Utilizing Batteries and Smart Panels for a Distribution Grid VPP

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Overview

- Study objectives – test a distribution grid services virtual power plan
- Locations and participant mix
- Developing accurate granular predictive models
- Operationalizing forecasts into precise battery instructions
- Study results
- Key takeaways

Pacific Gas & Electric

PG&E Territory

- 70,000 sq. mile service territory
- 26,000 employees
- Services 16+ million customers
- 5.5 million electric service accounts
- 4.5 million natural gas accounts
- 108,000 circuit miles of electric distribution lines
- 18,000 circuit miles of electric transmission lines
- 3,000+ feeders, 800+ substations, 16 distinct planning areas

Enabling Customer Solutions

- 1 in 7 of all electric vehicles in the US is in PG&E's service area
- 1 in 5 of all solar rooftops in the US is in PG&E's service area

Study objectives

VALUE DRIVERS

- Distribution infrastructure is sized to meet the local peak demand
- If flexible resources deliver load relief when local demand is nearing capacity limitations they may help avoid or defer growth-related distribution investments
- Resources must deliver the right magnitude of resources at the right locations for the right hours to deliver distribution load relief value

OBJECTIVES

Develop a VPP for distribution grid services

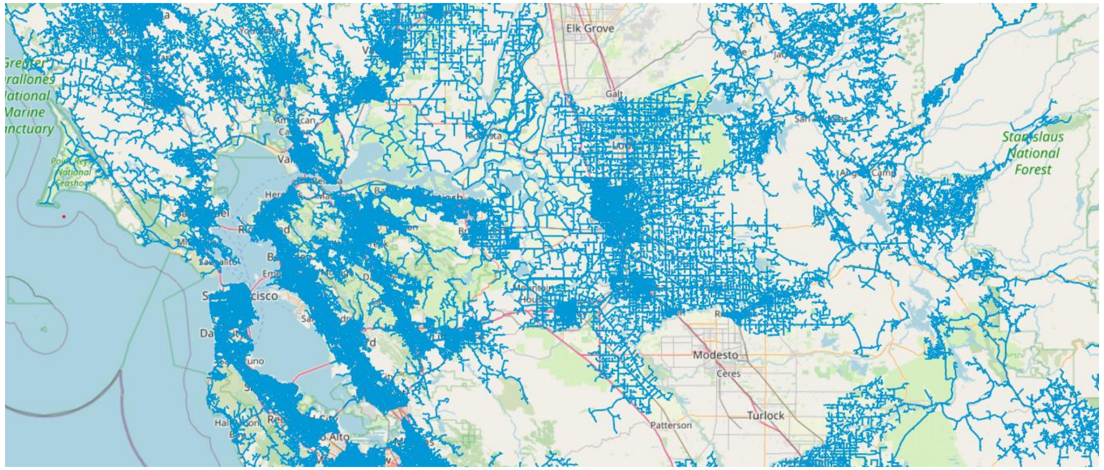
Test ability to send different dispatch instructions to different locations

Assess ability to shape load based on distribution needs

State of Project

- PG&E selected highly loaded circuits in our territory, with high potential for load management deferral (programs)
- PG&E contracted 3 large aggregators, who receive our signals to meet needed load shapes
- PG&E ran beta tests from April-June, and operations from July-October

Roles and responsibilities



sunrun — 1,000+ Batteries

NEXTera ENERGY — 600+ Batteries

SPAN — 100+ SPAN Smart Panels

- PG&E Provides grid data to determine need and location of shaping resources. PG&E remunerates 3rd party companies on a per device basis based on full participation in pilot
- Working with DSA, PG&E communicates load shape needs one week ahead, with same-day final dispatch instructions

- Our 3rd party partners have worked with OEMs and have used first-of-its kind software technology for managing battery export
- Battery and smart panel partners manage all direct customer interaction, including distribution of incentive payments to end-use customer
- Battery companies focused on NEM 2 customers with PPA
- Panel company provided an opt-in option for customers with panel installed

The Timing and Shape of Load Relief Need Varies by Location

- This heat map shows overloading at a feeder and a substation, with a generation curve overlaid for reference. The feeder has a multi-hour overload, with a shorter but peakier overload for the substation
- PG&E shapes are varied and overloading can occur at different hours and for varied durations
- Coincidence across distribution, transmission, and generation in one location, provides PG&E with opportunity to deliver higher impact with VPP

