120V Induction Stoves with Battery Backup

Final Report

ET23SWE0064

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Table of Contents

Table of Tables

Table of Figures

Acknowledgements

Cher-Ae Heights Indian Community of the Trinidad Rancheria

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Executive Summary

Building Electrification Challenges in California: In the context of California's 2045 climate goals, the transition to electric cooking appliances, particularly in retrofits, poses a significant challenge. Traditional electric ranges, including induction, often necessitate costly upgrades to electrical services due to their high-power demands. This is a notable hurdle in both rural areas and urban areas across the state, where such upgrades can be prohibitively expensive. The financial burden of electrical service upgrades, ranging from a few thousand dollars to over $30,000, is a major barrier to electrification in California.

Innovative Solution Stove: The 120V battery-integrated stove, also called the “Study Stove” in this report, offers a novel solution to the problem posed by electric cooking. A 120-volt induction range with a 5-kWh battery pack effectively limits its power draw to 1200 watts while delivering high cooking temperatures, with four burners and a convection oven. It utilizes existing 120-volt circuits, which are already required by code in homes with modern gas ranges, eliminating the need for expensive electrical service and wiring upgrades.

This report delves into the implementation and potential of the studied induction stove within California's electrification framework. Central to this study was the deployment of 36 Study Stoves at Trinidad Rancheria and how doing so reduced energy bills and enhanced resilience against power outages. The research objectives outline installation, participant feedback collection, and detailed energy usage analysis.

The report outlines the methodology for data collection, encompassing participant surveys and quantitative data from the stoves' integrated metering system. The team’s initial findings indicate a notable reduction in peak power consumption. Ongoing research questions will assess the stove's performance, including its impact on cooking habits, battery longevity, and installation challenges.

In this report, the team will provide a detailed analysis of data collected, user experiences, and a comprehensive cost comparison of the Study Stove against traditional 240V stoves. The report will culminate in conclusions and recommendations for program implementation and product development, offering insights crucial to California's building electrification and climate change mitigation efforts.

Abbreviations and Acronyms

Acronym	Meaning
240V, 120V	240-Volt, 120-Volt
BMS	Battery monitoring system
CO2	Carbon dioxide
DOD	Depth of discharge
EE	Energy efficiency
GHG	Greenhouse gas
kWh	Kilowatt-hour
MIDAS	Market Informed Demand Automation Server
SOC	State of charge (battery capacity remaining)
TCO	Total cost of ownership
TOU	Time-of-use utility rates

Introduction

One of the most problematic and impactful technologies for the building electrification movement has been electric stoves and ranges, especially in retrofits. Electrical load sizing requirements for traditional ranges, even induction ranges, often force electrification projects to upgrade their electrical service, which can be costly and time consuming. To circumvent this hurdle, the manufacturer's stove product, the Study Stove, was developed, 120-volt induction range that includes a 5-kWh battery pack, enabling it to limit its power draw to 1200 watts, while still delivering cooking temperatures up to 600°F for the oven and running four induction burners at full power. Using the built-in battery pack to provide any supplemental energy, it can subsist off the existing 120-volt circuit found accompanying all modern gas ranges. Doing so avoids the need for an electrician to wire a 240-volt, 50-amp circuit to the range, and potentially avoids triggering an electrical service upgrade.

Avoiding Electric Service Upgrades

As the State of California continues to work to meet its 2045 climate goals,[1] residential natural gas and propane stoves, heaters, and water heaters will all need to be phased out. Rural areas are likely to struggle with this change, due to infrastructure requirements.[2] These areas have on average a lower number of homes on a given transformer, meaning that rural homeowners are responsible for a proportionally higher cost of upgrading the transformer to a higher capacity. In addition, more EV infrastructure will need to be added to the grid as gasoline and diesel vehicles are phased out, which only further increases the strain on the grid and makes transformer upgrades more likely.

The financial burden that service upgrades introduce is not negligible in any case. In the best-case scenario, an upgrade may cost California homeowners $2,000 for just a new electrical panel. And in the worst case, the homeowner may face upwards of $30,000, depending on the level of utility infrastructure the homeowner is responsible for, and the updates required to bring the service line and service panel up to the latest utility standards. Homeowners everywhere are vulnerable to this cost impact of electrification. This additional, hard-to-predict cost can be the hurdle that prevents a homeowner from making the switch to electric power.

In all the cases observed in this project, it is a cost-effective practice to avoid these upgrades in favor of selecting appliances that reduce the impact on the overall electrical load calculations.[3] Electric stoves are one of the major bottlenecks in residential electrification projects, due to their large contribution to the overall calculated electrical load.[4] They typically require compromises in other areas to keep a home on an original 100-amp electrical service. This is less than favorable and may lead to reduced uptake of electrification retrofits in

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[1] https://www.gov.ca.gov/2022/11/16/california-releases-worlds-first-plan-to-achieve-net-zero-carbon-pollution/

[2] https://www.redwoodenergy.net/research/service-upgrades-for-electrification-retrofits-study-final-report-2

[3] https://www.redwoodenergy.net/watt-diet-calculator

[4] National Electrical Code, Article 220

residences. Today, many multifamily and single family retrofit projects end up keeping gas onsite for this very reason — the load calculations require a service upgrade if they get rid of the gas stoves. The Study Stove, a 120V induction stove with battery backup can provide an alternative to traditional 240V stoves that will make electrification more achievable for more families in California and across the nation.

Project Goals

The goal of the project is to evaluate the impact of introducing 120V electric ranges with battery backup to communities that are greatly affected by grid instability. The project aims to look at energy usage and operational costs compared with the previous cooking systems of participants, the qualitative cooking experience of participants with the stove, and the perceived benefit of the additional resiliency provided by the battery. To observe these metrics in an area of greatest impact, the stove deployment was focused on members of the Cher-Ae Indian Community of the Trinidad Rancheria, a Native Sovereign Nation in Humboldt County spanning from Eureka to Big Lagoon. This area is one of the most prone to grid outages through downed transmission lines or fire safety shutoffs by utility providers. Additionally, rural areas like the one selected for this study are more likely to utilize propane for heating and cooking. According to the U.S. Census Bureau, nearly 30 percent of homes use propane for heating,[5] and these areas are co-located with less natural gas and electrical infrastructure, which may lead to them being hard to electrify. Therefore, we can evaluate the impact of the stove in its theoretical best-use case.

[5] US Census Bureau, ACS 2022

Objectives

Specifically, the objectives of the study were to:

1. Install 36 Study Stoves in the homes of Trinidad Rancheria members and ensure that each unit is fully functional and properly sending data.
2. Administer and collect surveys from the participants to better understand the qualitative aspects of their experience using the induction stoves, after installation, and develop testimonials.
3. Monitor the stoves after installation to collect stove electricity-use data at the 15-minute level.
4. Analyze data collected from the stoves, the surveys, and from the stove installations, to determine the product's relative total cost of ownership, compared with a 240V stove, and to develop conclusions and recommendations for potential program implementation.
5. Cite outside and forthcoming market research to determine baseline costs due to 240V stove installations and electrical service upgrades.
6. Investigate the other benefits of the stoves for residents, including the improvements in indoor air quality and reduction in propane consumption, using the data and tools available.

Project Sites

Trinidad Rancheria

The Trinidad Rancheria, established in 1906 by the U.S. Congress, is home to the Cher-Ae Heights Indian Community, a federally recognized tribe. This tribe has ancestral connections to several Indigenous groups, including the Yurok, Wiyot, Tolowa, Chetco, Karuk, and Hupa peoples. Although these tribes share cultural and historical traditions, each has its distinct heritage. The tribal administration of the Rancheria oversees daily operations, various departments, and outreach programs aimed at improving the status of its members. Over recent years, this administration has expanded to include numerous programs that focus on cultural preservation, quality-of-life enhancement, self-sufficiency, tribal sovereignty, positive partnerships, and environmental protection.

The main Rancheria lands include significant areas near Trinidad, California, and Trust lands in McKinleyville, California. Especially in Trinidad but also in McKinleyville, planned and non-planned power outages are an almost weekly occurrence, due to the rural nature of the area and the insufficient grid infrastructure that is in the process of being updated or that needs to be updated. These power outages, compounded by the inaccessibility of natural gas in Trinidad, place significant burdens on the community, including a sporadic inability to cook. To circumvent these issues, many homes (seven of the participants) in Trinidad use propane tanks as fuel for heating, water heating, and cooking (Figure 1).

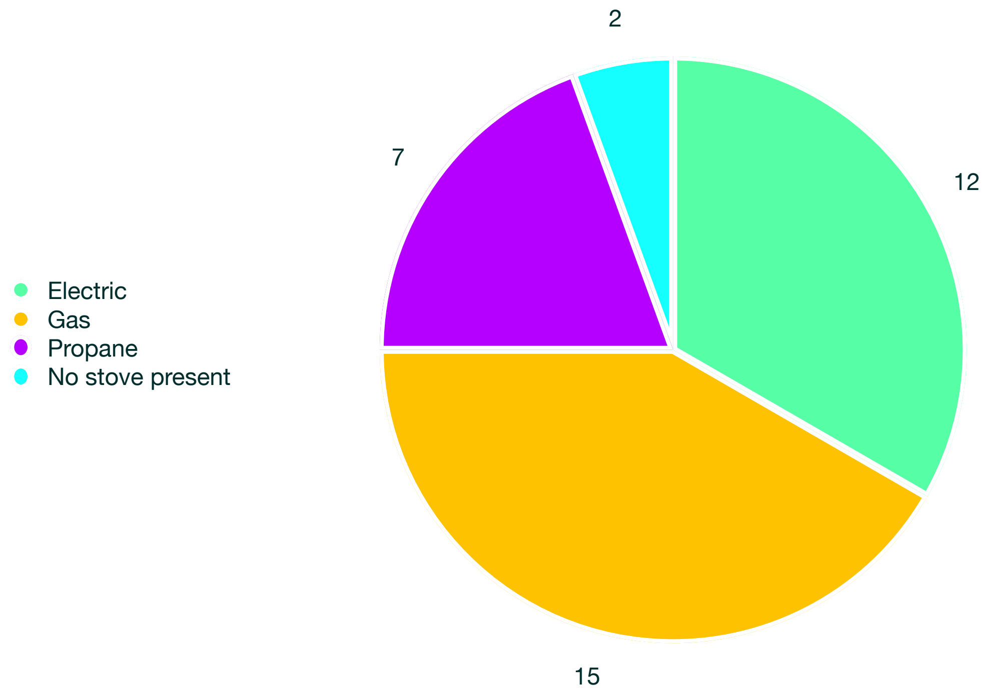

Figure 1: Breakdown of primary fuel type for cooking appliances in the home before the project for all participants.

This project site was successful at deploying 36 Study Stove units into 36 homes via partnership with tribal leadership and tribal members. These partners were able to provide the cachet needed to connect the team with community members who accepted the change to induction and inconveniences associated with installing a new stove. The team installed stoves at several Rancheria properties, the two main Rancheria properties in Trinidad, the Trinidad Off-Reservation Trust in McKinleyville, and in local members' homes. Additional tribal members home locations included Eureka, McKinleyville and Big Lagoon. In addition to the monitoring provided by the manufacturer's software developers and engineering team, the team worked closely with each home during and after installation to ensure the stove was functioning properly. The team also provided contact information to be available for maintenance calls if something should go wrong during the study or in the future.

The Trinidad Rancheria members who were interested in a stove included 42 members who signed up and 10 Rancheria staff who were interested in being on the waitlist. Initial installation began in September and 35 stoves were installed by October 1; one stove was installed on October 18 due to delays in getting replacement parts for a unit that malfunctioned due to a factory error. Each stove installation occurred only after an initial site safety visit had been completed, during which the participants agreed to keep the stove for the test period and measurements were taken to ensure the stove could be installed. If fitment was poor or there were other factors that made it dangerous or exceedingly difficult to install the stove, the home would have been disqualified in the first round. Each of the member homes that the team visited successfully qualified for a Study Stove installation; no disqualifications had to be made based on fitment, safety, or structural integrity.

Redwood Home Base

A prototype unit stove was installed on December 18, 2023, at Redwood Energy's home address and returned to the manufacturer in April of 2024. This allowed the Redwood Energy team to gain insight into how the stove performed and to have a testing space without disturbing participants at the Rancheria. The stove was used as a "daily driver," to cook for a family of five people, including children. The installation was temporary for the first few months of the project, and the stove is still owned by the manufacturer as one of their beta test units.

Figure 2: Project Team, (Dylan Anderson, left) moving the beta stove into the Redwood Energy home for testing.

During the installation and use of this beta unit, some key criteria were developed for qualifying homes for installation.

- Doorway and clear pathway of at least 28" width
  - The stove door can be removed so that the stove can be brought in sideways with a hand truck, as pictured above.
- The stove gas line must be accessible so that it can be capped.
  - If the pipe is accessible but there is no shut-off valve for the stove, the main gas line can be shut off temporarily and a valve can be added in addition to capping the line.

- Wi-Fi or cellular data connection was a requirement to receive data from the stove, and for the stove clock to show the correct time, and to provide crucial firmware updates.
  - This creates a technology barrier for people with poor access to the internet, including rural areas and people who are not interested in or cannot afford to have internet access at home.
- Setting the battery in place after getting the stove in place significantly improves the installation rigor and safety.
  - Final production units of the Study Stove did not include the removable battery. Rather, the battery was permanently installed to the chassis at the factory. This makes the installation a bit more physically challenging in terms of the stove's weight, but simplifies the installation process and allows for better quality control at the factory.

Methods and Approach

The data collection methodology for this project consisted of three major components:

7. Completing an intake form to determine if a home could have the stove unit installed.
8. Conducting surveys of each installation site to capture qualitative data and participant experience.
9. Collecting quantitative data through the built-in cloud monitoring in the Study Stove unit to develop performance analyses.

Intake

The intake form was designed to evaluate any compatibility issues with a given home and the requirements of the Study Stove unit. The form was implemented by a team member when first entering the home or when conducting a preliminary virtual tour of the home. A virtual tour as described here involves having a resident use a smart device with a camera to record points of interest for a team member to understand before scheduling an installation. Any compatibility issues with the electrical, kitchen dimensions, or presence of potential hazards were noted. The team then discussed possible ways to circumvent these barriers should any exist. If a home had incompatibility issues and if no solution was developed, the home was not considered for the installation of the Study Stove.

Out of the 36 homes screened, three homes had dimensional issues with doorways; a solution was found in all three cases. By temporarily uninstalling either the screen door or the main door, enough clearance could be generated to allow the unit through the pinch point. In the case of one home, an electrical plug was not within the range of the cord for the Study Stove unit, so an appliance-grade rated extension cord was utilized to circumvent this issue. No home that was processed through the intake system was rejected for this project.

