Domestic Hot Water and Grid Flexibility: A Field Study of Real-Time Price Optimization at Three Affordable Housing Multifamily Sites in California

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ABSTRACT

Achieving grid-interactive load controls is critical to the success of building electrification for significantly reducing greenhouse gas (GHG) emissions and energy use during peak grid conditions. This study presents a comprehensive analysis of 2022-2025 data from the first field demonstration of load flexibility controls for central heat pump water heater (HPWH) systems in response to time-varying electricity price signals. Price signals tested include actual PG&E utility rates, day-ahead PG&E hourly Flex Pricing, fictional price schedules obtained from Lawrance Berkeley National Laboratory's CalFlexHub, and real-time forecasted marginal GHG rates from the California Energy Commission's (CEC) Market Informed Demand Automation Server (MIDAS).

The project team uses an advanced system integration and control solution, the LOCUS (Load Optimization Control Using Storage) technology, to achieve this goal. The LOCUS technology enables plug-and-play integration of HPWH and storage equipment and intelligent controls of system operation to optimize performance according to price signals, hot water demand, and other system parameters collected in real time.

Three California multifamily sites serving low-income communities were included in this study of the LOCUS technology. These HPWH systems at the three multifamily sites represent diverse central HPWH system designs, which provides an opportunity to investigate how system performance is affected by key design parameters such as HPWH type, heating capacity, storage size, and recirculation controls, which will inform future HPWH system design practices. Previous work submitted under ACEEE Summer Study 2024 focused on one site and optimization using CalFlexHub rates. This paper focuses on marginal GHG optimization at all sites with some discussion relevant to the broad learnings of the project.

Introduction

Rapid changes in the grid supply and demand characteristics have caused the wholesale price and carbon intensity of electricity in California to vary substantially throughout the day and year (CAISO 2023). This price variation will continue to increase over time as more solar and other renewables enter the grid and appliances become electrified. In general, electricity production costs are currently substantially cheaper during the middle of the day when solar production is highest, and most expensive during the evening peak when production falls and demand increases. This additional strain on the grid encourages demand-side strategies to smooth out demand if we are to meet climate goals set by the state (Lawrence Berkeley National Laboratory 2020).[1]

[1] SB 100 was passed in September of 2018, which sets a goal of phasing out all fossil fuels from the state's electricity sector by 2045.

One of the technologies increasing grid load is the rapid addition of heat pump water heaters (HPWHs). Unlike electric space heating, which primarily increases winter grid load, HPWHs also add summer grid load and hot water demand schedules align closely with morning and evening grid peaks (Murphy, et al. 2021). This presents an opportunity to utilize thermal load shifting technologies to shift hot water production to off-peak hours as a means of reducing expensive and carbon-intensive electricity production to meet this added demand (Delforge P., Vukovich J. 2018). Previous studies (Brooks, et al. 2021; Advanced Water Heating Initiative 2024; Pfotenhauer et al. 2024) have demonstrated the potential benefit for HPWH load shifting and challenges associated with existing technologies.

Project Background

This research project (EPC-20-004), conducted under the California Energy Commission's (CEC) Electric Program Investment Charge (EPIC) program,[2] aims to test and demonstrate an advanced HPWH load control system that does the following:

1. **Responds** to hourly or sub-hourly price and demand response signals to minimize cost and grid impacts,
2. **Optimizes** energy use based on building owner/occupant preferences, and
3. **Provides** reliable and cost-effective load flexibility as a grid resource.

Under the grant EPC-20-004, the thermal load-shifting technology developed by ZYD Energy known as Load Optimization Control Using Storage (LOCUS) was tested in the field at three different sites and evaluated by the California Energy Commission EPIC grant team.[3] This project began in early 2021 and is slated for completion by early 2026.

LOCUS Technology Overview

This project uses LOCUS technology developed by ZYD Energy to retrofit central HPWH systems and demonstrate load flexibility controls. The core of the LOCUS technology is a flow router which uses strategically arranged pipes, electric valves, and circulation pumps to establish versatile and dynamic flow paths between water heaters and storage tanks. The flow router is coupled with an advanced controller, which controls the electric valves and circulation pumps in the flow router. Using intelligent algorithms, the controller aims to optimize overall system performance according to hot water demand forecast and grid control signals. With LOCUS technology, integration of water heaters and storage tanks is achieved by simply connecting each piece of equipment directly to the flow router. A system-level control coordinates water heating operation and storage tank utilization to manage electric load and improve system efficiency. (see Fig. 1).

[2] This program is designed to fund and invest in scientific and technological research to accelerate the transformation of the electricity sector to meet the state's energy and climate goals.
[3] The team consists of individuals noted as co-authors in this paper.

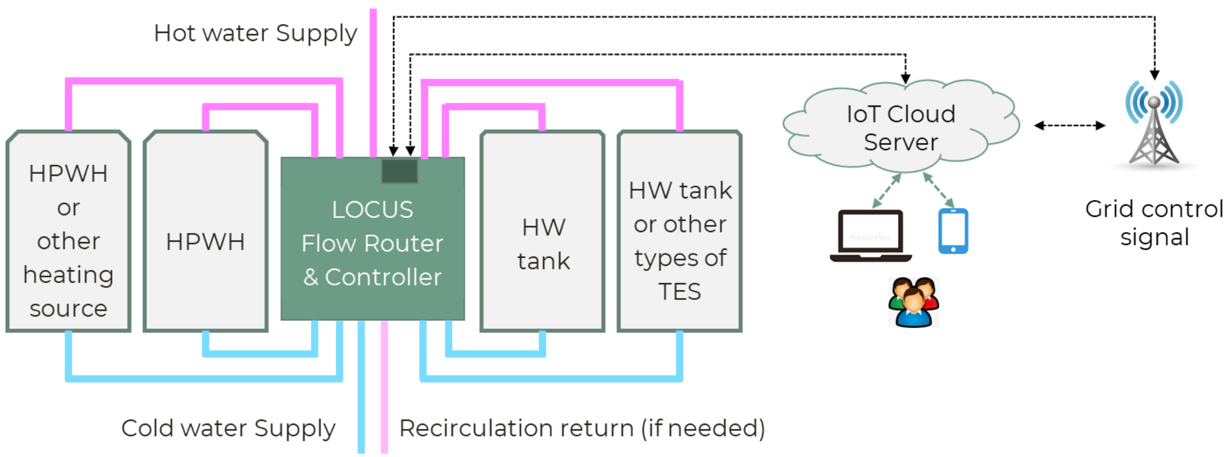

Figure 1. A simplified diagram of the grid-connected LOCUS flow router and controller.