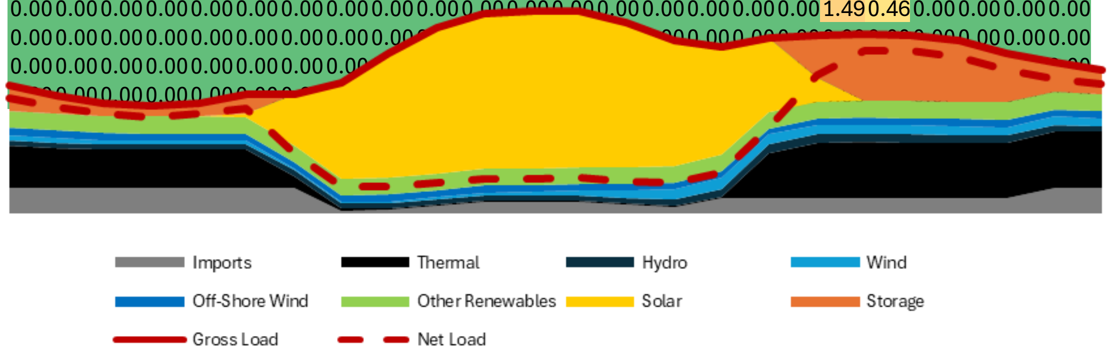
PG&E Grid 2030 Heatmap of overloading

Feeder

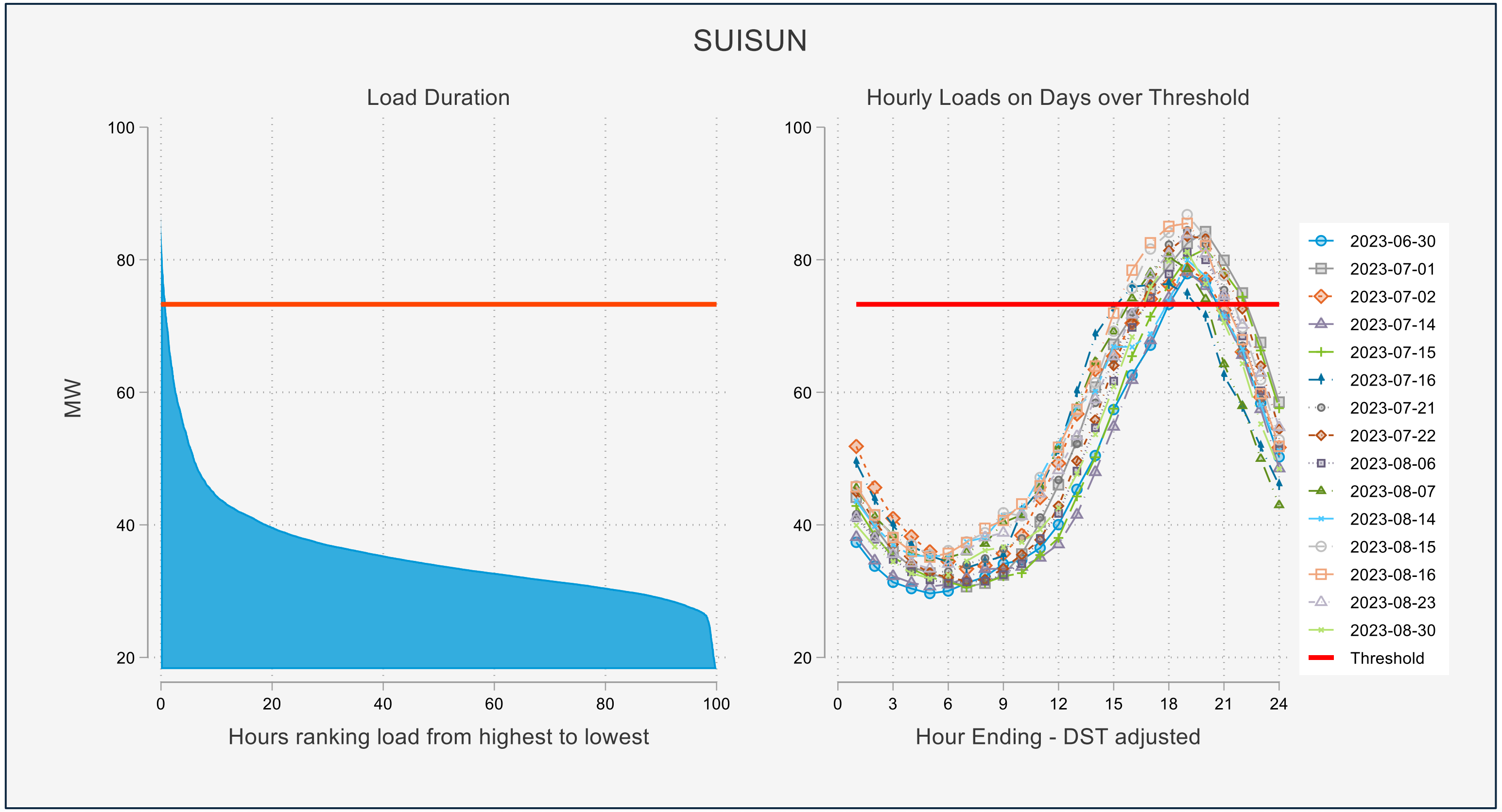
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.10	0.67	0.63	0.93	0.80	0.64	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.78	0.30	0.76	0.91	0.81	0.78	0.65	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.39	0.41	0.55	0.78	0.55	0.50	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.20	0.00	0.00	0.00	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Substation

Tx	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.58	3.25	5.53	4.10	2.39	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.78	6.38	7.60	6.11	3.31	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.44	2.09	1.90	2.95	3.95	1.57	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	[illegible]	0.00	0.00	0.00	0.00	0.00	1.49	0.46	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12	[illegible]	0.00	0.00	0.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

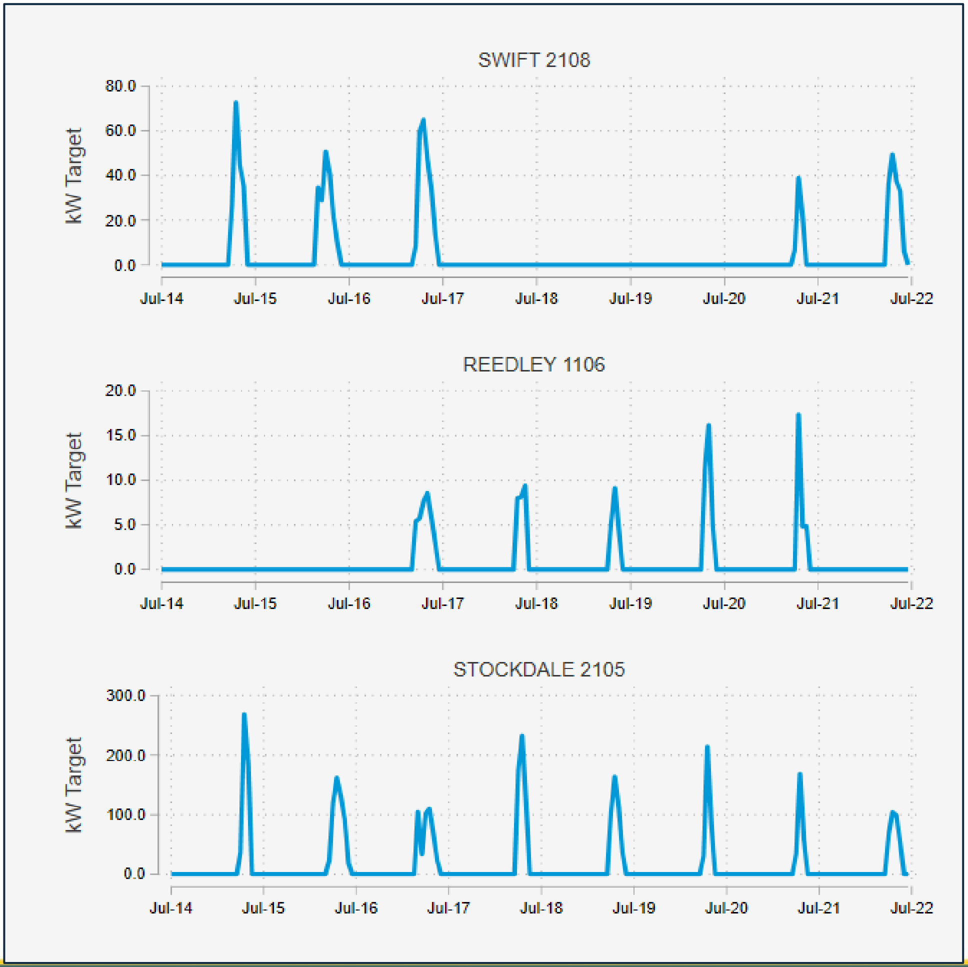


The avoid upgrades, the batteries need to keep loads below the operating limit



The distribution VPP needs to deliver the right amount of load relief on the right day and at the right hours for each feeder and substation

Each location gets different instructions



HOW WAS THIS ACCOMPLISHED?

Develop accurate predictive models
- Machine learning accuracy tournament
- Each location gets its own mode

Automate inputs needed for forecasts
- Forecasted weather
- CAISO System load forecasts

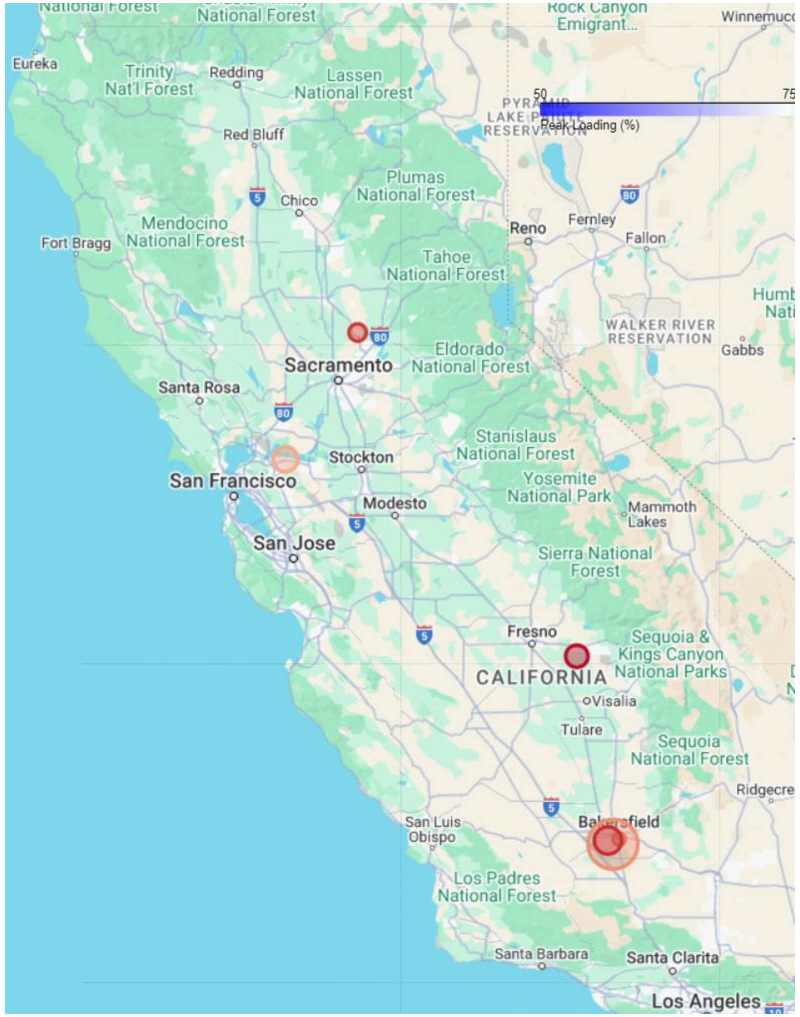
Convert demand forecasts into dispatch instructions
- Same day target kW by location and hour
- Weekly outlook