Installation

Once a location was verified as being compatible, the participant was consulted, and an installation was scheduled. For homes with gas stoves, the assistance of a third-party plumbing contractor was needed to ensure gas lines were properly capped. This project relied on two certified plumbing companies — Poletski's Appliances and Lizard's Plumbing — for the capping and testing of gas or propane lines at the homes which originally used those cooking fuels.

For all installations, the process was as follows:

10. All pinch points from the truck to the kitchen were measured to ensure clearance. Any moveable furniture obstructing that pathway was relocated temporarily to allow passage.
11. Potential safety issues due to presence of pets or small children were identified by the team and mitigated by the homeowner.
12. The packaging was removed, and the unit was moved into position.
13. The unit was plugged in, slid into place, and the feet adjusted so the height of the unit matched the height of the participants' counters.
14. The manufacturer's app (available on Google Play and Apple App Store) was then used to connect the unit to Wi-Fi so that data could be collected.
15. All burners and the oven were evaluated to ensure functionality.
16. When necessary, a burn-in was initiated for the ovens that did not complete that process in the factory.

Survey Methodology

Upon completion of the installation and troubleshooting process, a survey was conducted with each of the 36 participants. The surveys included 10 questions designed to capture user experience, frequency of usage, and overall perception of the Study Stove unit. A template of the questions asked can be found in Appendix B. These surveys were conducted either over the phone with participants, through email, or in person for cases where the participant was unreachable by the other two methods. Answers to each question were recorded and compiled for analysis by Redwood Energy team members. Additional qualitative assessments by participants were recorded during informal interviews conducted during the span of the study. These occurred in the homes of participants visits for stove repairs or Wi-Fi connectivity troubleshooting. These assessments were compiled and used as supplementary information regarding personal experience with the range.

For collecting and processing quantitative data, free-response answers were compiled and reviewed to find common threads between responses. For multiple choice questions, the analysis was quantified as a percentage of participants for each response. In all cases, participants were informed of the information gathering process and verbal consent was retrieved before the information was included in this report. Answers were anonymized to protect participants' identity.

Unit Operation Information Methodology

Data collection used the built-in set of temperature sensors and power monitors that could identify temperature data and energy consumption, broken down by components. The data was then sent by Wi-Fi connection to a cloud-connected service where it was pulled and processed for analysis.

For the power and energy data analysis, the team conducted the following:

- Verified data collection and quality for each installation site.
- Used quantitative analysis methods, including Python and Excel, to present data.
- Summarized survey results and used narrative analysis to present qualitative survey data.
- Aggregated 15-minute demand data to find statistical averages in peak demand.
- Determined average energy consumption per hour and per day.
- Determined estimated days of use during an outage event.

Data Collection and Metering Strategy

The Study Stove units that were deployed at Trinidad Rancheria were equipped with the same data collection equipment (sensors, loggers, and gateways) included with the beta stove installed at Redwood Energy used in the preliminary findings report. However, the 36 stoves used for the main study also had sensors for cooktop power and oven element power, which resulted in some modifications to the data the team wanted to collect. Originally, the team planned to collect case temperatures and oven temperatures to use them to disaggregate cooktop power from oven power, but because it was possible to directly collect oven power and cooktop power, it was less useful to gather case temperatures and oven temperatures. This equipment included a Wi-Fi/Bluetooth-enabled gateway and data logger with temperature sensors for monitoring the oven, battery charger, and stove top. The data logger ties into a Battery Monitoring System (BMS) that tracks power usage, power to and from the battery, cell voltages, system voltage, state of charge, any system errors, and overall grid energy use, among many other data points, some of which are proprietary.

Findings

This section will highlight the main findings of both the compiled survey results and the data accrued from the integrated censors on-board the Study Stove unit.

Data and Analysis

Prototype Unit, Power out of the battery (Stove Power)

The cooking event displayed in Figure 3 included two burners and the oven being used to broil. The peak overall power that the stove pulled from the grid only very briefly exceeded 1,500 watts during this cooking event. The peak power used by the battery to run the induction coils and the oven element was 3167 watts. Of this, 1,684 watts came from what the battery had already stored, and 1,482 watts came into the battery from the 120V power cord plugged into the grid. The battery power usage closely followed the total cooking power, and when the total cooking power dipped below approximately 1,500 watts, the battery could charge.

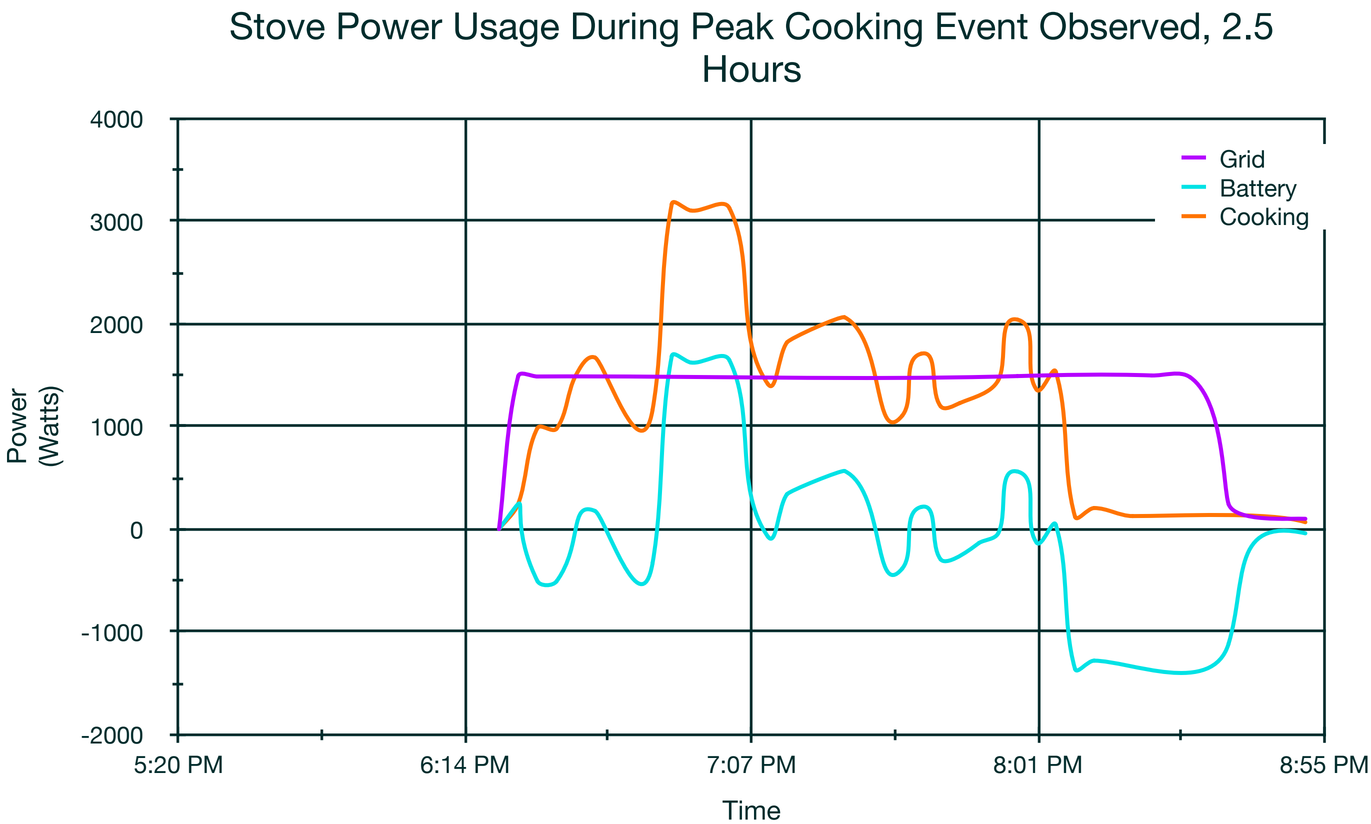

Figure 3: From the prototype unit: stove power at three different points: the grid, the battery, and the cooking elements.

Resident Cooking Usage Patterns

Residential cooking usage patterns are highly variable from resident to resident and over time. Total cooking energy demanded from the grid, including battery losses, standby power, etc. ranges from 0.6 to 3.2 kWh/day on average for residents. Of this, approximately 0.5 kWh accounts for standby loads, largely from the controller (approximately 20W continuous). Excluding standby and other losses, power used for cooking is roughly split between resident oven and cooktop demand (0.4 kWh/day for both cooktops and oven usage). The remaining power use includes the light and fans (AC powered), as well as losses incurred by charging or discharging. Figure 4 shows average breakdown of total energy used for different aspects of cooking. The exact magnitude of related charging or discharging is unknown but is assumed to be high due to inefficient trickle charging at a high state of charge.

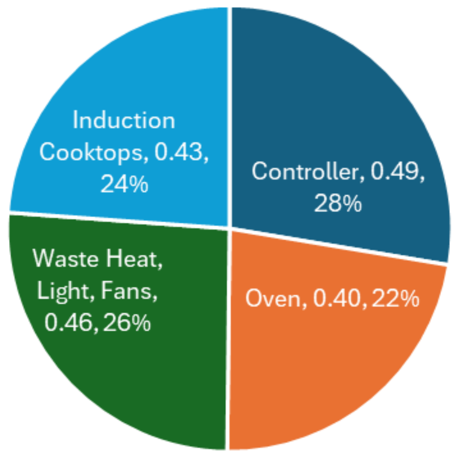

Figure 4: Breakdown of the different elements of a stove unit and their respective demand percentages from the grid.

The plot below in Figure 5 shows total daily cooking energy by residents at the grid level (includes charger and other losses). These values are predictably positively skewed in most residences, due to the presence of outliers often resulting from long oven draws. Few residences used more than 6 kWh per day during the period of record (0.7% of days). Most residences used far less, some infrequently, or not at all, as shown below.

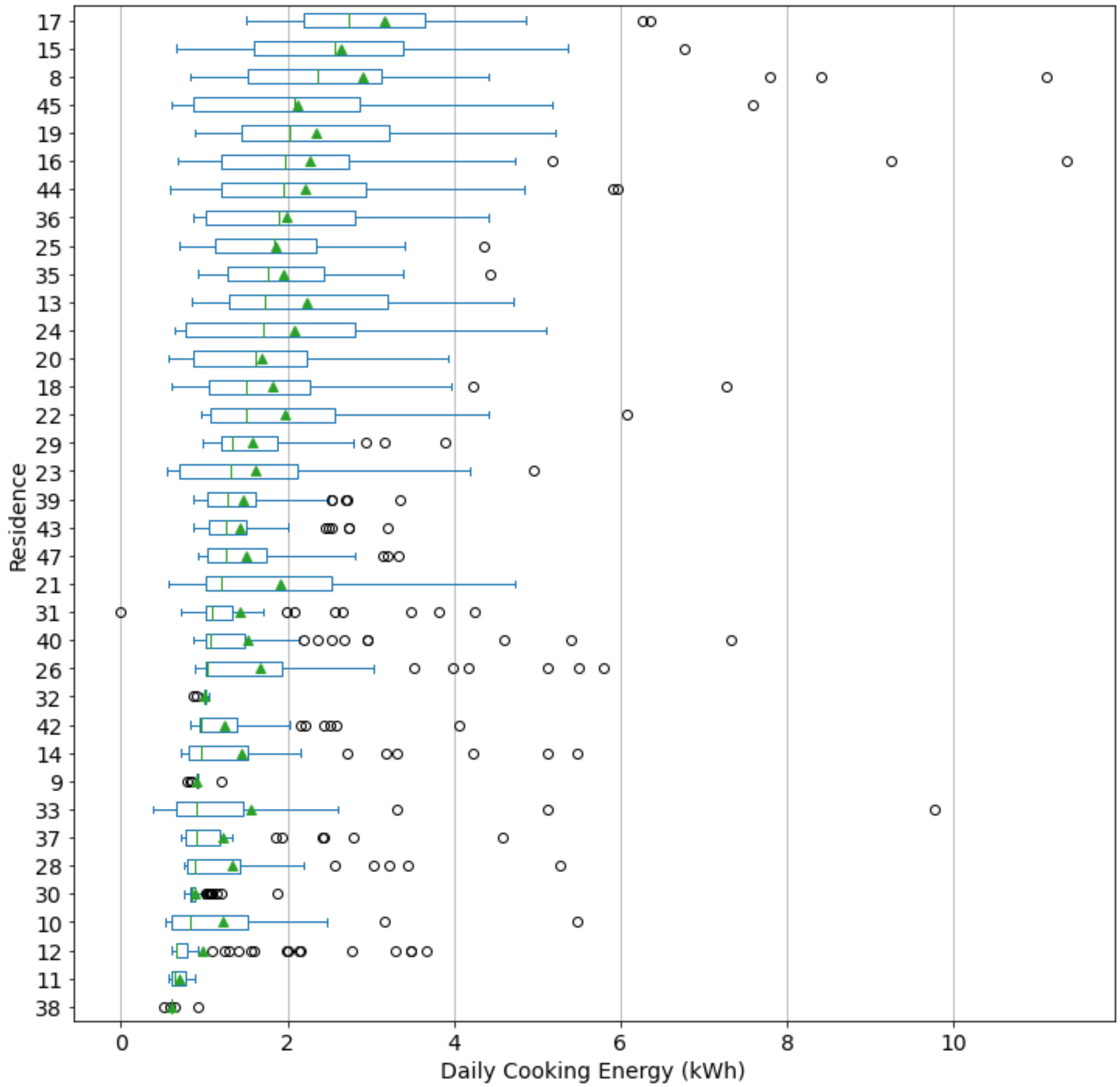

Figure 5: Side-by-side comparison of the variation between average daily energy consumption across all stoves unaffected by data quality issues.

The power use of most residents' stove peaks in the evening. In aggregate, the peak occurs from 5:30 p.m. to 7:30 p.m., with an absolute maximum at 6:21 p.m. of 187W. That 187W seems like a low figure at first glance, but because cooking events are relatively short, often lasting between half an hour and an hour, the average demand is highest where there is the most significant overlap in residents' cooking schedules. Figure 6 below shows the average hourly load shape of total power coming from the grid (including losses).

