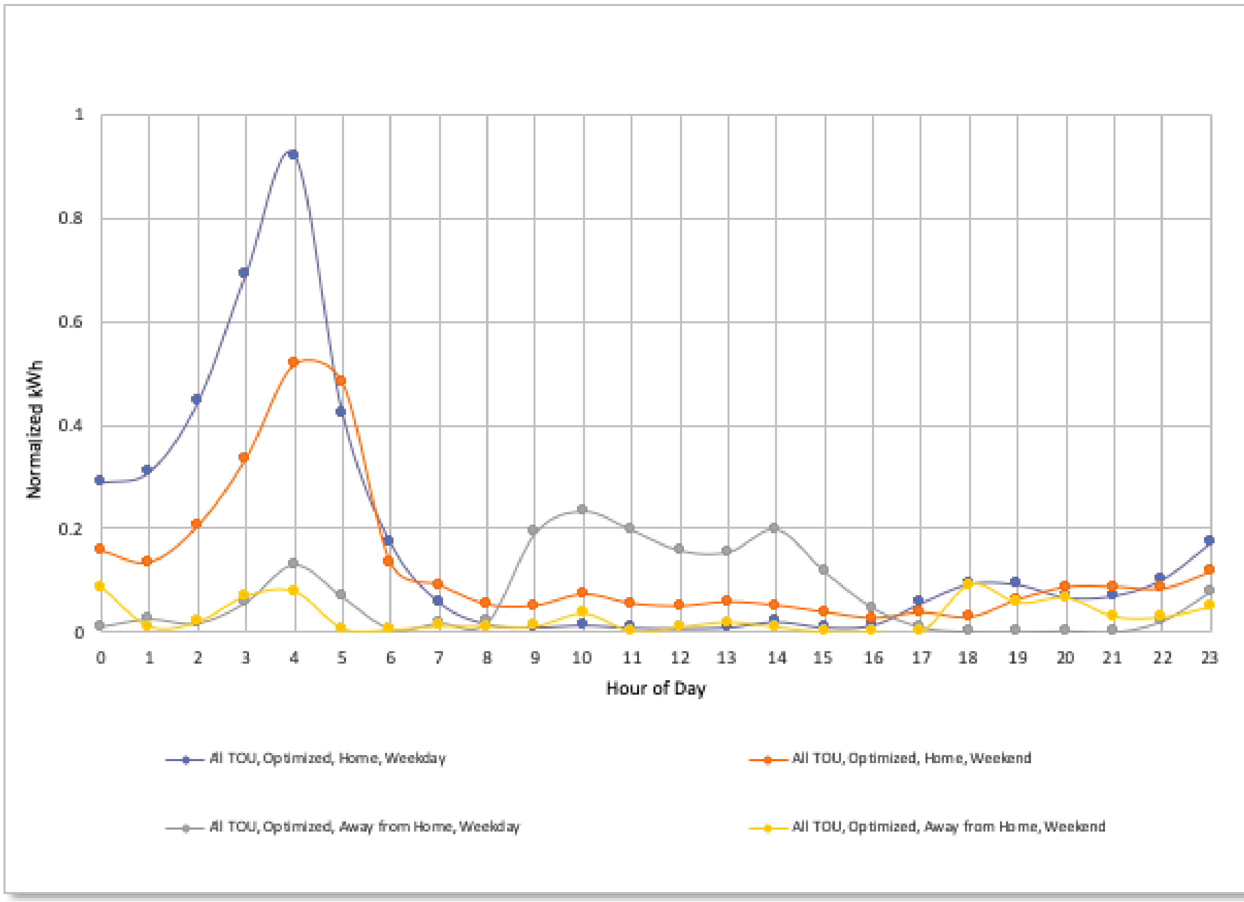
**Figure 8: Daily Average EV Charging Load Profiles for Non-Optimized Households Not on Time-of-Use Rates (normalized kWh)**




Source: UC Berkeley

Figure 8 and Figure 9 present the charging load patterns for households that were optimized. For the TOU rate cases, there was much less charging in the evening and early overnight hours for the home charging cases, relative to the non-optimized households. There was also slightly more away-from-home charging during the weekdays in the middle part of the day.

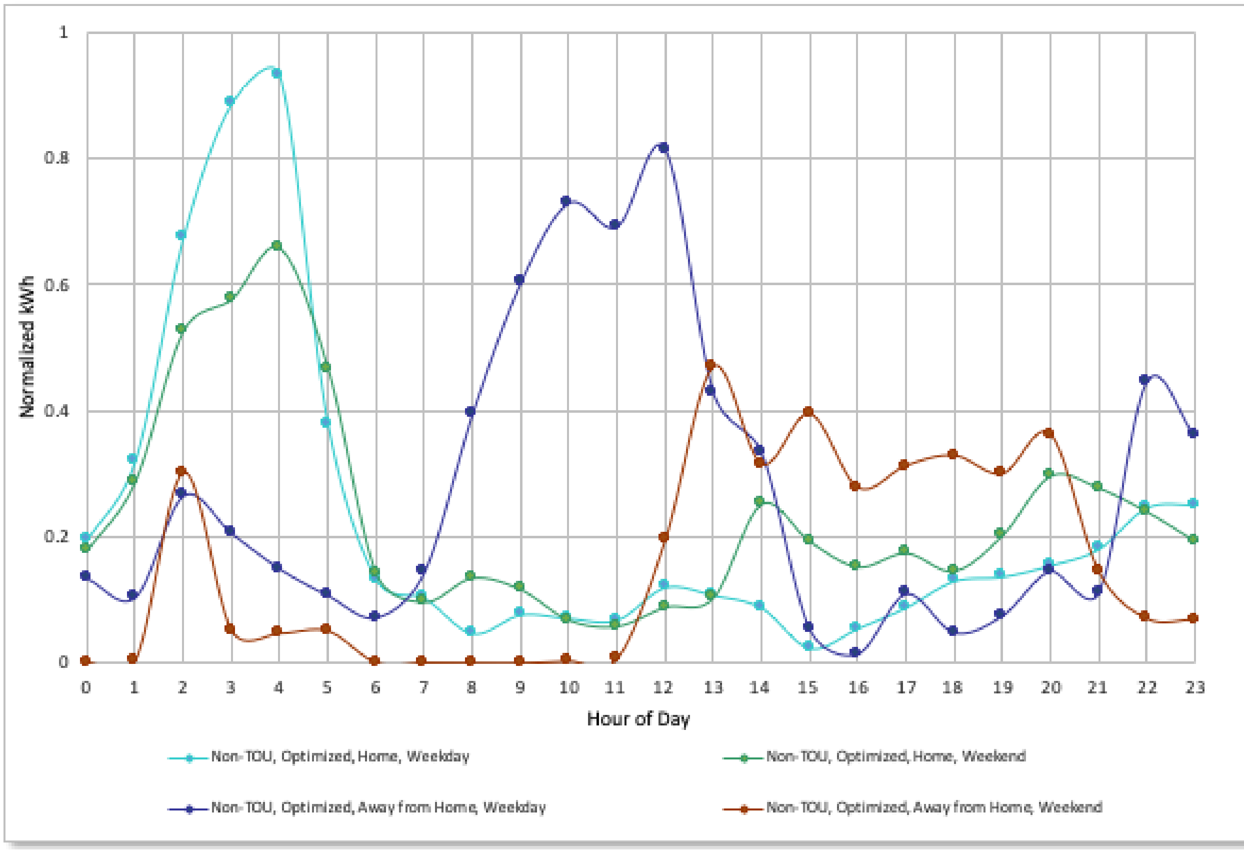
**Figure 9: Daily Average EV Charging Load Profiles for Optimized Households on Time-of-Use Rates (normalized kWh)**




Source: UC Berkeley

For the optimized households not on TOU rates, Figure 9 shows that some home-based charging was shifted to later in the overnight hours relative to the non-optimized households. It was also evident that there was slightly more weekday away-from-home charging during the late morning and early afternoon hours, due to the results of the optimization routines.

**Figure 10: Daily Average EV Charging Load Profiles for Optimized Households Not on Time-of-Use Rates (normalized kWh)**




Source: UC Berkeley

## Home Storage Installations

Parallel to the electric vehicle-focused ChargeForward pilot, BMW conducted a Home Energy Storage System (HESS) pilot. The HESS pilot featured four Bay Area residences with on-site storage systems. The systems consisted of an LG Chem battery and a 6-kW SMA Sunny Boy Storage inverter, in addition to the customer-owned electric vehicles. Three houses also had on-site solar. To participate in the HESS pilot, customers must also have been enrolled in the ChargeForward program, have had no plans to move during the pilot's duration, and have made their property available and accessible for installation and maintenance.

### Customer Interviews

To select the best participants for the small-scale pilot, BMW conducted phone interviews with three potential program participants in early 2018 to determine customer eligibility and gauge their interest in participating. The phone interviews were followed by in-person interviews that provided more background on the program and allowed customers to ask more detailed questions before committing to the pilot.

### Customer Feedback

After about a year into the HESS pilot, BMW gathered participant feedback via email. Some of the feedback was conflicting and indicated the need for more education for certain customers. Overall feedback was positive, and customers enjoyed the energy savings and environmental benefits of the system as indicated in Table 6.

**Table 6: Home Energy Storage System Customer Feedback**

| Category | Customer Praises | Customer Concerns |
|---|---|---|
| Size | Storage system has a small footprint, doesn't take up much space | Takes up wall space in the garage |
| Cost | Noticeable savings on electricity bill due to discharging battery during peak times | No transparency into how much money it's saving<br>Long return on investment if installed without subsidies |
| User interface | Minimal customer involvement needed after initial setup | User interface is difficult to understand |
| Environmental benefits | Positive environmental impact from minimizing excessive load on the grid | No transparency into environmental benefits |

Source: BMW of North America, LLC

## Key Findings from the Customer Experience

Surveys have proven to be the most effective method for receiving feedback on the customer experience, though one-on-one interviews allowed for more detailed content. Participants with more predictable schedules found the program easier to participate in since they could "set it and forget it" by remaining opted in with a set departure time. Most participants preferred plugging in and charging at home instead of away due to several uncontrollable factors with away charging infrastructure, including workplace valet charging, pay-per-plug-in-time versus pay-per-charge-time, and lack of available charging infrastructure.

Although saving money was a high priority for participants, many expressed an interest in learning more about the environmental effect of the program and their choices.

Participants were not driven purely by the monetary incentive to participate in the program. Several participants offered to be beta testers when ChargeForward tests new program features or provides supplemental data to help with data analysis. Participants tended to reach out when they noticed anomalies with earning program incentives, which was generally an indicator that there was a bug in the system.

Participants provided good suggestions for future program improvements based on their personal experience. For example, one participant suggested that because ChargeForward allows for targeted state of charge, and since he lives on a hill and could top off his battery every time he left the house, he therefore did not need to reach a full charge at home. Another participant wished for the same feature, citing that she receives free charging at work and only needed partial charge overnight.

Participants sometimes made comments indicating that consumers are embracing smart charging technology and want to see growth in the field. One participant noted in her survey response that ChargeForward was largely responsible for her continuing to lease BMW EVs to stay in the program. Occasionally when participants left the program, they expressed a desire and willingness to keep participating in ChargeForward if they could do so with an EV from another original equipment manufacturer.

Appendix J, Surveys and Focus Groups, provides additional findings from the customer experience.

## Use Case Analysis Results

The following sections present the results of two of the primary use cases for charge management tested under the project: the Home 24-Hour use case and the Overgeneration Away from Home use case. These were selected because they provide a good representation of the leading use cases in the project, as well as a contrast between a fully home-based use case and one that includes charging away from home. The full set of use case analyses is presented in Appendix C. The full set of use cases includes those that were based on home charging and away from home charging and optimized by the BMW system for either charging cost reduction or greater acceptance of renewable resources, such as in the case of the Earth Week use case.

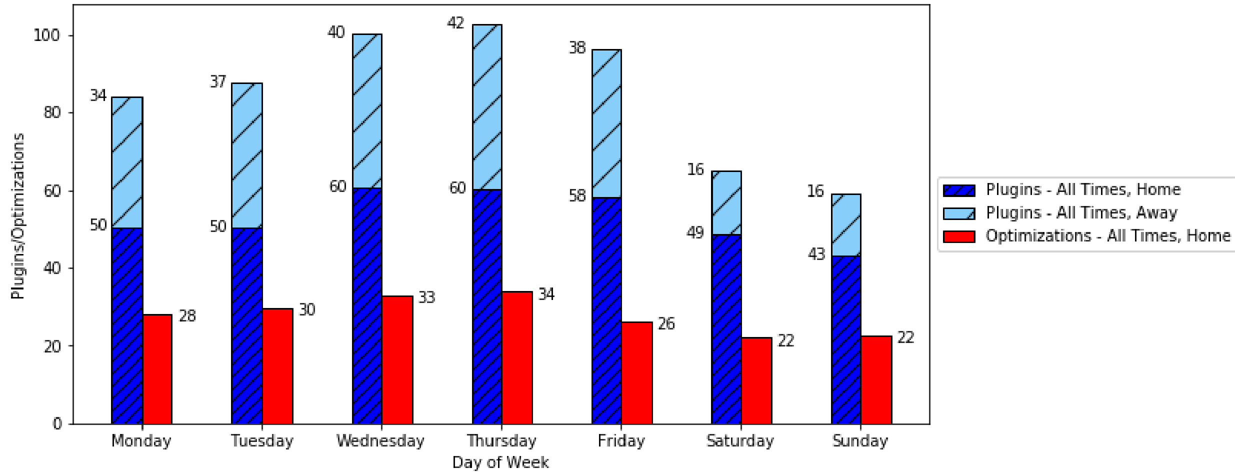
### Home 24-Hour Use Case

The Home 24-Hour use case was conducted from July 11 – October 14, 2018. This use case was a "home charging only" use case, as a follow up to the more basic Home Overnight use case. The BMW optimization method was significantly improved in August 2018, allowing for more optimizations. This related to a decision and implementation by BMW to estimate remaining charge time for vehicles, to compensate for cases in which that information was blocked.