LOCUS system-level control is achieved by managing system operation using a sequence of operational modes, each of which defines a specific way to use water heaters and storage tanks in the system. By creating multiple operational modes, LOCUS technology makes the system operation adjustable for flexible load controls. The sequence of operational modes is determined by optimization algorithms according to site-specific hot water demand forecast and electricity price and/or carbon intensity (depending on the optimization goal), which are real-time inputs to the system. Algorithm inputs also include other variables like heating capacity, storage volume, cold water supply temperature, etc., and an array of sensors is used to assess real-time operational status and adjust operation mode sequence accordingly. Because LOCUS system-level control is based on flow management without imposing any requirements on the HPWH's internal controls, LOCUS control is potentially applicable to all HPWHs systems. LOCUS optimization algorithms use high-level system configuration parameters, such as total heat pump heating capacity, total electric resistance heating capacity, and total storage capacity, to create optimal heating schedules specific to each system. To further optimize system operation, LOCUS technology implements flow management procedures based on the HPWH's performance characteristics. For example, for hybrid HPWHs, water flows for charging storage are adjusted to either avoid or trigger electric resistance heating according to the optimal heating schedule.

A simplified schematic of the different operational modes is shown in Fig. 2. While there are numerous possible operational modes depending on the configuration and complexity of the HPWH system, the primary function of the LOCUS is to charge and discharge storage tanks with regards to price optimality. For instance, this could mean midday peak charging when solar production in the grid is high and electricity is cheap and clean, and discharging while avoiding water heater operation during evening peak times when dirtier, more expensive, electricity is present. Note also that the LOCUS can be easily fully separated from the main system and operate in "bypass" mode. In this way, the system is not affected by LOCUS equipment failures, maintenance, or changes made to the algorithm requiring the system to be temporarily taken offline.

Figure: 2. A simplified diagram showing charge and discharge modes for a basic LOCUS-controlled system.

Description of Project Sites

Three separate all-electric multi-family developments in California (hereafter referred to by their location: Gilroy, Eureka, and Santa Rosa) were chosen for retrofits under this project. All three are diverse in their HPWH configuration and therefore provide an opportunity to study LOCUS technology under a wide range of conditions (see Table 1).

Table 1. Summary of buildings used in study.

Site	Monterey Gateway	Bayview Heights	Santa Rosa Veterans Housing
Location	Gilroy, CA	Eureka, CA	Santa Rosa, CA
Owner	Danco Communities	Danco Communities	Community Housing of Santa Rosa
CA CZ	4	1	2
Year Built	2019	2019	2019
Number of Stories	4	3	1
Number of Units	60 1BR, 15 2BR	50 Studio	14 tiny homes
Number of Occupants	83	50	14
Resident Type	Very low-income seniors, half special needs seniors	Formerly homeless, formerly homeless veterans	Formerly homeless senior veterans
Baseline DHW System	One central system (2 Colmac units) with recirculation	12 distributed Rheem HPWH systems, each serving 3-6 dwelling units, with recirculation	Two Sanden SanCO2 HPWH systems, each serving 7 tiny homes, no recirculation
Baseline Hot Water Storage Tank(s) Volume (Gallons)	415	145	83
Compressor Heating Capacity (kBTUh)	276.7	4.2	15.4

Site	Monterey Gateway	Bayview Heights	Santa Rosa Veterans Housing
Resistance Element Heating Capacity (kW)	27	3.8	N/A
Spec Sheet Compressor COP	4.0	3.7	3.84
Hot Water Distribution	Continuous recirculation	Recirculation controlled by aquastat	Trunk and branch with no recirculation
System Location	HPWHs on roof, tank and electric resistance water heater are in mechanical room	Inside a mechanical room, vented to and from interior lounges	Outside

Study Design and Timeline

The goal of this study is to demonstrate load flexibility and commenced as follows:

1. Prior to the retrofit, each site in this study was instrumented extensively to measure temperature, flow, and power. A baseline period of at least a year was established for each site, and data was collected and evaluated.
2. Each HPWH system was retrofitted, where additional storage was added, and the LOCUS control module and flow routers were installed.
3. A year of LOCUS control optimization testing took place, where various price signals[4] were tested and the performance of the load shifting was evaluated. Optimization against GHG marginal emission factors obtained from CEC MIDAS[5] was undertaken in multi-week tests during various seasons to capture grid diversity.

Site Baseline Characteristics

Baseline data was collected starting in March 2022 at all sites and at least a year was collected for all systems. These baseline data were used both a) to evaluate the performance of the LOCUS system, b) determine the necessary additional storage for retrofit, and c) as baseline data for training the LOCUS demand pattern algorithms and optimization. Full baseline characteristics are described in the baseline report but can be described as follows:

Santa Rosa: Average hot water demand for each system is 178 gallons per day (GPD) and 102 GPD (East and West, respectively). Both systems are dual-peaking (morning and evening) with peak hot water demand occurring at approximately 8:00AM and 6:00PM.

