DR Emerging technology (DRET)
Tesla Battery Study Results

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ABBREVIATIONS AND ACRONYMS

DER	Distributed Energy Resource
DRET	Demand Response Emerging Technology
DR	Demand Response
LCA	Local Capacity Area
VPP	Virtual Power Plant

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EXECUTIVE SUMMARY

PG&E's Demand Response Emerging Technology (DRET) group initiated a Battery Study to investigate the ability to utilize residential photovoltaic solar systems paired with a Tesla Powerwall home battery systems to support state electric grid reliability in times of high electricity demand by creating a virtual power plant (VPP). By default, residential batteries help offset household energy use. However, they do not export to the grid, leaving a flexible resource untapped when the electric grid is strained or electric prices are high. PG&E designed the pilot to assess whether it could enroll residential battery owners in a program to dispatch Tesla Powerwalls to send energy back into the grid during times of high demand.

The goals of the pilot included:

- Assess the ability to enroll existing battery owners into a program to use their battery for grid needs in exchange for payments.
- Determine the ex-post load impacts of the Tesla batteries when dispatched under varied event conditions.
- Assess whether and how much Tesla batteries are able to export to the grid during an event.
- Assess the ability of the existing dispatch algorithms to deliver a flexible, controllable grid resource.
- Compare evaluation methodologies to determine which data sources and evaluation methods produce reliable results.

The focus of the pilot was the performance of the battery storage technology. The main goal was to estimate the effect of the technology on peak demand reduction and assess the best way to measure the peak reduction based on the available data

PROJECT DESCRIPTION

For the pilot, PG&E worked with Tesla to reach out to approximately 7,000 customers (with approximately 12,600 batteries) and recruit them for the pilot. All recruitment took place in the Fall of 2021 via push-notification, and PG&E and Tesla dispatched events from October through November of 2021. PG&E offered customers an incentive of $1/kWh for energy dispatched over their typical use – the baseline – and customers were allowed to opt-out of events. A total of almost 1,300 customers (18.6%) enrolled in the program and participated in seven events for the pilot. The estimated Incremental load reduction prime (ILR') MWh for battery charge and discharge was 14.55 MWh and the total aggregate nameplate MW was 11.74 MW.

The evaluation team tested multiple customer-level models via a tournament and applied the best model to estimate a counterfactual. We applied this methodology to estimate load impacts using both utility household level and battery end-use data.

PROJECT FINDINGS/RESULTS

Table 1 summarizes the key research questions and findings from the study.

TABLE 1: SUMMARY OF KEY RESEARCH QUESTIONS AND FINDINGS

Research Question	Findings
Do customers enroll in programs that allow the utility to use their battery for grid needs in exchange for payments?	1,300 of the 7,000 (18.6%) customers recruited into the pilot enrolled. All recruitment took place in the Fall of 2021 via push-notification over a compressed timeline. PG&E offered customers an incentive of $1/kWh for energy dispatched over their typical baseline, and customers were allowed to opt out of events.
What are the ex-post load impacts using end-use battery data and premise data?	The incremental impacts are estimated to be ~4.5 kW in hour 1, ~3.0 kW in hour 2, and less than 1 kW in hour 3.
Do the existing dispatch algorithms to deliver a flexible, controllable grid resource?	The current battery dispatch algorithms deliver all of the resources, all at once, until the available energy storage is exhausted and reach its reserve capacity set by customers. Currently, the algorithms cannot deliver a consistent level of demand reduction over the event, deliver a requested level of output, or sustain the resources over a longer event duration. Tesla is in the process of modifying its algorithms, so their residential battery resources can be more flexible and controllable for grid needs in the future.
How do impacts using the end-use battery data (sub-meter) compare with impacts at the household level?	Load impacts estimated using household-level smart meter data were similar to those calculated using battery end-use data, with less than a 1% difference between the impacts on average.
Do the event calls lead to an increase in a household's net discharge to the grid during an event? And exporting of battery resources to the grid?	When dispatched for events, the batteries not only offset the household's energy use, but also exported energy back to the grid. Customers do not noticeably modify their energy use (of other end-uses) when the battery is used to support grid needs. Note: the events took place in the Fall where, due to moderate temperatures, household loads in the afternoons were relatively low. During future events in the Summer, when temperatures are higher and household loads are also higher due to air conditioning use, the discharge to the grid may not be as large.
What was the performance when consecutive events were called?	The batteries delivered consistent dispatch across consecutive event days. However, events were called during mild weather conditions typically with ample sunshine. The dispatch consistency may change if batteries are discharged under more extreme weather conditions as indicated above.
What is the full export capability?	On average, batteries were able to discharge 4.5 kW during the first hour for a full net export of 3.3 kW. However, this is not necessarily representative of battery export capability during peak

	system demand as batteries for this pilot were dispatched under moderate weather conditions.
How does the EM&V analysis compare with the settlement results?	For settlement with customers (and Tesla), the baseline usage is calculated as the same hour average over the past 10 days using battery end-use data. Any battery discharge above the baseline was considered the load impact. On aggregate, the impacts calculated using the settlement baselines are comparable to EM&V results, but were 5% higher on average.

PROJECT RECOMMENDATIONS

We recommend the following next steps for continuing research on the potential of this technology to reduce peak demand:

1. Test battery performance for varied seasons, weather conditions, and event durations.
2. Develop and test battery dispatch strategies to:
    - Provide a flat, consistent MW value over the event;
    - Allow grid operator to specify the battery output needed;
    - Allow grid or program operators to specify the shape of the energy output; and
    - Respond to wholesale market energy price signals.
3. Research how customer enrollment varies with:
    - Incentive structure;
    - Incentive amount; and
    - Outreach attempts.
4. Test other battery grid services:
    - Charge events;
    - Contingency reserves;
    - Frequency regulation; and
    - Under frequency/voltage relays.
5. Assess how batteries perform for different customer demographics.
6. Sub-metering shows promise on this single vendor study, so requirements should be developed and tested for broader adoption in the future.

INTRODUCTION

During the 2020 system-wide grid emergencies caused by the August and September heat waves, Demand Response (DR) provided by the three Investor Owned Utilities of California, were dispatched and heavily relied upon to provide load reduction relief during a time when rotating outages were imminent. Post-mortem analyses have led us to believe that the same grid problems will persist over the next few years. To meet the need for additional DR resources, PG&E has conducted several studies designed to enhance PG&E's current DR offerings and address the needs of parties that wish to participate in PG&E programs.

PG&E's Demand Response Emerging Technology (DRET) group initiated a Battery Study to investigate the ability to utilize residential photovoltaic solar systems paired with a Tesla Powerwall home battery systems to support state electric grid reliability by creating a virtual power plant (VPP). As of December 31, 2021, PG&E had over 31,000 homes with battery storage systems, with a combined installed nameplate capacity of 235 MW.[1] By default, residential batteries help offset household energy use. However, they may not export to the grid, potentially leaving a flexible resource untapped when the electric grid is strained or electric prices are high.

PG&E designed the pilot to assess whether it could enroll residential battery owners in a study to dispatch Tesla Powerwalls to send energy back into the grid during times of high demand.

The goals of the pilot included:

- Assess the ability to enroll existing battery owners into a pilot to use their battery for grid needs in exchange for payments.
- Determine the ex-post load impacts of the Tesla batteries when dispatched under varied event conditions.
- Assess whether and how much Tesla batteries are able to export to the grid during an event.
- Assess the ability of the existing dispatch algorithms to deliver a flexible, controllable grid resource.
- Compare evaluation methodologies to determine which data sources and evaluation methods produce reliable results.

For the pilot, PG&E worked with Tesla to reach out to approximately 7,000 customers (with approximately 12,600 batteries) to recruit them for the pilot. All recruitment took place in the Fall of 2021 via push-notification, and PG&E and Tesla dispatched events from October through November of 2021. PG&E offered customers an incentive of $1/kWh dispatched over their baseline, and customers were allowed to opt out of events. A total of almost 1,300 customers (18.6%) enrolled in the program and participated in seven events for the pilot. The estimated Incremental load reduction prime (ILR') MWh for battery charge and discharge was 14.55 MWh and the total aggregate nameplate MW was 11.74 MW.

[1] https://www.californiadgstats.ca.gov/download/interconnection_rule21_projects/. Downloaded March 10, 2022. Last updated January 31,2022. Note that this value includes all storage projects, not just storage projects tied to PV.

Assessment Objectives

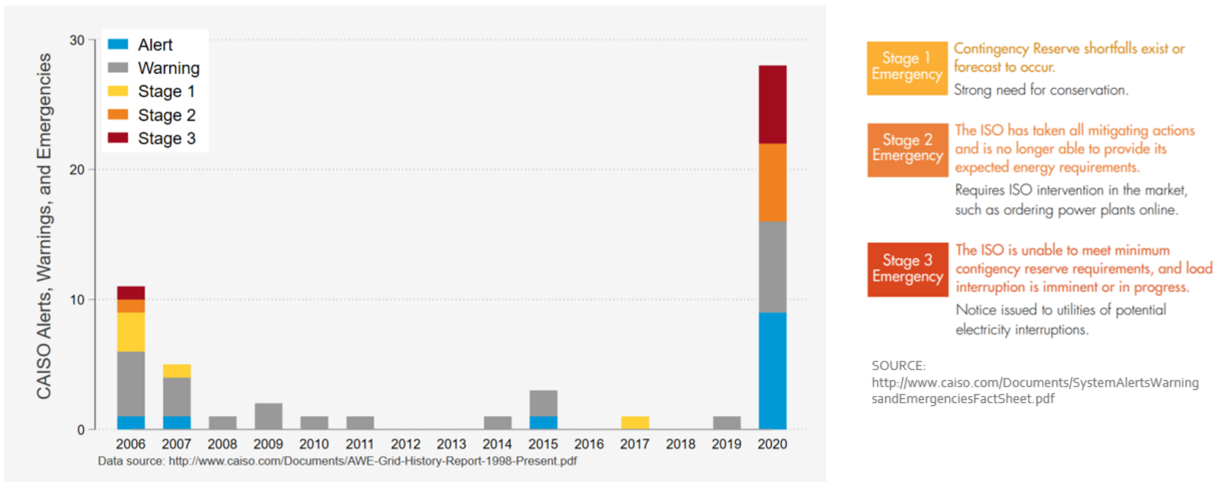
The focus of the pilot is the performance of the battery storage technology. The main goal was to estimate the effect of the technology on peak demand reduction and assess the best way to measure the peak reduction based on the available data. During the pilot, we seek to answer several key research questions:

- Do customers enroll in programs that allow the utility to use their battery for grid needs in exchange for payments?
- What are the ex post load impacts using end use battery data and premise data?
- Do the existing dispatch algorithms deliver a flexible, controllable grid resource?
- How do impacts using the end-use battery data compare with impacts at the household level?
- Do the event calls lead to changes in consumption at the household level?
  - Is there an increase in a household's net discharge to the grid during an event?
  - Do residential batteries export to the grid during emergency events? Or are they used solely to offset the households energy use?
- What was the performance when consecutive events were called?
- What is the full export capability?
- How does the EM&V analysis compare with the settlement results?

Background

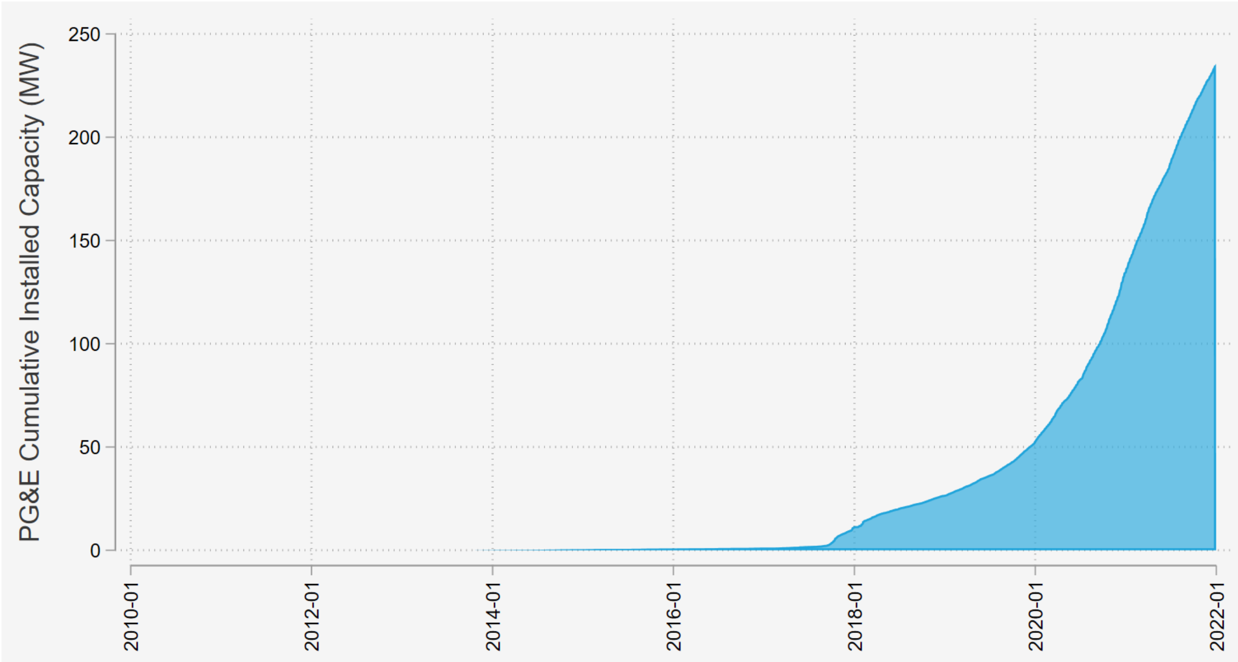
As noted above, during the 2020 system-wide grid emergencies caused by the August and September heat waves, DR was dispatched and heavily relied upon to provide load reduction relief during a time when rotating outages were imminent. Figure 1 shows the huge increase in alerts, warnings, and emergencies issued by CAISO in 2020. These grid emergencies are expected to continue going forward. While maintaining the current capacity of DR programs is crucial for situations like these, developing new programs will be just as important going forward. As system loads grow over time, through population growth and climate change, more resources will be needed to manage system peaks.