This use case was to broaden the optimization window beyond the 4:00 p.m. to 4:00 a.m. start window for charging, to adjust the incentive structure, and to determine the amount of load shifting that would result. For this use case, participants could receive $1 per day for setting a correct departure time (within an hour of actual departure) along with an additional $1 for each optimization, for a total of up to $2 per day.

The improvement in the optimization capability at this point is evident in Figure 20, where now the optimizations were up to an average of 34 on the peak day (Thursdays) of 60 total plug-in events. Overall, during the use case, about half of the home plug-ins were optimized.

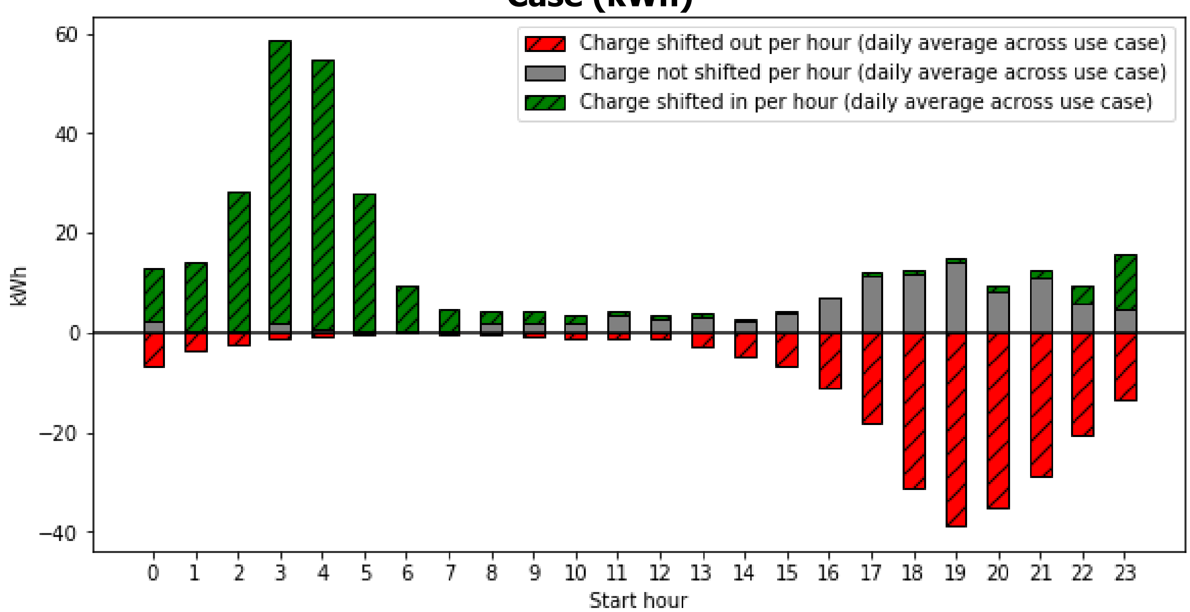
**Figure 20: Plug-ins and Optimizations by Day of the Week for Home 24-Hour Use Case**




Source: UC Berkeley

In terms of the charge shifted during the use case, Figure 21, on the next page, shows that the charge shifting profile is similar to the Home Overnight use case with a sample of 262 vehicles, but that some charge was shifted in and out (mostly in) during the midday hours. Once again, a relatively large volume of charge was shifted for the optimized vehicles, with charging added in the overnight hours and shifted out in the late afternoon and evening in response to fluctuations in grid LMP signals.

**Figure 21: Vehicle Charging Energy Shifted by Hour per Day in Home 24-Hour Use Case (kWh)**



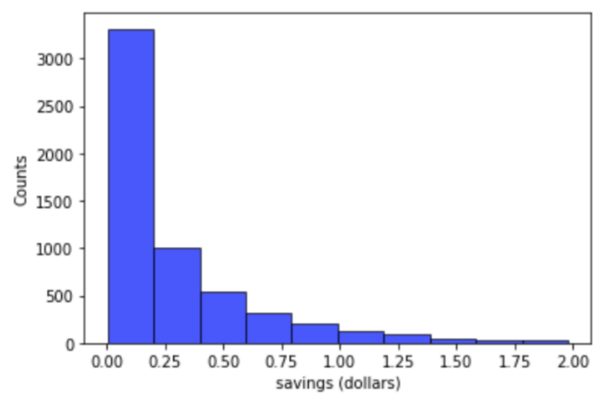

Source: UC Berkeley

Figure 22, on the next page, shows the grid operational cost savings from the optimization of the Home 24-Hour use case, as well as a histogram distribution of the cost savings per optimization event. In this case, grid operational cost savings refers to the reduction in the local prices of serving grid loads for EV charging, at the grid wholesale "bulk energy" versus retail customer level. As shown, the distribution of savings per event is similar in pattern to the

Home Overnight use case. Most optimization events produced savings of less than $0.20 per event. The average savings per event was $0.34 with a maximum in this use case of about $18, but this was an outlier case. Overall, grid savings of about $1,950 were realized by this group of 156 vehicles over a 13-week period and with 5,792 total optimization events.

**Figure 22: Grid Operational Cost Savings from Home 24-Hour Use Case**

| Category | Grid Savings |
|---|---|
| Total<br>(all vehicles over 13.5 weeks) | $1947.84 |
| Average<br>(per optimization) | $0.336 |
| Maximum<br>(per optimization) | $18.078 |
| Minimum<br>(per optimization) | $0.0023 |




**N=5,792 events and 156 vehicles.**

Source: UC Berkeley

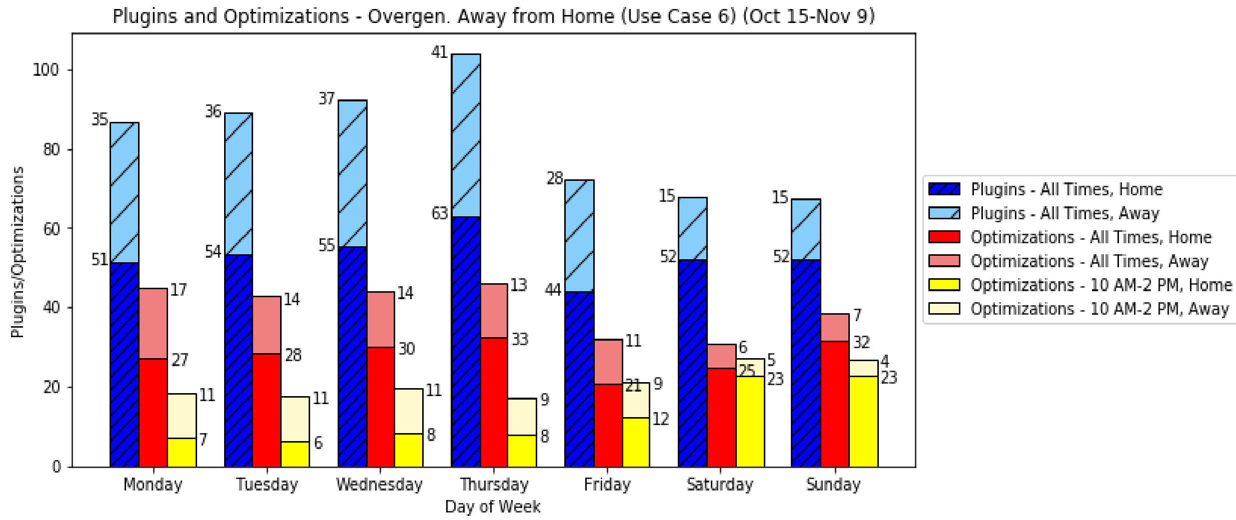
## Overgeneration Away from Home Use Case

The Overgeneration Away from Home use case involved both home and away-from-home charging events and was focused on absorbing more grid power for vehicles plugged in during the day at locations away from home. As an enhancement to the Home 24-Hour use case, drivers were additionally asked to plug in at locations away from home with an additional focus on seven midday hours when solar power can be in excess for the grid. The use case ran from October 15 – November 9, 2018, with 207 vehicles participating.

The goals of this use case were to assess to what extent there could be more optimizations when locations away from home were included, how incentives could affect daytime charging behavior, and how charge shifting patterns compared to the price signals that were provided and the baseline charging behavior.

As shown in Figure 3, on the next page, plug-ins and optimizations were still predominantly at home but with a significant number of additional optimizations. Also broken out are the optimizations during the target overgeneration hours during both the home and away-from-home events.

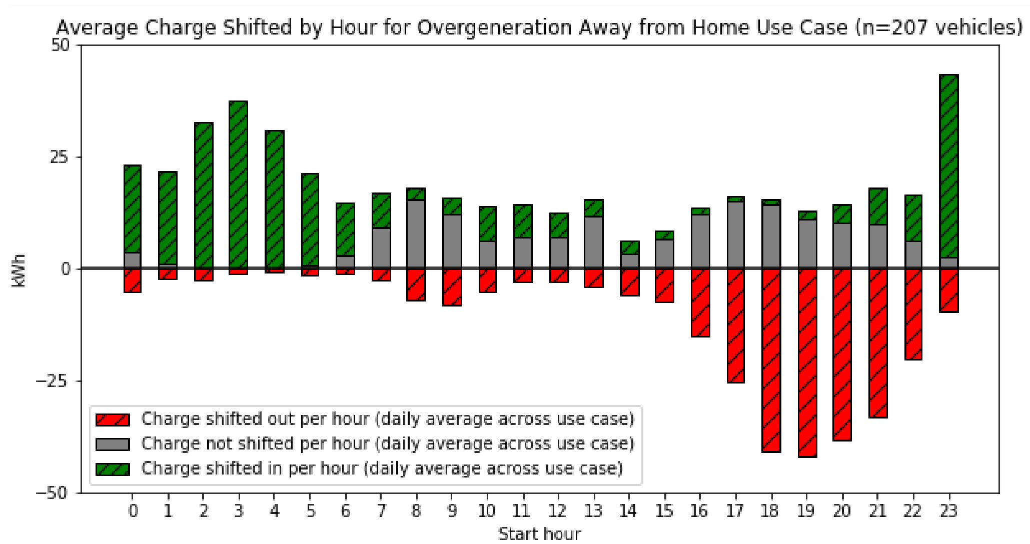
**Figure 23: Plug-ins and Optimizations by Day of the Week for Overgeneration Use Case**




Source: UC Berkeley

As for the other use cases, the average hourly charging energy shifted is shown in Figure 4. Here the team saw significant amounts of charge shifted into the daytime hours based on the grid overgeneration signal that was introduced. These charge shift patterns are more complex, where on some days in the middle of the day charge was shifted into the midday hours (due to overgeneration conditions), but on other days charge was shifted out of the middle of the day and into other times with lower grid electricity prices. Large amounts of charge were shifted out of the late afternoon and evening hours and into the overnight hours to find the lowest-cost electricity hours.

**Figure 24: Charging Energy Shifted by Hour per Day in Overgeneration Use Case (kWh)**



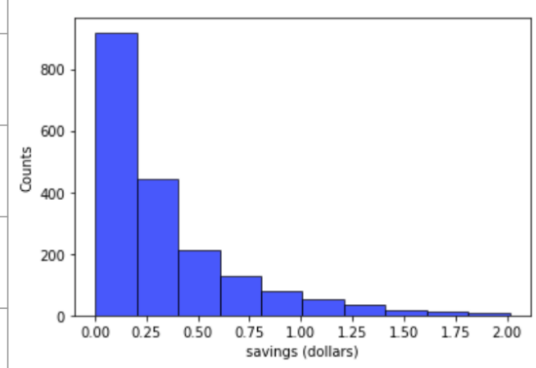

Source: UC Berkeley

Figure 5 shows the grid operational cost savings from this Overgeneration Away from Home use case, as well as a histogram distribution of the cost savings per optimization event. Most optimization events produced savings of less than $0.20 per event, similar to other use cases.

The average savings per event was $0.33 with a maximum in this use case of about $2.00. Overall, grid savings of about $637 were realized by this group of 129 vehicles over a three-week period and with 1,908 total optimization events.

**Figure 25: Grid Operational Cost Savings from Overgeneration Away from Home Use Case**

| Category | Grid Savings |
|---|---|
| Total<br>(all vehicles over 3 weeks) | $636.69 |
| Average<br>(per optimization) | $0.334 |
| Maximum<br>(per optimization) | $2.014 |
| Minimum<br>(per optimization) | $0.0019 |



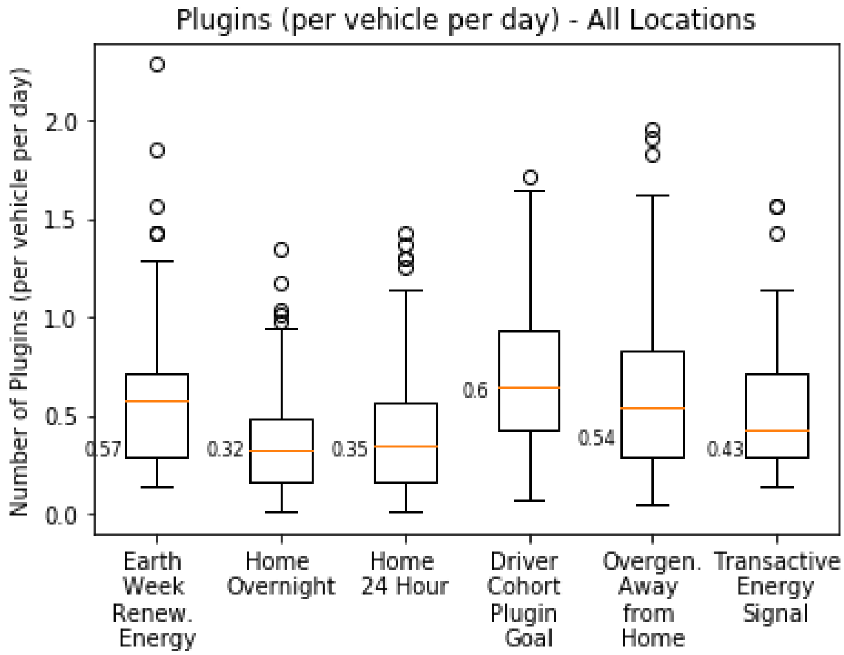

**N=1,908 events and 129 vehicles.**

Source: UC Berkeley

## Summary of Use Case Analysis Results

The following section presents a comparison of the results of the primary use cases. Again, the full set of use case results is presented in Appendix C. Figure 6, on the next page, shows a box-and-whisker plot for the number of plug-ins per day per vehicle at all locations across use cases. As shown, in all use case periods the drivers plugged in an average of less than once per day. Plug-ins were highest in the Driver Cohort Goal, with increasing plug-ins being a key focus of that use case, and lowest in the Home Overnight use cases, with the others falling in between.