[4] Price signals tested include actual PG&E utility rates, day-ahead PG&E hourly Flex Pricing, fictional price schedules obtained from Lawrance Berkeley National Laboratory's CalFlexHub, and real-time forecasted marginal GHG rates from the California Energy Commission's (CEC) Market Informed Demand Automation Server (MIDAS). The focus of this paper is on marginal GHG rates obtained from CEC MIDAS.
[5] https://www.energy.ca.gov/proceedings/market-informed-demand-automation-server-midas/

Average system COPs are 3.5 (East) and 3.6 (West). Average daily electricity consumption is 5.7 kWh (West) and 10.7 kWh (East). No significant hot water runouts were noted at either system and performance was seasonally very stable. Due to the small number of occupants, hot water demand varied substantially and hot water demand occasionally peaked at 300 GPD.

Gilroy: Average hot water demand at Gilroy is 2300 GPD, with little variance day to day due to the large number of occupants (95% of days fall below 2900 GPD). Hot water demand is morning and evening peaking, though a substantial midday plateau is present. Total system COP ranged from 1.6 in midwinter to 2.0-2.5 during warmer months. Total baseline electricity consumption is 259.3 kWh, with 9% of total energy comprised of electric resistance from the temperature maintenance tank.

Eureka: Average hot water demand at Eureka ranged from 48-206 GPD depending on the system with substantial variance from day to day due to the low number of occupants. Despite greater storage per person than at Gilroy or Santa Rosa, the small heat pump compressor (4.2kBTU/h heat output) could not keep up with demand. Additionally, recirculation often performed unexpectedly, with some systems experiencing periods of hours to months of constant recirculation. This not only increased system load, but de-stratified the primary tank and induced great amounts of resistance backup. System COPs were consistently less than 2.0, and in some systems averaged less than 1.0. Hot water runouts were frequent in higher-demand systems and overall performance was poor.

Market Informed Demand Automation Service (MIDAS) Price Signals

Forecasted and actual marginal CAISO (California Independent System Operator) GHG emission factors were obtained from CEC MIDAS, which reports in 5-minute increments. An example of historical data obtained for 2024 is shown in Fig. 3.

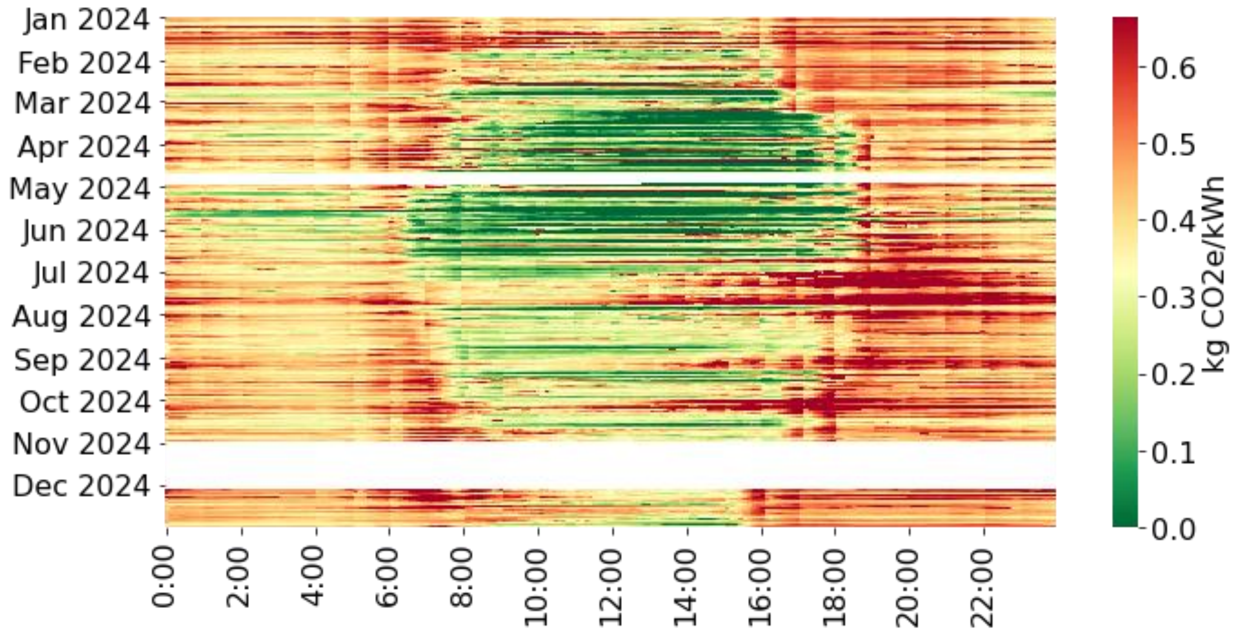

Figure 3. A heatmap of marginal GHG emissions factors (kg CO_2e/kWh) obtained from MIDAS for the year 2024. Note that data was not available for periods in white.

Site Retrofits

The retrofit at each site was undertaken over the course of a few days at various stages in the project with minimal impact to residents. This included adding the LOCUS control manifold and additional storage chosen based on Ecotope's Ecosizer tool (Ecotope 2020) and custom load shapes from baseline data collection. After retrofit, the systems were allowed to function without explicit LOCUS control based on optimization to evaluate performance and identify any potential issues that may need correcting prior to thermal load shifting experimentation. Storage capacity was increased from 83 to 163 gallons at Santa Rosa, from 415 to 1208 gallons at Gilroy, and at each system at Eureka where feasible and necessary an additional 80-gallon tank was added bringing each system's total storage to 145-195 gallons.