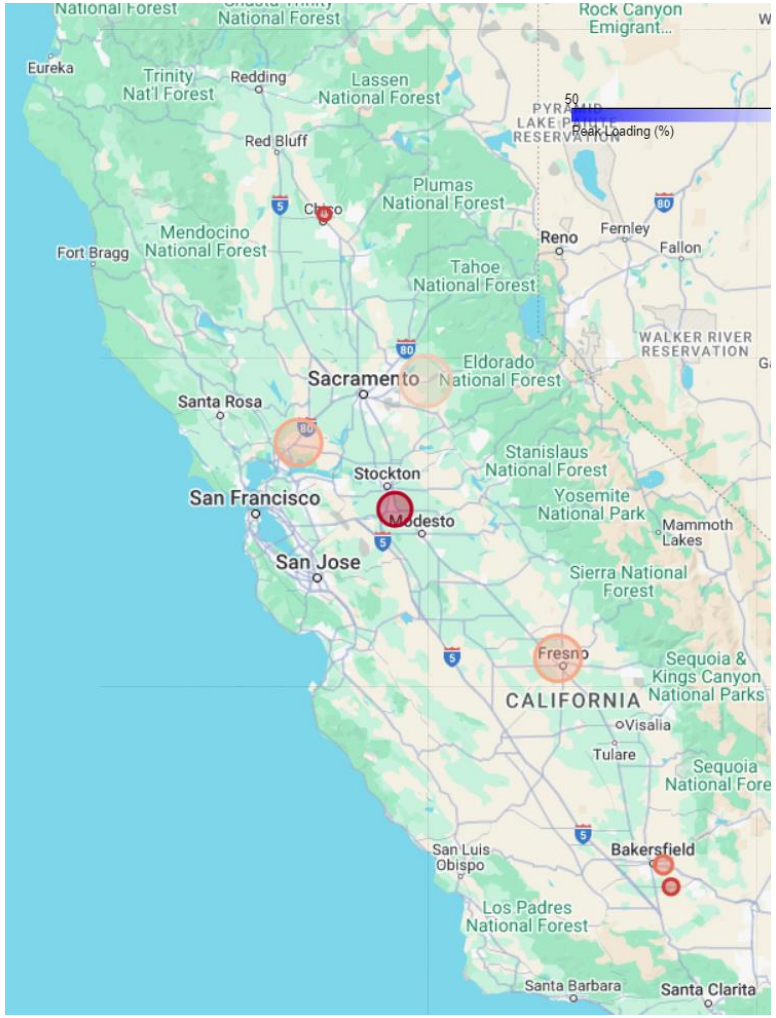
Automate communications and location dispatch to aggregators

Aggregators automate the dispatch of the batteries and tune the algorithms

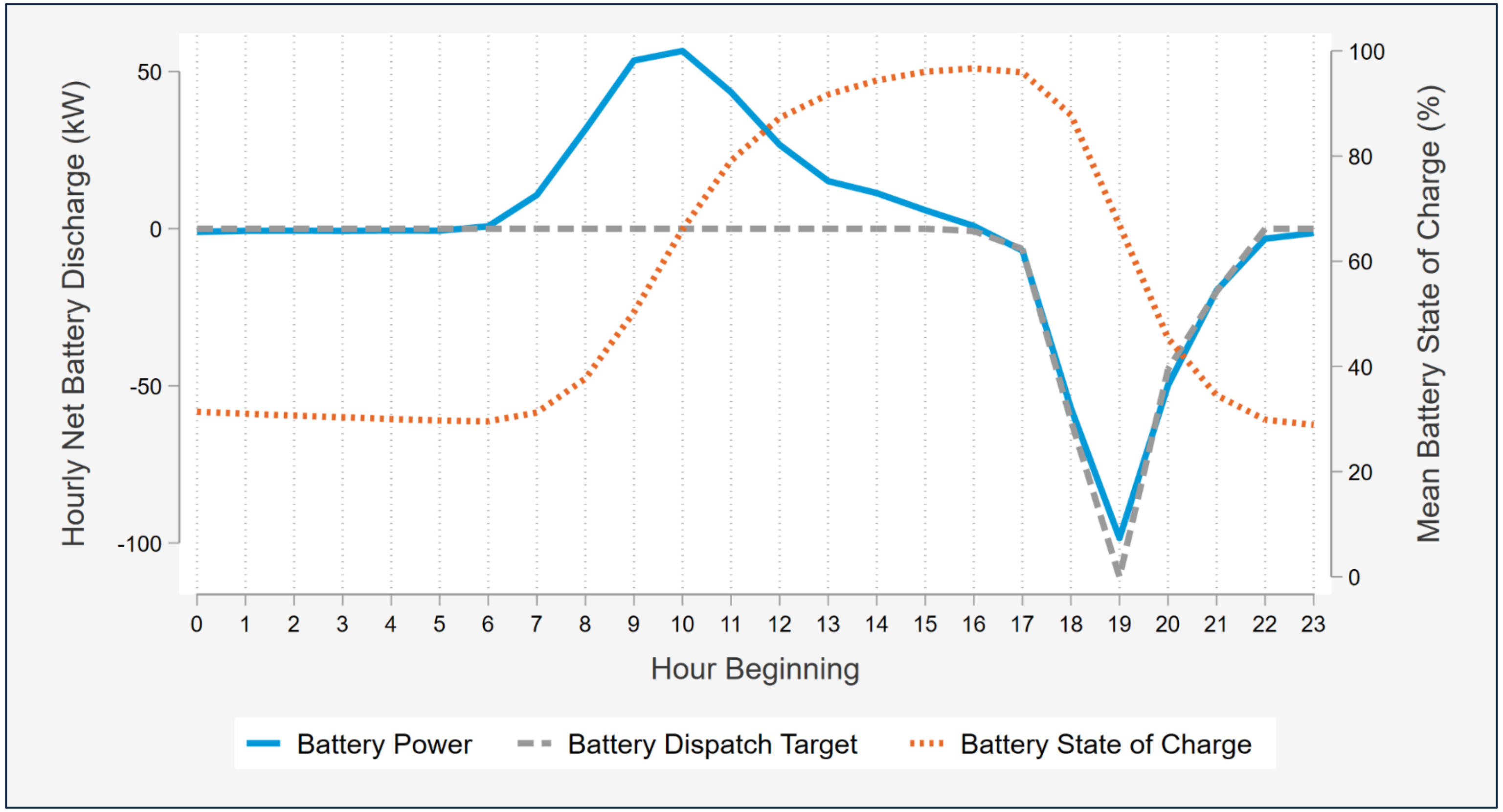
Participant Mix

- 9 substations
- 18 feeders
- 16 future state substation clusters
  - Artificially added solar and EV loads projected for 2035 in IPER forecast