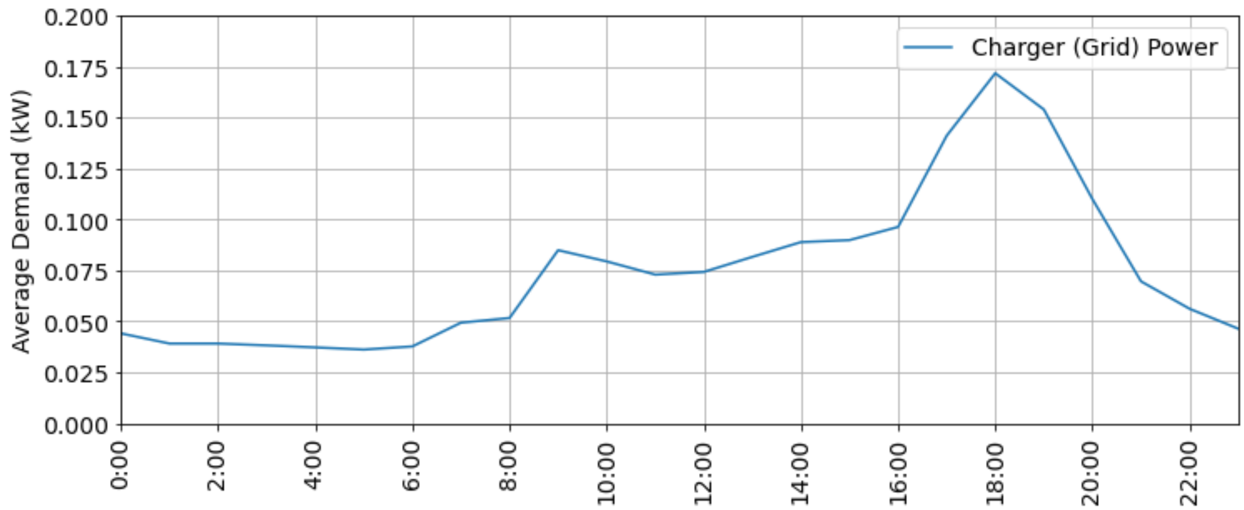

Figure 6: Average hourly power demand from the grid across all units with at least a month of data highlighting an increase in use from the 4-to-9 p.m. time period.

With the unscheduled charging mode in use for the period of study that this data comes from, the charging pattern precisely follows the energy demand pattern from the battery. When charging can be scheduled during the hours of 10 a.m. to 4 p.m., the charger power and the power demand on the battery will become delinked. Figure 7 shows a breakdown of time-of-demand from all loads in the stoves, including all auxiliary loads and losses (averaged across all residences).

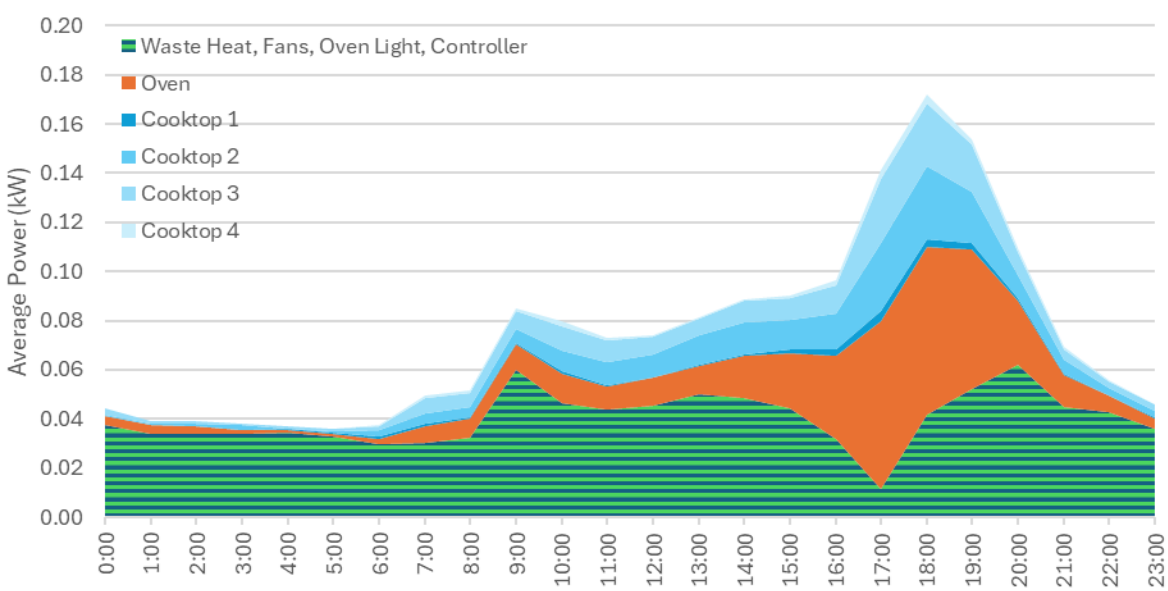

Figure 7: Breakdown of average power demand by hour and by element showing the influence of oven usage on grid demand.

Figure 7 illustrates the average power demand across different stove components over a 24-

hour period, capturing the energy use patterns throughout a typical day. The various components include the cooktop burners (labeled as cooktop 1 through cooktop 4), the oven, the controller, and miscellaneous loads like waste heat, fans, and the oven light.

From midnight until early morning, power demand was consistently low across all components, with minimal activity in the cooktop burners and oven. The primary power consumers during these early hours were the controller (in blue) and the miscellaneous loads (in green), which contribute a low but steady baseline power usage.

In the late morning, there was a gradual increase in power demand, particularly in the cooktop burners, which suggests a rise in cooking activity. This rise became more pronounced in the afternoon, peaking between 5 p.m. and 8 p.m. During this time, all four cooktop burners (shaded in light blue, representing individual burners) were active, and the oven (in orange) also showed a marked increase in power consumption. This peak corresponded with dinner preparation, where multiple stove components were used simultaneously.

After 7 p.m. (19:00 in Figure 7), power demand steadily decreased as cooking activities would wind down. By late evening, the usage levels dropped back to the baseline seen in the early morning, dominated once again by the controller and auxiliary loads. The pattern here is typical for U.S. residential stove use, with the bulk of energy demand during waking hours and most energy use associated with dinner time.

COMPARISON TO OTHER STUDIES

There are few highly accurate cooking studies available, and cooking is a very demographically sensitive and individually variable end use. Still, a comparison with other models or previous studies provided some context to this project, referred to as the "CalNEXT Study" in figures below. Figure 8 below shows per-bedroom data from this study and others (as well as various models that lean on meta-analyses). Note that five- and six-bedroom residences are small in number in this study and not statistically significant.

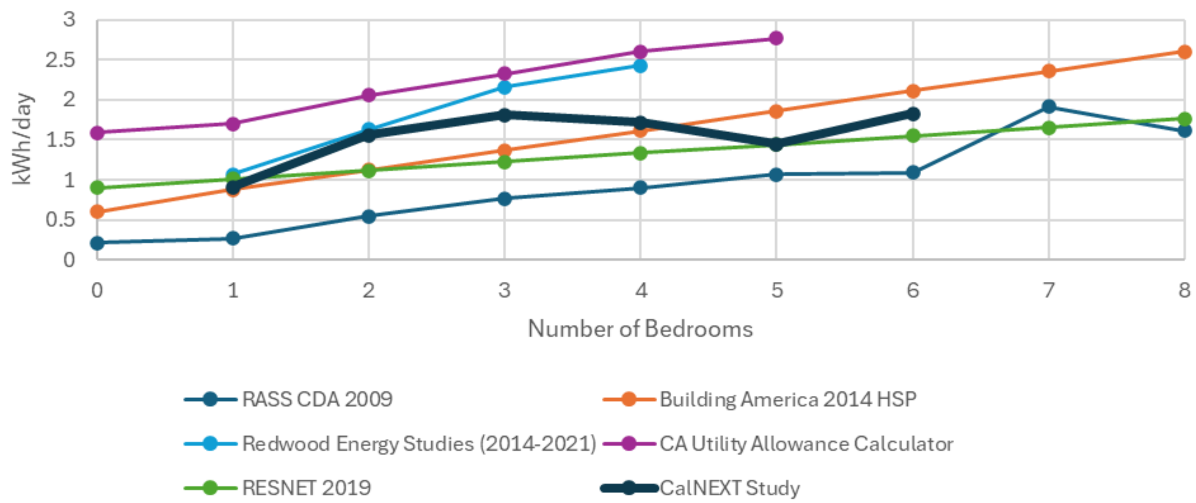

Figure 8: Energy usage and quantity of rooms in this 2024 CalNEXT study, compared with other recent studies showing a close correlation to the RESNET 2019 study for the Rancheria.

The figure below compares our 2024 CalNEXT Study to the Redwood 2014-2021 cooking study alone. While there are nuances, the overall load shape and magnitude are remarkably similar. Controller power and other losses are of course present in the CalNEXT Study data, so nighttime loads are higher.

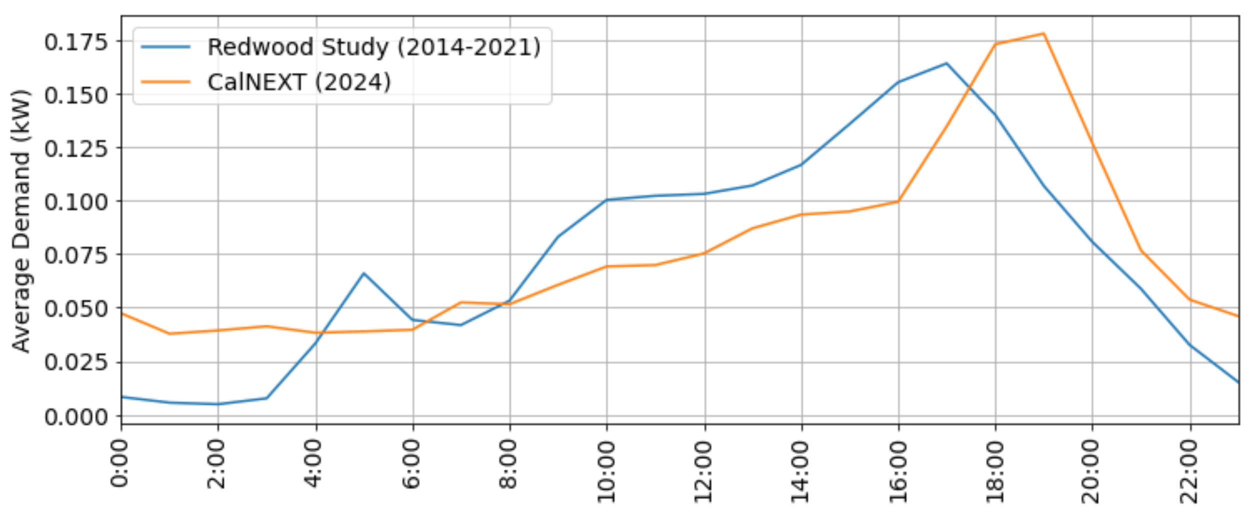

Figure 9: A comparative look at the average energy consumption by hour for the participants in this CalNEXT study versus the previous studies conducted by Redwood Energy across various locations in California and Oregon.

Battery Charging Power

The Study Stove has a total battery capacity of 5 kWh. The exact charging efficiency relative to a given state of charge is unclear, but the grid charging power was measured at 1.25kW (10.4 amps at 120V AC). This means that the battery can charge at a max rate of 0.25C, or a full charge in four to five hours. When charging occurred it was consistently 1200W with little fluctuation. In practice, other loads on the circuit could impact the current available to charge, but this was not apparent among any of the residences in this study.

A firmware update is in the process of being released to the Trinidad Rancheria stoves after the time of release of this draft of the report. Due to this time conflict, the team was not able to make use of data that includes this firmware update. This firmware update makes significant changes to the functionality of charging and addresses several complaints from residents in other areas of functionality, such as error messages and the length of time that fans run after cooking is complete. The change to the charging pattern will create a default schedule for charging, between 10 a.m. and 4 p.m. local time, except for the third week of November (which includes the U.S. holiday of Thanksgiving, which several participants from the Rancheria indicated they participate in). During hours outside the 10 a.m. to 4 p.m. range, the stove will only charge itself if its state of charge falls to below 45 percent. This default charging schedule provides enough charging time to satisfy the charging needs of all of the participants based upon the data the team has collected. The decision by the manufacturer to move to this charging schedule is informed not only by the stoves installed as part of this project but also by the stoves from orders that they have been fulfilling in the Bay Area and elsewhere.

Battery Sufficiency for Cooking Times

It is important to understand what fraction of cooking behavior can be supplied by the stove. There are several ways to look at this. The first is to simply consider a fully charged battery (5 kWh) and a reasonable charging/discharging efficiency of 0.8. In other words, the stove can indefinitely supply at least 1 kW of power. Only 6 percent of all one-hour periods exceed 1 kWh of demand. In other words, for 94 percent of the study period, the units' charging capacity exceeded demand.

If we look at the average state of charge during the period of record, we can see that no runouts occurred. Figure 10 below shows both the minimum and the 99th percentile state of charges for each unit. One stove fully discharged due to a long, resident-managed power outage,. There are a few stoves that were installed in homes in which the gas stove outlet was connected to a light switch in the home. If the local Wi-Fi router is still connected to the stove and powered on, the stove will continue to send data to the cloud, even though the stove is no longer connected to AC power.

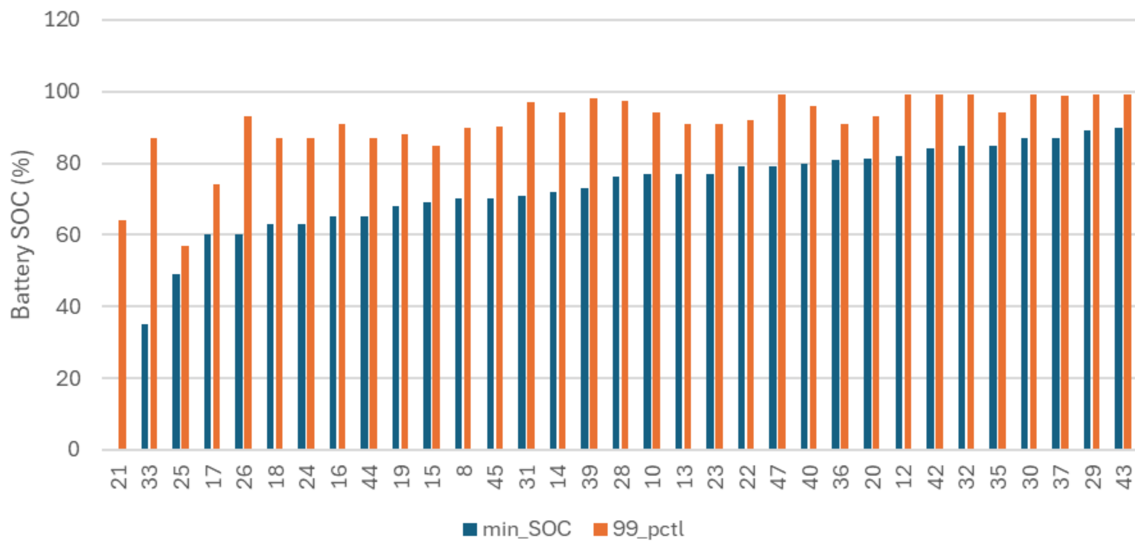

Figure 10: Individual profiles for a subsection of the stoves, showing the minimum and 99th percentile states of charge across the study period, to depict the range of values.