Testing and Analysis

Testing periods commenced using a minimum of 2 weeks per test, but often much longer depending on specific site variance. For instance, due to Gilroy's large size and consistent performance and hot water demand patterns, long test periods were less necessary than the other sites to obtain confidence in results. The LOCUS algorithm utilized MIDAS marginal GHG rate forecast, which covered a 72-hour time period with 5-minute interval and was updated every 5 minutes. The LOCUS would obtain these forecasts multiple times each day and optimize system operation schedules accordingly for the next 24 hours. In particular, MIDAS forecast data was retrieved at times when high or low marginal GHG rates were expected based on the previously retrieved values.

Data was collected over the course of the study period and normalized costs were calculated to compare to baseline (pre-retrofit) performance. An extended period of post-retrofit data was collected without LOCUS algorithmic control at Gilroy as a means of establishing a new baseline period. This was deemed necessary due to the substantial system changes present in this large system, whereas at Eureka and Santa Rosa performance was compared directly to pre-retrofit data.

Water flows, electric power, and system temperatures were closely monitored and analyzed on a weekly basis to identify problems and learn from system performance. Many metrics were considered in analysis and due to the changing nature of hot water demand, weather, and the carbon intensity of the grid, there is no way to obtain a perfect counterfactual. Indeed, even the grid itself became cleaner over the course of testing from 2022-2026. A robust literature review and meta-analysis of existing methods and our own data was undertaken to establish appropriate metrics but is out of scope for this paper. A couple of key metrics will be the focus of evaluation of optimization relative to marginal GHG factors:

- **kg CO_2e/kBTU**: kg of CO_2e relative to daily hot water demand.
- **kg CO_2e/kWh**: kg of CO_2e per kWh of electricity consumed by the system.

Both metrics were compared to baseline counterfactuals and can be expressed as a percent improvement relative to baseline conditions.

Study Results

A deep discussion of overall performance across all price signal optimization tests can be found in the final project report, which will be published in mid-2026. Detail will not be given to all learnings, but it is important to contextualize the results of marginal GHG optimization within the broader landscape of grid flexibility. Table 2 lists key variables that were identified as having major impacts on the relative success or failure of LOCUS optimization and are generally applicable to grid flexibility in general.

Table 2. Summary of key variables impacting efficacy of grid flexibility algorithms.

Category	Variable	Description
Hot Water Demand	Magnitude	Quantity of hot water used daily
	Shape	Time of peak(s) and size of peak(s). Shape of hot water use during other times, particularly pre-peak.
	Consistency	Consistency of both magnitude and shape of hot water demand, and if it changes from week/weekend, seasonally, etc.
	Predictability	How predictable is hot water use? Is variance random or explainable (for instance, weekday/weekend vs occasional large uses of hot water that are not explainable).
Price Signal	Shape	Time of peak(s) and size of peak(s) of price signal being optimized against ($, GHG, etc). Magnitude and shape of rate during non-peak times, time between peaks, etc.
	Consistency	Is the rate the same every day or does it vary?
	Predictability	Do we know in advance exactly what the rate is or are we forecasting this? How stochastic is the rate and how much does that vary from our forecasts?

Category	Variable	Description
System Design / Performance	Capacity / Recovery Times	Capacity of heat pump (BTU/h).
	Storage Volume	Volume of total storage of hot water.
	Seasonality	Change in performance across seasons (impacted by air temperatures, water temperatures, etc.)
	Ancillary Loads	Relative impact on system performance due to recirculation or other ancillary hot water loads.
	Controls Integration	Controllability of water heater operation and storage utilization can be controlled.
Risk Tolerance	Hot water runouts	Are occasional hot water runouts tolerable?
	Cost Increases	Are occasional cost increases due to optimization settings tolerable even if long-term cost reductions are present?

Optimizing GHG impacts is more complex than the other price signals tested for two primary reasons. Firstly, Price signals are highly dynamic. Unlike other price signals (such as utility rates), no two days are the same in terms of the timing and magnitude of peaks and troughs in price signal. Secondly, price signals are forecasted: Actual GHG emissions factors are not known ahead of time. Forecasts are often less stochastic than actual rates and increase in accuracy as the time-to-forecast decreases. Decisions by the LOCUS system must be made far in advance (early morning on the day of) and forecasts can change drastically over the course of the day. Due to the complexity of optimizing GHG impacts, the variables mentioned above become much more important and are multiplicative in their effect on optimization. For instance, a site that has lower average hot water demand but much greater occasional peaks may be more challenging to optimize than a site with greater hot water use overall but more consistency. Additional variables such as long recharge times or small volumes of secondary hot water storage may further multiply these challenges, and so forth.

Finally, it is worth mentioning that our ability to confidently *measure* impacts is also affected by the amount of uncertainty present in all the variables listed above and how well these variables are understood at each system. Measuring optimization impacts is more challenging for small systems with high levels of uncertainty across many variables.

High Level Quantitative Results

Results from GHG optimization using marginal GHG rates from MIDAS are listed in Table 3. Qualitative results and discussion with some examples are in the following sections.

Table 3. Summary Results from LOCUS optimization using GHG price signals from MIDAS. Note that only six systems were tested under MIDAS rates at Eureka, and monitoring issues prohibited analysis on two systems. Eureka systems are labeled with the convention FxRy where x is the floor number and y is the room number.