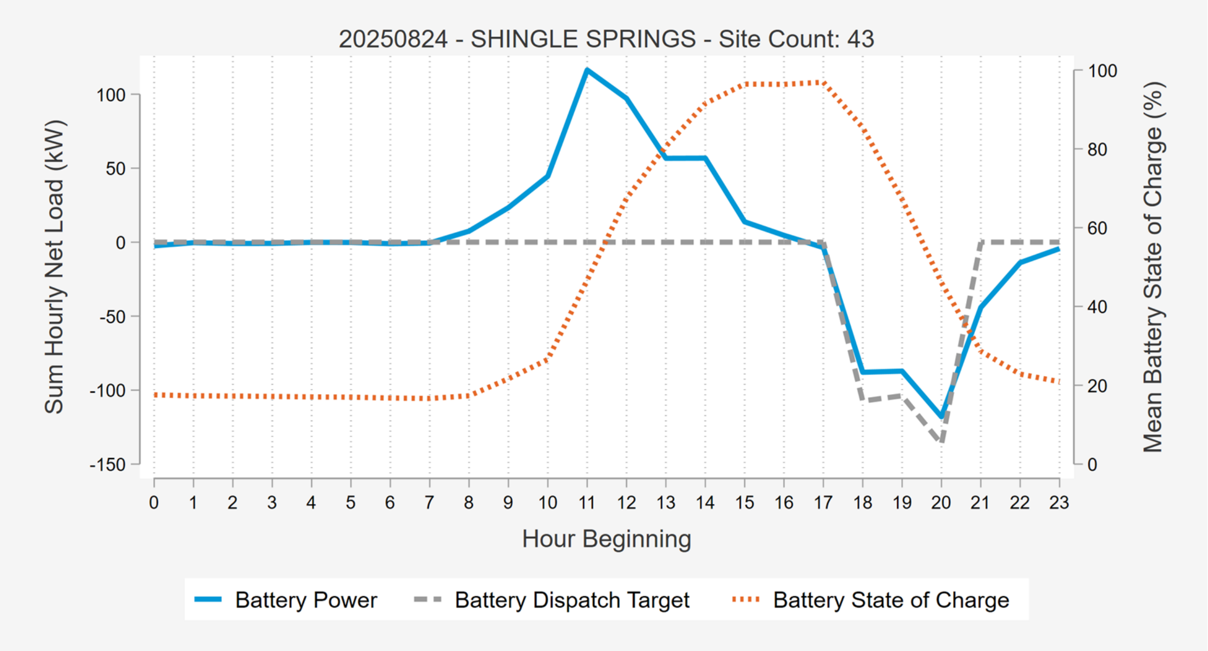


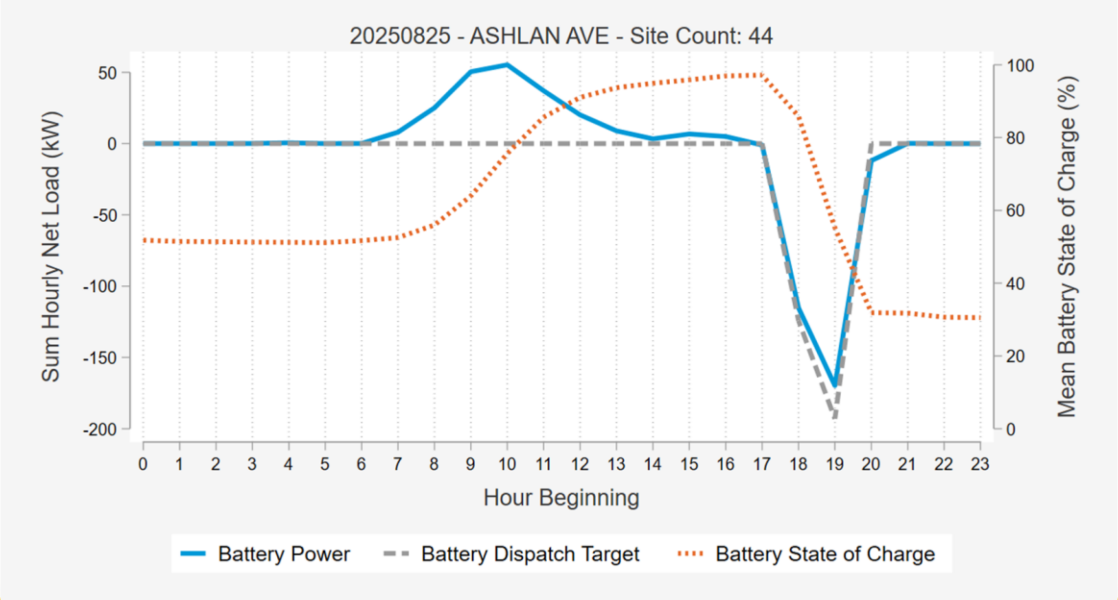
How closely did the did the VPP follow the target kW instructions (overall)?



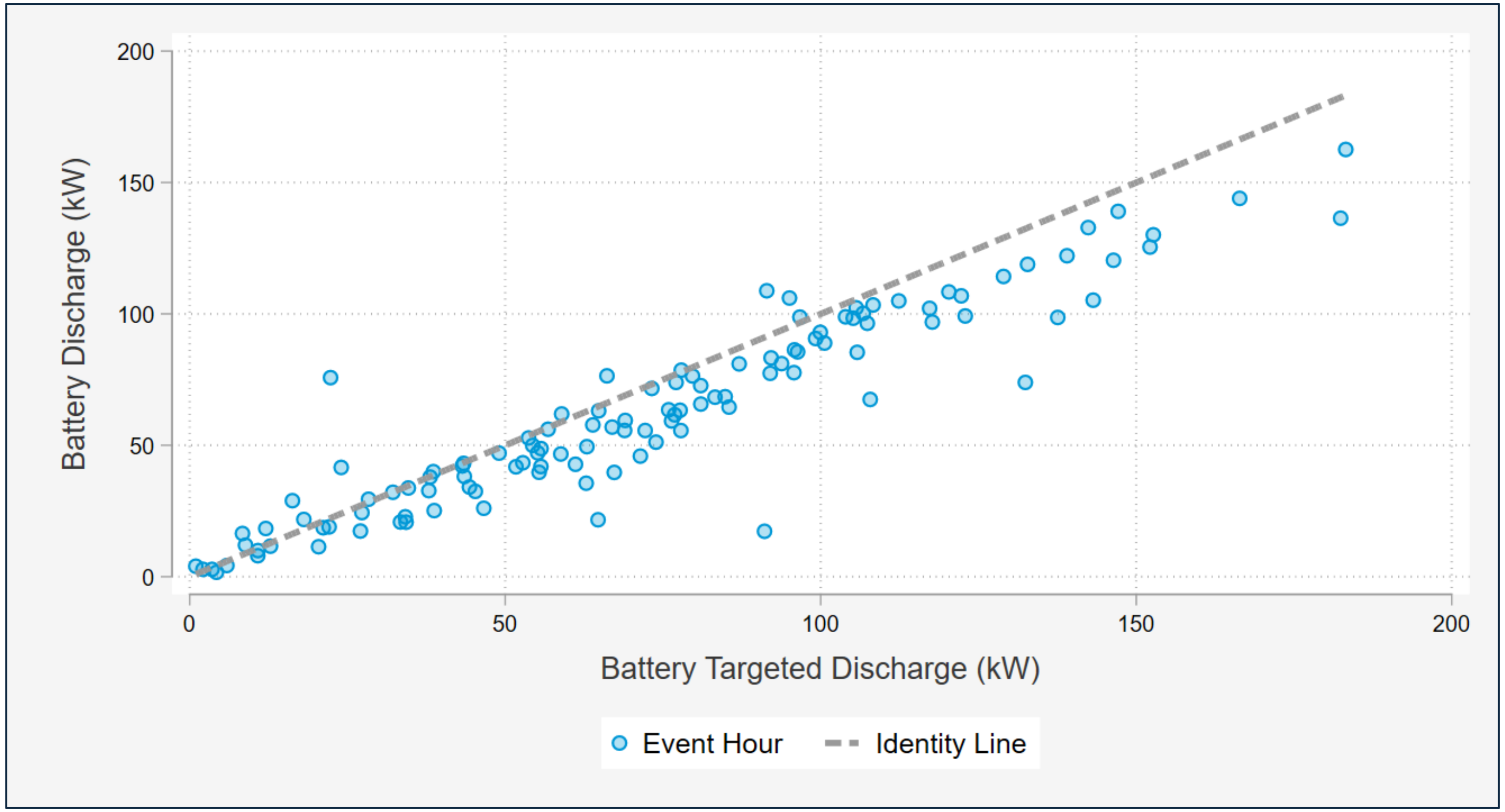
- Battery groups are able to closely follow dispatch instructions in the hours and locations requested.
- On a typical event day, batteries are close to 100% charge and will draw down to 20-30%.
- Results show the weighted average battery dispatch target and power readings at the group level across all event days.