A particular concern for a battery-connected stove is the risk of running out of battery capacity to deliver the power needed for cooking. During our study period, this never occurred in any household, although it is theoretically possible. One way to calculate the probability of a runout is to first look at energy demand by the stove on rolling five-hour periods and then count how many times this threshold was met, to determine the possible presence of runouts. The stove can recharge itself fully in five hours or less with no demand. It is therefore conservative to assume that, as long as the requested power does not exceed 5 kWh in a five-hour period, the stove can indefinitely supply power for cooking needs. In Figure 11 below, a rolling five-hour sum was calculated for each resident to determine the probability of such occurrences. Only a couple events exceeded 5 kWh in a five-hour period, and none of these residences had fully depleted batteries (see previous figure). Finally, it should be noted that this is a highly conservative measure for assessing availability for cooking. If an event begins with a full state of charge, the system should be able to provide at least 10 kWh during this five-hour period (excluding load shifting or power outages).

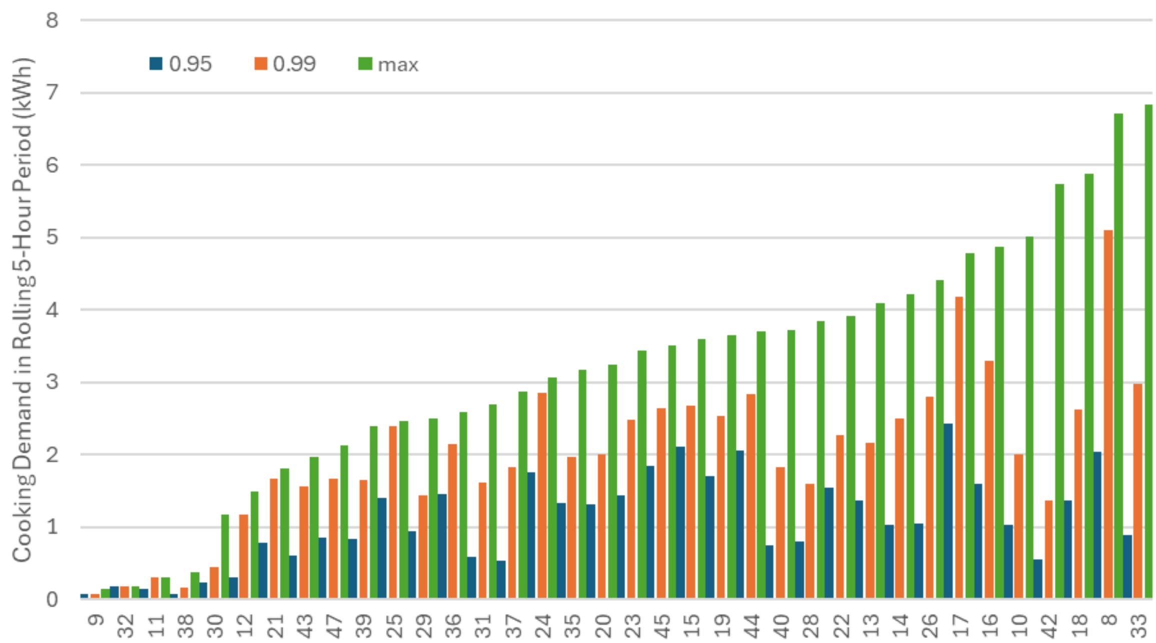

Figure 11: Comparison of the cooking demand across all stoves showing the relationship between common cooking events and the outlier events for each participant.

Load Shift Capability

Charging scheduling is not available yet but will be provided to stoves as part of a software update. The most recent firmware update, which the team's data was unable to include, due to the short period of time the team had the stoves, sets the stove to only charge during the hours of 10 a.m. to 4 p.m. Currently, the most recent version of the firmware limits the battery state of charge without charging to 45 percent, or effectively 2.75 kWh of battery capacity.

Table 1: Comparison of Price Estimations for Stove Usage Across Common Price Schedules for a Load-Flexible Approach Versus the Current Unscheduled Approach

PG&E Residential TOU Rate	Max Annual Value with 10 a.m. – 4 p.m. Charging Period	Annual Value Based on Unscheduled Charging
TOU-C	$54.60	$14.13
TOU-B	$67.21	$17.39
TOU-D	$71.08	$18.39

Resiliency

One of the key metrics and goals of this study was to determine the benefit to individuals who experience grid outages. During a power outage, the unit can supply grid-disconnected power by discharging from the battery and supplying DC power directly to mostly all the components, and through a small inverter, for the few components that require AC power. Over the span of the study, no grid outage data could be recorded for any participant due to the loss of Wi-Fi during grid outages, which was an unexpected outcome. However, due to electrical limitations or the direct actions of a participant, two units did experience artificial outages. For units 17 and 21, time-series data are shown in Figure 12 below, illuminating how the stoves behaved during these simulated events. For Stove 17, the circuit that supplied grid power to the stove was controllable by a light switch. Thus, anytime the participant shut off the lights on that circuit, the stove disconnected from the grid as well. This gave the team the opportunity to observe the unit's state of charge while disconnected. The longest period of time that the stove remained disconnected was 14.8 hours. During that time, approximately six percent of the total battery was expended. From this, it can be extrapolated that this stove has an upper limit of 10 days before the passive energy consumption depletes the battery.

Figure 12: Time-series data for Stove 17, showing the battery state of charge and power during a series of temporary outages.

The 20W standby load results in a 10 percent drawdown per day, so the length of time the stove is available caps out at approximately 10 days. Based on the cooking habits of this cohort, the actual time period ranges from 1.9 to 8.1 days. Of course, long-term outages are likely to affect behavior in several ways, so this value could vary substantially. Days of off-grid usage, a measure of resiliency, is shown in Figure 13, and calculations assume no change in behavior (emergency cooking, shifting microwave use to stove, etc.).

The box-and-whiskers plot compares the power usage of the Study Stove across various residential units, providing insight into demand variability and energy resilience needs. Each row represents the energy usage distribution for a particular unit for each day of the study period, showing the median, interquartile range, and outliers. This helps explain the stove's energy demands and assess the stove's built-in battery's capacity to meet these needs during peak cooking energy use events.

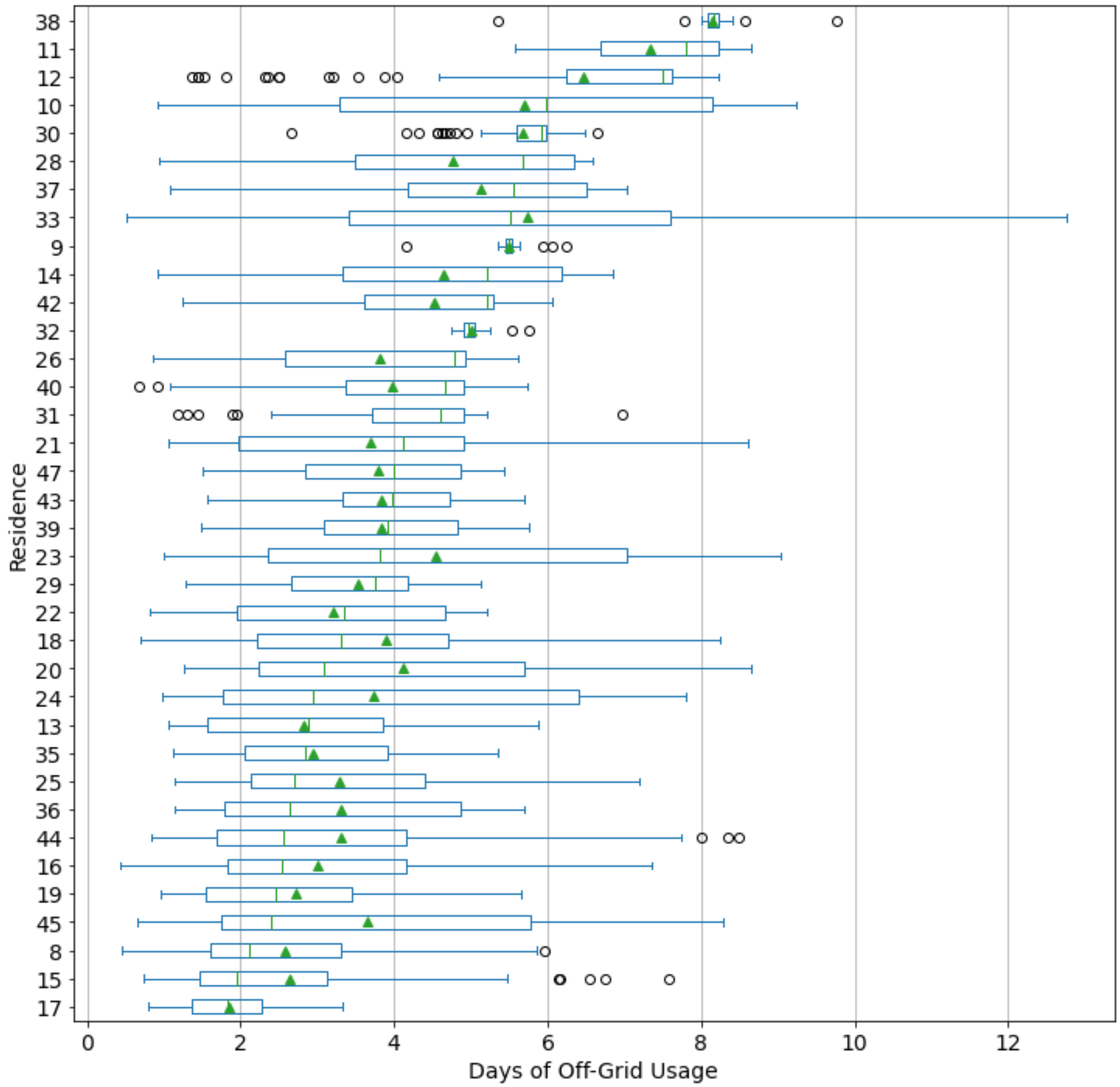

Figure 13: Predictive look at variance in resiliency (days of off-grid usage) based on usage patterns for each participant. These calculations assume no behavioral change by participants.

OBSERVATIONS

- **Power usage variability**: Across units, daily energy demands vary significantly, with some units having higher median usage and broader interquartile ranges, while others have lower and more consistent demands. This variability indicates the degree to which the stove usage patterns are affected by household size, cooking frequency, or specific user cooking and meal preferences.

- **Battery capacity and daily load**: With a 5-kWh nominal battery, the stove has enough capacity to cover moderate cooking activities throughout the day. For units with lower median power usage, this battery capacity could potentially meet most or all of a day's energy demands. For units with high usage, the battery may require intermittent recharging to avoid depletion. Within the 10 a.m. to 4 p.m. charging schedule, in some homes and on certain days the battery may begin charging during peak time-of-use rate periods. However, this behavior's effect on grid demand during high time-of-use rate periods is mitigated heavily by the fact that the charger will pull a maximum of 1250W from the grid, which is very significantly less than the draw of a 240V induction stove.

- **Recharge rate and resiliency during outages**: The 1.2 kW charging rate allows the stove to replenish its battery over at least five hours. In units with lower average usage, this recharging rate could be sufficient to maintain an adequate charge level throughout the day, especially if coupled with time-of-use optimization to charge during off-peak periods. However, units with higher usage may need supplemental energy sources or load management to ensure continuous operation during extended outages.

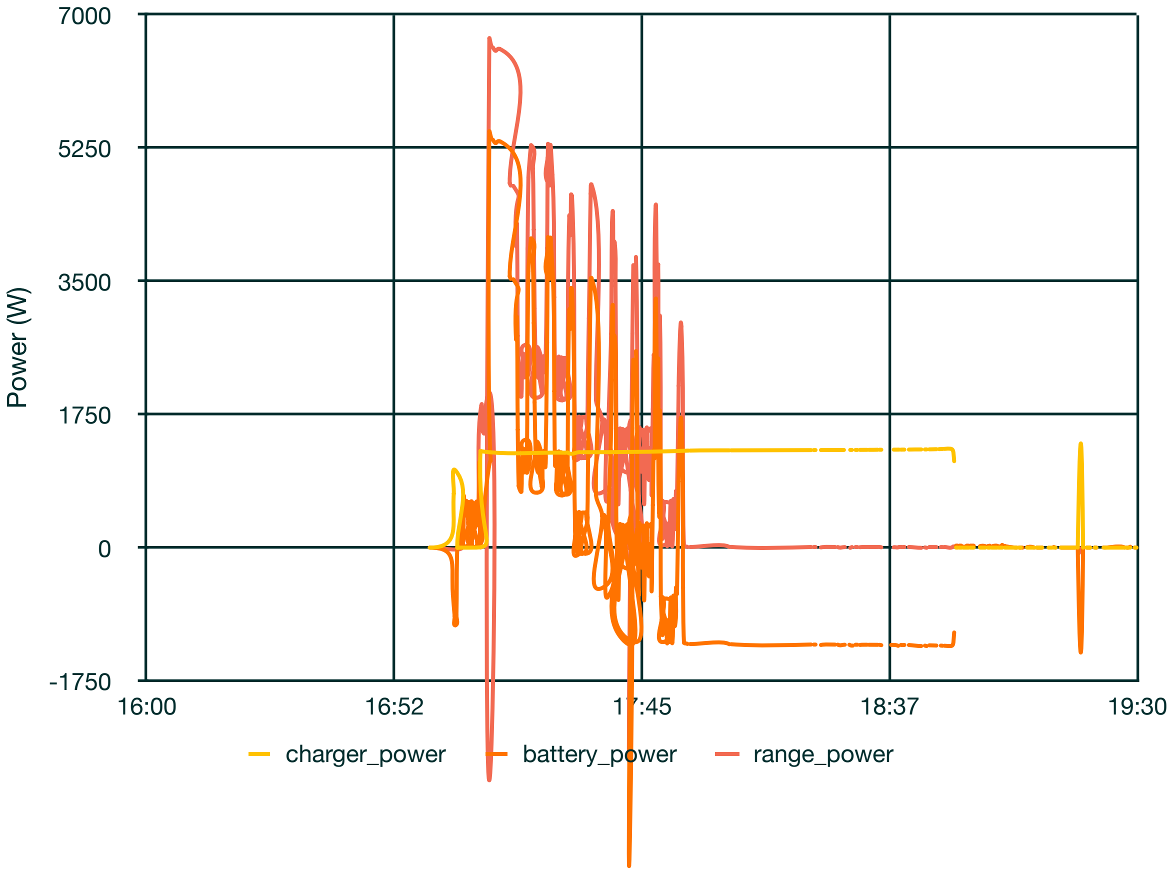

Figure 14: Time-series data highlights the most power-intensive cooking event observed.