	System	Test Period	Average Marginal GHG Rate (kg CO_2e/kWh)	Improvement Compared to Baseline (%)
Santa Rosa	East	8/26/2024 - 10/19/2024	0.368	9.70%
	West	8/26/2024 - 10/19/2024	0.361	3.10%
Gilroy		4/22/2025 - 5/16/2025	0.258	25.30%
Eureka	F1R1	7/28/2025 - 8/19/2025	0.424	0.00%
	F1R4	7/21/2025 - 8/19/2025	0.360	10.40%
	F2R1	7/23/2025 - 8/19/2025	No Data	No Data
	F2R3	7/21/2025 - 8/19/2025	0.366	8.60%
	F3R2	7/29/2025 - 8/19/2025	No Data	No Data
	F3R3	7/21/2025 - 8/19/2025	0.351	13.3%

It is important to bear in mind that the maximum possible reductions are limited not only by algorithmic efficacy or system characteristics, but also dependent on current grid mix. Maximum reductions at certain times of year are currently limited. Spring (ample midday solar and less stochastic peaks) is easier to optimize than late summer (more limited and stochastic midday troughs), for instance. The approximate maximum possible reduction during summer periods (Santa Rosa and Eureka testing) under the current grid mix is 40-50%, but 80-90% during spring periods (Gilroy testing).[6] Therefore, a significant amount of uncertainty exists with regards to reductions possible at Santa Rosa or Eureka.

Santa Rosa

Santa Rosa was the first site that underwent GHG optimization testing and had already undergone substantial other testing of CalFlexHub price signals. Performance at Santa Rosa was excellent which encouraged grid flexibility as well. SanCO_2 heat pumps have stable COPs and capacity over a vast temperature range and ¼" piping reduced distribution losses and times. The lack of recirculation also eliminated uncertainty with regards to tank stratification and heat pump operation. Finally, while they are relatively small systems (7 occupants per system), adequate heat pump capacity (2200 BTU/h per occupant) and storage volume (23 gallons per occupant at 150°F). The impacts of system design on performance are discussed in detail in the final report and in summer study proceedings from 2024 (Pfotenhauer et al, 2024) and will not be covered in detail. The primary takeaway here is that adequate and consistent baseline performance reduces uncertainty, which is especially relevant when dealing with time-variable price signals such as forecasted marginal GHG emissions.

Fig. 4 shows the average load shape during LOCUS optimization of GHG impacts. Reductions are clearly visible; load is shifted away from evening peak and concentrated during

[6] Relative to an average minimum daily carbon intensity for a given test period. This maximum reduction is not actually feasible for any of the sites tested, as daily GHG emission factors rarely persist for long periods of time and none of the systems have great enough heat pump capacities or enough storage to actually achieve such great reductions.

the late morning and early afternoon. The East system has greater hot water demand on average and the opportunity here for shifting load was greater, but this also limits how long heat pump operation can be avoided later into the evening or early morning the next day. Day-to-day reductions vary substantially, varying daily from an 87% decrease to a 50% increase in the average carbon intensity of electricity consumed by the heat pump compared to baseline (on a $kgCO_2e/kWh$ basis). This variance is largely a function of hot water demand variability and rate forecast uncertainty. Finally, note that purely by chance, $SanCO_2$ operation was already midday peaking due to morning hot water loads; The system was somewhat optimized relative to grid carbon intensity. This, combined with muted opportunity for carbon reductions in late summer[7], results in only 9.7% (East) and 3.1% (West) system reductions compared to baseline (on a $kgCO_2e/kWh$ basis).

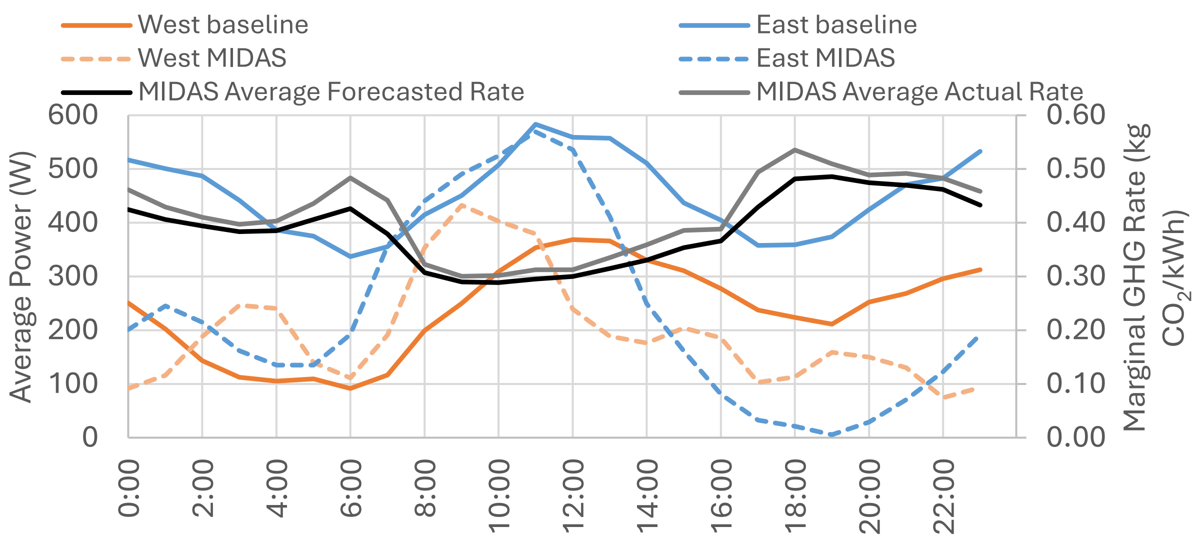

Figure 4. Average $SanCO_2$ load shape and marginal GHG emissions factors during the period of testing from 8/26/2024-10/19/2024. Baseline load shape is also included for reference. Note that on average forecasts are close to actual marginal emissions factors; see the following section for discussion of day-to-day volatility

Optimizing GHG impacts was challenging due to the unpredictability of marginal GHG rates. This is particularly salient at Santa Rosa due to its otherwise stable performance. Fig. 5 shows some example days that demonstrate the challenge of using imperfect forecasts. During the testing period at Santa Rosa, there were both daily over- and under-forecasts of marginal GHGs, resulting in the LOCUS system performing better than (9/15) and worse than (9/16) anticipated on different days. This uncertainty is the primary variable limiting GHG reductions (kg CO_2e/kWh). Also note that the GHG optimization testing at Santa Rosa was undertaken during the late summer when the grid is already constrained due to cooling loads and maximum reductions through optimization are much lower than compared to other times of year.