FIGURE 1. NUMBER OF CAISO ALERTS, WARNINGS, AND EMERGENCIES BY YEAR



PG&E received direct feedback from several DR aggregators and Distributed Energy Resource (DER) technology vendors that there is strong interest in participating in DR programs using residential battery storage, but they face barriers. Given their unique load patterns and energy usage, existing DR programs are not optimal for many residential and non-residential customers with battery storage technologies. In addition, customers may already be using these battery technologies to manage their household usage and, thus, leave limited potential resources for grid needs. A key objective for PG&E was to enhance existing demand response programs and remove barriers to allow customers with battery storage and solar to participate in demand response. Residential battery storage was of particular interest because it is a flexible, growing resource, as shown in Figure 2.

FIGURE 2: RESIDENTIAL BATTERY STORAGE INSTALLED NAMEPLATE CAPACITY IN PG&E TERRITORY[2]



PG&E designed this study for residential customers who owned Tesla Powerwalls. The goal of the study was to assess the potential contribution of Tesla Powerwalls to managing demand during peak periods. Figure 3 shows the relationship between system loads and the normal customer Powerwall battery use (absent a program intervention). While the relationship is positive, they dispatch less than 1.5 kW for daily TOU management, well short of the 5 kW of capacity each Powerwall can dispatch. In other words, customer batteries are not being used to their full capability when resources are needed most.

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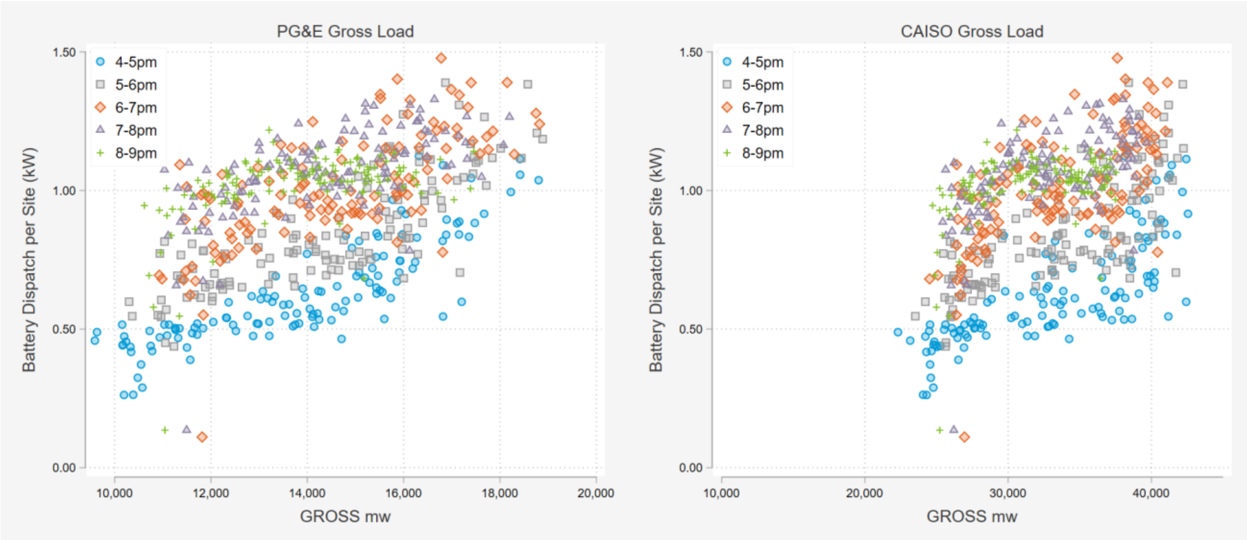
[2] https://www.californiadgstats.ca.gov/download/interconnection_rule21_projects/. Downloaded March 10, 2022. Last updated January 31,2022. Note that this value includes all storage projects, not just storage projects tied to PV.

FIGURE 3. POWERWALL DISPATCH PER SITE VERSUS SYSTEM LOAD



EMERGING TECHNOLOGY/PRODUCT

The Tesla Powerwall technology is a residential battery with a 13.5 kWh and 5 kW capacity. Customers that participated in the pilot owned 1.8 batteries on average (1,300 customers with 2,348 batteries). When the battery is being used by the homeowner, there are several default modes that the user can select for the Tesla Powerwall using the Tesla app, including:

- Back-up only
- Self-powered
- Time of use balanced
- Time of use cost saving

Figure 4 shows an example of how the user can select their mode. If the user selects one of the time of use modes they need to additionally select the percent of the battery they wish to reserve for power outages and customize the price schedule to match their time of use rate.

FIGURE 4: TESLA POWERWALL MODES

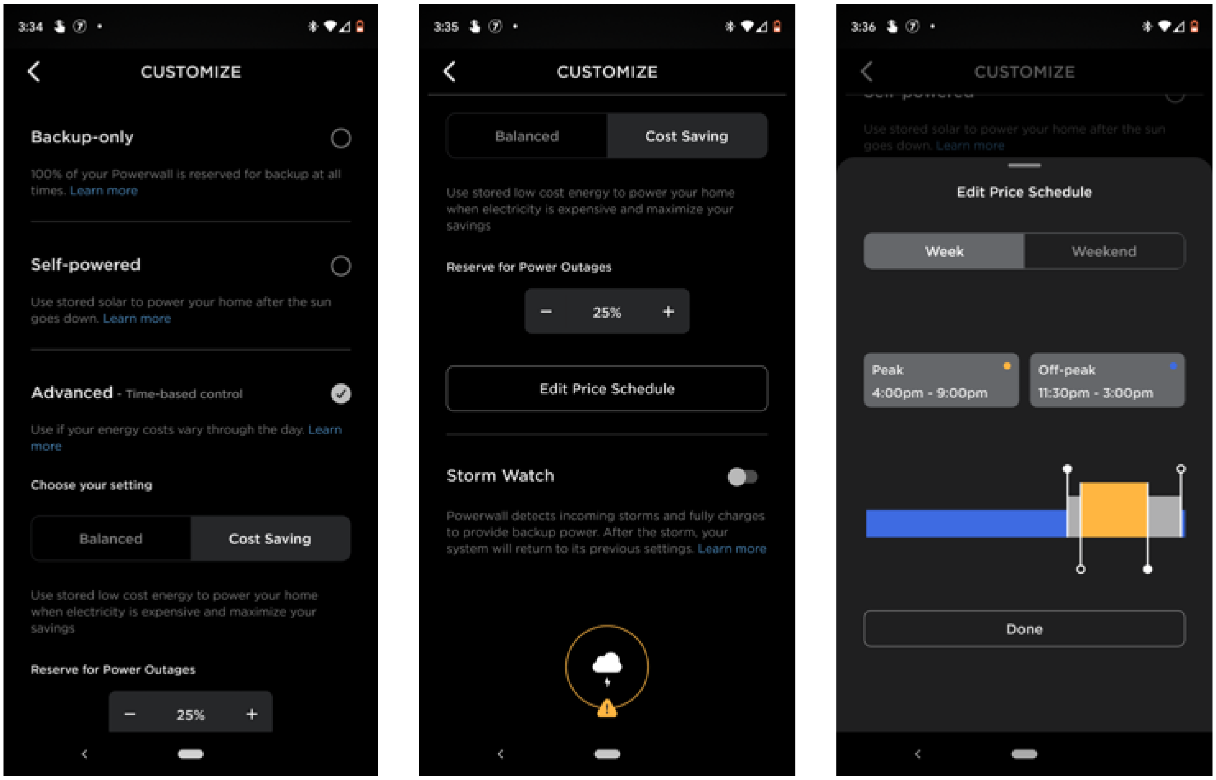
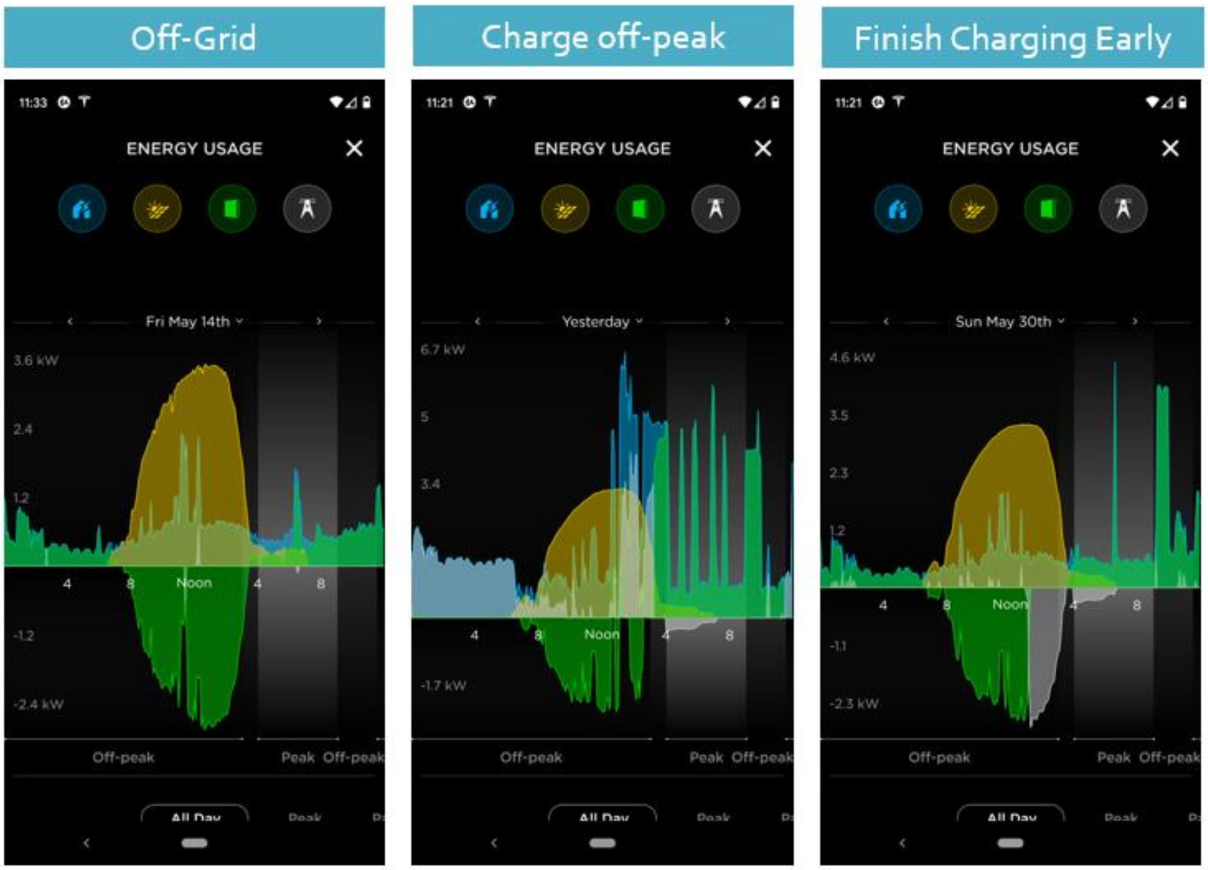


Figure 5 depicts some of the different ways that the Tesla Powerwall can be used absent an event. The battery charge/discharge patterns are depicted in green, solar generation is in yellow, household consumption is in blue, and net consumption is depicted in gray. Typically, we see the battery used to offset household consumption. The battery will typically charge using solar and offset household consumption in the late afternoon and evening, as seen in the first two panels. In some instances, the battery will finish charging relatively early in the afternoon and excess solar is discharged to the grid, as seen in the third panel.