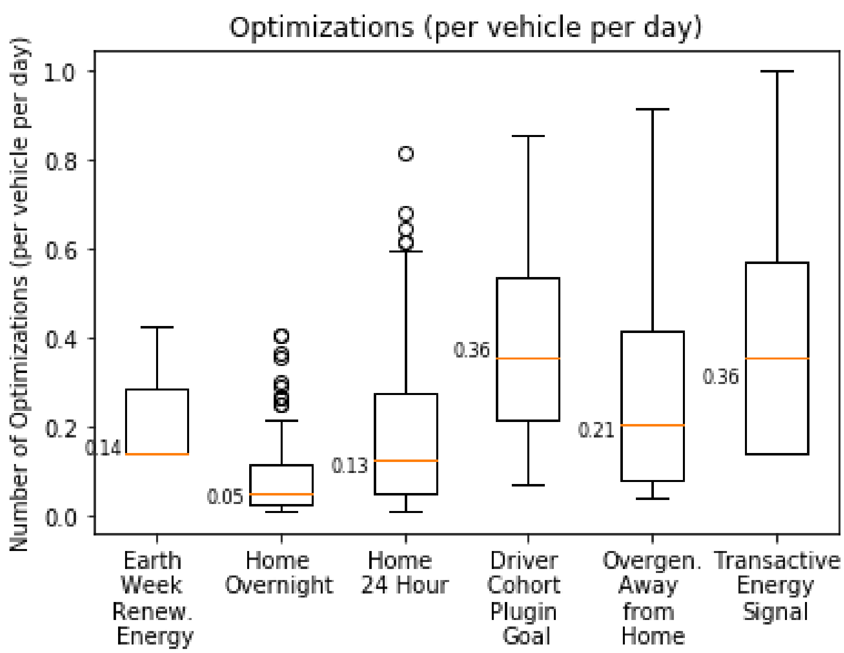
**Figure 26: Counts and Statistical Spread of Plug-ins per Day by Use Case**




Source: UC Berkeley

The counts of optimizations per day by use case are shown in Figure 7. The average optimizations per day were highest in the Driver Cohort Goal and Transactive Energy Signal use cases and generally trended up during the study as the ability to optimize vehicles was increased through project enhancements over time.

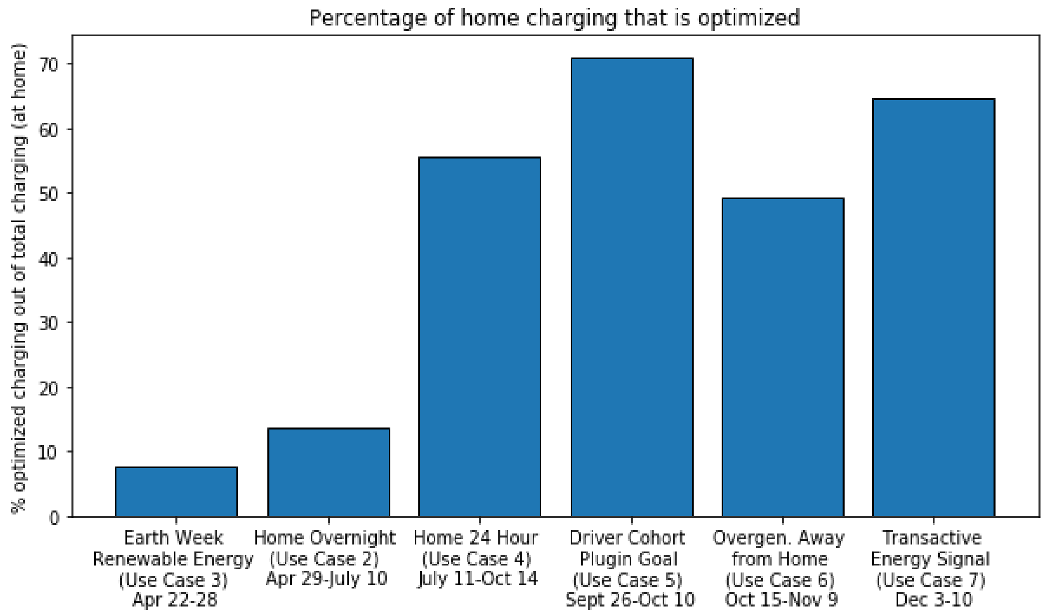
**Figure 27: Counts of Optimizations per Day by Use Case**




Source: UC Berkeley

Consistent with the previous figure, Figure 8 shows the percentage of home charging that was optimized by use case. This figure again shows general improvement over the course of the study, with peak performance during the Driver Cohort Plug-in Goal case but much higher optimization percentages after improvements were made in the BMW system in August 2018.

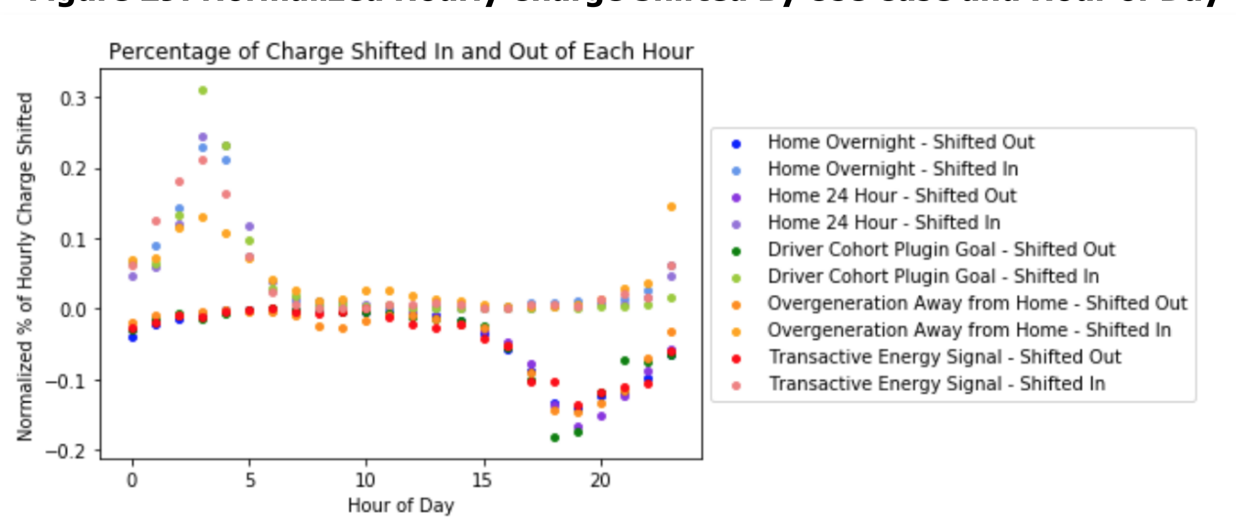
**Figure 28: Percentage of Home Charging Optimized by Use Case**




Source: UC Berkeley

Figure 9, on the next page, shows the percentage of charge shifted in and out of each hour of the day for the relative use case period for five of the project use cases. Values below zero represent charge shifted out of each hour, and values more than zero represent charge shifted in. As shown in the figure, the various use cases were collectively successful at shifting out nearly 20 percent of hourly charge at peak cost hours in the early evening, and up to 20 – 30 percent of hourly charge could be shifted back in during the early morning hours with low grid costs and congestion levels. This again shows the significant potential of managed and optimized charging through the ChargeForward program to shift EV load in ways that help to improve grid economics and operations.

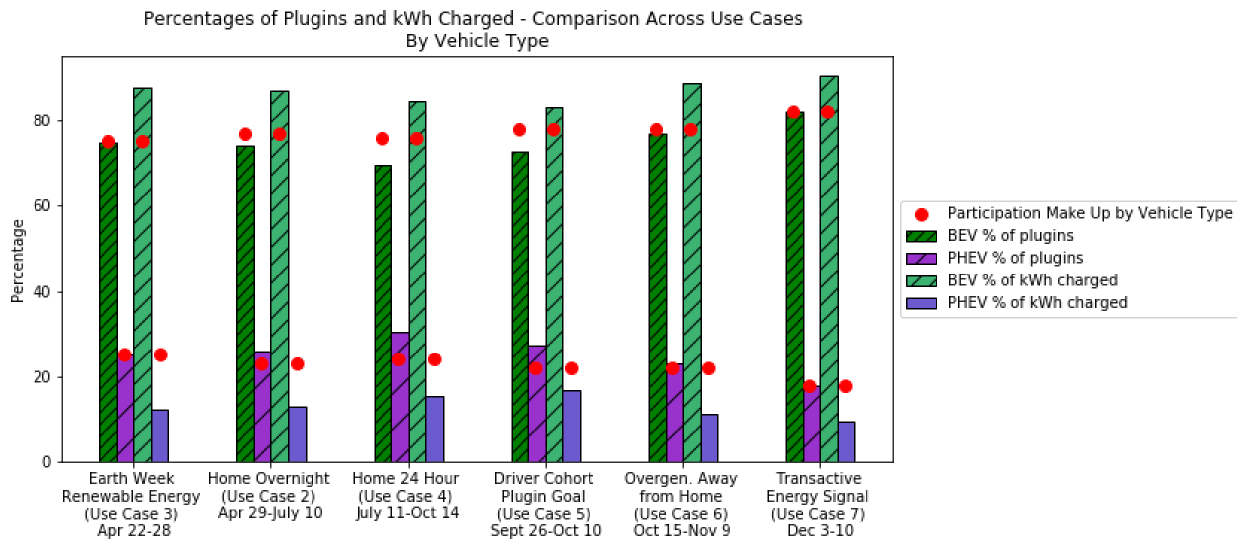
**Figure 29: Normalized Hourly Charge Shifted By Use Case and Hour of Day**




Source: UC Berkeley

Figure 30 shows the percentage of plug-ins and charging energy in kWh for each use case, broken out by BEV and PHEV vehicle types. Approximately three-fourths of the plug-in events were related to BEVs versus PHEVs, and an even higher percentage of the charging energy as would be expected because of the larger BEV battery packs. The red dots in the figure indicate that about 75 percent of participants were BEV drivers and about 25 percent were PHEV drivers, but this ratio varies from use case to use case.

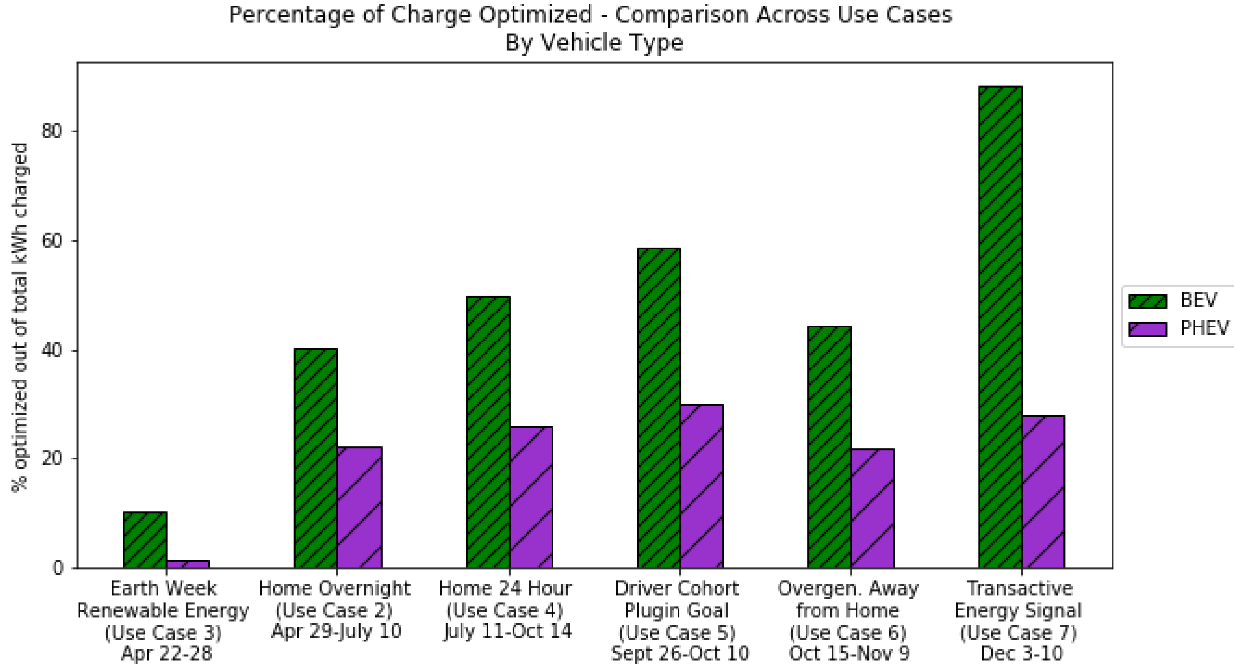
**Figure 30: Percentage of Plug-ins and Charging Energy by Vehicle Type and Use Case**




Source: UC Berkeley

Finally, Figure 31 shows a key comparison for the percentage of optimized charging that was shifted for each use case and by vehicle type. Again, the improvements in optimization effectiveness over time are evident, along with the much greater ability of BEVs to shift charge because of larger battery sizes and perhaps other factors. In the Transactive Energy Signal use case, more than 80 percent of BEV charging was performed under optimization. This result does not mean that all that charge was shifted, as shown in Figure 31, but it was performed under the optimization parameters.