[7] This minimal improvement is not estimated to be representative of annual reductions but does provide somewhat of a worst-case scenario. Unfortunately, due to communication and timeline issues, testing was not reproduced during other times of year at Santa Rosa.

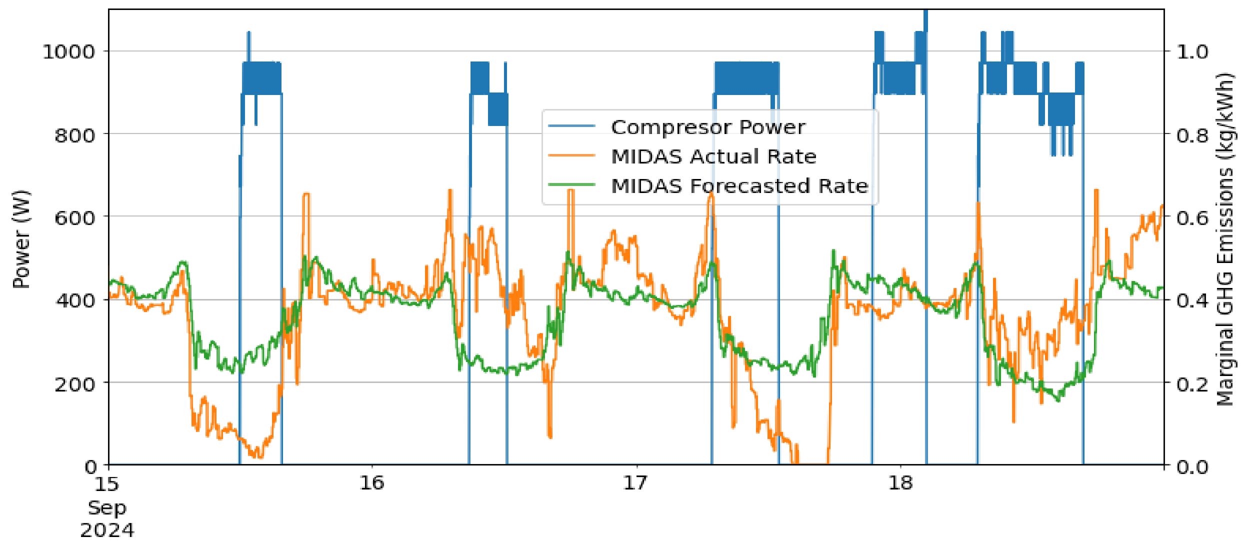

Figure 5. Example days during GHG optimization at Santa Rosa.

Gilroy

Overall, the performance at Gilroy was highly predictable and straightforward when optimizing for GHG impacts as well as under other testing (CalFlexHub, PG&E utility rates). No hot water runouts or other adverse side-effects of load shifting were noted. The system is large and hot water demand is consistent with predictable recirculation which eliminates a substantial amount of uncertainty. Heat pump capacity is also great (3333 BTU/h per occupant), allowing for somewhat more rapid adjustment if forecasts change. However, the primary limiting factor at Gilroy is hot water storage volume (1250 gallons total or 15 gallons/occupant post-retrofit). This limitation was mostly due to structural considerations; there was not enough physical space to increase secondary storage beyond 1250 gallons (from pre-retrofit storage capacity of 400 gallons or 5/gal per occupant).

Refer to Fig. 6 which shows the average load shape relative to the price signal during the period of testing. Note the substantial reductions in peak and increase in heat pump operation beginning around 8AM as solar begins to make up a greater proportion of grid load. Also note that by 8-10PM, heat pumps would need to recover despite high marginal GHG rates as storage was depleted. Despite storage limitations, consistency of hot water demand and low-carbon-intensity spring hours during the middle of the day resulted in an average carbon intensity (on a $kgCO_2e/kWh$ basis reduction of 25.3% during this period when compared to baseline. This demonstrates that while ample storage is important, predictability of hot water demand also has a substantial impact on algorithmic success.

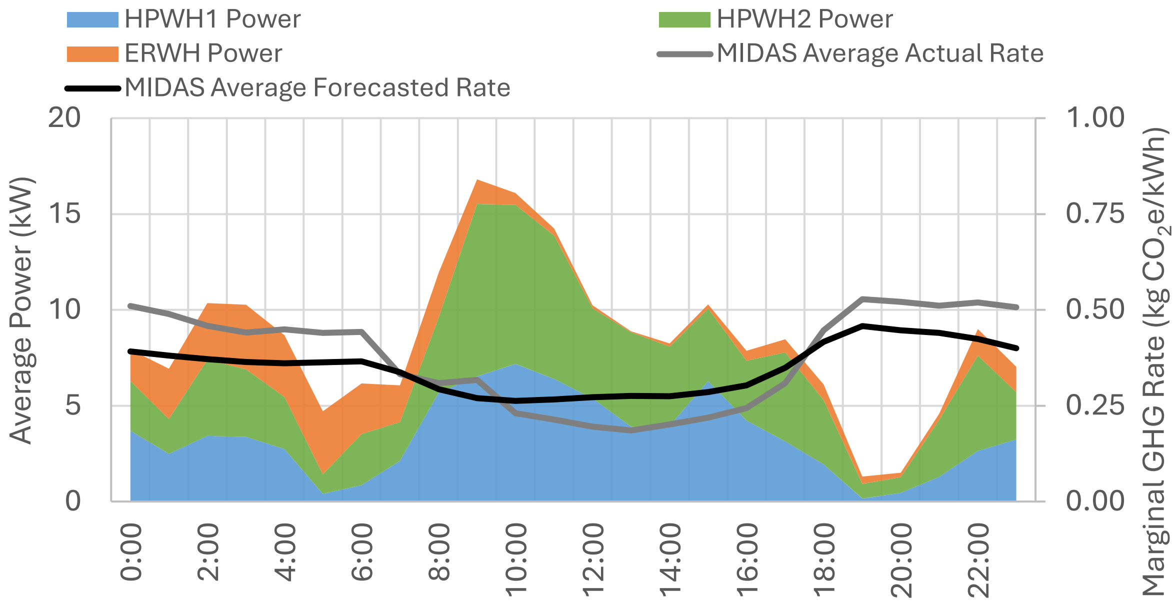

Figure 6. Average load shape at Gilroy during the period of GHG optimization (4/22/2025-5/16/2025).