FIGURE 5: SAMPLE TESLA POWERWALL BEHAVIOR ABSENT EVENT



The use of battery storage to offset residential energy demand is not new. However, as seen above, residential batteries are not widely used to support grid needs and export power to the grid when demand or prices are high. For the pilot, Tesla dispatched the battery during a 3-hour event window. To dispatch the battery, Tesla discharged the battery at its maximum authorized capacity[3] for as long as the battery was able to discharge at that capacity. The batteries were asked to discharge for a maximum three hours for each event.

METHODOLOGY

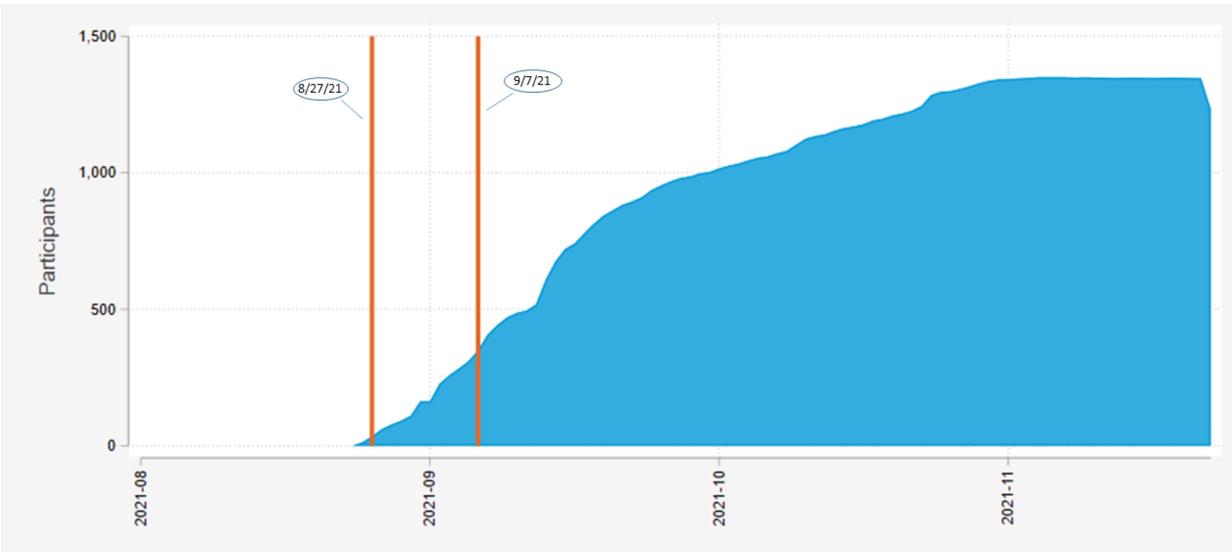
RECRUITMENT

PG&E and Tesla reached out to a total 7,306 Tesla customers with Powerwall batteries in PG&E territory to recruit pilot participants. To be eligible for the pilot customers additionally needed solar and an interconnection agreement to ensure that all battery charging was charged using solar energy. Customers were offered

[3] Each customer was able to set a reserve level for their battery. Tesla did not discharge the battery below the customer's reserve level.

$1/kWh of battery discharge over their baseline during events during the pilot. Tesla recruited customers using a push notification from the Tesla app. The Tesla app added the functionality to join via the app on August 27th and there was a push-notification sent to all eligible customers through their apps on September 7th. These two key dates are represented by orange lines in Figure 6. To streamline the enrollment process, customers could enroll in the Tesla app and were not required to provide any additional information when they enrolled. As a result of recruitment efforts, 1,367 premises enrolled in the pilot for an enrollment rate of 18.7%. Figure 6 shows enrollment over the course of the pilot. Most of the enrolled customers joined the program in September and October after the push notification was sent out, although it should be noted that customers continued to enroll in spite of no additional marketing from Tesla.

FIGURE 6. ENROLLMENT OVER TIME



DATA SOURCES

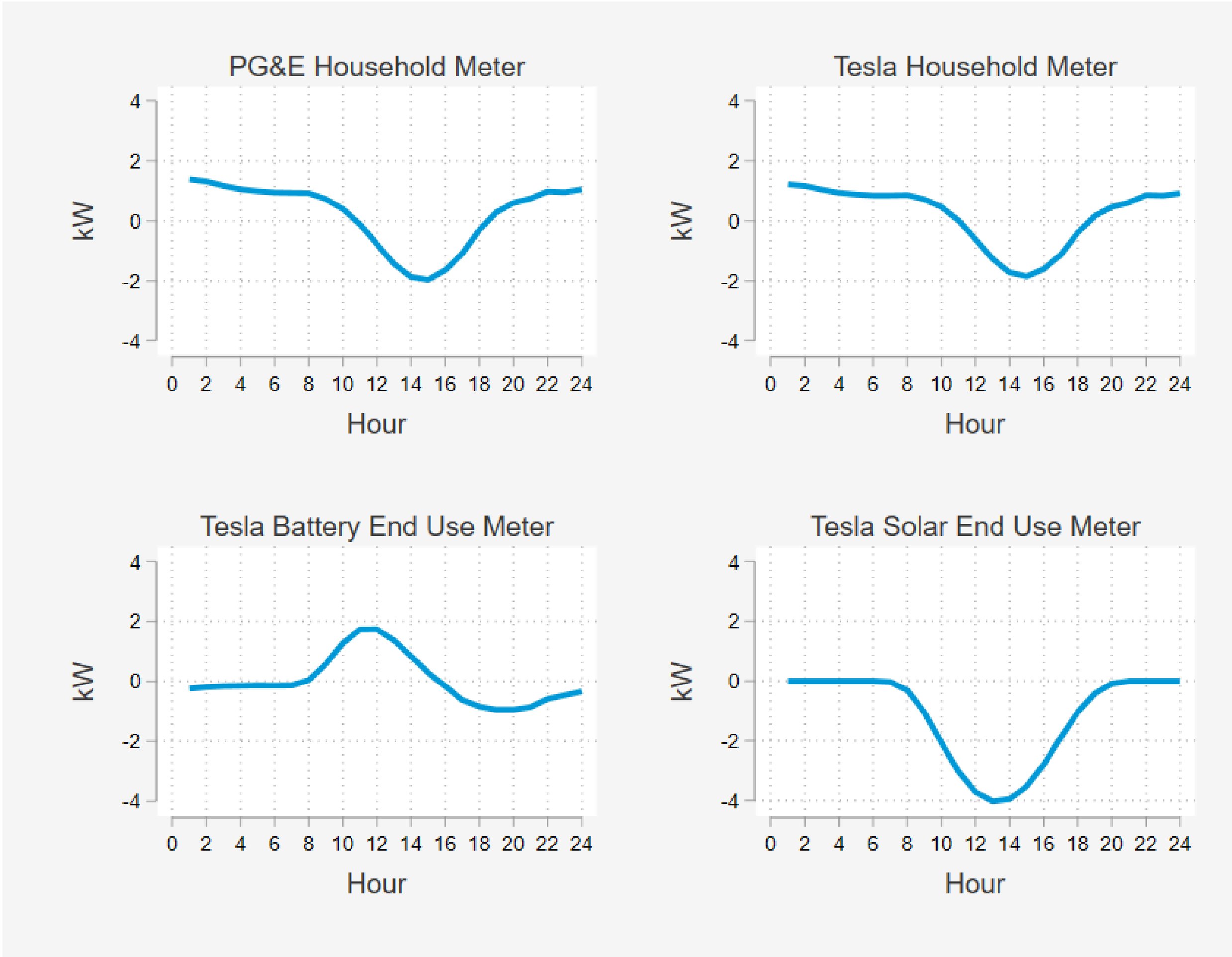
One of the key objectives of the pilot was to determine whether load impacts were the same with end-use and household-level data, or if one of the data sources was superior for estimating load impacts going forward. Tesla and PG&E provided the evaluation team with both end use metered (sub-meter) data and household level data to determine this. As a part of the analysis, the evaluation team assessed the quality of the use data and household level data provided by Tesla. PG&E also provided demographic information for customers and detailed information on event dispatch. The data sources for the evaluation included:

- **PG&E Participant characteristics**, which provided additional demographic information about program participants, including their rate, climate zone, EV status, and installation date of their Tesla Powerwall.
- **Tesla-metered historic participant battery charge/discharge data** in 15 minute increments for up to 1 year prior to the study implementation period and during the study period. The average load shape can be seen in

the bottom left figure of Figure 7, where positive load indicates the battery is charging and negative load indicates the battery is discharging.

- **Tesla-metered historic participant solar discharge data** in 15 minute increments for up to 1 year prior to the study implementation period and during the study period. The average load shape can be seen in the bottom right figure of Figure 7, where negative load indicates solar generation.
- **Tesla-metered historic participant household level data** in 15 minute increments for up to 1 year prior to the study implementation period and during the study period. The average load shape can be seen in the top right figure of Figure 7, where positive load indicates net consumption from the grid and negative load indicates net discharge to the grid.
- **PG&E metered participant household level data** in 15 minute increments for the same time period as the battery interval data. The average load shape can be seen in the top left figure of Figure 7, , where positive load indicates net consumption from the grid and negative load indicates net discharge to the grid.
- **Weather data** from the California Weather Advisory Council, like temperature and solar radiation, for the relevant climate zones and zip codes of program participants.
- **Individual Event characteristics and dispatch information from PG&E.**

FIGURE 7. AVERAGE CUSTOMER LOAD SHAPES



EVENT CONDITIONS

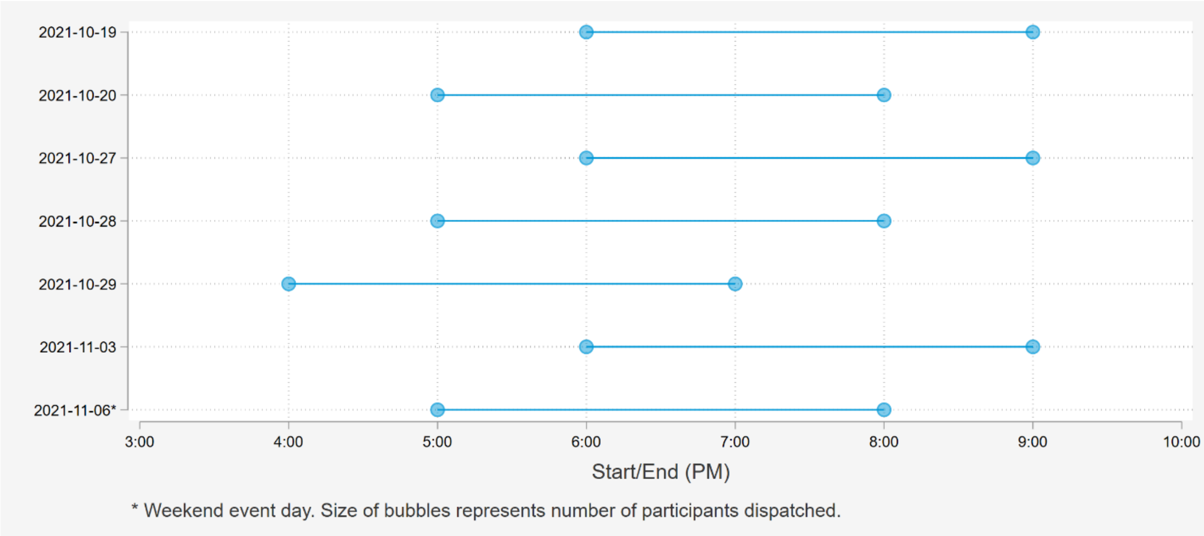
The VPP pilot, which became operational on August 29, 2021, was originally designed to dispatch the batteries through two channels:

1. Primary - CAISO's Alert Warning and Emergency (AWE) system.
2. Secondary – Optional Economic virtual power plant (VPP) dispatch.

However, no AWE events were called in the month of September. Therefore, the pilot dispatched events using the secondary channel in October and November.

PG&E called seven events called starting October 19th and ending November 6th. PG&E intentionally varied event start times, called weekday and weekend events, and called three consecutive events to understand how different event conditions affected battery performance. Figure 8 shows the start and end time of each event. Participation in each event stayed close to 1,200 throughout the study period, as shown by the size of the bubbles in Figure 8. Even though enrollment rose slightly between the first and last events, there was an increase in opt-outs over that time as well that counteracted the increased enrollment.

FIGURE 8. EVENT START AND END TIMES



The program began calling events in Fall, meaning that temperatures were relatively moderate. Table 2 shows average event temperatures, daily maximum temperatures, and whether the event was called on a weekday or weekend. Average event hour temperatures were 63 degrees Fahrenheit. The average daily max temperature for an event day was 70 degrees Fahrenheit.