**Figure 31: Percentage of Optimized Charge Shifted by Vehicle Type and Use Case**




Source: UC Berkeley

### Overall Use Case Analysis Findings

Overall, the team emphasizes that this pilot project focused primarily on at-home charging. A major finding is that in general the use cases show with a high level of confidence that optimizing charging at home will result in shifting EV charging load away from late afternoon and early evening into after midnight and early morning hours. This is an encouraging finding for the potential for managed charging to assist in mitigating what could otherwise potentially be a propensity for EV charging that significantly adds to peak-time grid loads.

Across the primary use cases shown in Figure 30, direct savings in utility grid costs to provide charging amounted to $3,167 during the aggregate use case periods by the population of study vehicles. More generalizable optimization modeling results that are representative of a full year of savings on a per-vehicle basis follow in the next paragraphs.

Also, only the Overgeneration Away from Home use-case in this pilot project directly addressed charging away from home. The team believes that additional efforts are needed to explore this potential more fully. Even from the individual use case examined here, there is evidence that charging optimization can shift load from late afternoon and early evening into the middle of the day. However, this pattern was affected by more variables than in the case of home charging. These variables include the availability of charging infrastructure at locations away from home, driver daily scheduling unpredictability, and differences in flexibility between PHEV and battery EV drivers.

## Valuing Grid Benefits

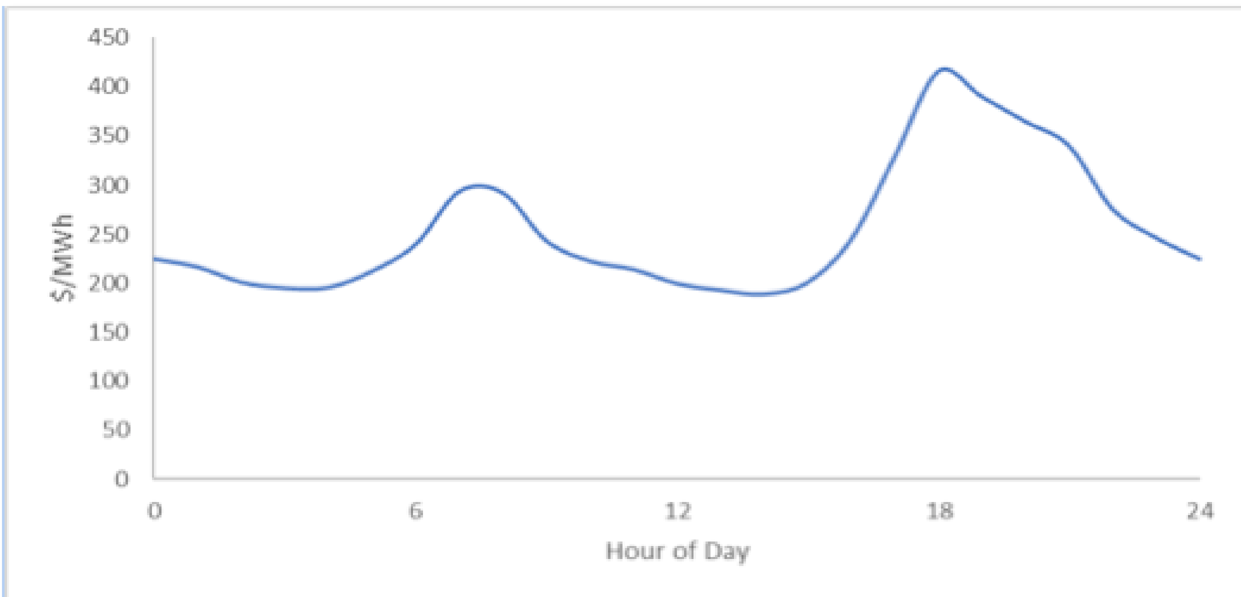
The flexible load potential of EVs can confer grid benefits in various ways, along with customer site benefits at residential and commercial levels, mainly in terms of utility bill rate reduction. As part of this project, Olivine Inc. performed three different assessments of grid-level benefits:

(1) benefits related to the use of the EPRI TE signal, (2) load decrease events at the SubLAP scale, and (3) load increase events based on the PG&E excess supply pilot (XSP).

### Optimization with the EPRI Transactive Energy Signal

In the first Olivine analysis, vehicle charging was optimized to minimize cost using the EPRI TE signal from December 3, 2018 – December 14, 2018. Figure 32, on the next page, shows the hourly average TE signal during that time period. The TE price signal at two different SubLAPs was used; however, only the average of the two is shown due to their similarity. As illustrated in the figure, the two peaks were located locally at 7:00 a.m. with a price of $294 and globally at 6:00 p.m. with a price of $415. These coincided with peak load times on the grid.

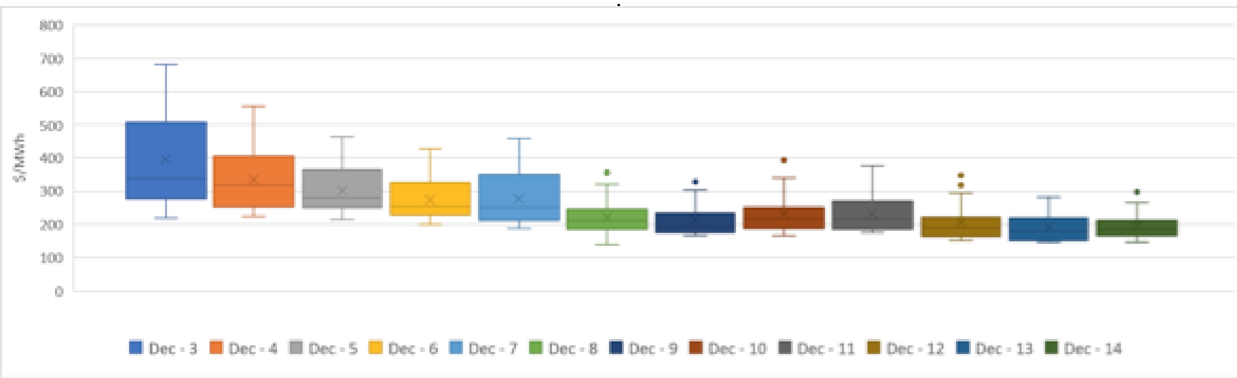
**Figure 32: Average Transactive Energy Signal Price by Hour, 12/3/2018 – 12/14/2018**




Source: Olivine Inc.

For comparison, Figure 3 shows the daily variability in the TE signal during the sample period. For each day, the box represents the middle 50th percentile of the prices, and the whiskers represent the top and bottom 25th percentiles. This figure shows a relatively steady decline in signal pricing from an average value of $380 at the start of the period to $197 by the end of the period.

**Figure 33: Daily Transactive Energy Signal Price Signal, 12/3/2018 – 12/14/2018**

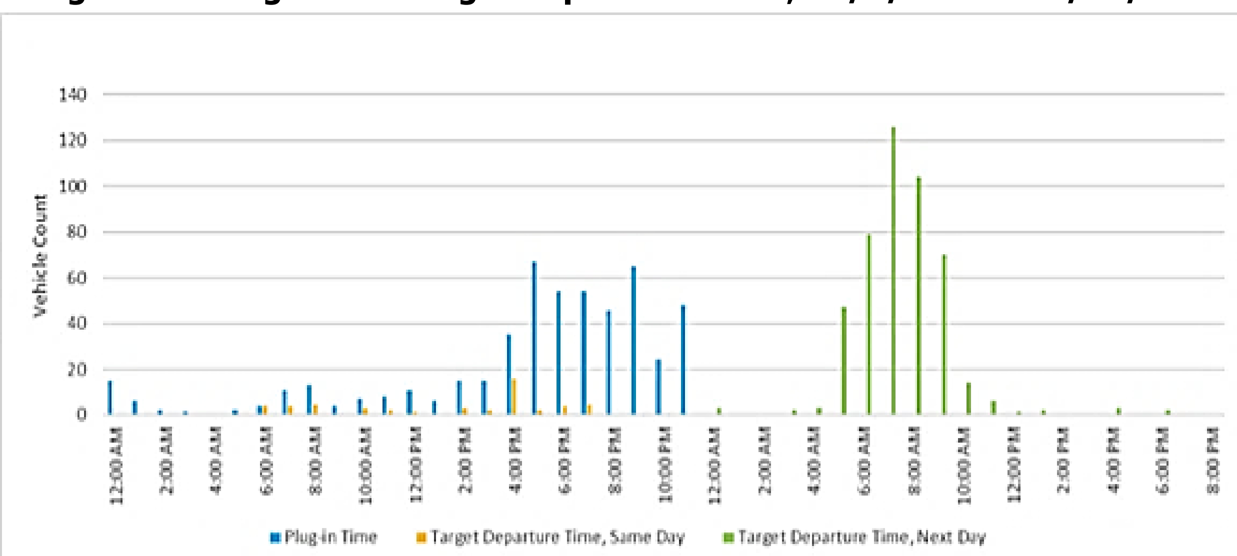



Source: Olivine Inc.

Based on the optimization schedule derived from the Olivine platform, vehicle charging was scheduled based on cost minimization and additional information provided by the vehicle driver including the desired departure time.

A breakdown of observed plug-in and target departure times for the optimization process may be found in Figure 4. Same-day and next-day departure times are represented by yellow and green lines respectively. The plug-in times were measured times, and target departure times were user-provided inputs set through the phone application (app). Vehicle owners used the app to identify when they would need their vehicle to be fully charged. They can also set these schedules in advance to avoid having to update the target time each time they plug in. As illustrated by the figure, the pattern for plug-in times aligns with expectations. Most plug-in times were from 4:00 – 11:00 p.m., and departure times were primarily the next day from 5:00 – 9:00 a.m.

**Figure 34: Plug-in and Target Departure Times, 12/3/2018 – 12/14/2018**

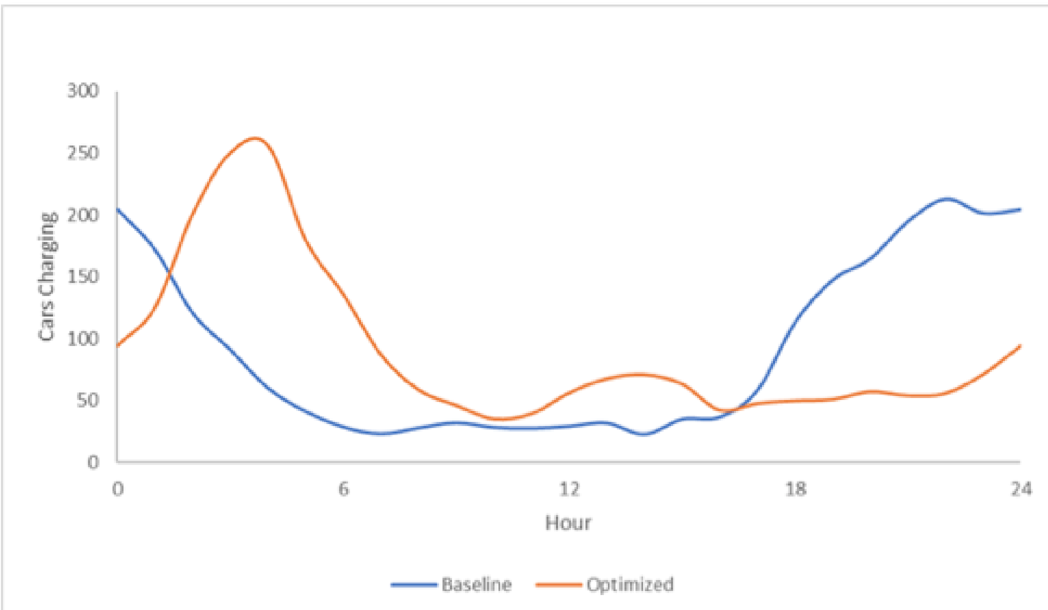



Source: Olivine Inc.

For baseline (non-optimized) charging, the charging start time was assumed to be the plug-in time and the stop time was assumed to be the start time plus the remaining charge time. This baseline assumed that in the absence of optimization, vehicles start charging immediately after plugging in. For many users, particularly those not considered early adopters, plug-and-charge was a reasonable assumption for baseline behavior (Hardman et al. 2018). Here the team noted that customers on TOU rates have been shown to behave differently, with many shifting charging to off-peak hours. This is typically after 9:00 p.m., although in this study customers' off-peak hours started at 11:00 p.m. for the EV rate. Understanding the effects of these shifts in baseline behavior on optimization may be the subject of future research.

Figure 5 shows the measured optimized charging (orange line) and the calculated baseline charging (blue line) by hour for all vehicles that were optimized during the sample period. Comparing the optimized charging with the baseline shows that the optimization algorithm shifted vehicle charging away from evening peak times when the TE prices are high and toward times of day when energy prices are low, typically in the early morning and midday.

**Figure 35: Optimized vs. Baseline Charging Schedules, 12/3/2018 – 12/14/2018**




Source: Olivine Inc.

Based on these optimized charging schedules, estimates were derived for the reduction in vehicle charging energy costs and the load shifted away from the evening peak. These values were intended to estimate both the customer benefit in energy cost savings due to managing the EV charging schedule better and the grid benefit in peak shaving due to the EV and Olivine DER Optimizer combination. The energy cost savings were derived based upon the TE price signal and represent potential cost savings if the TE price signal were to be implemented as a retail electricity rate.