Less than a week into testing the forecast data obtained from the MIDAS server reverted to what appeared to be an average annual load shape, although it was unclear exactly what it represented. This was ostensibly due to a data feed issue in the forecast, and this was not highly representative of either actual forecasts or historical marginal GHG intensities. This ultimately led to inconsistencies in LOCUS operation due to the incorrect forecast and likely had a dampening effect on the efficacy of optimization. This occurrence highlights the importance of accurate forecasts and the challenges of relying on external data for automated decision-making. See Fig.7.

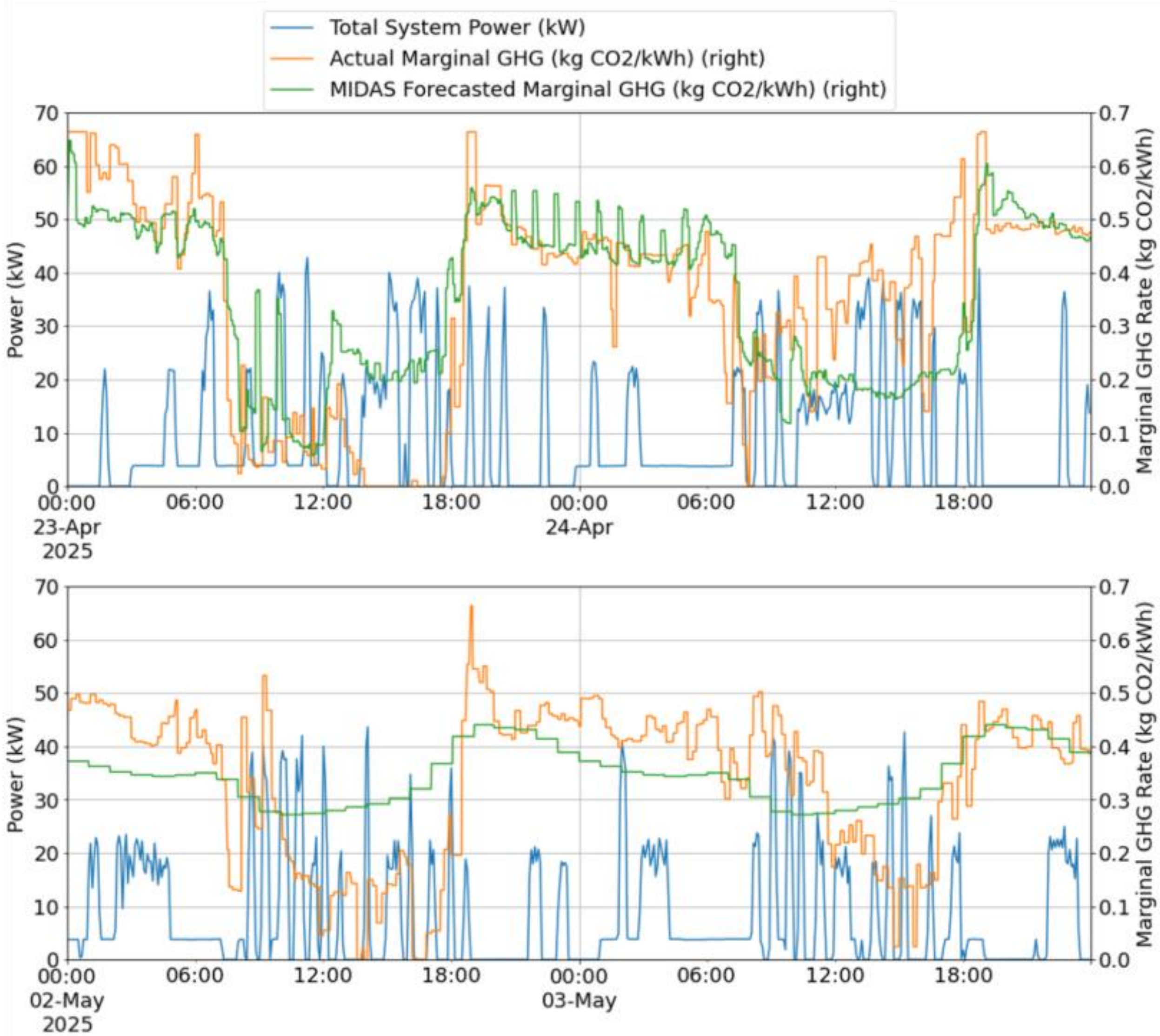

Figure 7. Subset of Gilroy GHG optimization testing using MIDAS. The upper plot represents two days where the forecast appeared to be correct. The lower plot represents a simplified forecast provided by the MIDAS server. This includes muted peaks and valleys compared to both actual marginal emissions factors and typical forecasts.

Eureka

Poor baseline performance generally led to poor load flexibility during testing. During the baseline period, most systems required resistance backup to operate especially during peak times. While the LOCUS was able to shift the time of operation of resistance backup, no amount of storage would have been able to eliminate it entirely. See Fig. 8 for an example from one of the systems. Reductions were, at best, during this summer test period approximately 10%. Testing during other seasons (spring) may have achieved better results, but long heat pump recovery times, highly variable hot water demand, and significant resistance runtimes will ultimately limit savings and increase uncertainty.