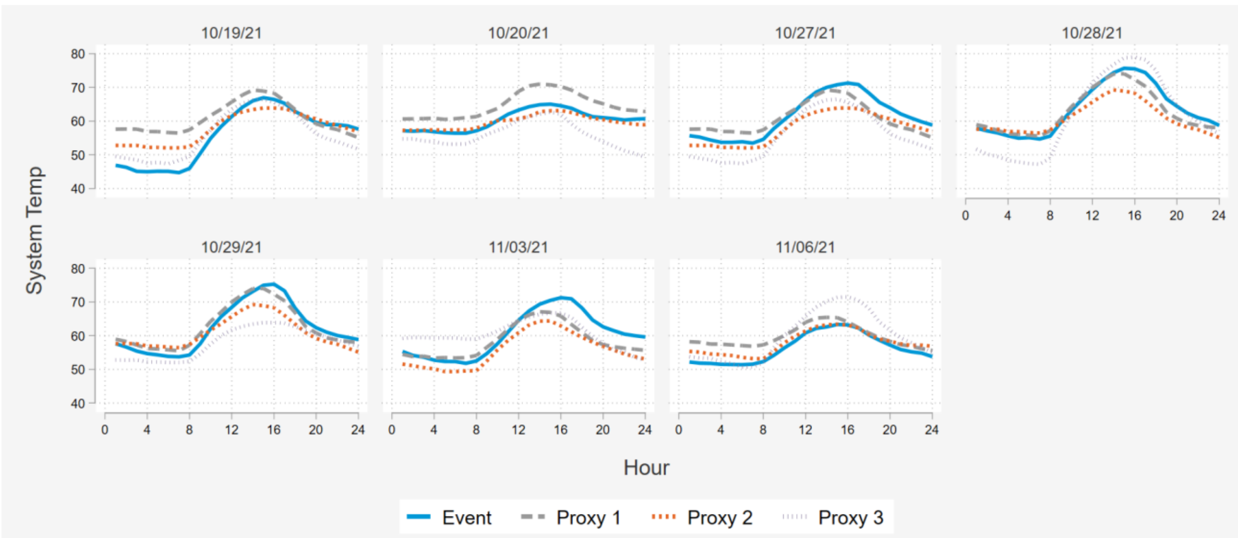
TABLE 2. SUMMARY OF EVENTS

Event No.	Date	Average Event Temperature (F)	Daily Max Temp(F)	Event Start	Event Duration (hours)	Weekday or Weekend
1	10/19/2021	60.0	67.0	6:00 PM	3	Weekday
2	10/20/2021	61.6	65.0	5:00 PM	3	Weekday
3	10/27/2021	63.9	71.3	6:00 PM	3	Weekday
4	10/28/2021	67.4	75.7	5:00 PM	3	Weekday
5	10/29/2021	68.7	75.3	4:00 PM	3	Weekday
6	11/3/2021	63.0	71.3	6:00 PM	3	Weekday
7	11/6/2021	58.7	63.4	5:00 PM	3	Weekend

LOAD IMPACT ESTIMATION

To estimate load impacts we ran a tournament between multiple customer-level models to estimate the accuracy of the counterfactual produced by each model. The most accurate model was applied for evaluation. We used the same methodology to assess impacts at both the household level and at the end use (battery storage system) level, but each data source had their own tournament to select the final model that was used for the analysis. Load impact estimation started with identifying proxy days for each event day. Since no set control groups were a part of this program and battery ownership makes it hard to create a matched control group, estimation needed to rely on enrolled customer pre-program baselines for determining the counterfactual. Figure 9 shows each event day and its three selected matches. The load shapes of all the event days are similar except for October 20th. On that day, there was less solar radiation leading to less solar energy being put back into the grid, leading to higher load in the middle of the day compared to other event days.

FIGURE 9. EVENT AND PROXY DAY SYSTEM LOAD



As noted above we conducted a tournament to identify the most accurate model to develop a counterfactual. We specified 16 models ahead of time and identified days comparable to the event days when no events were called (placebo or proxy days). We run the models excluding the placebo events (and actual events) and use them to predict the counterfactual for the placebo event days. Since no event is called, we know impacts were zero and, thus, can assess the actual and counterfactual values. Any difference between is the actual and estimated counterfactual is error. The process allows us to assess the bias and accuracy for the different models and pick the one that performs best.

The final model that we selected resembles the model depicted in Equation 1. Table 3 describes each component of the regression equation.

Equation 1. Ex Post Regression

$$kW_{ih} = \beta_{0h} + \beta_{1h} * Month * DOW + \beta_{2h} * AverageDailyTemp + \beta_{3h} * Solar\ Build_h + \beta_{4h} * Event\ Number + \varepsilon_{ih}$$

Table 3. Regression Description

Model Term	Description
kW_{ih}	Net electrical demand in kW for customer i, in hour h
β_{0h}	Mean demand for all customers on proxy days in hour h
β_{1h}	Regression coefficient for the month and Day of the Week interaction variable for hour h. Captures month and Day of the week-specific departures from the mean
Month	Numeric indicator of month of the year
DOW	Numeric day of the week indicator
β_{2h}	Regression coefficient for the average daily temperature of dates included in our dataset. Captures the effect of average daily temperature on loads
$AverageDailyTem$	Average temperature for each date in our dataset
β_{3h}	Regression coefficient for Solar Build in hour h.
$Solar\ Build$	Buildup of solar radiation throughout the day
β_{4h}	Regression coefficient of interest
$EventNumber$	Indicator variable of each event date that allows us to see event specific departures from the mean
ε_{ih}	Error term

The model in Equation 1 is run at the individual customer level and allows us to control for the time of year and weather to get the best prediction of impacts possible for each event. The dependent variable kW_{ih}, is the net electrical demand in kW for a given hour and premise. The three independent variables we use to control for weather and time of year are *Month*DOW*, *AverageDailyTemp*, and *Solar Build*. *Month*DOW* allows control for Month and Day of the week effects. *AverageDailyTemp* controls for the effect that temperature can have on loads. *Solar Build* controls for how the buildup of solar radiation through the day can have an impact on customer loads, especially for customers in this program as they all have Solar panels and batteries. *EventNumber* is the independent variable of interest. Its coefficient β_{4h} captures the effect of each individual event on the customers load for the hour h. In order to create the reference loads for each hour of the event, this impact is added back to the observed loads on the event days.

The analysis was performed on both PG&E whole home meter data and Tesla's battery end-use data. We expect the load impacts to be similar across both data sources, as the only change in the customer's energy usage should be coming from the battery itself during the events.

Impacts for each event were also calculated separately for settlement purposes. Olivine was contracted for settlement and employed a 10/10 baseline matching method. This means, to create individual customer baselines, they took averages of the previous ten non-event weekdays and compared those to each event day.

RESULTS

PARTICIPATION

Figure 10 show the location density of participants in the VPP program. Most of the participants were concentrated in the Bay area, but there were some further from the coast as well. The Bay Area tends to have moderate weather relative to customers that are further inland. Therefore, the results of this study are far more applicable to customers that live in the Bay Area but could vary of customers were recruited further inland.

FIGURE 10. VPP PARTICIPANT LOCATION DENSITY

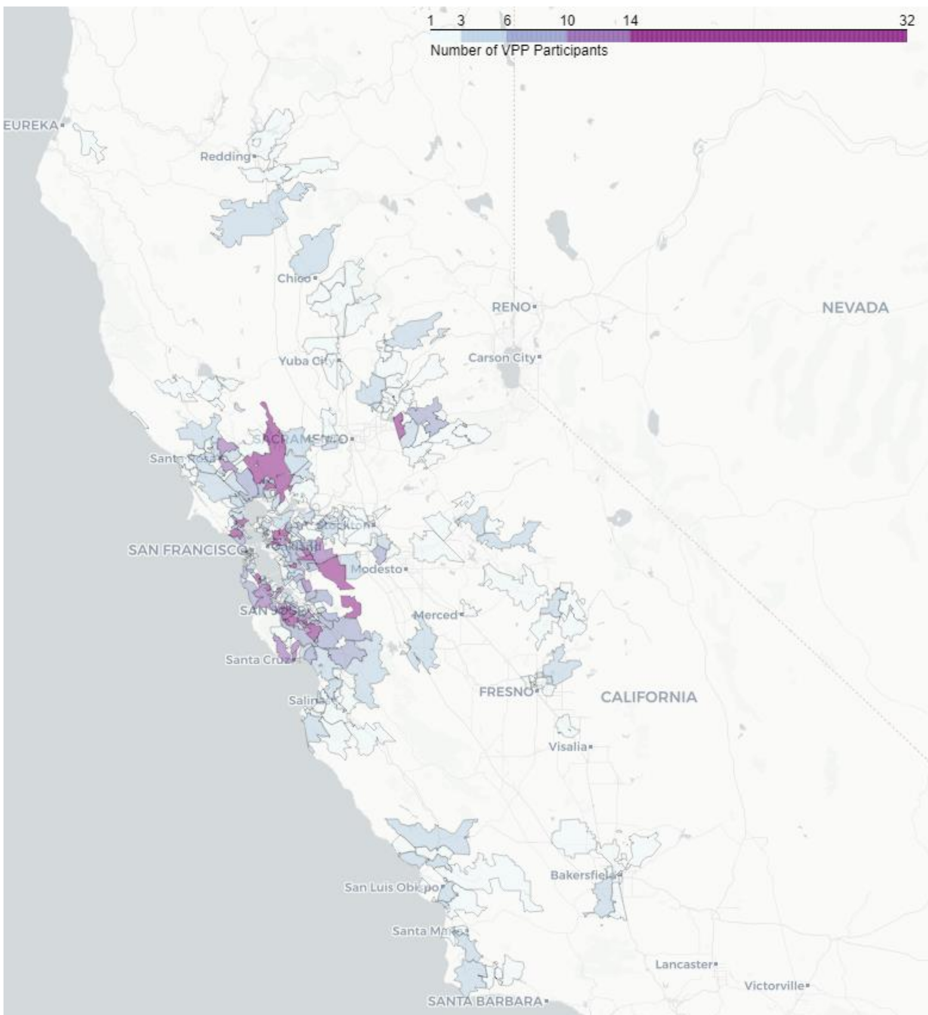
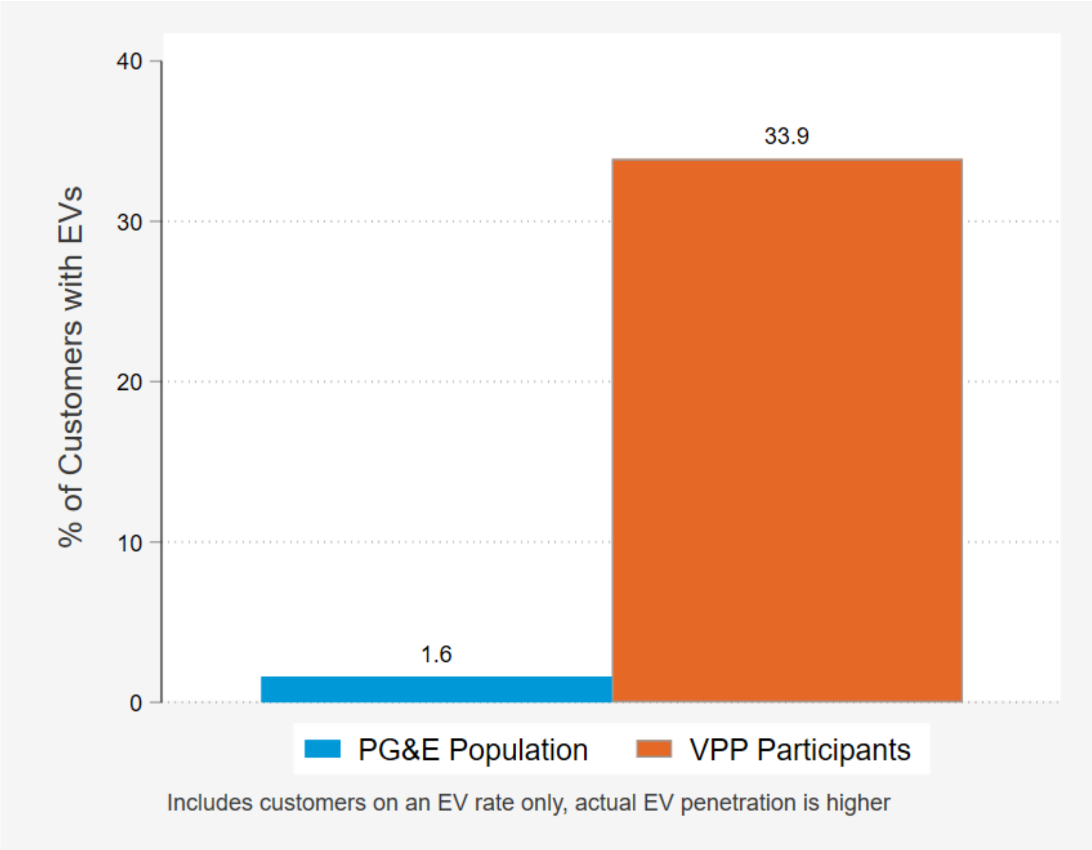


Figure 11 compares the proportion of VPP participants who own electric vehicles (EVs) to the general PG&E population[4]. Participants in the VPP program are much more likely to be on rates designed for electric vehicles. This is significant because customers on rates for electric vehicles have lower super-off-peak prices and higher peak period prices. They likely have different load patterns from non-EV owners. Electric vehicle ownership also adds noise and volatility to the whole home data from when customers charge their vehicles. Since all the charging happens behind the meter, there is no way to distinguish it from all other loads, making it more challenging to measure the load impacts from events.