Overall, in this use case a reduction in peak load of 92 kW was found, and energy costs related to EV charging were reduced by 15 percent. This was the average for all vehicles during this use case period. This also assumed that all vehicles used the same TE pricing signal in both the baseline and optimized cases.

### Optimization with Load Decrease at the SubLAP Level

In the second Olivine analysis, the ability of the EVs participating in TCM to form a grid-resource for load decrease was examined. In this use case, the Olivine DER Optimizer controlled the EV fleet so that it could be evaluated for its potential to become a formal grid resource in day-ahead energy markets as a California ISO proxy demand resource. For aggregated resources to qualify for this program, they must be located in the same SubLAP, be served by the same load-serving entity, must be capable of providing 100 kW of measurable load curtailment, and must have a minimum overall size of 500 kW to participate in ancillary services markets.

The results of this analysis are presented in Appendix T, describing the performance of the load decrease events at the household level. The overall result is that a clear trend could not be established regarding the effectiveness of the load decrease events for participating EVs and including the total load from a given household. There were only between 4 and 10 vehicles optimized during the event and many of them would not have been charging in the baseline case. The ability of EVs to participate in "baseline determined" load decrease events was challenging, and household load likely dominated the overall load decrease performance observed in this pilot.

### Optimization with Load Increase Using the Excess Supply Pilot

The last use case examined by Olivine assessed the EV fleet with the Olivine DER Optimizer as a demand resource for load increase. This type of event may be called when the grid would benefit from increased load, such as during times of excess supply from increased renewable energy generation. The load increase events used for this use case were triggered by selecting the highest forecasted values in the XSP data feed. This result indicates a time when increased demand is likely to benefit the grid.

Taken as a whole, the performance in the load increase events was better than the load decrease events. Another finding is that at-home vehicle demand was more elastic in the case of load increase than load decrease for these use cases. Vehicles could charge during high XSP hours more often than they were able to avoid charging during peak hours. Analysis details are provided in Appendix V.

Overall, analysis of these use cases provides insight into the value and capabilities of the BMW EV fleet paired with the Olivine DER Optimizer. The combined system has shown the ability to act as a grid resource by shifting load to times that are more advantageous to the grid, as well as to benefit customers by lowering customer energy costs. The system has also shown that with proper levels of enrollment, it can operate in both demand increase and decrease scenarios. Again, this has the potential to benefit both the grid and the customer. EVs are currently expected to gain increased market share, and as the number of EVs increases, optimizing their charging and leveraging them as a grid resource will continue to gain value.

### Distribution Value

Distribution-level avoided costs include energy values such as LMP, capacity, and avoided distribution capacity value (utility's costs related to its distribution infrastructure and operation) that result from the behavior of a distributed energy resource (DER), such as managed charging. The distribution value associated with LMPs was calculated by Kevala Analytics, Inc.

("Kevala") in its distribution analysis for the Total Charge Management project (see Appendices G and H).

Ten commercial and residential Northern California electric vehicle charging sites were selected, and a utility distribution avoided cost methodology was applied to specific feeders to determine which hours could be used to capture potential revenue from optimized charging. The methodology included geospatial, temporal, and economic analysis, with the findings summarized in Table 7.

**Table 7: Summary Data for All Sites**

| | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 | Site 8 | Site 9 | Site 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Circuit Capacity (MW) | 8.53 | 2.46 | 11.65 | 12.44 | 21.62 | 11.69 | 8.88 | 8.53 | 12.31 | 10.41 |
| Circuit Projected Peak Load (MW) | 7.36 | 1.59 | 9.86 | 11.31 | 12.41 | 6.86 | 8.39 | 8.49 | 10.56 | 7.83 |
| Total Distributed Generation (MW) | 0.35 | 0.04 | 2.30 | 1.03 | 1.03 | 0.39 | 0.64 | 0.26 | 1.04 | 0.41 |
| Load Type | Coastal | Coastal | Inland | Inland | Inland | Inland | Inland | Coastal | Coastal | Coastal |
| Peak Res (MW) | 4.76 | 0.73 | 7.92 | 1.42 | 8.60 | 1.19 | 6.20 | 0.48 | 0.00 | 5.58 |
| Peak Com (MW) | 2.68 | 0.85 | 1.94 | 1.71 | 3.81 | 2.35 | 2.18 | 2.68 | 3.21 | 2.16 |
| Peak Ind (MW) | 0 | 0 | 0 | 8.19 | 0 | 3.32 | 0 | 5.33 | 7.35 | 0.00 |
| Inflection Point* (kW) | 5500 | 1400 | 8000 | 10000 | 9000 | 5750 | 6000 | 7750 | 9400 | 6000 |
| Annual Avoided Cost ($) | $535,714 | $535,714 | $714,285 | $714,285 | $535,714 | $535,714 | $535,714 | $714,286 | $321,428 | $535,714 |
| Area above the Inflection (MWhs) | 475 | 80 | 260 | 160 | 400 | 350 | 500 | 60 | 350 | 400 |
| # hours above the inflection | 0 | 51 | 69 | 426 | 235 | 346 | 223 | 259 | 335 | 146 |
| % hours above inflection | 2.63% | 0.58% | 0.79% | 4.86% | 2.68% | 3.95% | 2.55% | 2.96% | 3.82% | 1.67% |

| | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 | Site 8 | Site 9 | Site 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Value per MWh ($/MWh) | $1,127.82 | $6,696.43 | $2,747.25 | $4,464.28 | $1,339.29 | $1,530.61 | $1,071.43 | $11,905 | $918 | $1,339 |
| Value per hour per vehicle ($) | $ 07.44 | $ 44.20 | $ 18.13 | $ 29.46 | $ 8.84 | $ 10.10 | $ 7.07 | $ 78.57 | $ 6.06 | $ 8.84 |
| Offset load (MW) | 2.06 | 1.57 | 3.77 | 0.38 | 1.70 | 1.01 | 2.24 | 0.23 | 1.04 | 2.74 |

*** The inflection point is a calculated value based on the circuit capacity and slope of the plotted load duration curve to determine which hours were of high value**

Source: Kevala (from Appendix G, Research of Distribution Grid-Related Constraints)

The study also explored the concept of LMP+D (locational-based pricing bound by distribution capacity values) as it applies to optimizing EV charging in response to price signals. The analysis compared price variability and cost savings in day-ahead and hour-ahead markets across two weeks in April, August, and December, and across 25 commercial and residential charging sites in Northern California. The calculations for each site were dependent on location, distribution infrastructure, local demand, and local distributed generation (see Appendix H).

The findings indicate that in almost all cases, charging in an hour-ahead market resulted in lower costs than charging in day-ahead (9.94 percent lower than day-ahead for residential), and that day-ahead market hours were more predictable than hour-ahead. The residential charging window was more predictable than commercial, and avoided distribution capacity events for residential fell reliably during evening peak hours (8:00 to 10:00 p.m.), providing a more reliable opportunity to avoid residential charging during evening hours.

Due to predictably lower-priced hours in August and December and more variable hours in April, choosing the right charging behavior depended more on seasonality than location. For the 25 selected sites, the range of potential distribution capacity payment was found to be from $0 to $278.43 per year per vehicle. These values were dependent upon a utility procurement mechanism that only compensated vehicles for participating in events that are called when they are likely to be charging. The response opportunities were less frequent when vehicles were attempting to charge during the lowest cost charge windows when compared to unmanaged charging. Therefore, understanding how baselines are calculated to determine normal charging behavior is important (Appendix H).

## Net Wholesale Value from Optimization Modeling

The following sections present the results of the optimization modeling exercise that shifted charging from higher to lower price periods. Model 1 examined the potential to shift charge using actual available charging infrastructure at fixed locations. Model 2 examined the potential to shift charge across locations and assumes that charging infrastructure is available at both away-from-home and at-home locations in the future.

### Modeled Results

Using the project's optimization modeling approach, charge timing was shifted to periods of lowest cost, resulting in electricity savings from a wholesale market perspective. The details of these methods are provided in Appendix F, Optimization Model Analysis.

Table 8 shows the result for the fixed-location scheduling using the Model 1-based optimization. Since this model concerned only the parking instances with the potential for charging (that is, the vehicle is plugged in), the total hours where charging was possible was much smaller than the total hours of the month (282 vehicles for 24 hours for 30 days = 203,040 hours), or around 36 percent of the time. The implementation of this model used the actual charging power observed for each vehicle and results in the same amount of energy used for charging in a session as in the non-optimized cases (that is, the end state-of-charge is the same). As shown in the table, about 63 percent of the total charge was shifted by optimization in this modeled case, to take advantage of the lowest cost hours at a fixed location. The average savings in cost at the grid level was about $46 per vehicle per year, with a maximum of up to $163 per vehicle per year for the best case.

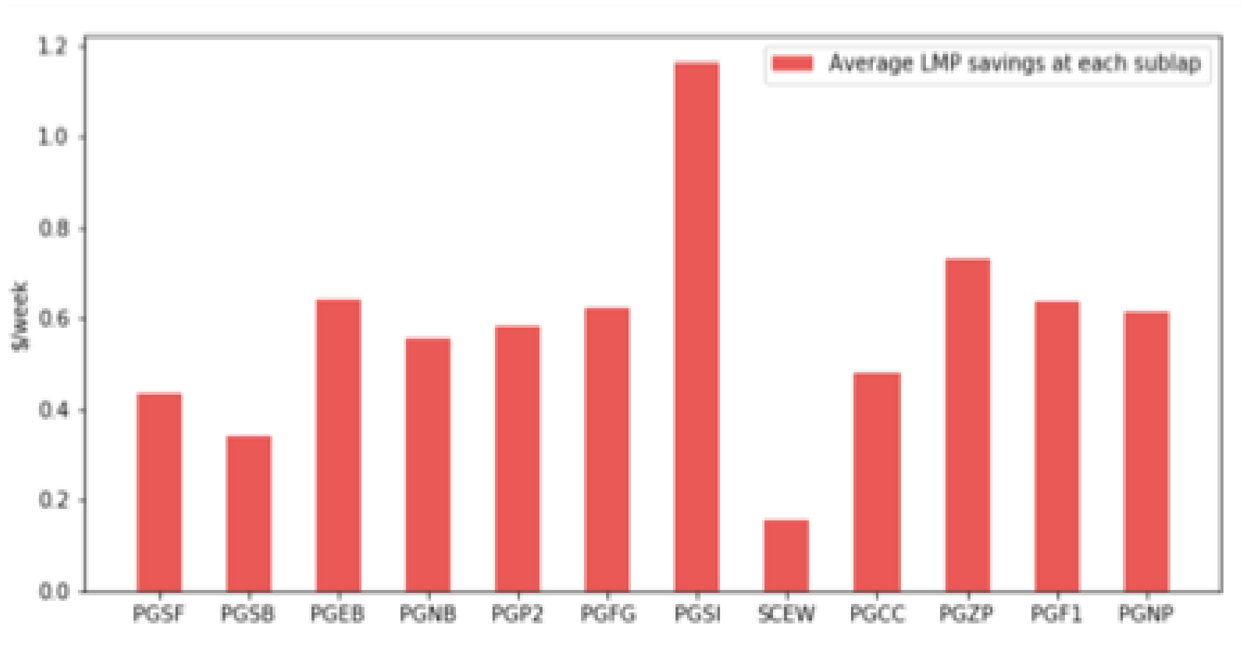
**Table 8: Summary Values for Fixed-Location Optimization Modeling**

| Optimization Modeling Description | Value |
|---|---|
| **Energy** | |
| Original charge shifted out | 72.80% |
| Optimized charge that was shifted in | 72.80% |
| **Economics** | |
| Average LMP cost savings per vehicle per year | $46.19/vehicle/year |
| Max LMP cost savings per vehicle per year | $359.00/vehicle/year |
| Min LMP cost savings per vehicle per year | $0/vehicle/year |

Source: UC Berkeley

**Error! Not a valid bookmark self-reference.**6 shows considerable variation in findings across a dozen examined SubLAP zones. Average savings from an example week in June 2018 were found to be highest in the PGSI zone (Sierra area) at more than $1.00 per vehicle per week, with others in the approximate range of $0.40 to $0.80 per vehicle per week. Most of the project charging occurred in the PGSF (San Francisco), PGSB (South Bay Area), PGEB (East Bay Area), PGNB (North Bay Area), and PGP2 (Peninsula), with a small amount occurring in the PGCC (Central Coast), PGFG (Geysers area), PGSI (Sierra area), PGF1 (Fresno area), PGNP (Western side of Central Valley), PGZP (Kern area), and SCEW (Western Southern California Edison) areas.