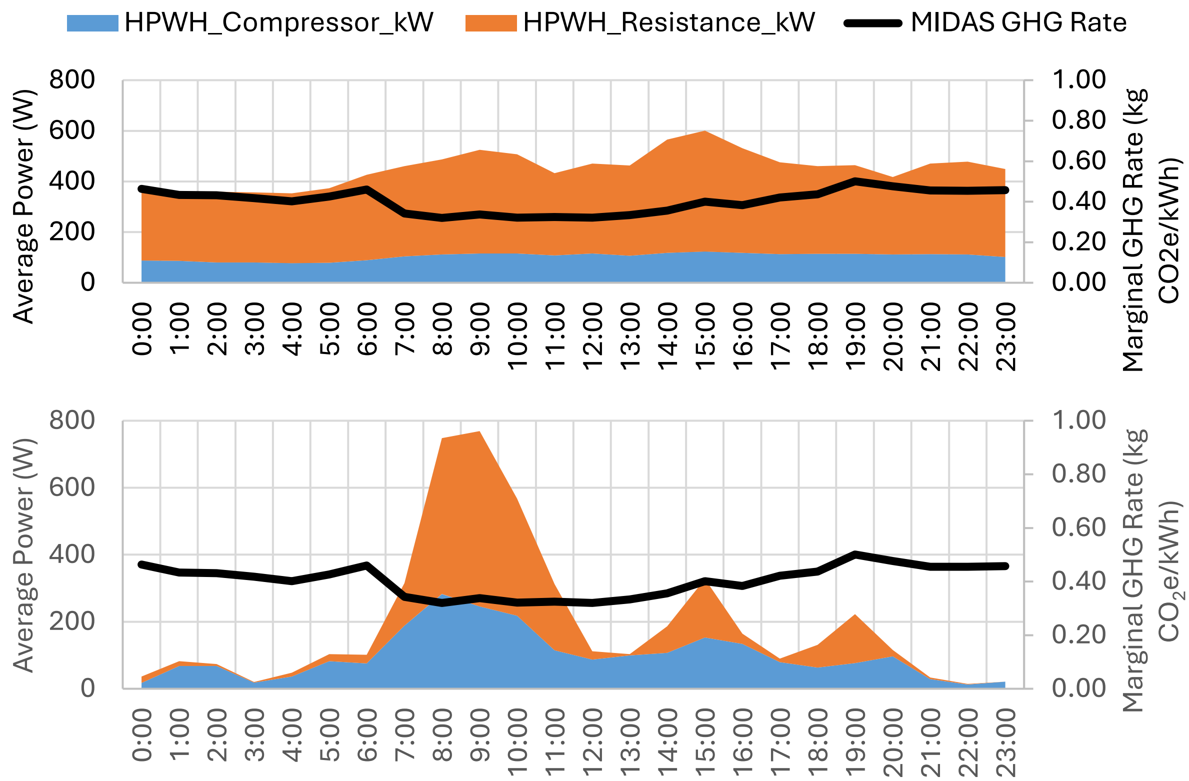

Figure 8. Average load shapes at Eureka F2R3 during GHG optimization testing using MIDAS. The upper and lower plots represent baseline and testing load shapes, respectively (average GHG price signal for reference).

Conclusions and Recommendations

The greater body of this work includes additional recommendations and learnings more broadly relevant to general grid flexibility, but most are applicable to this specific analysis.

- The LOCUS system can successfully reduce the GHG impact of water heating by shifting load to times where the grid is cleaner using GHG forecasts obtained in real time. The LOCUS can be integrated into almost any water heating system and its algorithmic efficacy depends on the quality of data given to the model.
- The consistency and magnitude of these savings is generally greater for large systems with fewer variables.
- Overall success of optimization is dependent on many factors, including hot water demand patterns, system design, and the shape of the price signal being optimized for. Additionally, the consistency and magnitude of achievable savings is a risk/reward function that is dependent on the tolerance for risk. Systems with undersized storage will struggle to fully maximize peak reductions, and systems with small heat pump capacities will struggle to shift load to low-cost times regardless of storage volume.
- Actual marginal emissions are substantially more volatile than forecasts and the timing of secondary storage charging is not always optimal as a result of inaccurate forecasts.
- Measuring savings accurately is complex, especially for small systems with many variables.

The LOCUS should be further tested under more real-world circumstances, ideally on projects that are right-sized and commissioned to avoid challenges in the implementation of the LOCUS, and an emphasis should be placed on simplification and standardization to lower product costs and maintenance needs of the LOCUS. The team encourages manufacturers of skid-mounted, standardized central HPWHs to adopt load shifting control technologies in their products via code measures, incentive programs, and educational efforts.

We also encourage central HPWH-sizing software developers (Ecosizer) and code-making bodies (e.g., CEC's Title 24) to support modeling the energy benefits of LOCUS-like technologies. Central HPWH design tools should be standardized (e.g., Title 24 with Ecosizer built-in) to be a part of all central HPWH designs and avoid the difficulties encountered with undersized storage at Gilroy and undersized heat pump capacity at Eureka. The "state of charge" of a water heater tank is hard to determine with current modeling and monitoring tools. Central HPWH Title 24 commissioning should be standardized to avoid operational problems with incorrect plumbing, miswiring, lack of insulation, and non-functioning heat pumps such as at Gilroy. The lack of commissioning makes even the best designs fail and is a common finding among projects like this.

Finally, we recommend further study of the benefit of TOU rates for load shifting with central HPWHs, which are the single largest load on the common area meter, and advance central HPWH demand flexibility within incentive programs to bring these financial benefits first to low-income housing developments and build a trained contractor network.

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