Two illustrative locations, two different providers



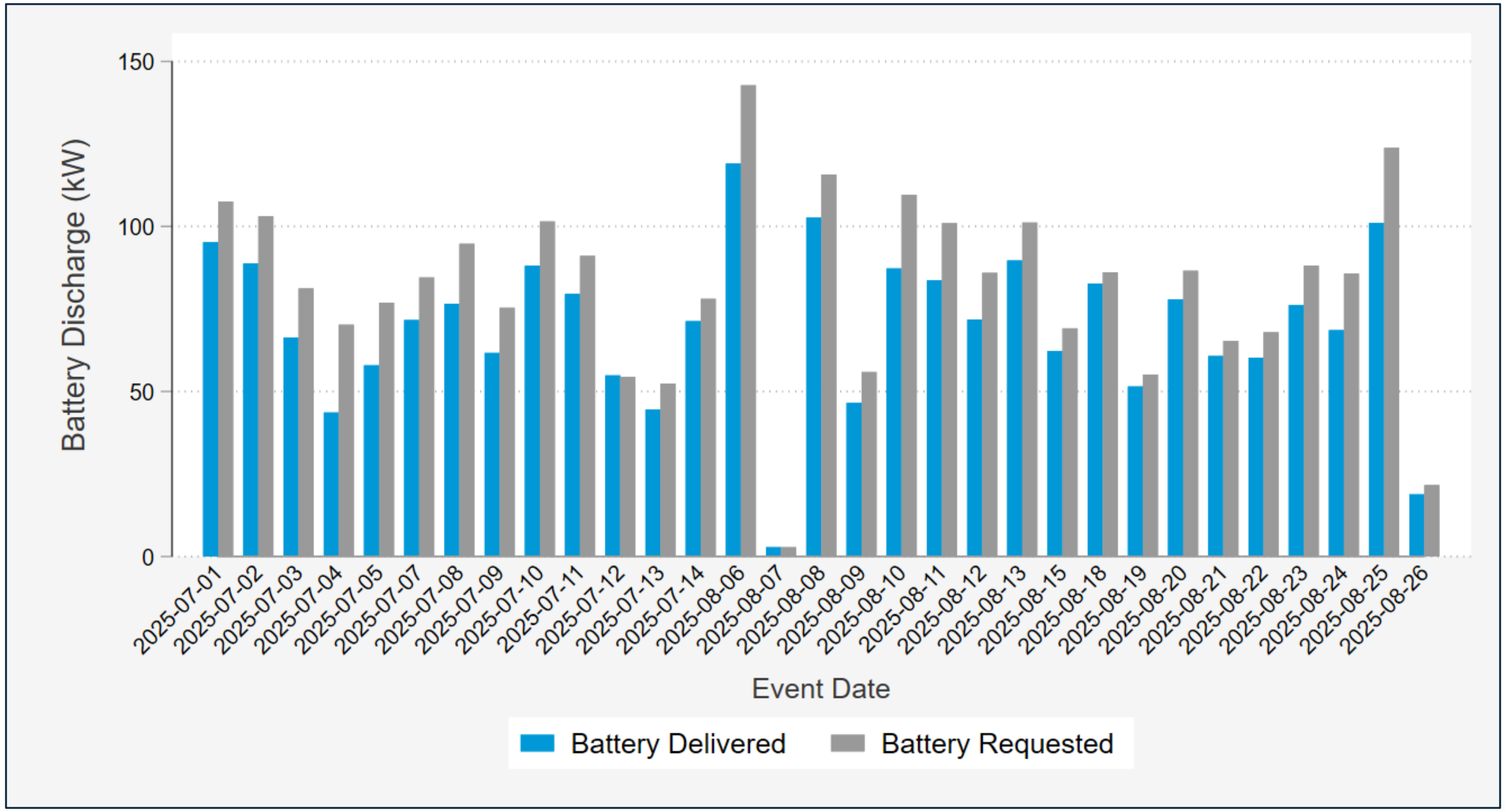


Did the batteries deliver the requested load relief?



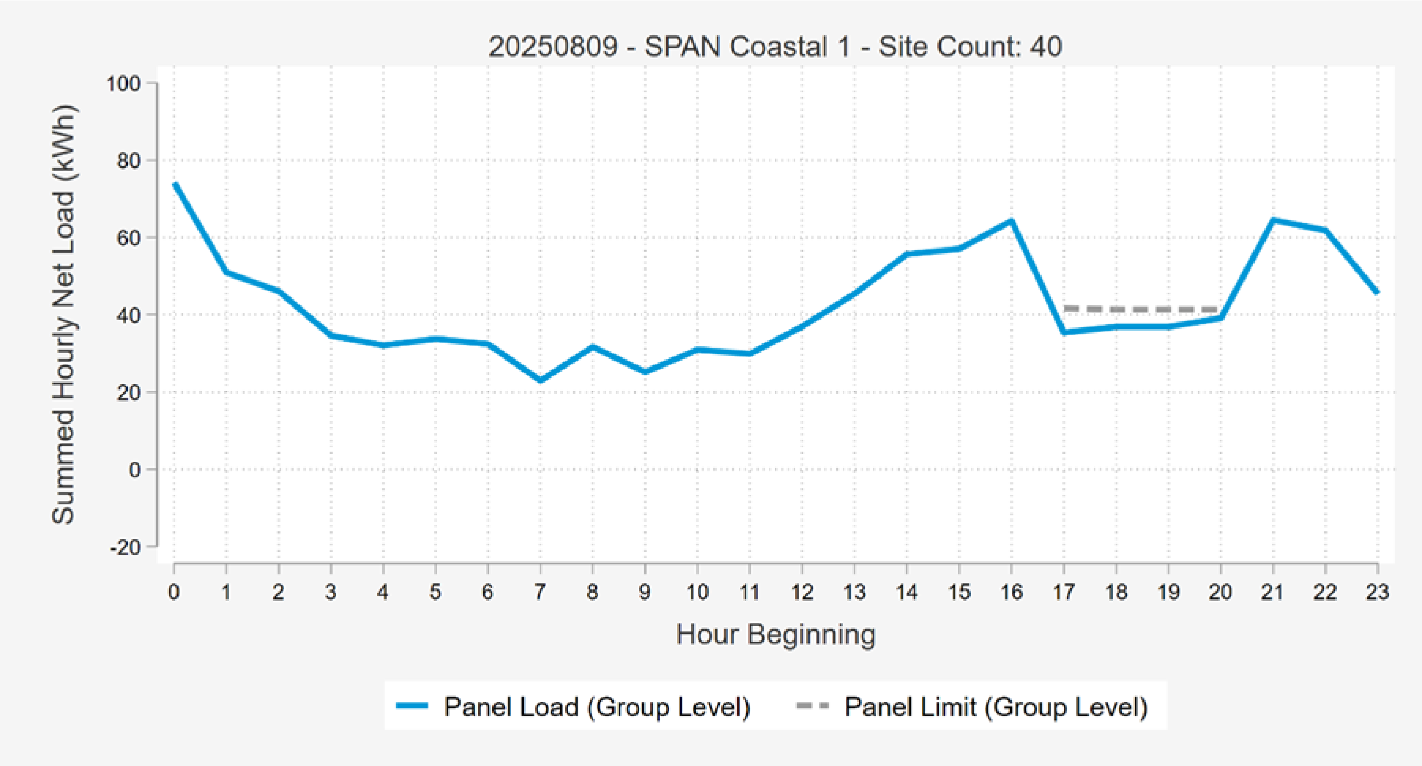
- Consistent 90%+ realization rate overall and individual locations
- Batteries at the target substations and feeders got close to the dispatch target but do not fully reach it