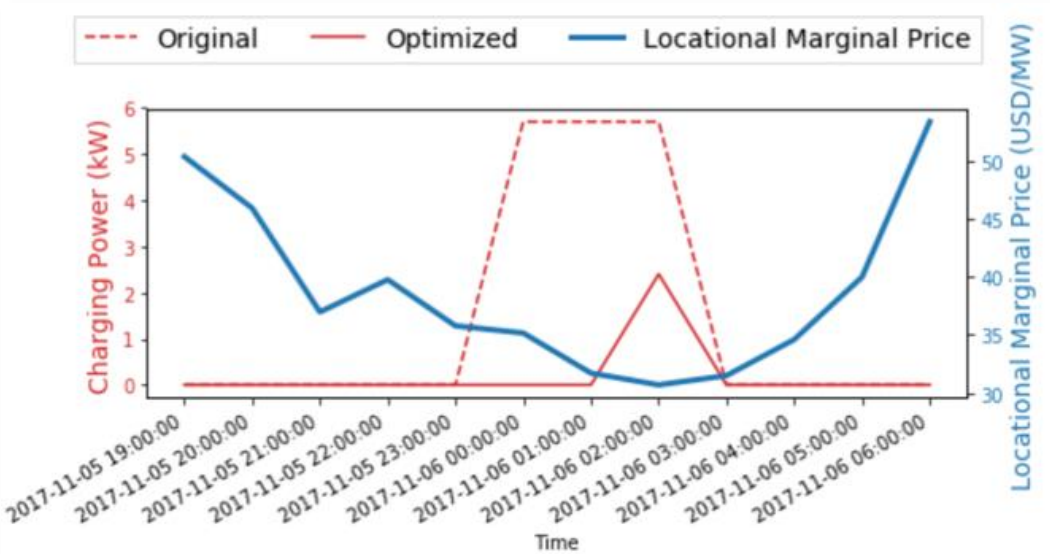
**Figure 11: Grid Cost Savings from Charge Shifting Among SubLAP Zones for Example Week**




Source: UC Berkeley

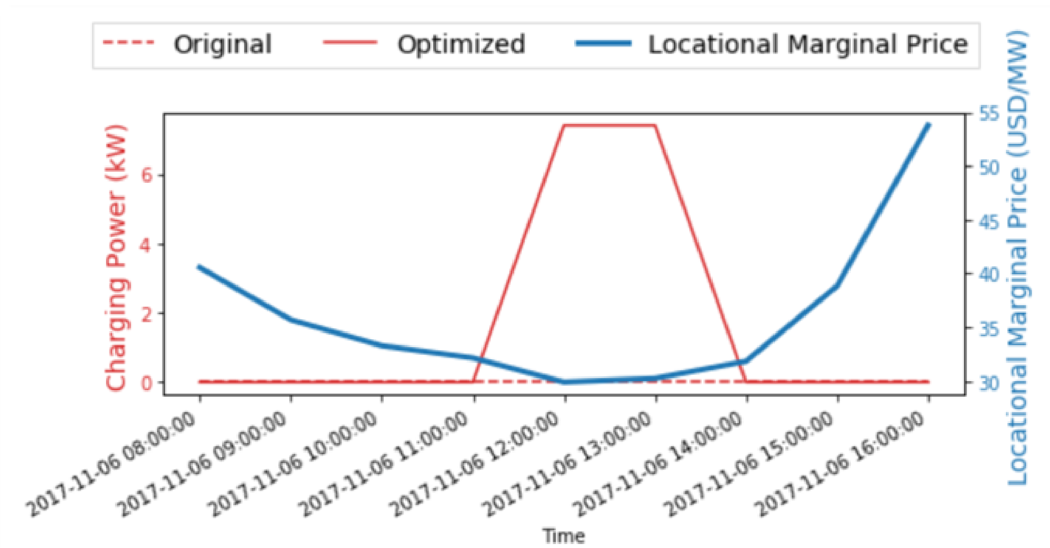
Figurative results of the inter-location (Model 2) optimization are shown in Figure 7 and Figure 8. In the inter-location scheduling, the optimal charging energy per parking event may be different from the original data set. For instance, Figure 7 shows that the optimization result indicated not to charge the vehicle due to moderate LMP costs around midnight. Figure 8 shows that the optimization result indicated to charge the vehicle due to the low LMP cost on the next day around noon, potentially at a different location if that was where the vehicle was plugged in. Also, this model assumed charging power levels of 7.4 kW for full battery EVs and 3.6 kW for PHEVs based on the power level capabilities of the vehicles.

**Figure 12: Optimized and Original Charging Patterns from Inter-location Optimization Modeling (kW and $/MW)**




Source: UC Berkeley

**Figure 13: Optimized and Original Charging Patterns from Inter-location Optimization Modeling (kW and $/MW)**




Source: UC Berkeley

Note that the optimization model had a hard constraint to meet the mobility needs; the energy consumption needs of the vehicle during driving would always be met. Therefore, the optimal charging pattern ensured that the vehicle was above a minimum level that also included the required travel energy consumption. If the optimization could not find a solution to meet this constraint, the result was not produced from optimization failure. In this optimization result with some level of data pre-processing there was no such failure.

Table 9 shows the statistics for an optimization run for four different example weeks, focusing on a grid cost minimization case. As shown there was some variation in average weekly savings per vehicle, ranging from about $0.58 per vehicle per week in the fall season to about $1.16 per vehicle per week in the winter season, but with savings as high as about $7 per vehicle per week for the vehicles with the highest level of savings based on driving and charging patterns, and $0 in savings for the lowest case vehicles. After weighting these results by season for an entire year and across all vehicles, an average savings per vehicle of about $56 per vehicle per year was obtained.

**Table 9: Summary of Results from Inter-Location Optimization Modeling of Charge Management - Cost Minimization Case**

| | Summer August 2018 | Fall Sept. 2018 | Winter Dec. 2018 | Spring March 2019 | Annual |
|---|---|---|---|---|---|
| Min. LMP Savings ($/vehicle/week) | $0 | $0 | $0 | $0 | |
| Max. LMP Savings ($/vehicle/week) | $15.91 | $3.009 | $7.188 | $3.885 | |
| Avg. LMP Savings ($/vehicle/week) | $1.650 | $0.575 | $1.161 | $0.935 | |
| Seasonal Totals Per Vehicle Based on Avg. Savings (13 weeks) | $21.450 | $7.475 | $15.093 | $12.155 | |
| Annual Total Per Vehicle Based on Avg. Savings | | | | | $56.173 |

Source: UC Berkeley

The research team noted that unlike the fixed-location scheduling, optimization Model 2 may change the hours of charging as long as it meets the energy consumption demand of the EVs. Also, the optimization tends to exploit low cost LMP hours by using its maximum charging power and to avoid expensive LMP hours by reserving charging during those periods. Therefore, the optimization result tends to decrease the total charging hours with more frequent charging instances and a higher average charging power.

The team noted that unlike in the fixed-location scheduling, inter-location scheduling used parking instances in the data with or without charging as potential charging locations. Therefore, the home and away locations had a similar sample size of around 160 vehicles. Since vehicles tended to park and charge at longer hours at home, the total parking and charging hours were larger at home than away. One interesting finding is that the total LMP cost increased slightly for the away locations. This means that vehicles that did not charge away from home before are recommended to charge there. This makes intuitive sense, as vehicles may be parked away from home, that is, at work, at cheaper LMP hours especially with solar generation. When vehicles return home after work hours, it is more economical to avoid charging as the LMP starts to increase sharply. This shows that the optimization result recommends that charging be shifted away from those early evening home hours.

Next, the LMP cost savings in different SubLAP regions are explained briefly. PGSI that covers Sacramento and PGP2 that covers San Mateo and Palo Alto are two example SubLAPs that had the maximal and minimal cost savings, respectively. One interesting finding is that the difference between the savings in the SubLAPs, as exemplified by PGP2 and PGSI, was not mainly due to difference in LMP prices but the difference in charging loads. For instance, the PGSI zone does not necessarily have lower LMP hours than PGP2. However, the original charging energy was 74 kWh for PGSI, which was much less than PGP2 with 3,198.4 kWh during the optimized time window. It is possible that more savings in different regions were correlated more to the energy demand than to the energy prices. More detailed relationships should be studied in future research.

### Comparison of Model 1 and Model 2 Results for Cost Minimization

Assuming a wide availability of charging infrastructure, the Model 1 with fixed locations and the Model 2 with flexible locations show significantly different results. As expected, potential grid cost savings were somewhat higher with Model 2. In Model 1, the average savings per vehicle were $46 per year; whereas, the average grid service level savings with Model 2 were $56 per vehicle per year. The maximum savings per vehicle were much higher than the average levels, but only in specific cases that could take advantage of low and high LMP prices on the grid. For the Model 2 maximum savings case, the project team estimated up to $390 per vehicle per year of savings.

## Charge Management for Greenhouse Gas Reduction and Greater Renewables Acceptance

In addition to the grid cost minimization case previously presented, the Model 2 analysis was further extended to examine two alternate objective functions: (1) minimization of GHG emissions, and (2) maximization of charging during periods of high renewables percentage on the grid to improve acceptance of intermittent renewable energy. These alternate objective functions are somewhat similar, as times of high renewables percentages also typically have low GHG emissions intensities, but with subtle differences.

First, the GHG emission mitigation case shows the potential for charge management to reduce GHG emissions when this is the objective. As shown in Table 10, the total GHG reductions vary somewhat by season, as analyzed in this weekly simulation that is then built up into seasonal and then annual totals. Overall, the GHG emission reduction case shows the potential to reduce emissions from vehicle charging by nearly 300 kilograms per vehicle per year in this San Francisco Bay Area case. At some point this effect would become saturated but will continue to scale with increasing levels of renewable electricity that are expected with the California state policy to move toward a fully decarbonized electricity grid by 2045.

**Table 10: Summary of Results from Inter-Location Optimization Modeling of Charge Management – GHG Emission Reduction Case**

| | Summer August 2018 | Fall Sept. 2018 | Winter Dec. 2018 | Spring March 2019 | Annual |
|---|---|---|---|---|---|
| Estimated GHG Reductions (kg of GHG/vehicle/week) | 7.16 | 5.17 | 6.76 | 3.8 | |
| Seasonal Totals Per Vehicle Based on Avg. GHG reductions (13 weeks) | 93.08 | 67.21 | 87.88 | 49.4 | |
| Annual Total GHG Reductions (kg of GHG per vehicle per year) | | | | | 297.6 |

Source: UC Berkeley

Second, in the case where charge management was optimized in response to a grid renewable energy percentage signal, the research team also found a noteworthy ability of managed charging to increase the uptake of renewable energy. Compared with the non-optimized baseline, the research team estimated that more than 1,200 kWh of additional renewable energy could be used to charge each participating vehicle per year, as shown in Table 11. This could help to reduce renewable energy curtailment that is expected to become a growing issue for the California grid (Lipman et al. 2020).

**Table 11: Summary of Results from Inter-Location Optimization Modeling of Charge Management - Renewables Percentage Maximization Case**

| | Summer August 2018 | Fall Sept. 2018 | Winter Dec. 2018 | Spring March 2019 | Annual |
|---|---|---|---|---|---|
| Estimated Renewable Energy Increased Uptake (kWh/vehicle/week) | 22.5 | 29.7 | 20.3 | 20.6 | |
| Seasonal Totals (13 weeks) (kWh/vehicle) | 292.5 | 386.1 | 263.9 | 267.8 | |
| Annual Total Renewable Energy Increased Uptake (kWh/vehicle) | | | | | 1,210.3 |

Source: UC Berkeley

## Implications for Future Vehicle-Grid Integration Programs

Managed charging can be an effective way to shift load and take advantage of renewables overgeneration. Though this program largely focused on at-home charging and shifting into night-time hours, several use cases indicated the potential for charging away from home and during daytime hours. Lessons learned and considerations for future managed charged programs include opportunities for further studies as well as ways to improve the effectiveness and implementation of these types of programs.

## Opportunities for Charging Away from Home to Absorb Excess Solar Generation

This pilot focused primarily on charging at home, which observed a successful shift in charging away from the evening peak and into the late night and early morning hours. Due to public and workplace charging infrastructure constraints, it was difficult to manage charging away from home; therefore, only the Overgeneration Away from Home use case featured both home and away charging. Program participants also indicated that it is more convenient to charge at home. There is an opportunity to conduct more managed studies for charging away from home, particularly at the workplace, while also making it convenient for the participants to maintain their mobility.

Incentives and education have been shown to motivate customers to plug in more frequently and for longer periods of time. The Earth Week use case saw a 63 percent increase in daytime charging coinciding with solar generation, with a 225 percent increase in daytime charging during the day that the highest incentives were offered. This indicates that with the education and the right incentive structure, charging behaviors can be altered to take advantage of excess renewable generation. Findings from this project suggest that EV drivers are generally receptive to allowing for charge management strategies. However, in this emerging area of implementation there are clearly opportunities for better integration of driver preferences, motivations, and mobility constraints with the evolution of technology platforms to enable better grid performance and renewable energy integration. Key aspects include providing customers with a flexible and understandable interface while still meeting mobility needs and addressing privacy and security concerns.

## Baseline Calculation Considerations

Rate structures can influence customer charging behavior, as highlighted in the Vehicle Charging Load Profiles and Utility Rate Structures section of this report. Rate structures are one of the many factors that need to be taken into consideration when formulating an accurate baseline, which will be one of the bigger challenges facing future VGI programs. Also challenging baseline determination is a feature in most vehicles that allows drivers to delay charging to coincide with lower rate periods. Understanding the variables affecting customer charging behaviors before committing them to a managed charging VGI program will be critical to determine the effects of future programs and VGI as a resource.

## VGI and Demand Response

There are opportunities for more studies to quantify the value of managed charging as a resource for demand reduction. No clear trends were observed for load decrease events at the SubLAP level, which used day-ahead market signals and whole household data, as detailed in the Optimization with Load Decrease at the SubLAP Level section of this report. The SubLAP study also used household energy data and found that it was difficult to discern EV charging events where Level 1 chargers were used (see Vehicles as an Aggregated Resource). Additional studies would be needed to quantify the demand response value, and they may need to be supplemented with vehicle telematics data.

Furthermore, an initial estimate of stacked benefits from managed charging suggests that the largest value is from demand response, but that there are additional values from energy arbitrage, grid distribution cost savings, and avoided carbon emissions that could in total be of similar magnitude. Preliminary estimates suggest that these combined values of managed charging could be on the order of $300 per vehicle per year. See Appendix X for further discussion.