FIGURE 11. SHARE OF PG&E POPULATION AND VPP PARTICIPANTS ON ELECTRIC VEHICLE RATES

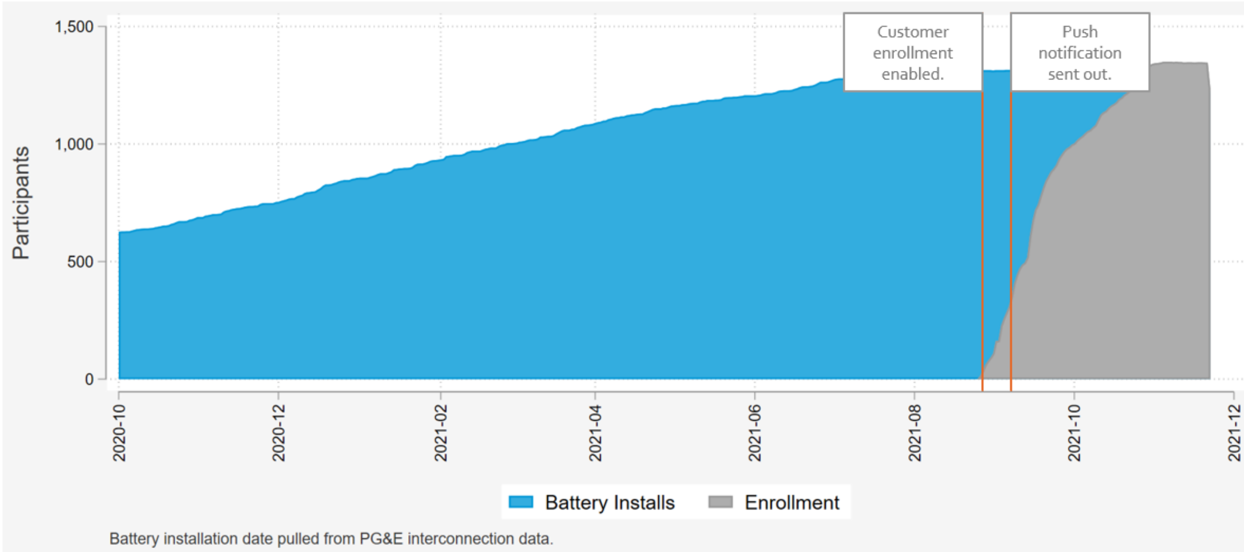


DATA ANALYSIS

In order to create a counterfactual, we need information on how customers behave outside of events. For the VPP program, we needed to ensure we had enough non-event data after the customer installed their battery. Once a customer installs a battery, the whole home energy usage patterns recorded at the utility meter fundamentally changes. Figure 12 shows participant battery installs in blue and enrollment in gray over time. 80% of participants had at least 6 months of battery usage data before enrolling in the program.

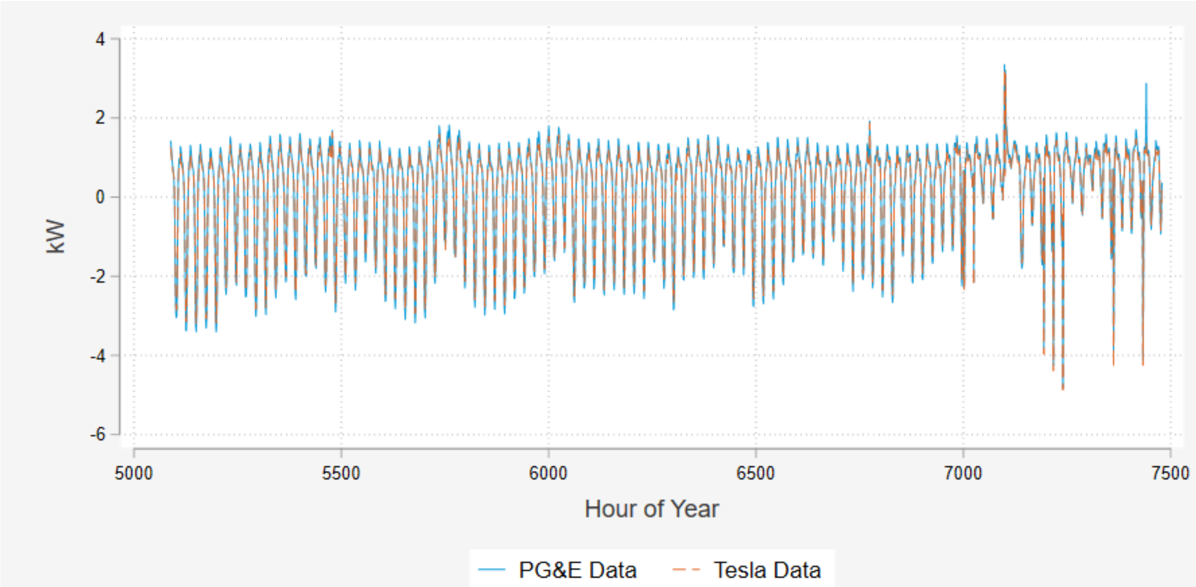
[4] Data on the PG&E population is based on a sample of 50,000 residential customers.

FIGURE 12. BATTERY INSTALLATION AND PROGRAM ENROLLMENT



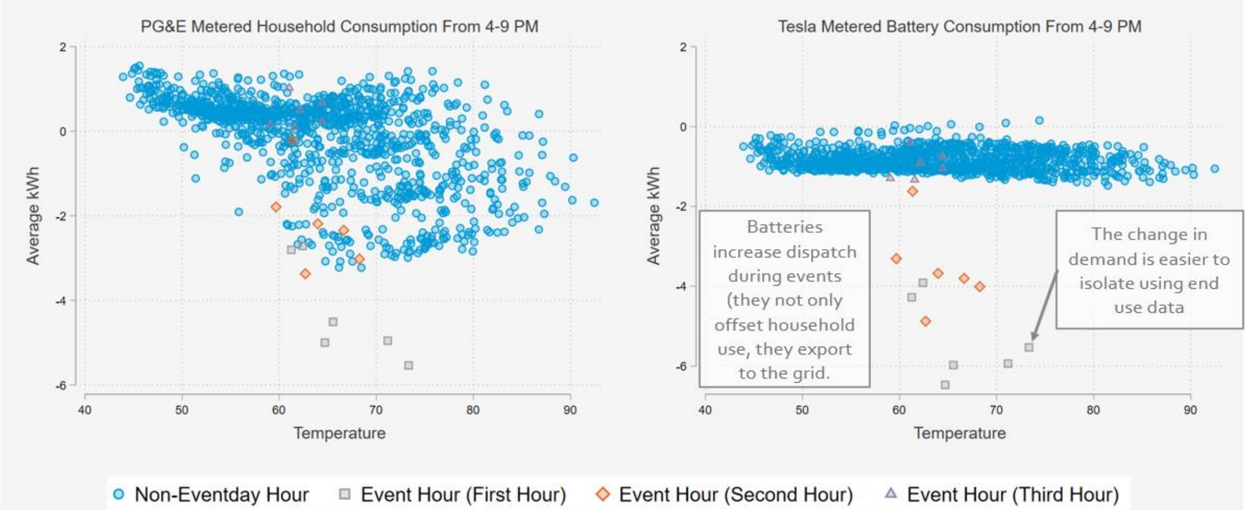
We had two sources of household level data: data provided by PG&E and data provided by Tesla. Figure 13 compares the average customer load shape using Tesla whole-home data and the PG&E meter data from August 2021 to November 2021. Overall they are very similar, with a correlation of 99.8%. For individual customers, though, there is noise in the data. In some cases, the signs for data seem to be switched. While we run our model at the individual customer level, we report average customer load impacts for all events and hours, which provide accurate estimates for the program's true effects. For this evaluation, we used PG&E household level data. However, the similarity between the two data sets indicates that Tesla household data can also be used as a reliable data source for estimating impacts going forward.

FIGURE 13. AVERAGE CUSTOMER HOUSEHOLD LOADSHAPE, PG&E VS. TESLA DATA



As noted above, for the evaluation we used PG&E household level data and Tesla battery end use data. Figure 14 compares the average PG&E whole home and Tesla battery end use kWh consumption for the average customer per hour (4-9 PM) in 2021 with event hours highlighted. For whole home load, negative values represent discharge to the grid and for Tesla battery end use consumption negative values represent the battery discharging. Most customers in the VPP program also have solar and tend to export to the grid during the middle of the day. The negative household load in the figure below is also partly driven by solar exports, as the magnitude of household exports is larger than the magnitude of the battery discharge. Both figures show that there is a clear effect from the events, which are in the middle temperature range, but it can be seen more clearly in the battery end-use data. We can also see that during events the batteries are not only offsetting the home's energy usage but discharging substantial amounts of energy to the grid.

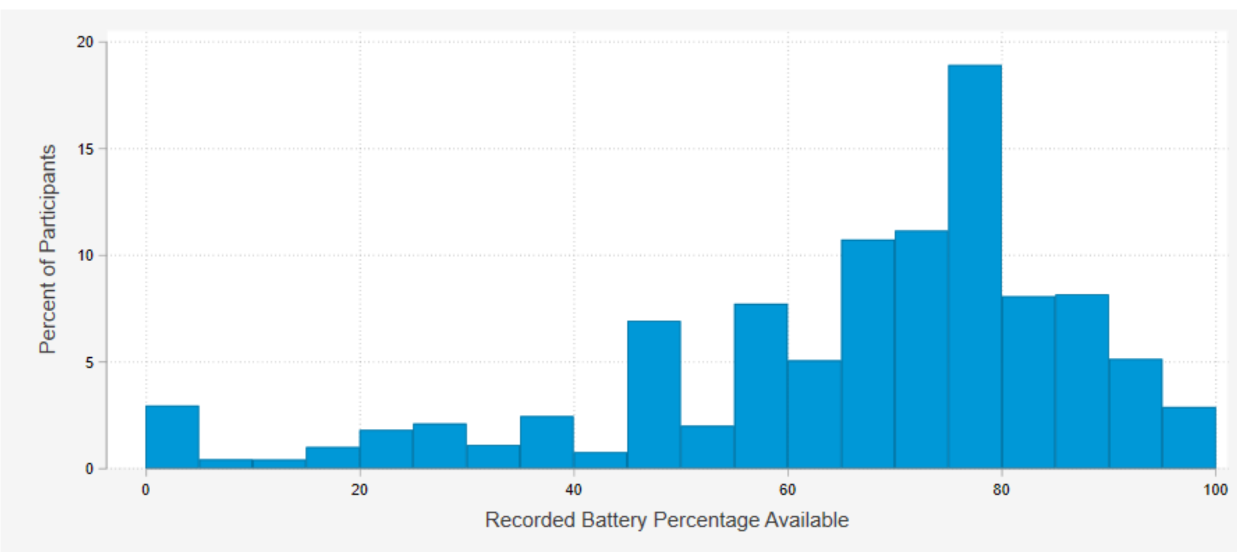
FIGURE 14. PG&E WHOLE HOME AND TESLA BATTERY END USE AVERAGE CONSUMPTION VS. TEMPERATURE (F)



Each point represents the average customer's consumption for a single hour during 2021. Hours are limited to 4-9 PM.

Customers are able to reserve a percentage of their battery for backup power. In addition to the metered participant battery charge/discharge data, Tesla recorded the percent reserve of customer batteries. On average, customers reserve about 35% of their battery's capacity, leaving 65% of a battery's capacity available for use in the home or for grid needs. Figure 15 shows a histogram of the battery percentage available for participants. While some customers reserve most of their battery for backup power, over 50% of customers allowed for more than 70% of their battery's capacity to be used for grid needs or to manage household energy use. We did not include the percent reserve in our model when calculating load impacts. We calculated load impacts using only the household level data and battery end use data.