Did the resource tend to over or under-deliver the target kW by date?



- Consistent performance over the study period
- Most of the issues were resolved in the beta testing period
- Variation is from different locations being dispatched on different days

Early Takeaways of SPAN performance in SAVE



- SPAN developed a custom algorithm to prioritize and limit loads over multiple hours
- The field was conducted on roughly 120 sites. These sites were skewed to milder SF Bay Area climates
- The ability of SPAN to limit loads was assessed using both AMI data and panel meter data for each circuit
- We are seeing effective limiting at the panel level
- Further testing and development on customer adoption and behavior is needed

Key Takeaways

1. The timing and magnitude of load relief needed for distribution grid VPP varies by location

2. The batteries were able to deliver the requested kW at each location with high precision

3. The ability to deliver specific amounts of resources was tested with multiple vendors and battery systems

4. Accurate predictive models are critical to integration of battery storage into grid services

5. Scaling and automating the granular forecasts requires understanding how battery providers ingest data via APIs

6. The algorithms to shape battery dispatch were improved over time – beta testing was key

Questions?

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DATA DRIVEN RESEARCH AND INSIGHTS

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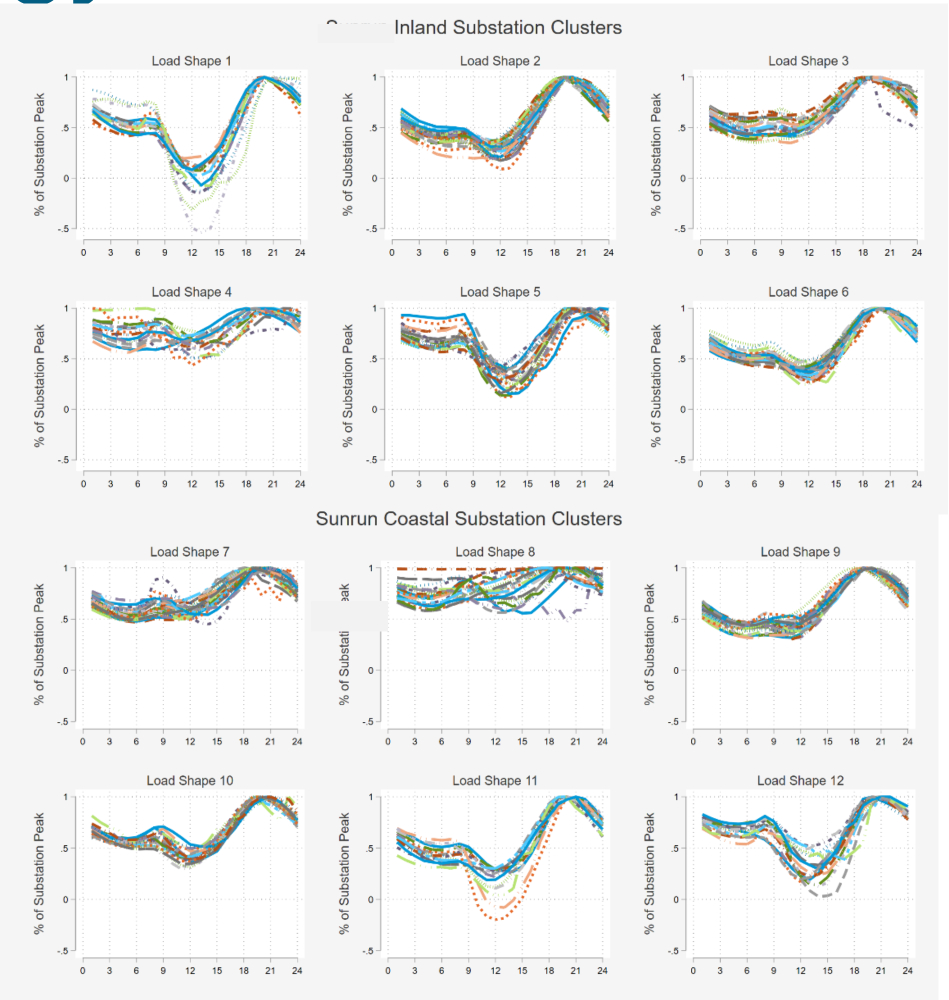
PG&E

Site Selection Methodology

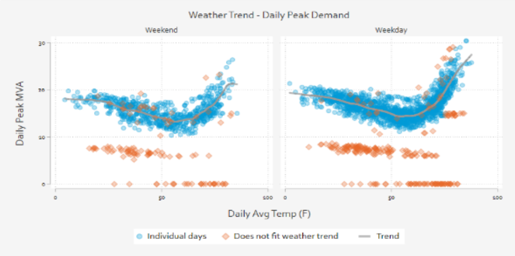
- Process Substation & Feeder Forecast Loading Data
- Merge in Battery Sites
- Retain feeders and substations which contain sizeable battery penetration and clean Pi Tag data
- From site candidates: keep the highly loaded locations (2030) until participation quota is reached
- Finalize site selection with PG&E Team



Demand Model development for each location

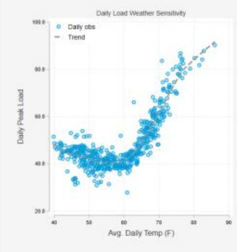
Data Prep Cleaning

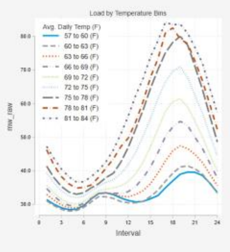
- 2022-2024 SCADA data for each feeder and substation
- Merge in local weather a day-ahead CAISO forecasts
- Remove historical DR days
- Identify load transfers
- Remove outages and meter recording issues
- Avoid mixing data issues such as load transfers with load growth/declines



Exploratory Data Analysis

- Explore relationship of all possible predictive variables for DER adoption
  - ✓ Correlation
  - ✓ Plots
  - ✓ Bivariate regressions
- Identify the key predictors of adoption
- Identify non-linear patterns