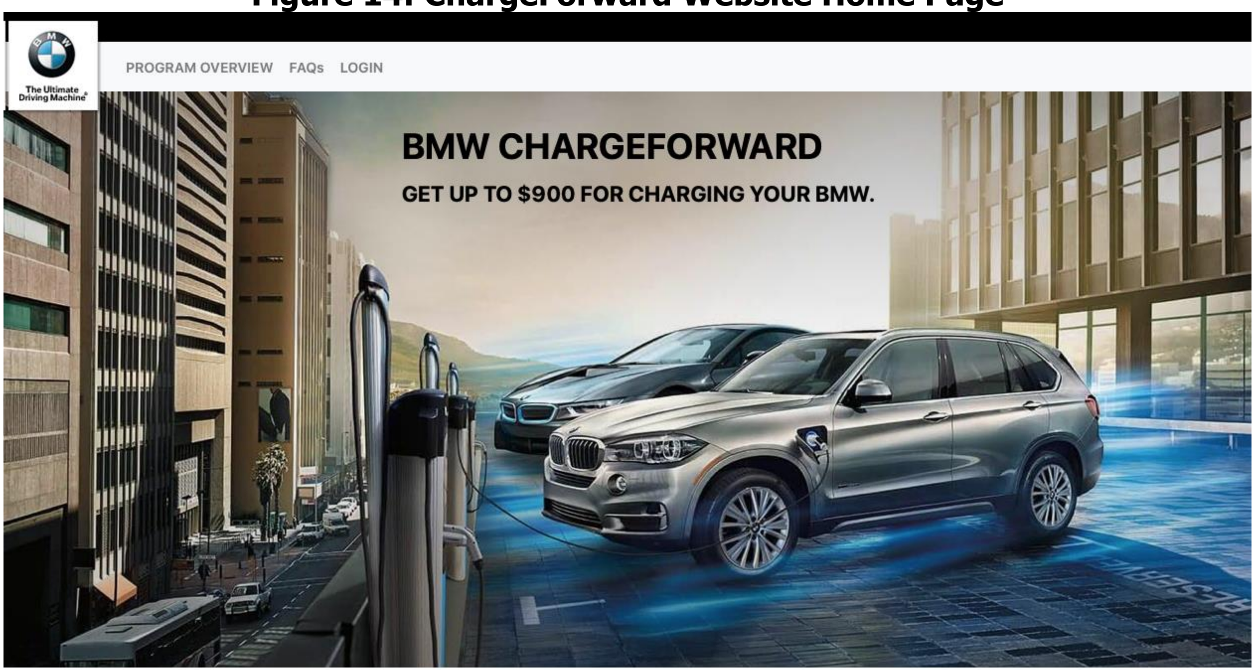
# CHAPTER 4: Technology/Knowledge/Market Transfer Activities

## Introduction

Developing original information on the potential for EV charge management and disseminating it widely is a key goal of the project.

Large amounts of data and information were developed through the project. This includes the technical dimensions of EV charge management with user interfaces and back-end software solutions, findings from various vehicle-grid integration (VGI) use cases and optimization analyses, and social dimensions regarding driver motivations and responses to incentives to participate in VGI programs. Figure 39 shows the home page of the ChargeForward program webpage, that contains considerable additional information about program participation as well as VGI and EV charge management more generally.

**Figure 14: ChargeForward Website Home Page**




Source: BMW of North America, LLC

Figure 40 shows the program overview page linked to the home page of the ChargeForward program. This portal allows prospective and current ChargeForward participants to access general program information.

**Figure 40: ChargeForward Website Program Overview**


Source: BMW of North America, LLC

## Technology Transfer Activities

The key activities of this project Task 7 included the preparation of the following materials:

- An *Initial Fact Sheet* at start of the project that describes the project;
- A *Final Project Fact Sheet* at the project's conclusion that discusses results;
- A *Technology/Knowledge Transfer Plan and Report* that includes:
    - An explanation of how the knowledge gained from the project will be made available to the public, including the targeted market sector and potential outreach to end users, utilities, regulatory agencies, and others;
    - A description of the intended use(s) for and users of the project results;
    - Published documents, including date, title, and periodical name;
    - Copies of documents, fact sheets, journal articles, press releases, and other documents prepared for public dissemination;
    - A discussion of policy development impacts;
    - The number of website downloads or public requests for project results.

This project Technology Transfer Report consists of documenting the following activities, some of which are listed in Table 12:

- Presentations at professional conferences
- Presentations at meetings and executive briefings
- Peer reviewed journal articles
- Conference papers including those listed in Table 12
- An additional 40-50 page "glossy" summary brochure of the key ChargeForward 2.0 and TCM project features and findings, externally funded by BMW North America LLC (https://bmwmovement.org/bmw-releases-chargeforward-report/)

These activities are targeted toward the following groups:

- The general public including California electricity ratepayers
- Electric utility representatives and trade groups
- EVSE manufacturers and EV industry groups
- Policymakers and regulators
- NGOs and advocacy groups
- Academic researchers

**Table 12: TCM Project Technology Transfer Activities**

| Team Member | Event | Presentation Type | Location and Date | Audience |
|---|---|---|---|---|
| Adam Langton | European Union (EU) Commission presentation | Slide presentation | Brussels, Belgium, Feb 1, 2018 | EU Committee staff and nongovernmental organization (NGO) stakeholders |
| Adam Langton | Coal + Ice Symposium | Panel participant | San Francisco, Calif, Sept 10, 2018 | Public audience |
| Adam Langton | EVs and the Grid symposium | Panel participant | Los Angeles, Calif, Oct 10, 2018 | Energy, government, and NGO stakeholders |
| Adam Langton | California ISO symposium | Panel participant | Sacramento, Calif, Oct 17, 2018 | Energy, government |
| BMW NA team | Consumer electronics show | Conference display | Las Vegas, Nev, January 8–11, 2019 | Show attendees |
| Alissa Harrington | 2019 CEC EPIC symposium | Podium presentation | Sacramento, Calif, February 19, 2019 | EPIC symposium attendees |

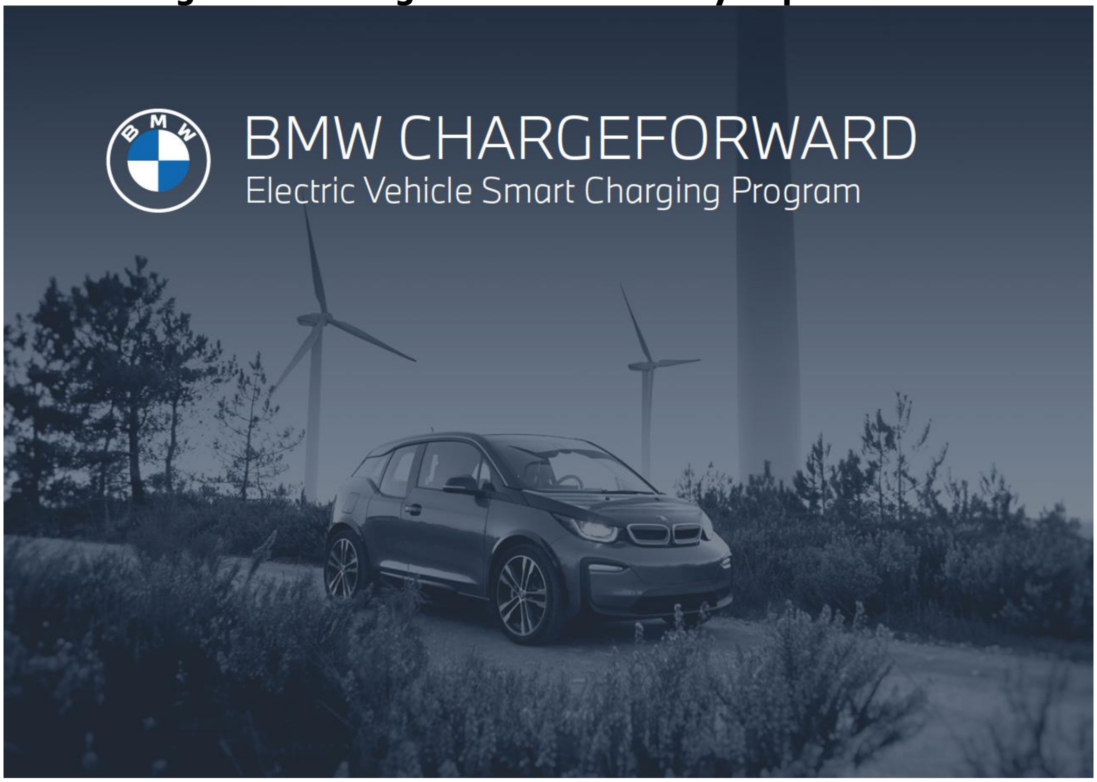
| Team Member | Event | Presentation Type | Location and Date | Audience |
|---|---|---|---|---|
| Adam Langton | Grid Edge Summit | Panel participant | San Diego, Calif, June 18, 2019 | Energy, government, and NGO stakeholders |
| Adam Langton | Washington, D.C. stakeholder event | Slide presentation | Washington, D.C., Oct 7, 2019 | East Coast utility and NGO stakeholders |
| Adam Langton | Sacramento stakeholder event | Slide presentation and panel | Sacramento, Calif, Oct 8, 2019 | Sacramento government, energy, and NGO stakeholders |
| Tim Lipman | Sacramento legislative briefing | Podium presentation | Sacramento, Calif, February 28, 2020 | Sacramento legislative representatives and staff |
| UC Berkeley team | IEEE Conference on Technologies for Sustainability (SusTech) 2020 | Conference paper and presentation | Orange County, Calif, April 23–25, 2020 | IEEE conference attendees |

**The presentations listed are available in Appendix Y.**

Source: BMW of North America, LLC.

An important technology transfer outcome of the project is that in July 2020, BMW released a final 48-page glossy summary report for the ChargeForward 2.0 program for wide dissemination, using internal funds after the close of the Energy Commission grant. The cover page of the report is shown in Figure 41 below and it can now be accessed online (https://bmwmovement.org/bmw-releases-chargeforward-report/).

**Figure 41: ChargeForward Summary Report Cover**




Source: BMW of North America, LLC

## Utility Partnership Activities and Market Expansion

Utility-automaker partnerships help maximize the benefits of smart charging. Automakers depend on the utility for grid-related data used to optimize charge shifting and maximize grid and customer benefits from smart charging. This includes understanding which hours to shift charge into/out of depending on grid conditions, such as periods of peak demand, overgeneration, or high/low cost. Utilities benefit from the automaker-customer relationship, which helps ensure that their customers' mobility needs are fully addressed, such as having a guaranteed state-of-charge during scheduled departure times.

BMW worked closely with PG&E in designing the use cases implemented in this pilot. PG&E's hourly renewable energy data was used in the Earth Week Renewable Energy use case and the Overgeneration use case for daytime optimizations against renewable energy instead of LMP data. The data was also integrated into the participant web portal, showing how much of a vehicle's charging came from renewable energy and giving PG&E customers first-time visibility into their renewable energy usage. The hourly renewable data was also incorporated into the optimization models, used to better understand the effect of smart charging when aligned with renewable energy instead of price.

# CHAPTER 5: Conclusions/Recommendations

This chapter presents conclusions reached based on the project data collection, analysis, and findings and recommendations to further the rapidly evolving field of VGI. It also stresses that certain limitations and caveats to the study, delineated after the project findings summary, are important to putting its results and findings in the proper context.

## Conclusions

Broadly speaking, the project demonstrated that a telematics-based approach can be highly effective in shifting EV charging load to provide grid and environmental benefits. This engagement also leads to heightened customer awareness that can change behavior regarding plugging in more often and enable the use of EVs as flexible load for utility grids.

### Total Charge Management Use Case Findings

The central aspect of this TCM project was the execution of a series of carefully considered use cases that explored different aspects of charge shifting, including the setting (home and away from home), the goals of the use case, the incentive structure, and additional aspects unique to the individual use cases. Important findings of the use cases include:

- Demonstration of the ability to use vehicle telemetry to optimize vehicles and perform charge management at both home and away-from-home settings.
- A high level of statistical significance with the increase in plug-in frequency for use cases that encouraged increasing plug-in frequency (a key prerequisite to charge management).
- With PG&E support, identification of periods of highest benefit to the grid and the ability to shift into those periods.
- A better understanding of incentives necessary to engage drivers, including upper bounds of engagement based on highest incentives.
- A better understanding of barriers and obstacles, for example, data collection challenges and encouraging drivers to set departure times that could be improved in future projects.
- Improved understanding of limitations related to charger availability for load shifting across days and locations that will be improved in the future with greater charger availability.
- The need for customer education about plugging in during the middle of the day, coupled with future provision of higher levels of workplace charging infrastructure.

### Net Grid Value

The optimization modeling for cost minimization reveals a potential for lowering the utility-level costs of providing charging to EVs under a managed charging regime. Based on average values and a weekly analysis that is then expanded to annual totals, the research team finds that each vehicle can save about $56 per year in wholesale level grid costs by charging at low cost times while still meeting driver mobility needs.

For a sample of 25 sites in northern California, a location-specific distribution capacity program design shows average savings of $62.50 per vehicle per year, based on EV charging behavior that optimizes for lowest price in the hour-ahead market. These values depend on the location, associated distribution infrastructure, local demand, and local distributed generation.

### Renewables Acceptance

This project demonstrated both real and potential opportunities for charge management coupled with customer behavior to improve the acceptance of renewable energy on the California grid. In the optimization modeling case (somewhat idealized) up to 1,200 kWh of additional renewable energy could be accepted per vehicle per year in a near-term simulation. This can increase the storage capacity of renewable resources on the grid to help meet state Renewable Portfolio Standard goals, improving their cost-effectiveness, and lowering the carbon intensity of EV charging.

### Greenhouse Gas Emissions Savings

Vehicle electrification is a key pillar in California's strategy to reduce GHG emissions. As California's electrical grid continues to move toward full decarbonization by 2045 in response to SB 100, increasing levels of EVs in California can provide a win-win strategy to help make best use of the increasing levels of intermittent renewables that are inevitable to meet these goals. The project findings suggest that managed charging of EVs can reduce approximately 300 kilograms of GHGs per year per vehicle on an average but somewhat idealized basis. On the higher end, some vehicles will be able to reduce significantly more than this average (and can be incentivized to do so) as in this San Francisco Bay Area simulation using advanced optimization modeling tools and considering current grid conditions. As the number of EVs in California grows, along with the contribution of renewable sources of electricity, these evolving dynamics and appropriate charge management implementation strategies will be of great importance to help maximize the GHG reduction potential of both the electricity and mobile source sectors.