Figure 14 shows the peak power-demand cooking event observed in our study. The data resolution is 12 seconds, meaning a data point was collected and stored every 12 seconds. During this cooking event, the oven and the range were both in use. The convection fan was observed to be running from 17:12 to 17:54, as was the oven light. The peak total power drawn by the stove from the battery was 6687 watts, which would have been 27 amps on a 240V stove as observed by the electrical panel. During this event, the battery charger drew a peak power of 1260 watts from the grid, and the battery supplied a net 5,465 watts of power “off-grid” for that moment. The electrical panel in the home would have observed 5.25 amps of load on the main breaker, and 10.5 amps of load on the 120V 15A breaker that the stove is connected to. While the team was not able to find out from the participants what they were cooking this evening, it was possible to dive deeper into the data collected by the stove for debugging.

Figure 15: Breakdown of the position each stovetop element was set to during the peak cooking event.

During this event cooktops 2, 3, and 4 on the unit were observed to be engaged, with varying power levels not exceeding 20 percent. Qualitatively, 20 percent power is used for a low heat, like keeping a medium pot of soup hot or for making a roux, bechamel, or fondue. Ten percent is used for an exceptionally low heat like keeping chocolate or butter melted.

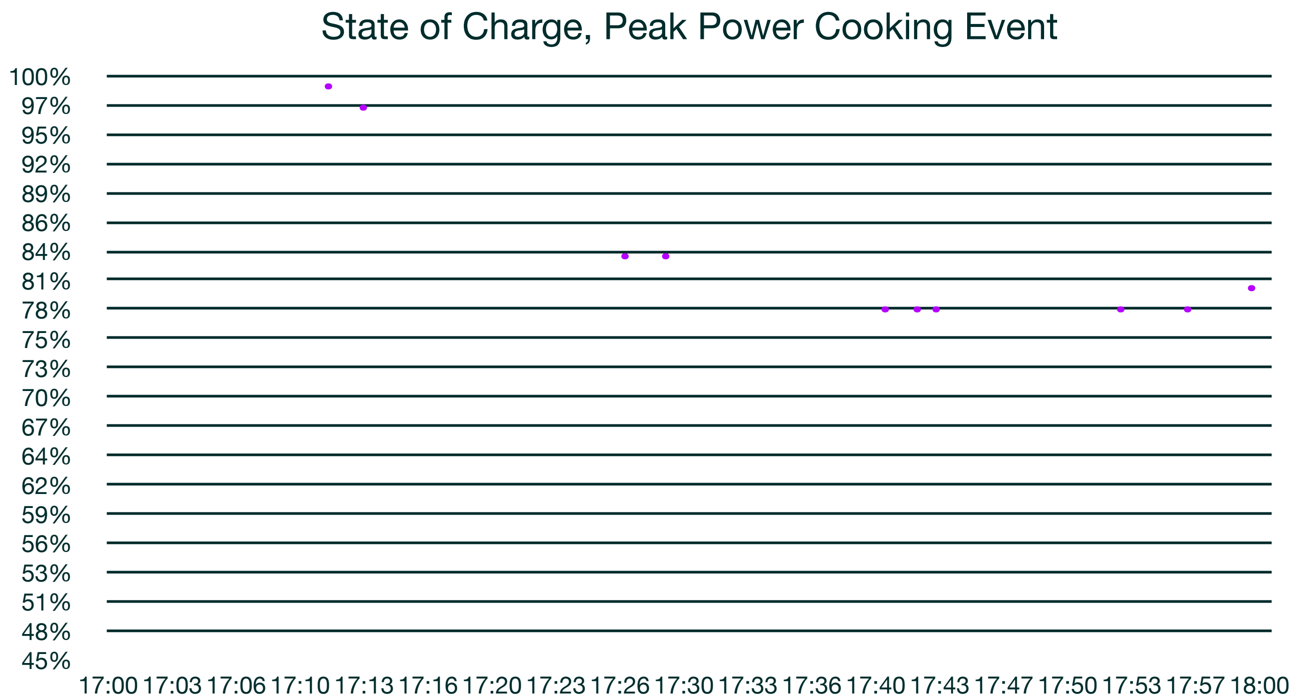

Figure 16: State of charge over time for the peak cooking event showing the depth of discharge the battery experienced through the event.

Over the course of this cooking event, 2.03 kWh of energy was used by the stove. Of that, 1.19 kWh of energy was the change in state of charge, which dipped to 77 percent at 17:44 and slowly began to recover after that (Figure 16). This cooking event occurred before the firmware update that will change the charging schedule. Had this event occurred post-update, with a starting state of charge of 100 percent, the stove battery would have hit 59.4 percent by the end of this event and would have avoided pulling power from the grid at all during the peak rate period.

Total Cost of Ownership

The total cost of ownership (TCO) comparison in Table 2 highlights the cost benefits and considerations of different stove types in Pacific Gas and Electric (PG&E) and Sacramento Municipal Utility District (SMUD) territories over 10, 15, and 20 years. The typical gas stove offers the lowest upfront cost at $1,300, with a low yearly energy cost of around $56.23. Over the course of 20 years, this results in a total cost of ownership of approximately $2,425. The Study Stove and any typical 240V induction stove are much more expensive to operate than a gas stove, based on current electric rates and gas rates — high electric rates are a cost barrier to electrification. Electric rates, in particular in the CPUC-regulated IOU territories, have been rising faster than inflation for several years in a row at the time of writing, making it difficult to model the total cost of ownership reliably for any electric appliance in this environment.

Table 2: A Comparative Cost Analysis For Study Stove Versus Potential Alternatives

Total Cost of Ownership of Various Stoves and Configurations				
Typical Gas Stove TCO				
Stove Cost	Yearly Energy Cost	10-Year TCO	15-Year TCO	20-Year TCO
$1,300.00	$56.23	$1,862.29	$2,143.44	$2,424.58
Typical 240V Induction Stove TCO				
Stove Cost	Yearly Energy Cost	10-Year TCO	15-Year TCO	20-Year TCO
$1,500.00	$233.62	$3,836.18	$5,004.28	$6,172.37
Study Stove TCO With Rate Arbitrage				
Stove Cost after Federal Incentive	Yearly Energy Cost	10-Year TCO	15-Year TCO	20-Year TCO
$4,200.00	$238.64	$6,586.35	$7,779.53	$8,972.71
Study Stove TCO in SMUD Territory				
Stove Cost after Federal Incentive	Yearly Energy Cost	10-Year TCO	15-Year TCO	20-Year TCO
$4,200.00	$86.71	$5,067.10	$5,500.65	$5,934.20
Study Stove TCO With Rate Arbitrage + 0.5 kW Solar Offset				
Stove Cost + Solar	Yearly Energy Cost	10-Year TCO	15-Year TCO	20-Year TCO
$5,600.00		$5,600.00	$5,600.00	$5,600.00

In a utility territory with rates that are more comparable to the rest of the United States, 20 years on, through rate arbitrage and without any other intervention, the Study Stove is less expensive to own than a $1500 240V induction stove is in PG&E territory. However, the benefit of lower rates will also apply to a typical induction stove, which would have a 20-year total cost of ownership of $2,768. Applying an intervention such as installing at least 500 watts of solar along with the Study Stove, which would be enough to offset the average yearly energy use of the stove in most of California, brings the total cost of ownership down enough to match a typical 240V induction stove, even with the added cost of the solar.

The total cost of ownership for Study Stove is always lower than that for the cost of installing a 240V induction stove that requires a panel or service upgrade.

Table 3: Cost Comparison Of Electricity Across Different Rate Plans And Load Flexibility Strategies

PG&E 2024 Residential Electricity Rate	Average Annual Value of Battery Arbitrage with 45% SOC Charging Floor	Annual Value Based Solely on Using 120V Charger – Unscheduled, No SOC Floor, Setpoint 100% SOC	Average Yearly Energy Cost Without Battery Arbitrage	Average Yearly Energy Cost With Battery Arbitrage	Equivalent Gas Stove Energy Use Cost at Tier 1 PG&E Rate Oct 2023 – Oct 2024
TOU-C	$54.60	$14.13	$333.74	$279.14	$56.23
TOU-B	$67.21	$17.39	$293.67	$226.45	$56.23
TOU-D	$71.08	$18.39	$309.72	$238.64	$56.23

Table 3 shows the potential energy cost savings of using the Study Stove with different PG&E residential time-of-use ("TOU" in the table and below) tariffs in 2024, comparing costs with and without battery arbitrage and with unscheduled 120V charging. It also shows the equivalent cost of a gas stove under PG&E's tier-1 rate for reference.

17. **TOU-C Plan:** Under the TOU-C rate, using battery arbitrage (charging at off-peak times) can yield an annual savings of up to $54.60. When charging solely with a 120V charger and without a state-of-charge floor, the yearly savings are lower at $14.13. Without battery arbitrage, the average annual energy cost is $333.74, but with battery arbitrage, it reduces to $279.14, showing a substantial cost benefit. However, when compared with a gas stove, which only costs $56.23 annually, TOU-C remains significantly more expensive, despite savings from battery arbitrage.

18. **TOU-B Plan:** This rate plan offers higher savings than TOU-C, with a maximum annual arbitrage value of $67.21, due to its greater variation between peak and off-peak rates. With 120V unscheduled charging and a setpoint of 100 percent state of charge, the yearly savings reach $17.39. The average yearly cost without battery arbitrage is $293.67, but by leveraging battery arbitrage, this cost can be reduced to $226.45. While TOU-B brings the total cost closer to the equivalent gas stove energy cost, it still remains higher overall.

19. **TOU-D Plan:** TOU-D provides the highest potential for battery arbitrage savings, reaching up to $71.08 annually. Charging solely on 120V without scheduling the charging and with a battery setpoint of 100 percent state of charge brings the yearly savings to $18.39. Without battery arbitrage, the energy cost per year is $309.72; battery arbitrage reduces it to $238.64, indicating that TOU-D is beneficial for those who can take advantage of off-peak rates. Nevertheless, even with TOU-D's cost savings, gas remains a significantly lower-cost option at $56.23 per year.

Overall, while battery arbitrage provides meaningful savings across all rate plans, TOU-D offers the highest potential for reducing costs. Table 3 highlights that, though more efficient than typical induction stoves, the Study Stove with battery arbitrage still incurs higher energy costs than a gas stove in PG&E territory, primarily due to electricity rates.

Table 4: Estimated Payback Period For The Study Stove Unit, Given Various Rates, Battery-Enabled Load Shifting, And Solar Offsetting Strategies

Payback Period of Various Installation Scenarios				
PG&E Residential Time-Of-Use Rate	Simple Payback of Stove with Rate Arbitrage	vs. Gas Conversion Only, Including Wiring	vs. Gas Conversion and Electrical Panel Upgrade Only, No Service Wire Upgrade	vs. Gas Conversion with 0.5 kW Solar PV Offset (100% Yearly Energy Offset)
TOU-C	77	40	-5	14
TOU-B	62	33	-4	16
TOU-D	59	31	-4	15

Rate arbitrage alone is not enough to overcome the high initial cost of the Study Stove, compared with other alternatives. In this scenario, the Study Stove is installed to replace a standard 240V induction stove with no electrical work needed. Because there is no efficiency gain, even with the relatively low to non-existent installation costs, the benefit of rate arbitrage alone is not enough to create a payback within the lifespan of the stove. The upfront cost of the Study Stove is currently $6,000, which, after federal tax credits, comes to $4,200.

Comparing the installation of a Study Stove in a home that had a gas stove to the cost of converting that home to a 240V induction stove without a service or panel upgrade shows that the lower cost of installation alone is not enough to overcome the high upfront cost of the Study Stove. The cost of an induction stove was modeled at $1,500, and electrical work was modeled at $500.

AVOIDING SERVICE UPGRADES

In a comparison of Study Stove installation versus the cost of converting a gas stove to a 240V induction stove plus service or panel upgrades, there is an immediate payback for choosing the Study Stove. This payback is due to the cost of a panel upgrade alone, even ignoring potential costs incurred by the customer from the utility due to a service upgrade.

One of the best use-cases for the Study Stove is preventing service upgrade requirements in homes that are electrifying. Service upgrades in single family homes can be prohibitively expensive, from $2,000 to more than $30,000 if a transformer upgrade is triggered by that homeowner. More typically, the all-in cost to the customer of a single-family home service upgrade ranges between $5,000 and $10,000. That range is about what an expected passing first quote from an electrician might look like for the utility side of costs before generating a full bid, but often electricians working with customers cannot predict exactly what will be required by the utility until the utility completes its engineering review. This high and variable cost risk compounds in mixed-fuel apartment complexes with gas stoves. Low-rise and especially high-rise apartment buildings can incur extremely prohibitive costs if required to perform a service upgrade in every unit. Most mixed-fuel apartments in California do not have a 240V circuit in any of the residential units, unless there is a centrally ducted air conditioning system on the tenant electrical panel. By avoiding a service upgrade for every unit in the complex or high-rise, ownership of apartment buildings could save hundreds of thousands of dollars at each property by installing the Study Stove rather than a typical 240V induction stove.

Lithium Iron Phosphate Battery Chemistry and Lifespan

As the Study Stove is a new product and includes a lithium-based battery, its lifespan is uncertain. Studies on lithium iron phosphate (LFP) battery technology, which is used in the stove, indicate that the chemistry is likely to surpass a 10-year lifespan, but there are still unanswered questions about the expected number of charging cycles and the charging setpoints for this product. The research team did not have enough time with the product to examine battery degradation in the data. Based on modeling with System Advisor Model, from data Journal of the Electrochemical Society study often cited by the National Renewable Energy Laboratory and used to build the SAM software, a lithium iron phosphate battery's relative discharge capacity can be maintained at 80 percent for a very large number of cycles when using a depth of discharge of 10 to 20 percent, at standard temperature and pressure. The figure below shows degradation at various DOD cycles for the battery pack in the Study Stove.

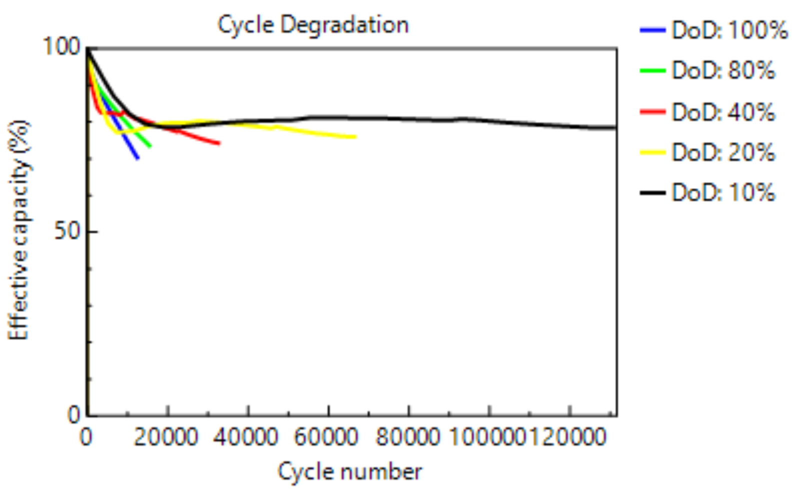

Figure 17: Relationship between depth of discharge and the lifespan of the battery for the battery included within the Study Stove, based on lab testing from the battery manufacturer.