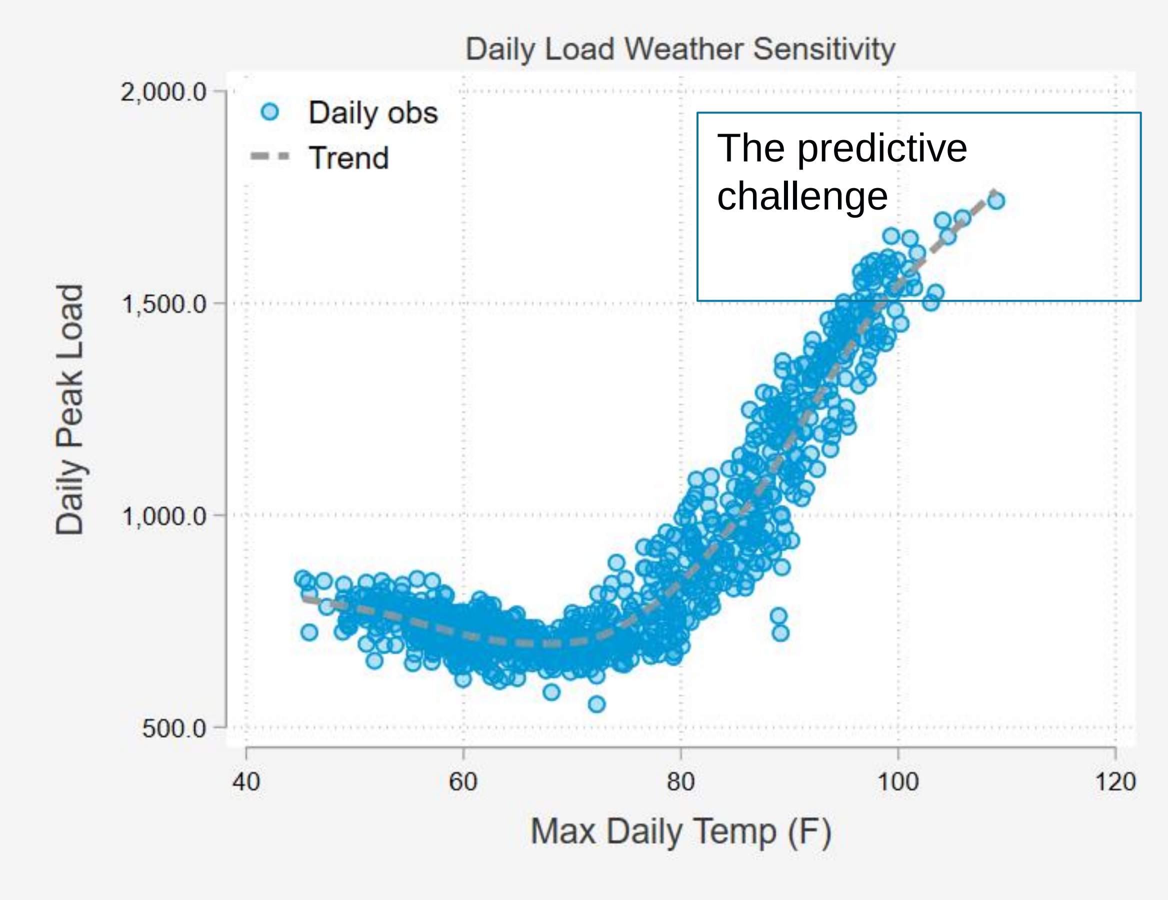
Model Tournament

- MORE DETAIL IN NEXT SLIDE

Apply model

- Run model using all historical data for each location
- Store model for each location
- Produce a function to forecast demand based on weather forecast and other explanatory variables:

Predictive models



STEP 1 — Identify the days when accurate predictions are needed most

STEP 2 — Split data into testing and training data

STEP 3 — Train models on predictive features

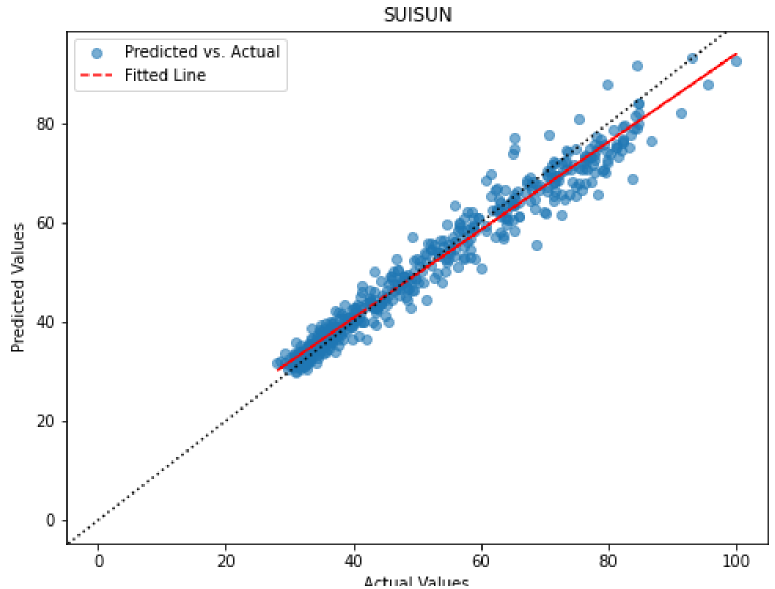
- Spline regression
- Random Forest Regressor
- Gradient Boost Regressor
- Light GBM
- Net Elastic Regressor
- XGBoost

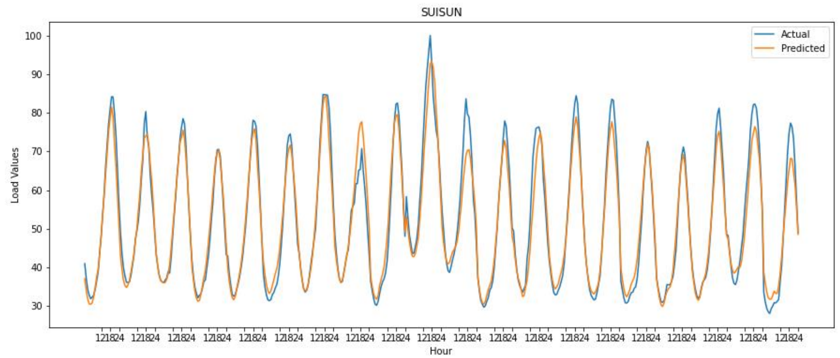
STEP 4 — Assess accuracy using testing data by comparing out-of-sample predictions to actuals

STEP 5 — Select best unbiased model

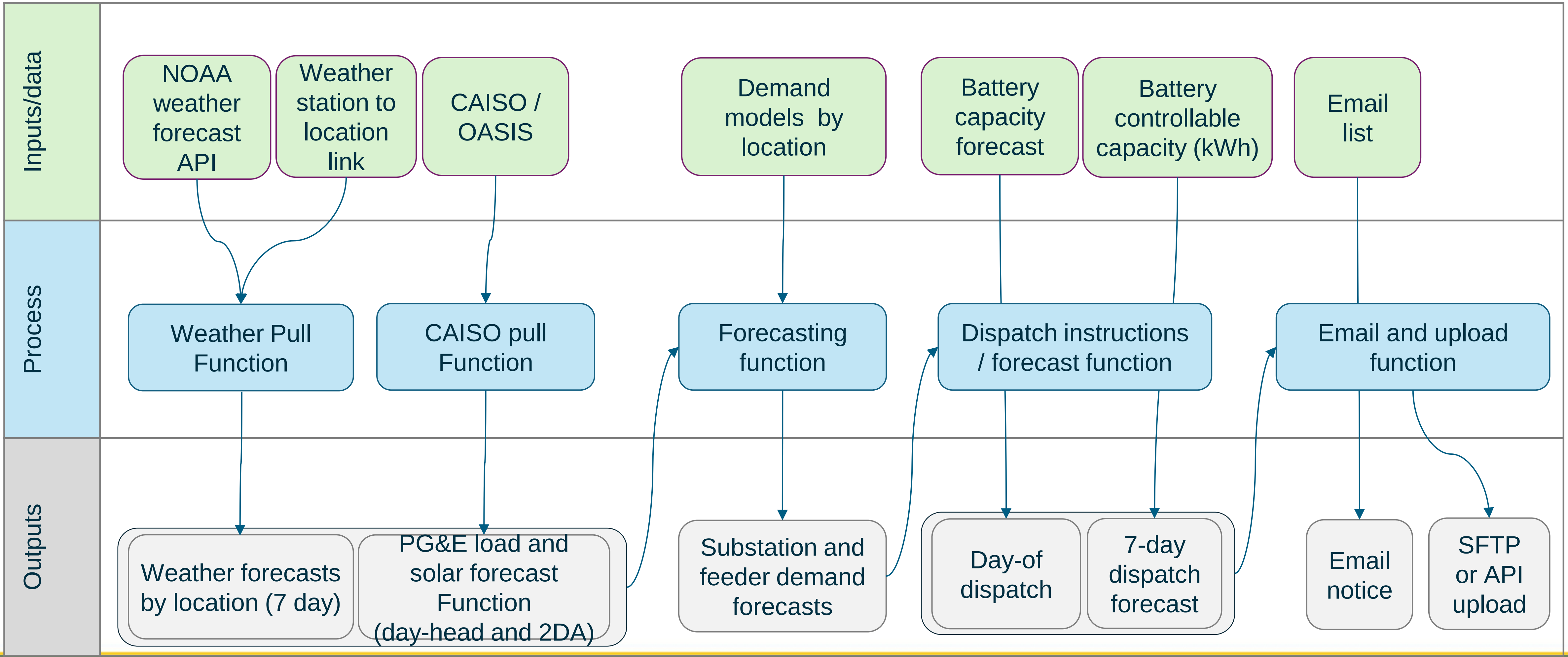
Performance metrics using testing data (top 50 days over 3 years)