FIGURE 15. BATTERY PERCENTAGE AVAILABLE



Event Day Reductions

Load Impacts

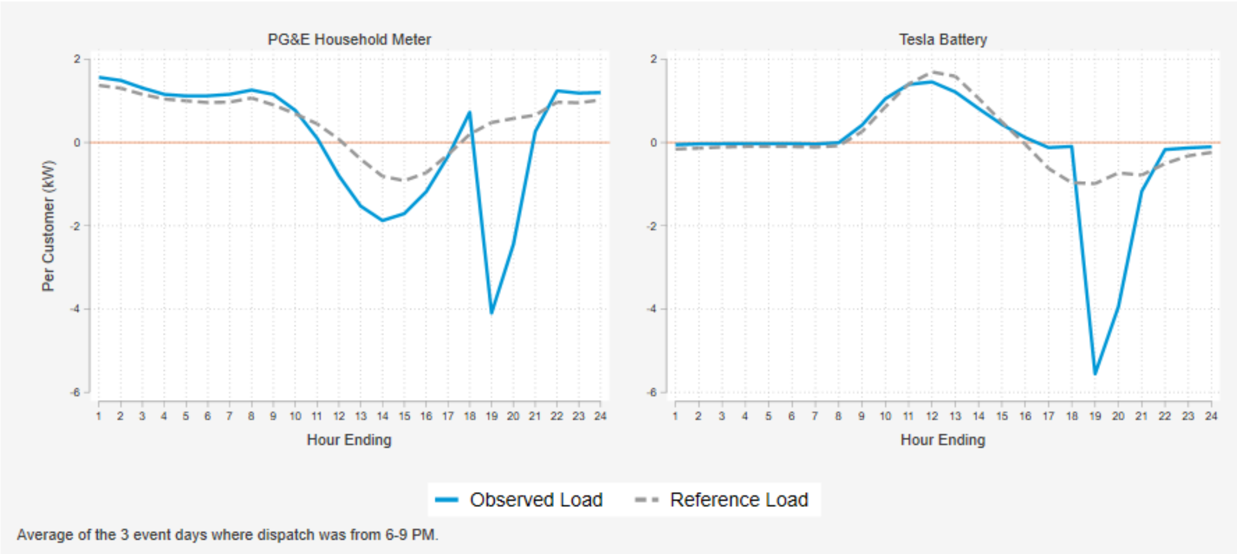
Figure 16 shows a summary of the events, including start time, average event temperature, and average impact using both PG&E whole home and battery end use data. All events for the VPP program lasted three hours from their start time. The two average events at the bottom of the figure represent the average impacts for events of their respective time periods. The events deliver incremental load impacts, but they decay over time. The first hour of the event, on average, delivered an impact of 4.6 kW, followed by 3.0 kW, and less than 1 kW in hours two and three, respectively. Impacts estimated with whole-home data are similar to those estimated using the battery end-use data. PG&E called three consecutive event days on 10/27, 10/28, and 10/29 without any decay in performance across the event days. The Saturday event on 11/6 showed load impacts similar to all the weekday events. On 10/19, Tesla had technical issues with dispatch that may contributed to lower average impacts. After the first two events we see the magnitude of program impacts increase.

Figure 16. Event Summary

Date	Event Start	Average Event Temperature (F)	AMI Hour 1	AMI Hour 2	AMI Hour 3	Battery Hour 1	Battery Hour 2	Battery Hour 3
10/19/2021	06:00PM	60.0	3.01	2.08	0.22	3.33	2.36	0.40
10/20/2021	05:00PM	61.6	3.04	0.84	-0.31	3.22	0.77	-0.40
10/27/2021	06:00PM	63.9	5.09	2.89	0.22	5.08	2.86	0.15
10/28/2021	05:00PM	67.4	5.21	2.95	0.05	5.18	2.91	-0.03
10/29/2021	04:00PM	68.7	5.07	3.27	0.32	5.00	3.29	0.13
11/3/2021	06:00PM	63.0	5.63	4.10	0.76	5.31	4.43	0.62
11/6/2021	05:00PM	58.7	5.62	3.90	0.64	5.15	3.66	0.95
Average Event Day (05:00-08:00PM)	**05:00PM**	**62.6**	**4.62**	**2.56**	**0.13**	**4.52**	**2.45**	**0.17**
Average Event Day (06:00-09:00PM)	**06:00PM**	**62.3**	**4.58**	**3.03**	**0.40**	**4.57**	**3.21**	**0.39**

Figure 17 shows the observed load shape and the estimated reference load for the Average event day (6-9 PM) using PG&E household data and Tesla battery data. For household data positive numbers indicate demand and negative numbers indicate net export. For Tesla battery data positive numbers indicate the battery charging and negative numbers indicate the battery discharging. The shapes during the day are different between the two, but the event load impact (the difference between the reference load and observed load) is almost identical. The average estimated hourly impact per customer is 2.67 kW using the PG&E data and 2.73 kW using the Tesla Battery data, a difference of 0.07 MW.

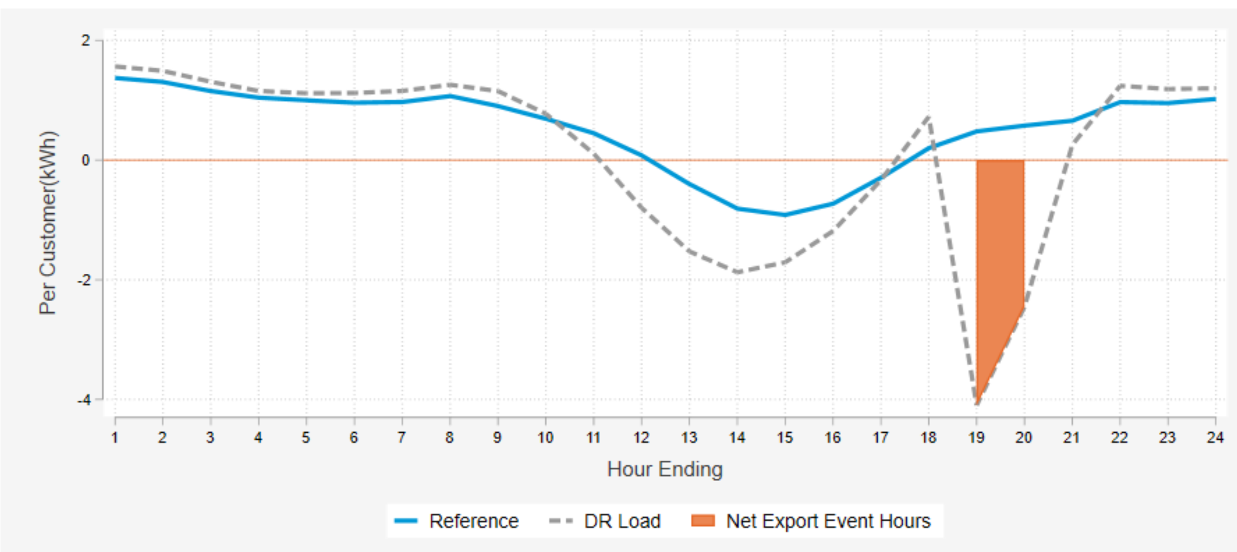
FIGURE 17. AVERAGE EVENT DAY 6-9 PM. PG&E METER DATA VS. TESLA BATTERY END-USE DATA



HOUSEHOLD LEVEL IMPACTS

An objective of the study was to test whether, during events, participant battery systems would export energy to the grid or if they would only offset the household's energy usage. Figure 18 shows the reference and observe load for the average event from 6-9PM. On average, batteries exported 3.27 kW to the grid in the first two hours of all the events. However, the events took place in the Fall where, due to moderate temperatures, household loads in the afternoons were relatively low. During future events in the Summer, when temperatures are higher and household loads are also higher due to air conditioning use, the discharge to the grid may not be as large.

FIGURE 18. AVERAGE EVENT 6-9 PM, PG&E METER DATA



IMPACTS BY DEMOGRAPHIC

Figure 19 shows aggregate impacts for each event by EV ownership status. While 33% of the customers in the VPP program are on rates designed for electric vehicles, they account for 45% of the aggregate impacts. The left section of Figure 20 shows the hourly impacts on the average event day from 6-9 PM by EV ownership. Impacts in all hours are higher for customers with EVs. One potential explanation for this is that EV customers are more likely to have multiple batteries than customers without EVs.

The right section of Figure 20 and Figure 21 show impacts by local capacity area (LCA), a geography used for resource adequacy planning. Figure 21 shows aggregate impacts. The Greater Bay Area accounts for most of the load impacts followed by North Coast and North Bay, where most of the participants are located. The right panel of Figure 20 shows average hourly impacts for each local capacity area and event hour. The first even hour load reductions are between four and six kW with a drop off in hours two and three. Humboldt is an outlier due to its small sample size, only representing a single customer. All other local capacity areas have similar impacts. Almost all the aggregate savings numbers are driven by the number of customers rather than by performance differences by geography.