Based on the data, the greatest peak power-draw cooking event from all the data collected created a depth of discharge (DOD) of 23 percent (i.e., SOC of 77 percent), and by far the majority of cooking events do not exceed a 10 percent DOD. Cooking once per day on the stove, even if it were up to a depth of discharge of 20 percent, the stove can maintain 80 percent relative capacity (i.e. SOC 80 percent) up to at least 20,000 cycles, which is the equivalent of 54 years. NREL modeling indicates it has a potentially much greater capacity duration, potentially as much as 60,000 additional cycles at 20% DOD per cycle.

Due to the low depth of discharge and the substantial number of cycles that lithium iron phosphate battery chemistry can absorb, it is highly likely that the Study Stove battery will maintain a high relative capacity longer than 20 years. Comparing this with typical stoves, such as traditional electric resistance coil type or natural gas stoves, this is a standard lifespan for a residential kitchen stove. In apartment complexes, stoves are typically replaced on a 20-year cycle.

The team also found that the firmware update to a default charging schedule of 10 a.m. to 4 p.m. will not cause a detrimental impact to the stove.

User Experience – Survey Results

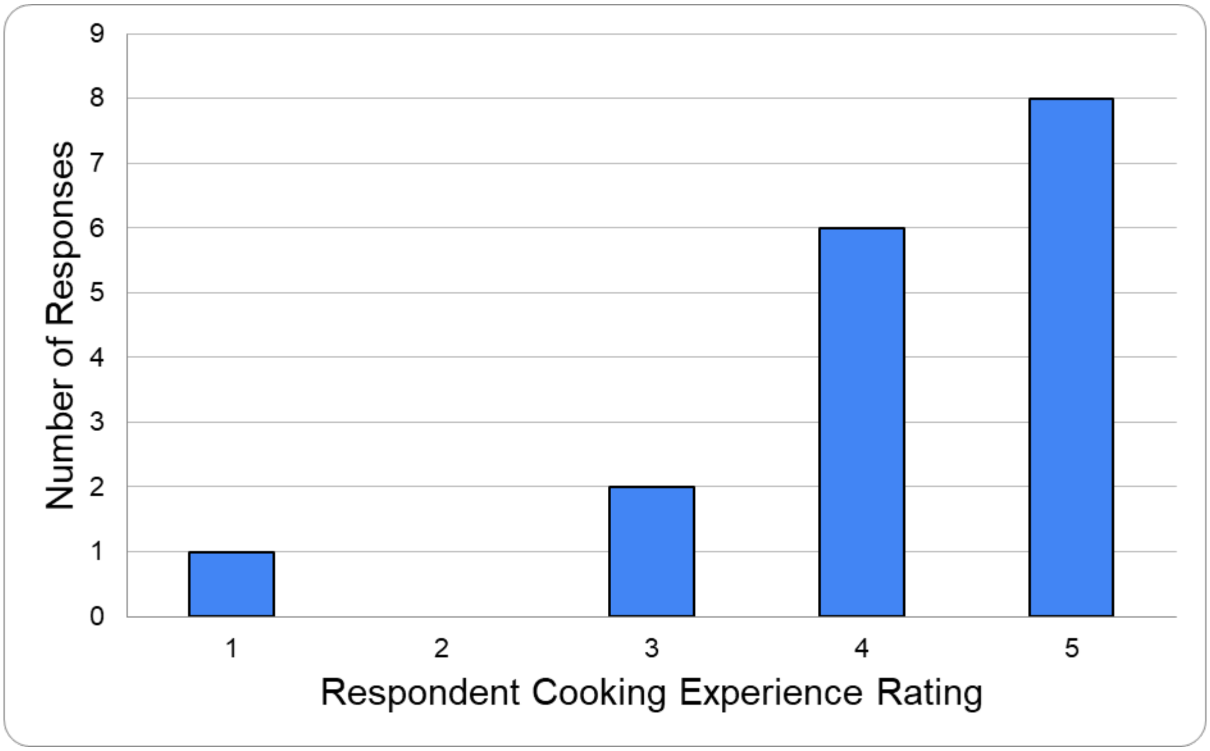

Figure 18: Survey responses to the question, "How would you rank your current cooking experience out of 5 on average?"

Seventeen of the 36 participants who had stoves installed responded to our user satisfaction survey, a response rate of 47 percent. As seen in Figure 18, 14 of the 17 user-satisfaction survey responses were positive, two respondents were neutral, and one was not satisfied. This translates into an 82-percent satisfaction rate among responders. Users who were unsatisfied were bothered by constant fan noise or energy usage. These issues can be fixed through firmware updates in the future for the stove, including, but not limited to, a battery management user interface to be included in an upcoming customer-facing app.

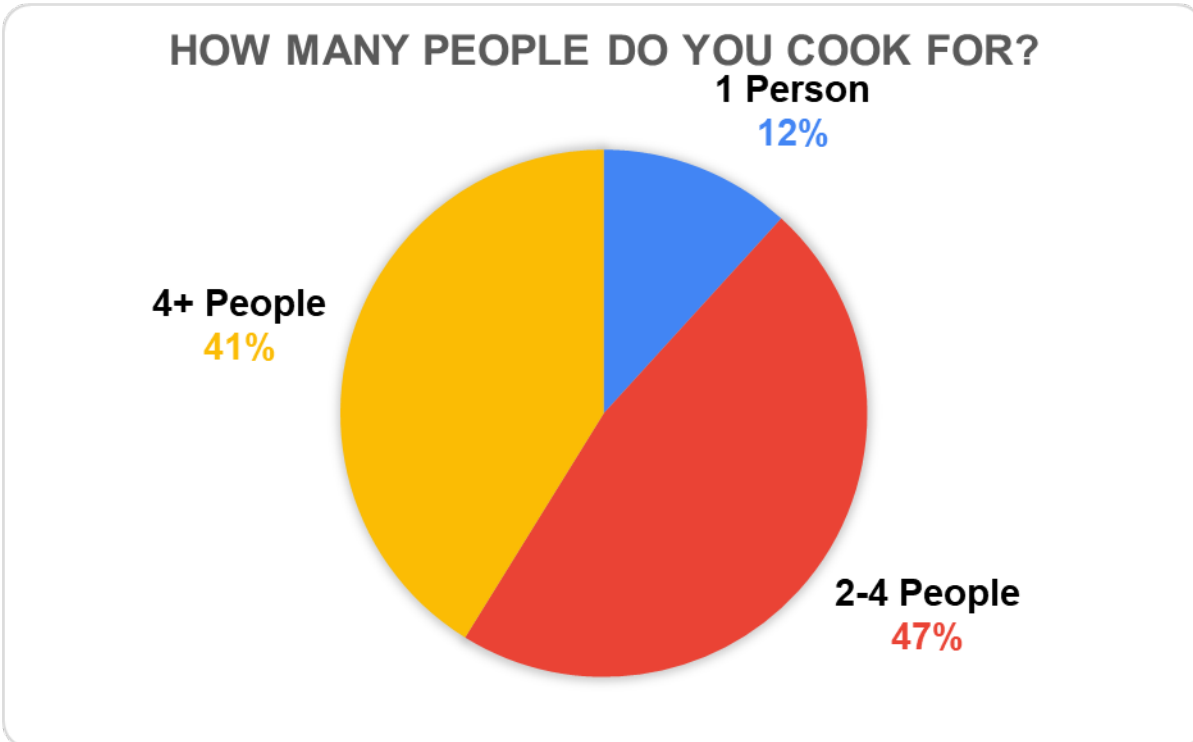

Figure 19: Survey results of the agreement level to the question, "How many people have you been cooking for?"

Users who responded to the survey continued to explain their specific cooking habits, such as the component used and the quantity of people for whom they are cooking. Figure 19 shows that 88 percent were cooking for multiple people in a cooking session. In those cooking sessions, 94 percent were using their stove top one to three times a day and the rest used it more (Figure 20). Seventy-one percent used the oven one to three times a day (Figure 21) and the remainder typically did not use the oven.

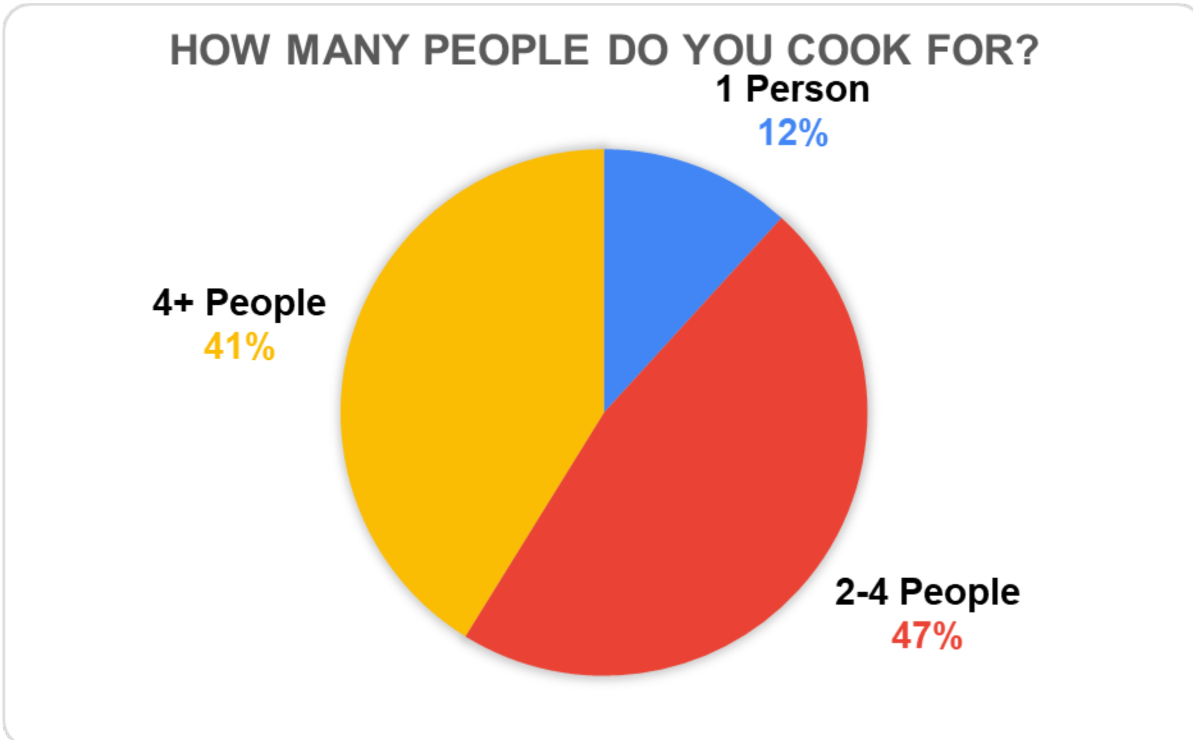

Figure 20: Results from the survey question, "How many times a day have you been using the stove top?

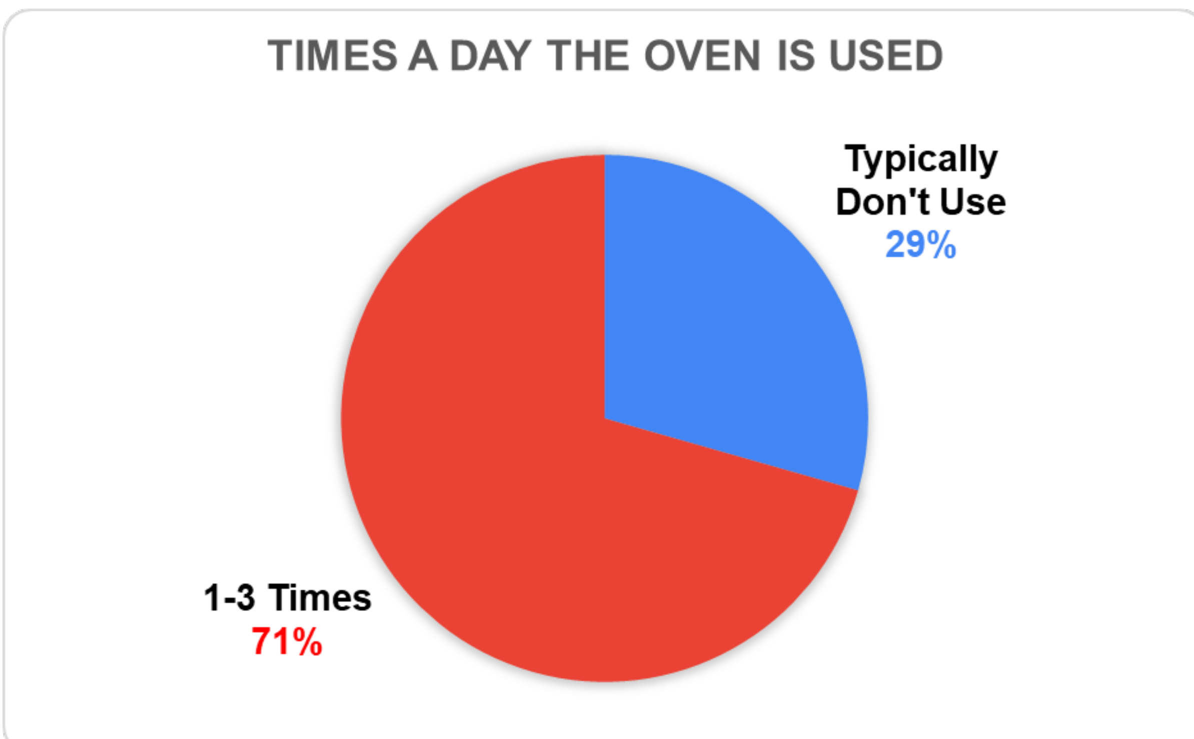

Figure 21:Survey results from the question, “How many times a day have you been using the oven?”