## Study Limitations and Caveats

Some limitations to the study should be noted. The project relied upon voluntary participation among BMW EV drivers in the San Francisco Bay Area, which introduces two issues: (1) self-selection bias, and (2) generalizability outside of Northern California. Participants in the study were compensated monetarily, somewhat reducing the effect of self-selection bias, but the extent of this bias is still unclear. Since the study was limited to participants in Northern California and mostly in the San Francisco Bay Area, an area known for innovation and generally progressive-minded citizens, additional research in other regions of California and the United States will be helpful to understanding how applicable these results are to other areas.

- The number of workplace charging opportunities is limited.
- Customer enrollment to establish eligibility for participation was time consuming.

- A limited number of pilot programs limit EV drivers' exposure to hourly time varying rates on a day-ahead basis, which in turn limits their potential to change charging behavior in terms of plugging in more.
- Customers were unable to participate in more than one type of load control program due to utility rules, even though the programs were device based and could easily be complementary.
- No clear ways exist to combine different value streams to enable customers to maximize benefits of smart charging.

Further, in its implementation, the project encountered some non-technical and technical barriers. Non-technical challenges included some difficulties with availability of customer electricity usage data, registering households as demand response resources, permitting for home storage installations, and limited access to distribution infrastructure data. An additional issue was the potential effect on customers' bills of certain charging strategies based on local utility rate structures. Technical challenges included some issues with the initial implementation of charging optimization that were resolved with data access improvements. Another issue was delays associated with the interconnection of home energy storage systems, but these were ultimately resolved.

## Recommendations

Based on project findings and lessons learned, the project team makes the following recommendations for advancing EV managed charging concepts.

- Focus publicly funded charging investments on increasing workplace charging opportunities, which are currently limited.
- Increase EV drivers' exposure to hourly time varying rates on a day-ahead basis to support changes in driver charging behavior.
- Simplify programs to make them hassle free for participants. For example, reduce the time involved in customer enrollment to establish eligibility.
- Combine multiple value streams from the utility and wholesale markets into a larger value that could be effective as a customer incentive to maximize benefits of smart charging and motivate higher levels of participation in the future. Accomplishing this at scale would require utility rates or programs that capture multiple value streams into a single tariff or program.
- Revise utility rules to enable customers to participate in more than one type of load control program, as the programs are device based and can easily be complementary.

## Summary

This program, the largest real-world managed EV charging effort in the United States, has made important strides in understanding the potential and challenges for this concept. The project has demonstrated a significant potential for a voluntary, incentive-based program to shift EV charging load across time periods to those that are most amenable to improved grid operations, as well as potentially shifting charging among geographic locations. Due to the current challenges with managing away-from-home charging, primarily due to limited infrastructure, there is great potential for subsequent research projects focusing on managed workplace or fleet charging once charging infrastructure becomes more consistently available.

# CHAPTER 6: Benefits to Ratepayers

The concept of EV charge management has the potential to provide efficiencies for utility grid operations that can reduce overall costs to utility ratepayers. Customers can also reduce their bills directly by charging during lower priced TOU billing periods. Reducing grid operational costs through reduced wholesale procurement during high cost periods and avoiding the need for distribution-level system capacity expansion can eventually flow back to all ratepayers through avoided future rate increases. Rate design that incentivizes EV drivers to shift their vehicle charging to help. EV charge management can also help with accepting increased levels of renewable energy on the grid by mitigating renewable energy intermittency and overgeneration.

This TCM project has documented grid service cost savings in this report that amount to over $3,000 for this relatively small fleet of a few hundred vehicles over the course of time for the handful of use cases examined. This project has helped to validate the ability of a managed charge program to provide relatively dramatic load-shifting capability for EVs that still maintains driver mobility needs, providing important impetus for future investigations.

EV load-shifting can assist with three important grid operational challenges in California, which are growing in importance as the state grid conditions evolve in the following ways:

- Encouraging EV charging during the morning ramping period can help mitigate ramp-down in the net load curve, as solar PV rapidly comes onto the grid and traditional generators are forced to turn down.
- As solar PV further comes online in the middle of the day, EV charging can help to fill this midday valley in the net load curve, helping to flatten it out and furthering the acceptance of renewable solar generation.
- EV charging can be avoided during the early evening ramp-up period as the solar resource fades away and grid service costs are typically at their peak.

## Importance of Managed Charging to Ratepayers

Managed, or smart, EV charging benefits both the grid and ratepayers. EV drivers most commonly plug in to charge in the early evening (when they get home) and immediately begin charging, which coincides with when the grid is most stressed due to high demand. Most drivers do not plug in and schedule their charging to begin at times that would be most beneficial to the grid --- around mid-day when the grid has excess energy from solar overgeneration, or late at night when overall demand is low.

Optimized shifting of charging to times when it is more beneficial for the grid reduces power reliability issues and may delay rate increases due to equipment upgrades. This also contributes to grid reliability by allowing utilities to use electric vehicle charging as a resource to manage intermittent renewables.

## Economic and Emissions Benefits

There are direct cost benefits of shifting charging out of high-price hours for TOU customers. These periods may also correspond to times of grid congestion, where grid operations can be improved by shifting charging to less congested times. When scaled, the benefits are expanded to ratepayers through delaying equipment upgrades and repairs. Finally, there are emissions benefits to making better use of intermittent renewable resources, which are increasingly facing periods of curtailment where grid prices can go negative at certain time periods, meaning there is a clear benefit to absorbing power at these times through managed EV charging.

### Wholesale Market Cost Savings

The main grid cost savings come from shifting vehicle charging out of congested grid pricing periods, when the LMP price is high (early evening hours), into times when the LMP price is lower (around midnight). However, it is common to see a disconnect between changes in wholesale grid prices and retail electricity prices seen by ratepayers. Some utilities such as San Diego Gas and Electric Company are conducting pilots that expose customers to day-ahead pricing that reflects underlying grid costs and would align better with charge management.[1] Though it is beneficial to expose customers to real-time pricing, it is also important to consider additional customer incentives to influence behavior in managed charging programs.

### Potential Avoided Cost Savings

EVs can also provide a distribution system-level service for utilities to lower distribution costs, thereby resulting in an avoided cost value that equates to deferral of utility equipment upgrades associated with power reliability or load growth. These benefits are passed down to ratepayers by delaying rate increases due to equipment upgrade costs.

A Kavala study (see Appendix G) analyzed ten charging sites within PG&E territory and assessed the potential impacts of optimized charging. The report provides the potential distribution-level utility avoided cost savings associated with optimized charging at those sites. These savings vary considerably by location, making them hard to generalize, but they can be very significant. Values can range from a few dollars up to as high as almost $80 per hour per vehicle at the sites with the highest potential for avoided costs.

### Emissions Savings from Managed Charging

Managed charging has the potential to reduce GHG emissions by aligning more charging energy with renewable generation, reducing the amount of charging energy from high GHG producing power sources. However, because the most effective managed charging program would likely include both shifting charging to periods of excess renewable generation (around noon) and periods of lowest grid congestion and cost (around midnight), overall emissions savings involve complex trade-offs regarding the specific time periods involved.

In the project optimization modeling, an objective function of charging at times of the lowest levels of GHG emissions was explored, including inter-locational charge optimization while still meeting driver mobility needs. An average level of savings of about 300 kilograms per year per

[1] See: PG&E, SCE, SDG&E pursue subscriptions, time-of-use rates to drive more California EVs

vehicle was found to be achievable, albeit requiring a higher level of daytime charging infrastructure availability in the future.

Emissions savings are only expected to become significant in programs that focus on shifting charging to peak renewable periods, shifting typical evening charging to daytime charging coinciding with solar overgeneration. However, these types of programs would currently not be effective due to the lack of enough workplace charging infrastructure that enable daytime charging. Expanded availability of workplace charging and other charging available for midday use will be important to realizing this potential.

### ChargeForward Program Sustainability Impact

ChargeForward program participants drove over 2 million zero-tailpipe emission miles in 2018. The percentage of renewable energy charging can be expected to increase in the future as California's grid continues to move toward higher and higher levels of renewable energy provision in response to state goals.

These renewable miles were partly the result of the program charge management optimizations, especially related to the Earth Week and Overgeneration Away from Home use cases. Overall, 5,669 optimizations were sent to the vehicles in 2018 at home and away-from-home locations with 5,222 and 447 optimizations sent to home and away, respectively.

## Groundwork for Future Projects

This program, the largest real-world managed EV charging effort in the U.S., has made important strides in understanding the potential and challenges for this concept. The project has demonstrated a significant potential for a voluntary, incentive-based program to shift EV charging load across time periods to those that are most amenable to improved grid operations, as well as potentially shifting charging among geographic locations. Due to the current challenges with managing away-from-home charging, primarily due to limited infrastructure, there is great potential for subsequent research projects focusing on managed workplace or fleet charging once charging infrastructure becomes more consistently available.

# GLOSSARY AND ACRONYMS

| Term | Definition |
|---|---|
| BEV | Battery electric vehicle |
| California ISO | California Independent System Operator |
| CEC | California Energy Commission |
| CISR | customer information service request: the PG&E CISR form allows customers to disclose their electricity-related information to third party demand response providers so that they may participate in demand response programs (such as Total Charge Management), per PG&E's Electric Rule 24 |
| CPUC | California Public Utilities Commission |
| DER | Distributed energy resource |
| DR | Demand response |
| EPIC | Electric Program Investment Charge |
| EPRI | Electric Power Research Institute |
| EV | Electric vehicle |
| EVSE | Electric vehicle supply equipment (includes charging stations) |
| GHG | Greenhouse gas |
| HAN | Home area network |
| HESS | Home Energy Storage System |
| ISO | Independent system operator |
| LMP | Locational marginal pricing |
| LMP+D | locational marginal pricing (LMP) and avoided distribution capacity value (D): the construct by which a distributed energy resource (DER) is valued based on a utility's avoided costs from the DERs |
| NGO | Nongovernmental organization |
| PEV | Plug-in electric vehicle |
| PG&E | Pacific Gas and Electric Company |
| PHEV | Plug-in hybrid electric vehicle |
| PV | Photovoltaic |
| RPS | Renewable Portfolio Standard |
| SubLAP | Sub-load aggregation point |
| TAC | Technical advisory committee |
| TCM | Total Charge Management |
| TE | Transactive energy |
| TNC | Transportation network companies |
| TOU | Time of use |

| Term | Definition |
|---|---|
| TSRC | UC Berkeley's Transportation Sustainability Research Center |
| U.S. | United States |
| V2G | Vehicle to grid: a concept where electric vehicles can send electricity back into the grid, or vary their charging rate |
| VGI | Vehicle-grid integration |
| XSP | Excess Supply Pilot |

# REFERENCES


California Independent System Operator. 2014. California Vehicle-Grid Integration Roadmap: Enabling Vehicle-Based Grid Services, February.

Clean Vehicle Rebate Project. 2019. CVRP Rebate Statistics. https://cleanvehiclerebate.org/eng/rebate-statistics

Hardman, Scott, Alan Jenn, Gil Tal, Jonn Axsen, George Beard, Nicolo Daina, Erik Figenbaum, Niklas Jakobsson, Patrick Jochem, Neale Kinnear, Patrick Plötz, Jose Pontes, Nazir Refa, Frances Sprei, Tom Turrentine, Bert Witkam. 2018. "A review of consumer preferences of and interactions with electric vehicle charging infrastructure." Transportation Research Part D: Transport and Environment 62 (2018): 508-523.

Kim, W., V. Añorve, and B.C. Tefft. 2019. American Driving Survey, 2014 – 2017. AAA Foundation for Traffic Safety.

Lipman, T. (TSRC, University of California – Berkeley). 2020. An Open-Source, Open-Architecture Software Platform for Plug-In Electric Vehicle Smart Charging in California. California Energy Commission. Publication number: Energy Commission-500-2020-005.

Noel, L., G.Z. De Rubens, J. Kester, and B.K. Sovacool. 2019. Vehicle-to-Grid: A Sociotechnical Transition Beyond Electric Mobility, Energy Climate and Environment Series, Palgrave Macmillan.

Singh, K., N.P. Padhy, and J. Sharma. 2011. "Influence of Price Responsive Demand Shifting Bidding on Congestion and LMP in Pool-Based Day-Ahead Electricity Markets," IEEE Transactions on Power Systems, Volume 26, pp. 886-896.

Veloz. 2019. Sales Dashboard. https://www.veloz.org/sales-dashboard

# APPENDICES

To request one or multiple appendices for this report, please contact Adam Langton of BMW North America, LLC. at adam.langton@bmwna.com.

- Appendix A: Customer Enrollment Lessons Learned
- Appendix B: Charging Behavior Optimization Report
- Appendix C: Use Case Analysis
- Appendix D: Vehicle Telematics Report
- Appendix E: Customer Home Load Report
- Appendix F: Optimization Model Analysis
- Appendix G: Distribution Analysis #1
- Appendix H: Distribution Analysis #2
- Appendix I: Customer Communication Tools Document #1
- Appendix J: Surveys & Focus Group Analysis
- Appendix K: Telematics Data Collection Protocol
- Appendix L: Earth Day 2018 Use Case
- Appendix M: Dispatch Demonstration Report
- Appendix N: Program Design Document
- Appendix O: Size and Categorization of Resource Report (#1)
- Appendix P: Functional Report on Away from Home Charging
- Appendix Q: Telematics Data Comparison Plan
- Appendix R: Size and Categorization of Resource Report (#2)
- Appendix S: Customer Communication Tools Documentation #2
- Appendix T: Vehicle Grid Resource Report
- Appendix U: Away-from-home Communication Test Results
- Appendix V: Vehicle-Renewable Integration Analysis
- Appendix W: Advanced Distribution Use Case
- Appendix X: Sustainability Assessment
- Appendix Y: Technology Transfer Presentation Links