Location	Model	Avg. Actual	Avg. Predicted	RRMSE	RRMSE2	Weighted RMSE	R2	MAE	MAPE	% Bias
ASHLAN AVE	LightGBM	67.44	65.81	5.00	0.07	4.46	0.96	3.57	0.05	-2.41
BAKERSFIELD 2109	ElasticNet	9.74	9.80	0.63	0.06	0.60	0.95	0.50	0.06	0.64
HICKS 1116	RF	3.97	3.90	0.64	0.16	0.57	0.90	0.46	0.19	-1.77
HICKS 2101	RF	4.59	4.35	1.65	0.36	1.37	0.66	1.16	0.50	-5.30
LINCOLN 2108	ElasticNet	4.60	4.53	0.55	0.12	0.54	0.86	0.42	0.10	-1.70
MAGUNDEN	ElasticNet	39.79	39.96	3.30	0.08	3.25	0.91	2.70	0.08	0.42
MANTECA	LightGBM	70.08	69.67	2.29	0.03	1.82	0.98	1.31	0.02	-0.57
MC KEE 1103	LightGBM	3.54	3.42	0.58	0.16	0.50	0.84	0.34	0.10	-3.62
MC KEE 1107	LightGBM	4.66	4.53	0.48	0.10	0.42	0.94	0.34	0.08	-2.79
MORGAN HILL	RF	50.36	50.32	4.39	0.09	3.89	0.91	3.16	0.06	-0.10
MORGAN HILL 2108	ElasticNet	9.58	9.34	0.86	0.09	0.83	0.84	0.66	0.07	-2.43
MORGAN HILL 2109	RF	8.42	8.14	1.09	0.13	0.92	0.84	0.75	0.08	-3.28
MORGAN HILL 2111	ElasticNet	7.01	6.93	0.68	0.10	0.62	0.83	0.48	0.07	-1.08
REEDLEY 1106	ElasticNet	6.11	6.10	0.57	0.09	0.60	0.86	0.39	0.09	-0.27
SARATOGA 1107	ElasticNet	3.64	3.64	0.44	0.12	0.38	0.87	0.31	0.09	0.02
SHINGLE SPRINGS	RF	26.98	26.53	2.27	0.08	2.16	0.96	1.67	0.07	-1.64
SPAN Coastal 1	ElasticNet	1,959.04	1,958.80	83.28	0.04	78.02	0.97	65.04	0.03	-0.01
SPAN Coastal 2	XGBoost	2,176.36	2,126.47	166.41	0.08	161.59	0.54	130.38	0.06	-2.29
SPAN Inland 1	ElasticNet	1,408.71	1,392.41	56.74	0.04	55.16	0.93	44.82	0.03	-1.16
SPAN Inland 2	ElasticNet	2,615.37	2,577.72	159.50	0.06	139.32	0.97	105.71	0.04	-1.44
STELLING	LightGBM	36.09	35.28	3.51	0.10	3.40	0.82	2.60	0.07	-2.25
STOCKDALE 2105	RF	10.61	10.55	1.01	0.10	0.99	0.94	0.63	0.07	-0.54
SUISUN	ElasticNet	52.06	51.26	3.82	0.07	3.58	0.95	2.90	0.06	-1.55
SWIFT 2107	LightGBM	6.76	6.70	0.77	0.11	0.69	0.92	0.56	0.09	-0.88
SWIFT 2108	LightGBM	7.03	6.70	1.27	0.18	0.94	0.83	0.72	0.11	-4.75
SYCAMORE CREEK	RF	33.65	33.16	3.78	0.11	3.36	0.91	2.66	0.08	-1.44
Sunrun Coastal 1	ElasticNet	1,083.11	1,130.34	203.78	0.19	200.78	0.65	160.71	0.16	4.36
Sunrun Coastal 2	XGBoost	1,291.57	1,278.61	55.16	0.04	54.41	0.79	42.31	0.03	-1.00
Sunrun Coastal 3	XGBoost	985.37	979.03	42.43	0.04	39.78	0.99	31.86	0.04	-0.64
Sunrun Coastal 4	ElasticNet	462.41	447.70	44.23	0.10	39.20	0.91	29.36	0.06	-3.18
Sunrun Coastal 5	ElasticNet	124.36	125.47	8.91	0.07	8.35	0.99	6.72	0.24	0.89
Sunrun Coastal 6	ElasticNet	133.09	131.09	6.63	0.05	6.45	0.98	5.50	0.05	-1.50
Sunrun Inland 1	ElasticNet	184.22	181.49	19.72	0.11	19.22	0.98	15.76	0.37	-1.48
Sunrun Inland 2	XGBoost	656.02	654.25	41.05	0.06	37.64	0.99	31.19	0.07	-0.27
Sunrun Inland 3	ElasticNet	921.81	924.69	38.98	0.04	37.93	0.98	32.35	0.04	0.31
Sunrun Inland 4	ElasticNet	585.46	570.93	30.57	0.05	28.08	0.90	23.35	0.04	-2.48
Sunrun Inland 5	ElasticNet	353.11	342.55	19.36	0.05	18.89	0.98	15.64	0.05	-2.99
Sunrun Inland 6	ElasticNet	889.81	884.82	28.93	0.03	28.49	0.99	23.12	0.03	-0.56
TEVIS 2104	ElasticNet	6.24	6.38	0.89	0.14	0.89	0.96	0.66	1.15	2.24
TEVIS 2105	ElasticNet	11.03	11.00	0.73	0.07	0.69	0.96	0.52	0.05	-0.26
WEEDPATCH	ElasticNet	17.27	16.90	1.94	0.11	1.83	0.79	1.55	0.09	-2.13
WILLOW PASS 2108	LightGBM	6.34	6.09	1.07	0.17	0.95	0.84	0.78	0.13	-3.95





Process for forecasting and dispatch



Process for defining load limiting at a site

1. Identify the top 10 load hours for two years (20 total, location specific)
2. Calculate distribution peak load (DPLC) contribution for each SPAN premise
3. Provide DPLC to SPAN
4. SPAN determines the attainable load limit for each site
5. Payment is based on difference between the DPLC and observed loads on event days