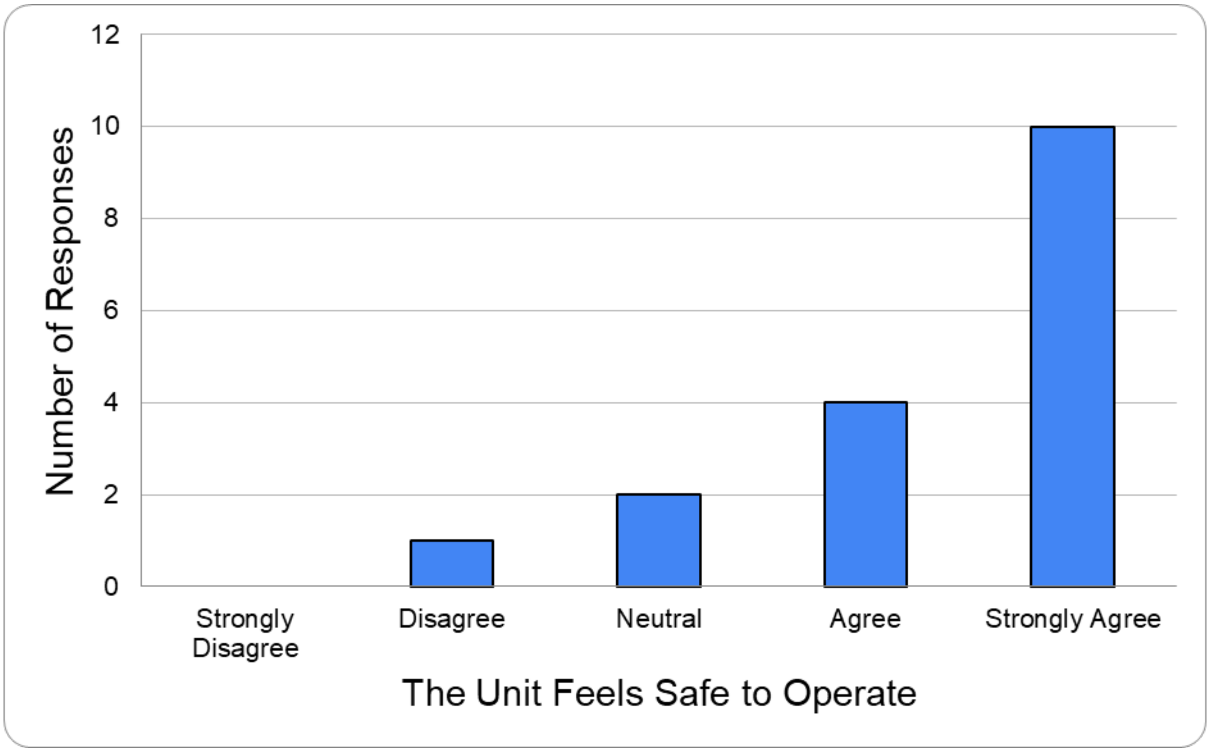

Figure 22: Survey results of the agreement level to the question, “Does the Study Stove unit feel safe to operate?”

Fourteen of the 17 respondents said they felt safe while operating the Study Stove, highlighting child usage and pets touching the oven door while on Figure 24 in the textual comments. The last three fell into the category of having malfunctioning stoves or the occurrence of a circuit fuse “tripping.”

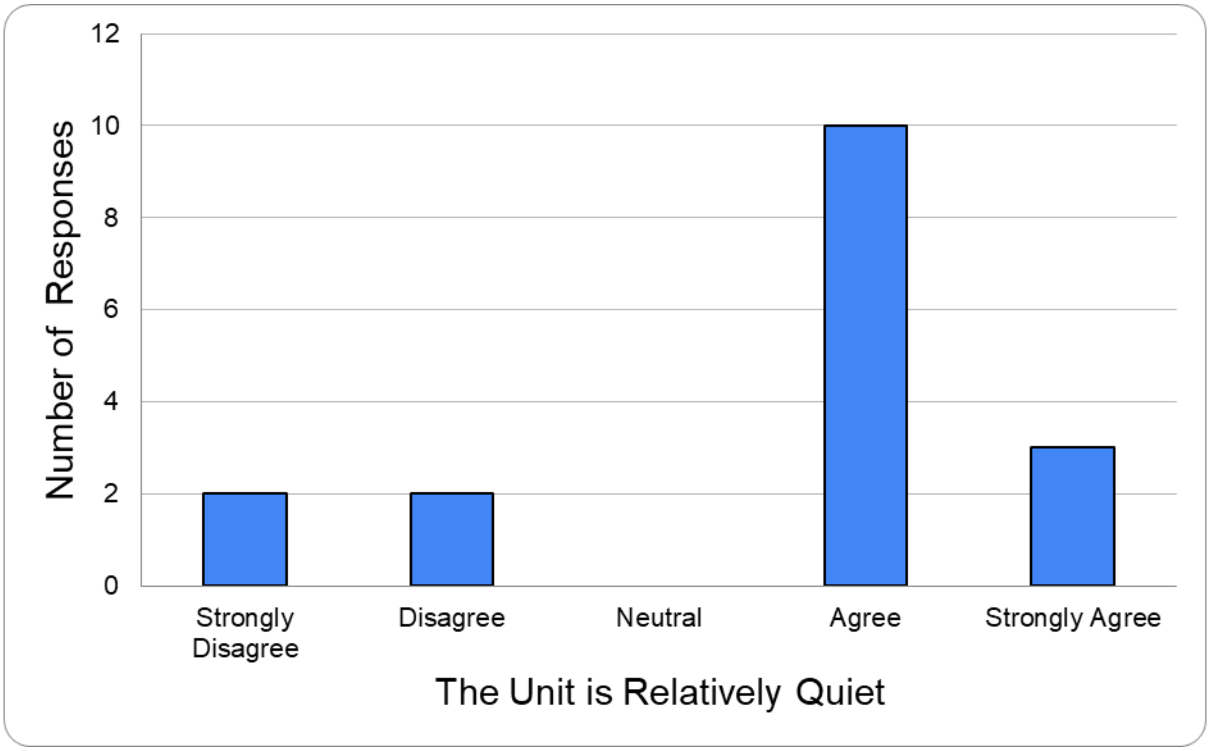

Figure 23: Survey results of the agreement level to the survey question, “Is the unit is relatively quiet?”

Thirteen of the 17 survey respondents affirmed that the unit is relatively quiet. Issues with malfunctioning fans and loose screws around duct or vents were identified as the main causes of disagreement with this statement.

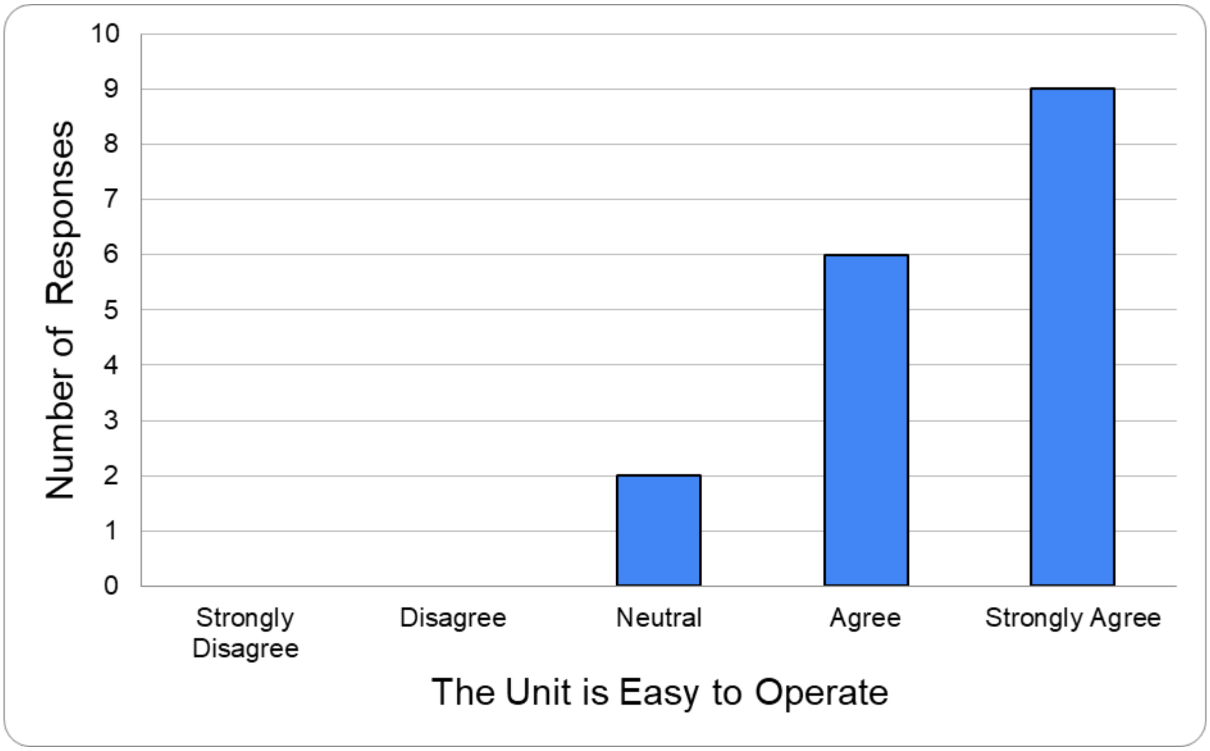

Figure 24: Survey results of the agreement level to the question, "Is the Study Stove unit is easy to operate?"

Fifteen of 17 respondents to the survey agreed that the unit is relatively easy to operate. Two that were neither in agreement nor disagreement were thrown off by some of the choices made, such as the oven heating element being on top, knobs turning clockwise, and display interface showing a percentage instead of a temperature. However, no one claimed this appliance was difficult to operate. This is also reflected in Figure 25, which shows that 16 of the 17 affirmatively agreed the device dials and displays were easy to read. One respondent answered in with neutrality, based on the directionality of the dial being the opposite of typical stove knobs.

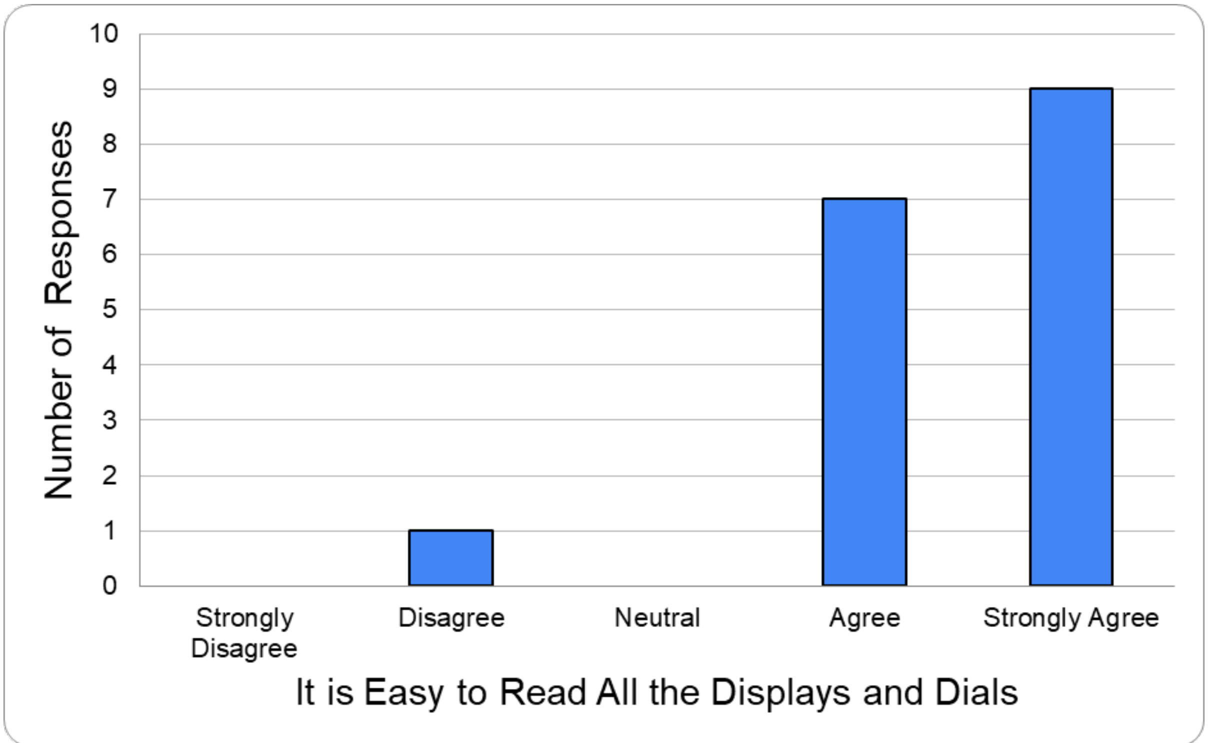

Figure 25: Survey results of the agreement level to the survey question, "Is it easy to read all the displays and dials on the device?"

Again in Figure 25, 16 of 17 respondents indicated affirmative agreement with the question statement, and the same respondent who responded neutrally in Figure 24 now answered this question with "Somewhat Disagree", citing the dials.

INSTALLATION

Installation of the product was simple and compared well to a like-for-like installation of a stove in a home, such as replacing a glass-top radiant range with a new glass-top radiant range. All participating homes that had gas or propane stoves had a 120V outlet that could be used. When a gas stove is being removed, a professional plumber should be deployed, such as the one from Lizard's Plumbing used by the team, to permanently cap the gas line to the stove. There are variances in the type of gas line and gas fitting used in every home, and the procedure differs for each. For a stove with a typical half-inch iron pipe with normal threads, after shutting off the valve if present, gas-rated PTFE tape is used on the threads and "pipe dope" is added to the threads inside the gas cap. For gas pipes with a "flare" fitting at the end of the pipe, only a flare cap can be used, and it must be used without tape or pipe dope. Only one home with a gas stove had an ungrounded outlet behind the stove which could not be used.

For homes with 4-wire 240V electric stoves, ETL-listed[6] products were investigated that can be used as a temporary GFCI[7] adapter to provide a 120V outlet to the device, but standard code-

[6] An ETL listing is a certification that a product has been tested and meets certain safety and quality standards.

[7] Ground-fault circuit interrupter.

compliant kitchen counter outlets that existed within the home were used, due to the stove being a 1200W device which can share an outlet with many kitchen counter devices. It is also important to make sure the outlet that the stove is plugged into is properly grounded. Inexpensive electrical testing devices exist that can indicate if an outlet has been installed without a ground wire. Traditional 240V stoves are not always grounded. Some are installed and plugged into a 3-wire 3-prong outlet, which only provides L1, L2, and neutral wires, with the stove grounding itself to its own chassis. If a potential buyer of the Study Stove product has an existing electric stove, the conversion of a 240V outlet to a 120V outlet will be less expensive than running a new 240V circuit would be, but there is still a cost associated with that work, so being able to use countertop 20-amp 120V outlets where possible is a great benefit.

A greater issue that presents itself during installation is the weight of the stove, at approximately 350 pounds. At minimum, two well-trained appliance professionals such as those at Poletski's Appliances are required to move the new stove into the home, especially when the home is post-and-pier construction, has a tall foundation, or is a manufactured home with a stairway into the unit. While it is technically possible to move the stove up a full flight of stairs, a quality "stair stepper" hand truck is a must-have due to the risk associated with worker exhaustion. A company installing this product full-time should invest in a 20-inch pallet jack and a quality hand truck with an electric motor to make receiving and installing the product as smooth and safe as possible.