FIGURE 19. AGGREGATE EVENT IMPACTS BY EV OWNERSHIP

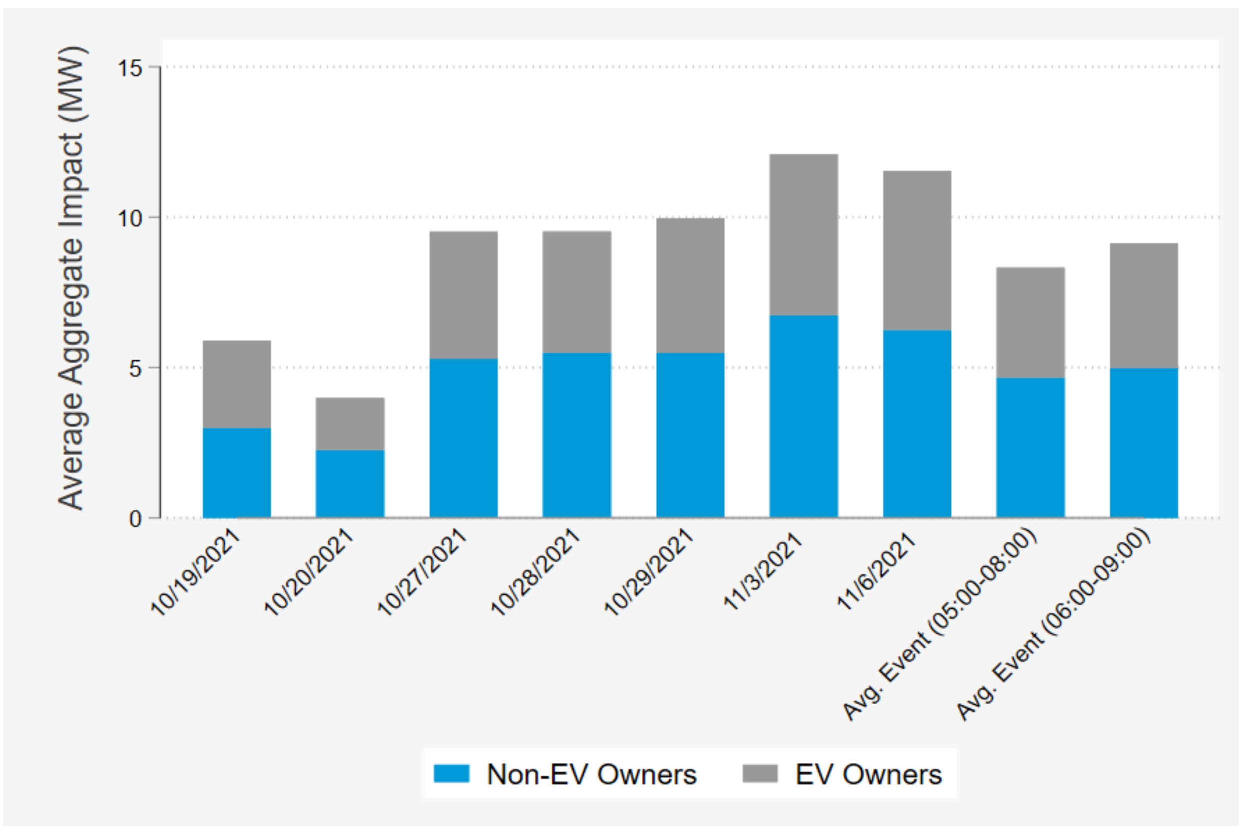


FIGURE 20. AVERAGE HOURLY IMPACTS (6-9 PM) BY EV OWNERSHIP AND LCA

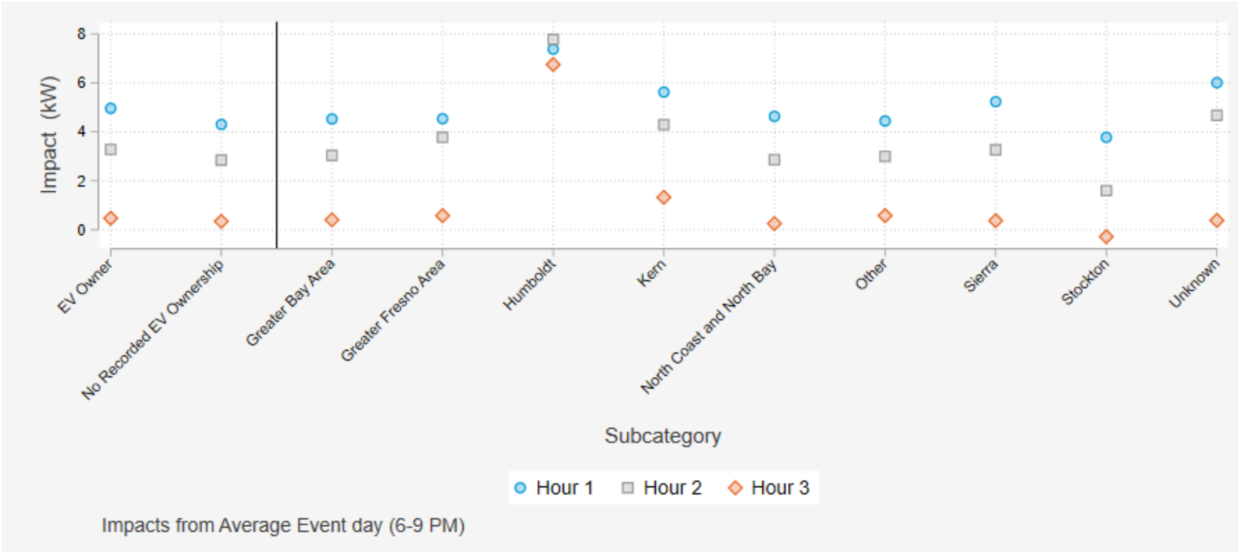
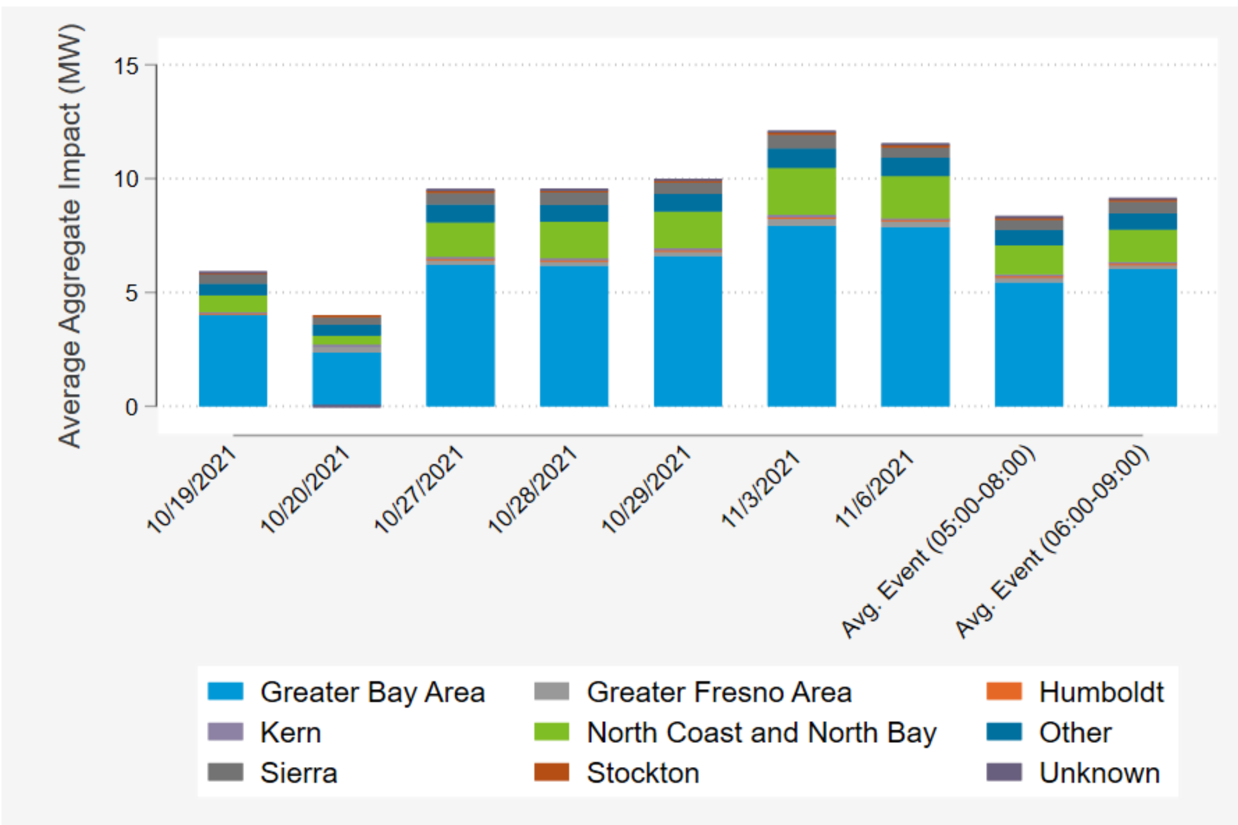


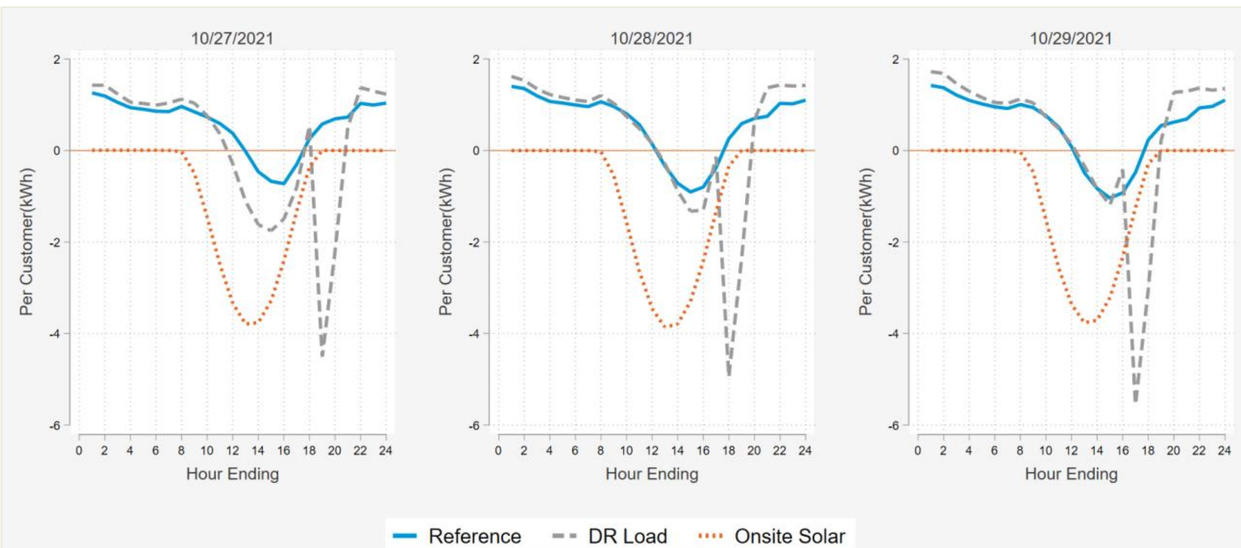
FIGURE 21. AGGREGATE EVENT IMPACTS BY LCA



Dispatch Consistency

A key question for the study was whether load impacts decayed across consecutive event days due to customer fatigue. Figure 22 shows the observed loads, reference loads, and onsite solar generation for the three consecutive events called on 10/27, 10/28, and 10/29. The batteries delivered consistent results on all three days. The first hour of all three events delivered more than 5 kW of impacts per customer, the second hour delivered around 3 kW, and the third hour had negligible impacts. All three of these event days had ample solar generation, indicating clear days, which allowed for the batteries to be quickly recharged. Cloudy conditions could decrease the effectiveness of the program on consecutive events in the future. This program also took place in the Fall, which, due to moderate temperatures, tends to have lower household loads. On all three days, customers exported energy to the grid prior to the events, indicating relatively low household consumption on these days. In the summer, when temperatures and loads are higher, the pattern of consistent impacts may not hold. Further research, including summer events, are needed to further test impact consistency on consecutive event days.

Figure 22. Program Impacts and Solar on Consecutive Event Days



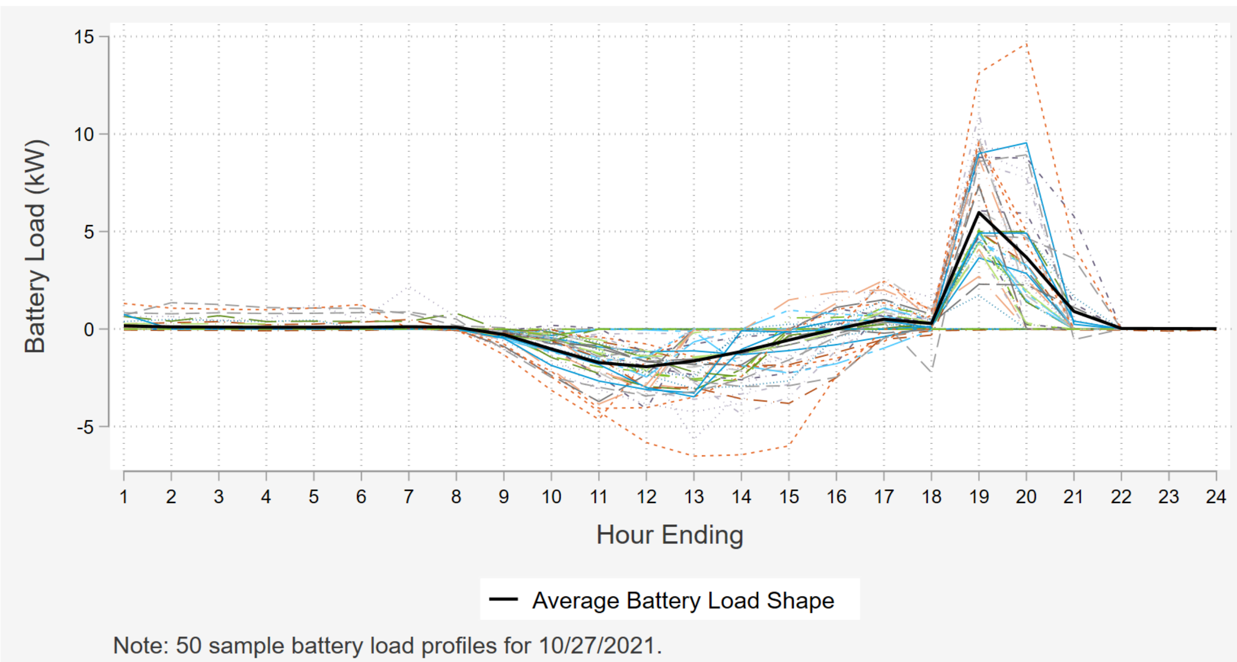
As a part of the evaluation we also examined the proportion of customers that responded to the event signal when they were dispatched. Table 4 depicts the percentage of customers whose battery had a change in load greater than zero in the first hour of each event. In effect, this shows the share of batteries that actually responded to the event call. For all events, the dispatch percentage was greater than 92%. The only outlier is the event on 10/20 where 92.3% of batteries were dispatched, which likely contributed to the lower average impacts we see on that day. Figure 23 shows the battery load shapes for a random sample of 50 customers on 10/27, with the average shape highlighted in black. While there is variation across customers, the event response can be seen clearly for most customers.

TABLE 4. BATTERY DISPATCH PERCENTAGE

Date	% Dispatched*
10/19/21	98.18%
10/20/21	92.25%
10/27/21	97.39%
10/28/21	98.35%
10/29/21	96.05%
11/03/21	98.16%
11/06/21	98.58%

* >0 change in Battery Load (kw) in hour 1 of event

FIGURE 23. SAMPLE BATTERY LOAD SHAPES ON 10/27/2021



DATA SOURCE AND BASELINE METHODS COMPARISON

Figure 24 compares the aggregate savings of each event when using PG&E meter data and Tesla Battery end use data. Impacts were very similar on all event days with less than a 1% difference between the impacts on average.

FIGURE 24. AGGREGATE EVENT IMPACTS CALCULATED USING PG&E METER DATA VS. TESLA BATTERY DATA

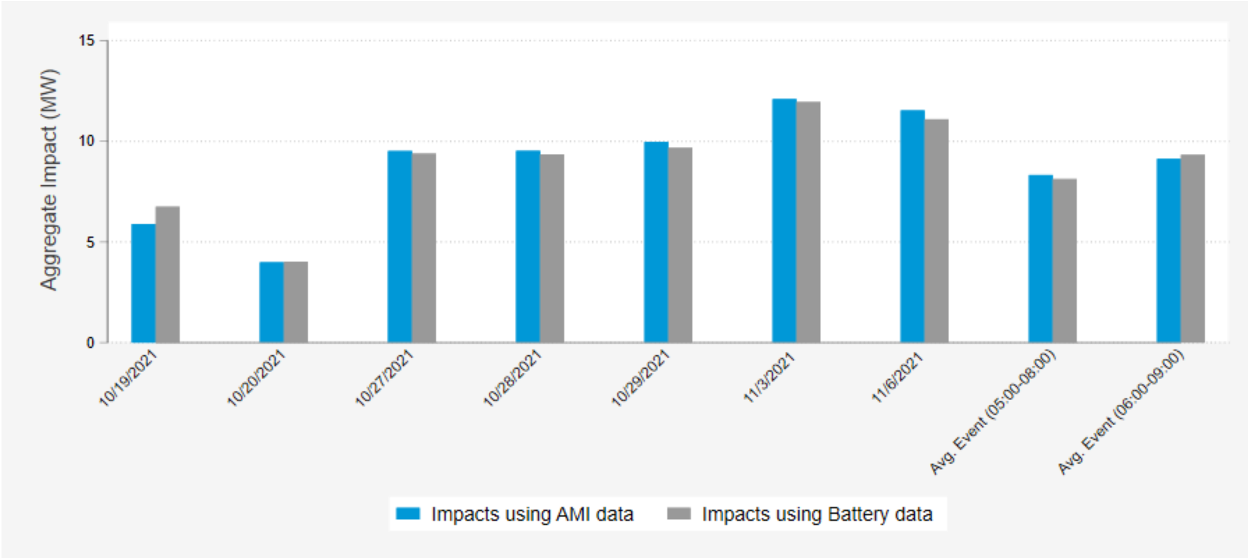
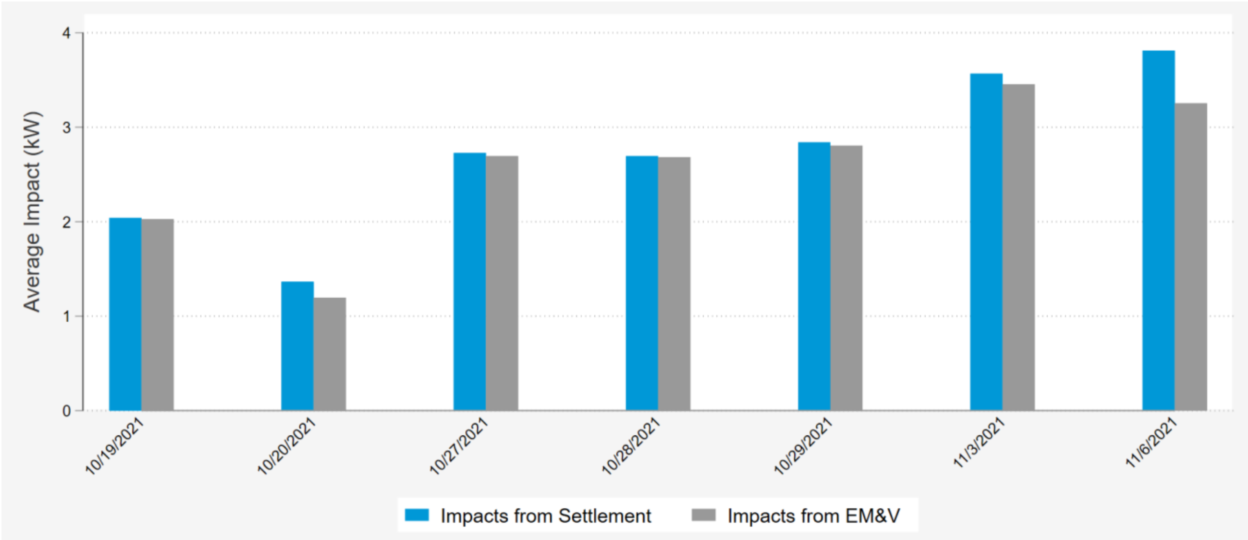


Figure 25 compares the evaluation and settlement load impacts. For settlement with customers (and Tesla), the baseline usage is calculated as the same hour average over the past 10 days using battery end use data. By contrast, the evaluation relied on regression analysis. The estimated load impacts were similar for the two approaches, but impacts calculated for settlement were on average five percent higher. Overall, Settlement calculations paid out a total of 66.0 MWh of dispatch across all events, while EM&V estimated a total of 62.2 MWh.

FIGURE 25. SETTLEMENT VERSUS EM&V IMPACTS COMPARISON



POTENTIAL CHANGES DURING SUMMER DISPATCH

As mentioned previously in this report, all 2021 events took place in the Fall under relatively mild conditions where household energy usage did not vary much day-to-day because of weather. An important question is whether batteries are used more during the summer to offset household energy use, leaving less resources available for grid exports. Figure 26 shows the average load shape of VPP participants by temperature bin. Customers still export to the grid in the middle of the day under higher temperatures, which means they are still able to charge their batteries. In the evening, after solar generation ends, customers have much higher loads, which would need to be offset before batteries are able to export to the grid during Summer events.

FIGURE 26. AVERAGE PARTICIPANT LOAD SHAPES BY TEMPERATURE BIN

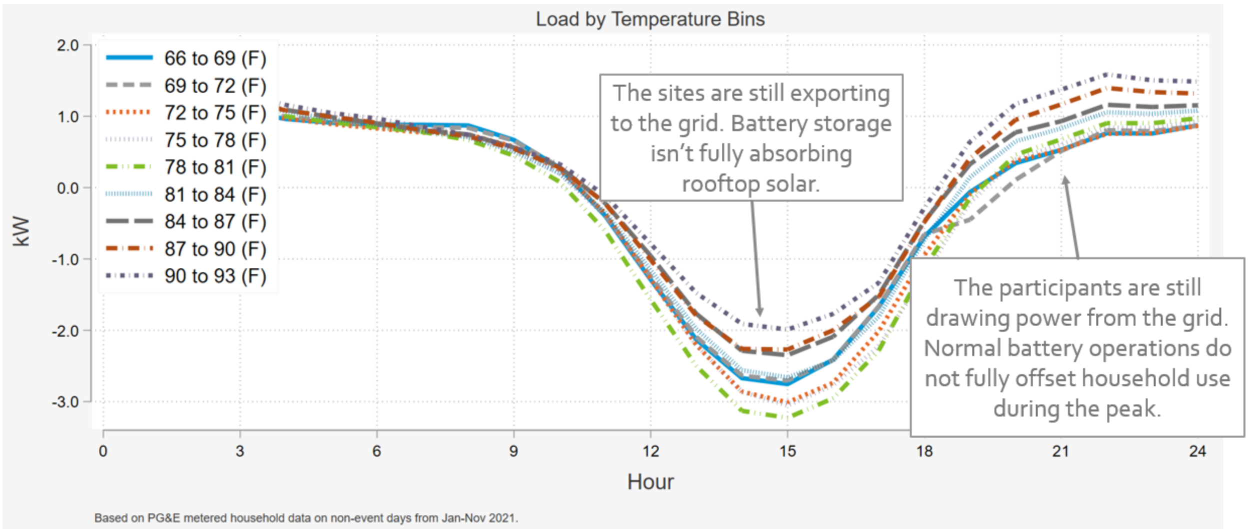
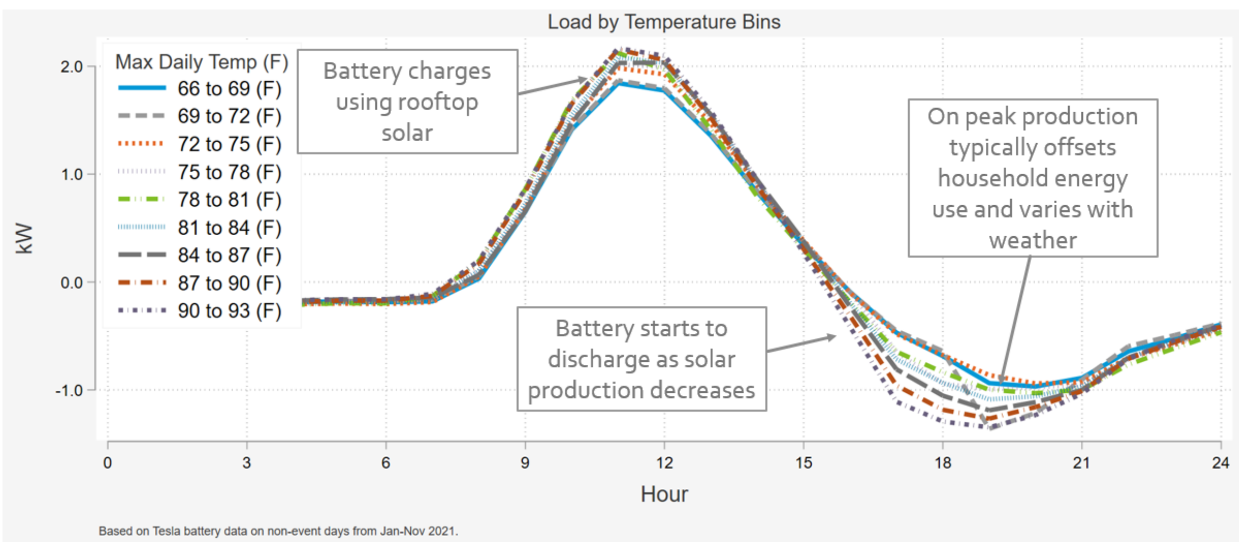


Figure 27 shows average Tesla battery load shapes by temperature bin. Batteries tend to import more energy during the middle of the day on hotter days, as there is more sun for solar production and also discharge more energy later in the day. Absent any event operations, batteries discharge roughly 1 kW from 4-9 pm.

FIGURE 27. BATTERY LOAD SHAPE BT TEMPERATURE BIN



CONCLUSIONS & RECOMMENDATIONS

There is strong evidence that Tesla Powerwalls are able to reduce peak demand when dispatched. Table 5 summarizes the key research questions for the study as well as our findings.

TABLE 5: SUMMARY OF KEY RESEARCH QUESTIONS AND FINDINGS

Research Question	Findings
Do customers enroll in programs that allow the utility to use their battery for grid needs in exchange for payments?	1,300 of the 7,000 (18.6%) customers recruited into the pilot enrolled. All recruitment took place in the Fall of 2021 via push-notification over a compressed timeline. PG&E offered customers an incentive of $1/kWh for energy dispatched over their typical baseline, and customers were allowed to opt out of events.
What are the ex-post load impacts using end-use battery data and premise data?	The incremental impacts are estimated to be ~4.5 kW in hour 1, ~3.0 kW in hour 2, and less than 1 kW in hour 3.
Do the existing dispatch algorithms to deliver a flexible, controllable grid resource?	The current battery dispatch algorithms deliver all of the resources, all at once, until the available energy storage is exhausted and reach its reserve capacity set by customers. Currently, the algorithms cannot deliver a consistent level of demand reduction over the event, deliver a requested level of output, or sustain the resources over a longer event duration. Tesla is in the process of modifying its algorithms, so their residential battery resources can be more flexible and controllable for grid needs in the future.
How do impacts using the end-use battery data (sub-meter) compare with impacts at the household level?	Load impacts estimated using household-level smart meter data were similar to those calculated using battery end-use data, with less than a 1% difference between the impacts on average.
Do the event calls lead to an increase in a household's net discharge to the grid during an event? And exporting of battery resources to the grid?	When dispatched for events, the batteries not only offset the household's energy use, but also exported energy back to the grid. Customers do not noticeably modify their energy use (of other end-uses) when the battery is used to support grid needs. Note: the events took place in the Fall where, due to moderate temperatures, household loads in the afternoons were relatively low. During future events in the Summer, when temperatures are higher and household loads are also higher due to air conditioning use, the discharge to the grid may not be as large.

What was the performance when consecutive events were called?	The batteries delivered consistent dispatch across consecutive event days. However, events were called during mild weather conditions typically with ample sunshine. The dispatch consistency may change if batteries are discharged under more extreme weather conditions.
What is the full export capability?	On average, batteries were able to discharge 4.5 kW during the first hour for a full net export of 3.3 kW. However, this is not necessarily representative of battery export capability during peak system demand as batteries for this pilot were dispatched under moderate weather conditions as indicated above.
How does the EM&V analysis compare with the settlement results?	For settlement with customers (and Tesla), the baseline usage is calculated as the same hour average over the past 10 days using battery end-use data. Any battery discharge above the baseline was considered the load impact. On aggregate, the impacts calculated using the settlement baselines are comparable to EM&V results, but were 5% higher on average.

In addition to the key findings, we draw the following conclusions from this study:

- Overall, dispatch of individual sites was consistent, ranging from 92.2% to 98.6% of sites showing evidence of dispatch for each individual event.
- Program participants have up to 65% of the battery storage capacity (kWh) available for dispatch, on average, with the remainder reserved for backup power.
- Participants were highly concentrated in the Bay Area and more likely to be on EV TOU rates.
- Historical data shows that household data and battery end-use data vary with weather during 4-9 PM peak hours. Fewer battery resources may be available during the hottest days. Therefore, we recommend further testing during the summer to assess if the incremental battery response varies with more extreme weather conditions.

While this technology has a lot of potential, several aspects of the technology warrant further study. We recommend the following next steps for continuing research on the potential of this technology to reduce peak demand:

1. Test battery performance for varied seasons, weather conditions, and event durations.
2. Develop and test battery dispatch strategies to:
    - Provide a flat, consistent MW value over the event;
    - Allow grid operator to specify the battery output needed;
    - Allow grid or program operators to specify the shape of the energy output; and
    - Respond to wholesale market energy price signals.
3. Research how customer enrollment varies with:

- Incentive structure;
- Incentive amount; and
- Outreach attempts.

4. Test other battery grid services:
    - Charge events;
    - Contingency reserves;
    - Frequency regulation; and
    - Under frequency/voltage relays.
5. Assess how batteries perform for different customer demographics.
6. Sub-metering shows promise on this single vendor study, so requirements should be developed and tested for broader adoption in the future.