TECHNICAL ISSUES

The initial product presented several maintenance issues that colored the feedback from the participants. One was that the convection fan, used to cool the oven compartment, ran too often. In many homes it would run all the time. This is being resolved with a software update to change fan setpoints. Additionally, two of the stoves came from the factory with convection fans that were fastened with screws that were slightly too small in diameter. Although this did not present a hazard, it did create a nuisance noise issue: The units sounded somewhat like old dryers. When combined with the issue of the convection fan running too often, this created a major headache for two participants. The team expects that these issues will be addressed in further revisions of the product.

One stove was installed in a member home and did not present with any issues until days later, when the member reached out and told the team that the circuit breaker on their electrical panel for the stove was tripping often and that the stove was no longer charging. When a Redwood Energy team member arrived and worked with the participant, it was determined that the issue was a faulty AC inverter from the factory, which powered auxiliary components but not the actual stove elements or oven.

Another stove had a more complex firmware issue that appeared to be an incomplete or interrupted firmware installation from the factory. The specific issue caused the response time to be poor when turning the dials and eventually caused the oven element to fail to respond. The manufacturer software team was able to upload a new copy of the firmware and resolve the issue with that stove.

The stoves have been confirmed to be fully spill-proof in the field, and in all installations, participants were warned that they should not store heavy objects above the stove (such as cast-iron pans or heavy pantry storage), due to the risk of breaking the tempered glass with a falling object greater than it is rated for. One stove did have its internal GFCI triggered by a spill, which was able to be resolved by resetting the stove using the reset button at the bottom front of the stove behind the kickplate. This reset event could have been made easier for a customer to resolve with the addition of an accessible power switch.

Stove Technology Summary

The Study Stove is a nominal 120V induction range with a battery backup to power itself during cooking events, along with the 120V grid power it has available. It can draw up to 1250W from the grid and leans on the battery during high-power cooking events, charging the battery backup primarily after the cooking event is over. It can provide resilience for cooking and even charging small devices with an available 120V AC outlet that is powered by the battery. It provides enough power for cooking that most users are unlikely to notice any drawbacks from its use, versus a traditional 240V stove.

The Study Stove unit is likely to fill a key market gap in residential and small-volume commercial kitchen appliances. 120V induction ranges have the potential to unlock a significant amount of electrification projects sooner than otherwise would have been possible with only 240V options. It has the potential to be used for demand response programs such as OhmConnect or others and has the potential to eventually respond to grid signals and alternative load flexibility programs such as the CEC MIDAS[8].

Recommendations

Product Recommendations

Reduce Trickle Charging

To optimize battery performance and longevity, it is essential to implement smart charging algorithms that minimize trickle charging when the stove is not in active use. Trickle charging, while useful for maintaining battery levels, can lead to reduced efficiency and increased heat generation, which may ultimately shorten battery life. By developing a system that only engages the charger when the battery level drops below a specific threshold, manufacturers can enhance the overall efficiency of the stove. High-efficiency charging circuits can be designed to activate only when needed, further reducing energy waste. This approach not only helps in maintaining battery health but also lowers the environmental impact of the product.

[8] https://www.energy.ca.gov/proceedings/energy-commission-proceedings/inactive-proceedings/market-informed-demand-automation

Power Switch on Front of Stove

Adding an intuitive power switch for battery-powered stoves is crucial for user satisfaction and safety. A straightforward process that allows users to turn on the stove with minimal steps will enhance usability and help to reduce the 30 percent high standby losses by potentially as much as half from the charging system and internal boards. This switch would need to be in addition to the AC shutdown switch but could replace the existing reset button on the front of the stove. Safety is paramount, so incorporating features such as a child lock or a timer that automatically shuts off the stove after a predetermined period can prevent accidents. While these features could be incorporated into the manufacturer app, the team finds that needing to use the app creates a technology barrier that should be circumvented via the use of a physical switch, similar to the manufacturers choice to use physical switches for the fan and light and physical knobs for the oven and cooktops.

Cooktop Power-Level Indication

Transitioning from percentage-based power level indicators to temperature settings can significantly improve the cooking experience for users. Many home cooks are more familiar with temperature ranges, (e.g., simmer, medium, and high) than with abstract percentages, which can vary based on stove design. A clear, intuitive interface that reflects temperature levels can help users better gauge their cooking needs.

Evaluate Ungrounded Outlets

It is essential to conduct comprehensive testing to understand how ungrounded outlets might affect the internal components of a battery-powered stove. If research indicates that ungrounded connections pose risks—such as affecting circuit performance or increasing the likelihood of electrical faults—clear guidance must be provided to consumers. Manufacturers should offer recommendations for safe outlet usage or develop stoves that incorporate protective measures against the potential risks associated with ungrounded power sources. This commitment to safety not only protects users but also enhances brand reputation.

Include the Option for the Stove to Come with an Internal Cellular Modem

Incorporating an internal cellular modem into off-grid stoves would be helpful, particularly for users in remote areas like reservation lands where utility infrastructure is often limited. This feature would enable continuous data transmission, allowing for real-time monitoring, seamless firmware updates, and efficient troubleshooting. With its own battery power supply, the stove can operate independently of traditional power sources, ensuring reliability in underserved regions. Enhanced connectivity not only empowers users by providing them with crucial performance insights but also supports the integration of renewable energy sources.

Program Recommendations

The product is eminently useful as a distributed energy resource or for demand response, with the potential capability to provide grid services without making compromises to customers or end user satisfaction. While the eventual deployment of the demand response capability and charging scheduling capability in the mobile app for the product is still forthcoming, it appears that the stove has enough battery capacity to meet the needs of end users while responding to demand response events or avoiding peak time-of-use rates. Because the capability to avoid peak time-of-use rates offers some potential for cost recoup, in addition to the product's applicability for incentives and rebates, the $6,000 price tag does not reflect the full value of the product — it is likely worth more to customers as an investment in a distributed energy resource.

Cooking Technology and Energy Efficiency is Not Sufficiently Studied

Induction cooking technology is a promising frontier for energy efficiency, but its impact on household energy use remains surprisingly understudied. While early adopters have been drawn to induction's rapid heating and precision and its potential to reduce carbon footprints, the broader understanding of this technology's efficiency benefits is limited. To ensure its widespread adoption and maximize its contributions to the transition to making use of renewable energy, more research should be funded outside the lab to confirm and collect data on its energy-saving capabilities in real-world conditions.

The current gap in understanding stems in part from induction technology's relatively recent introduction to U.S. markets. Early studies have demonstrated that induction cooktops can be more energy-efficient, compared with traditional electric or gas cooking, because of their precise heat control and reduced waste heat. However, these findings are based on controlled laboratory conditions, which do not fully capture the complexity of everyday household use. Factors such as seasonal variations in cooking habits, the types of cookware used, and the interaction of induction cooktops with other household appliances can greatly influence energy efficiency and quality of life.

The learning curve associated with induction cooking, particularly for those transitioning from gas or traditional electric stoves, continues to pose a significant barrier to adoption and effective use. Without proper education, unaccustomed users may not realize the full energy-saving benefits of induction technology, or worse, they may come away from their new relationship to cooking with doubts about its usefulness. More studies are needed to explore how different educational interventions impact users' efficiency outcomes. Providing insight into the relationship between user knowledge, cooking practices, and energy consumption would guide policymakers and manufacturers in developing better educational materials that ensure consumers maximize the benefits of this technology and improve adoption rates of induction as the technology transitions out of the early-adopter phase.

There is a great need for more diverse, community-focused studies that evaluate induction cooking's efficiency across different demographics and residential contexts. Households vary significantly in cooking patterns, energy needs, and socioeconomic constraints. For instance, although countertop round-bottom induction woks exist and work well, many potential induction users are concerned that they will no longer be able to cook with a round-bottom high-heat wok if they make the switch. By understanding how these issues affect technology adoption, future efforts and technology updates can be tailored to target the unique needs of different user groups. Expanding the scope of research beyond small, controlled trials to include diverse populations can provide valuable insights into how induction technology can be optimized and scaled for different communities.

To foster meaningful improvements in energy efficiency through induction cooking, funders must continue to recognize the value of comprehensive research and investment in educational outreach. Funding such studies will not only address existing knowledge gaps but will also help unlock induction technology's full potential to transform the way our society cooks, saves energy, and reduces greenhouse gas emissions.

Induction Technology Requires Education to be Most Effective

Induction technology is still relatively new to the U.S. market. There is a fairly significant learning curve with using this technology that can be difficult to overcome. Early adopters and energy efficiency aficionados are more able to absorb this learning curve because they are often fascinated with the technology and the benefits it provides, but for a general market it can be more difficult.

In this project, all participants were provided with a free set of induction ready cookware, including three saucepans and at least two frying pans. These cookware sets were stainless steel, which created a reported learning curve around cooking foods that tend to stick to the pan such as eggs, ground beef, pancakes, etc. With stainless steel pans, it is necessary to let the oil get hot enough to create a barrier between the food and the pan so that the food does not chemically bond to the steel of the pan.

A better choice would have been to offer a set of cookware with a ceramic non-stick cooking surface that is compatible with induction. Due to time and budgetary constraints, the team was not able to provide this equipment. It had budgeted $200 per participant for cookware sets and regretfully that was not enough to provide everyone with ceramic non-stick sets. In 2024, a better budget would set at least $250 per participant for a cookware set which 1) is ceramic non-stick, 2) includes at least 11 pieces, and 3) is compatible with induction.

The team educated participants before, during, and immediately after installation of the stove, and continuously throughout the monitoring period, providing information and support for any issues the participant was experiencing. Future projects that bring induction technologies to any community need to incorporate even more education into the project, allocating time to create educational materials that specifically target the various audiences the community induction technology is being provided to. Various audiences within the community will have unique needs. For instance, older residents may need more support with new dials that move in a different direction, or in using new cookware.

Appendix A: Prototype Unit Data

Relevant data from prototype unit:

- Battery charging power.
- Power out of the battery
- Battery state of charge
- Oven power
- Cooktop power

The data from the prototype unit was collected in one-second intervals and resampled to three-minute intervals. The peak observed power draw from the grid was 1.75 kW during the study period, consistent with the rating of 1800W. During cooking events, the stove limited its grid power draw to 1500W. In subsequent revisions of the product and in the final product, the stove was limited to charging at 1200W.

PROTOTYPE UNIT BATTERY STATE OF CHARGE

Figure *26*: Battery state of charge over the initial prototype data collection period (22 days).

As shown in Figure *26*, battery state of charge did not fall below 89 percent during the initial data collection period with the prototype stove. The vast majority of the time, the stove kept the battery charged to 100 percent state of charge. Typically, lithium-ion batteries are not recommended to be kept at 100 percent state of charge, however with lithium iron phosphate this behavior is generally beneficial because depth of discharge is a concern. At the early stage, the Redwood Energy project team identified that the use of more of the battery capacity over the course of the day may be preferable, and that increased avoidance of energy use during peak cost grid hours may be worth adding to the product. A significant amount of residential energy costs can be mitigated by avoiding peak time-of-use rates.

Appendix B: Early Research Questions

Figure 27: Protype unit being installed at Redwood Energy Home Base.

The following research questions were initially cited by the team as useful after working with the stove over the preliminary report period. Some of these questions were answered, and some of these questions were reformatted or in light of the data and in order to be more useful.

RESEARCH QUESTIONS DISCUSSION

Original Research Question: How many average meals can be made without grid power at full charge?

- What energy use (kWh) is an “average cooking event”?
- How many burners are used and how much is the oven used on average?
- How many meals/cooking events are cooked per day or week?
- If power was lost to the home, how well did the unit perform?

Some of the above research questions were reformatted in light of the variability of cooking events and the lack of usefulness of that data within this study. The team instead looked at the energy use of each stove unit over the course of each day and each five-hour interval in the study period, characterizing the stove's ability to meet cooking demand without running out of battery. The above questions were reworded to:

- How does the stove perform in a five-hour interval?
- How many kWh pass from the battery to the stove elements each day?
- How much is each induction element used and how much is the oven used?
- How many days can the stove be useful without grid power?

Original Research Question: How much grid power is used by the stove?

- Average
- Range (max/min)
- During peak grid hours (3 to 9 p.m.)?
- What is the peak observed 15-min grid power demand of the stove?

The above questions were all answered in the data visualizations and interpretations within the report.

Original Research Question: What is the overall perception of safety of the stove?
The above question was answered using survey data from participants in this report.

Original Research Question: What is the overall perception of aesthetics of the stove?
The above question was answered using survey data from participants in this report.

Original Research Question: Was there a net change in participants' cooking habits?

- Net number of meals/day or per week?

Due to time constraints surrounding the stove manufacturer delivery date shifts, this data was not able to be included in the surveys as a finding. The project team was only able to perform one survey tranche, and this was communicated early to SCE. Anecdotally, some respondents did indicate that they have difficulty getting the new stove to properly cook a pizza, due to the oven only having an element at the top. The solution to this issue has been to preheat the oven with a pizza stone, to provide heat and heat transfer to the bottom of the pizza, which was often undercooked without this intervention.

Original Research Question: How much battery degradation occurred during the study period?

- Depth of discharge?
- Changes in state-of-charge behavior?

Due to the timing of the delivery of the stoves by the manufacturer, the stoves have not yet completed enough cycles for the team to be able to gain valuable insight into changes in the state of charge. With research already existing into lithium iron phosphate battery chemistry and degradation at various DOD, the team expects that the battery lifespan will correspond well to consumer expectations on the lifespan of a stove.

Original Research Question: Is the location of gas hookups in homes a prevalent issue for installing the unit?

- Prevalence of gas hookup issues requiring a gas plumber?
- How often can a homeowner DIY install the unit?

The team and subcontractors installed Study Stoves into 15 homes with natural gas and seven homes with propane stoves. The team found that an appliance professional, such as one from Poletski's Appliances, is highly enabled to install the stove for a homeowner, but if gas hookups are present and uncapped, a homeowner would not be able to install the Study Stove unit as a replacement for a gas stove, without enlisting the help of a professional.

Original Research Question: Prevalence of 30-inch or wider doorways (this comes from safety qualification visit)?

- How often would we have to take the oven door off?
- How often do we have to take the house door off?

The team found that in the course of installation, all but three homes had doorways greater than or equal to 30-inches wide. The stove comes from the manufacturer with the oven door handle not installed, which makes the packaging less wide and allows the box to be brought into nearly every home without interventions made to the doorway.

Original Research Question: What issues arise when the battery is at a low state of charge?

- Oven temperature
- Burner power
- Battery voltage, potential mismatch with AC grid?

The team found, as shown in the report, that during the unmanaged charging regime, no stove reached a state of charge below 60 percent, which is not considered a low state of charge. When stoves automatically managed charging, the stove continued to prevent SOC falling below 60 percent unless there was a power outage. The team can confirm that there are many safety features incorporated into the stove and that the Battery Management System is robust enough that, while issues with oven temperature and burner power would be experienced, voltage mismatch with the AC grid is not of concern at a low state of charge.