CALIFORNIA
ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Getting to All-Electric Multifamily Zero Net Energy Construction

Gavin Newsom, Governor

March 2023 | CEC-500-2023-006

PREPARED BY:

Primary Authors:
Amy Dryden, Andrew Brooks, Meghan Duff, Association for Energy Affordability
Greg Pfotenhauer, Franklin Energy
Nehemiah Stone, Stone Energy Associates
Sean Armstrong and Emily Higbee, Redwood Energy

Project Manager: Amy Dryden, adryden@aea.us.org

Principle Investigator: Nehemiah Stone

Contract Number: EPC-15-097

PREPARED FOR:
California Energy Commission

Adel Suleiman
Senior Electrical Engineer
ENERGY EFFICIENCY RESEARCH OFFICE

Virginia Lew
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

Jonah Steinbuck
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The authors would like thank the many folks who were part of the team for their dedication and commitment to this valuable work and for providing in-kind support, technical assistance and expertise, and in some cases matching funds: Corporation for Better Housing, Winn Co, MidPen Housing, BLH Construction, Nexi, Pacific Gas and Electric, Breen Engineering, Rheem, MitsAir, Sanden, Ecotope, David Baker Architects, Build Equinox, Mitsubishi, Logic Beach, Abraxas Energy Consulting, USDA Rural Development Division and the California Tax Credit Allocation Committee. We would also like to thank the Technical Advisory Committee who individually and collectively provided feedback throughout the project. In addition, many staff at AEA, Franklin Energy and Redwood Energy supported the project from tenant engagement to modeling and data analysis as well as troubleshooting on-site issues.

We would also like to thank our Commission Agreement Manager Adel Suleiman and his colleagues at the California Energy Commission's Energy Research and Development Division for supporting this project over the past 4 years and building science research to help California meet its greenhouse gas emissions reduction and zero net energy goals.

PREFACE

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

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

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

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

Getting to All-Electric Multifamily Zero Net Energy Construction is the final report for the research project (ECP-15-097) conducted by AEA, Franklin Energy, Redwood Energy, and Stone Energy Associates. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

Compared with single-family homes, little empirical data have been gathered on the performance of water heating systems in multifamily buildings, and even less on energy use patterns for cooking, lighting, appliances, and other plug loads. Although currently there are twice as many single-family residences as apartments in the United States, the multifamily sector is becoming a larger percentage of new construction. It is therefore important to maintain focus on improving the efficiency and grid impacts of multifamily buildings to achieve California's ambitious climate goals.

This project monitored second-by-second energy and one-minute intervals of water usage in four-zero net energy-designed multifamily buildings, a total of 206 residences with:

1) Individual heat pump water heaters.
2) Central heat pump water heaters.
3) A central combined heat pump system.

The four projects are in different California Climate Zones: Sonoma and Napa counties (in wine country), the San Francisco Bay Area, and the Central Coast wine country. Circuit-level monitoring equipment installed in each apartment allowed the team to develop an accurate picture of tenants' electrical usage. Tasks included:

1) Providing technical assistance during the project for 50 percent of the projects.
2) Monitoring the project systems and identifying opportunities to optimize systems to achieve their intended performance.
3) Conducting an evaluation of zero net energy.

This study found that all-electric construction is cost effective for different multifamily building types. It identified many of the technical and practical issues that design and construction teams are facing with achieving zero net energy in multifamily building construction. To scale and expand the market of all-electric and zero net energy projects, this study detailed findings and developed recommendations relating to design and construction, codes and standards, and operations and maintenance to ensure the success of future projects.

Keywords: Multifamily, all-electric, zero net energy, domestic hot water, central heat pump water system, heat pump water heater

Please use the following citation for this report:

Dryden, Amy, Andy Brooks, Emily Higbee, Greg Pfotenhauer, Meghan Duff, Nehemiah Stone, and Sean Armstrong. 2023. *Getting to All-Electric Multifamily Zero Net Energy Construction*. California Energy Commission. Publication Number: CEC-500-2023-006-D.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

As carbon reduction opportunities for buildings are better understood, under-researched topics in multifamily buildings are receiving new attention. Compared with single-family homes, relatively sparse empirical data have been gathered on the performance of water heating systems in multifamily buildings, and even less empirical data have been gathered on energy-use patterns for cooking, lighting, appliances, and other plug loads. Although there are currently twice as many single-family homes as apartments in the United States, the multifamily sector is becoming a larger percentage of new construction. More single-family units were built in California than multifamily units in 2019, which was the first time in nine years. It is therefore important to focus on improving the efficiency and grid impacts of multifamily buildings to achieve California's climate goals.

California's electricity supply is becoming cleaner as the state advances toward its 2045 goal of 100-percent renewable energy. Installing new gas-fired equipment today such as gas boilers for domestic hot water, will, however, lock in sources of greenhouse gas emissions for 15 to 20 years. Domestic hot water systems account for roughly 40 percent of energy consumption in multifamily buildings in California. Installing high-efficiency heat pump water heaters would greatly advance decarbonization of this end use.

California legislative and regulatory efforts are accelerating electrification of the built environment. For example, the California Public Utilities Commission is currently implementing Senate Bill 1477[1], which mandates creation of two new programs that promote the use of highly efficient, low-carbon space-heating and water-heating appliances for both new and existing buildings. The California Public Utilities Commission's Self-Generation Incentive Program additionally allocated nearly $45 million toward expansion of heat pump water heaters into the market. Several key regulatory barriers have also been removed, so many energy efficiency programs are moving toward replacing gas appliances with electric appliances.

Because multifamily buildings can be more complex to design and operate than single-family residences, there are greater challenges in achieving all-electric zero net energy, so it is imperative to fully understand multifamily-specific issues.

These challenges include:

1. The need to quantify impacts from post-occupancy data.
2. Divergent interests in decision-making that affect building performance.
3. Technical design and construction considerations for low-rise versus high-rise buildings.
4. Shared owner/tenant incentives.
5. Cost, performance, and installation questions for unitary versus central systems.
6. Site constraints for multifamily developments.

---

[1] https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1477.

Energy efficiency in multifamily buildings is a social equity issue. The Benningfield Group found that approximately 88 percent of multifamily households are renters, and that renter household incomes are roughly half those of owner-households." The California Department of Housing and Community Development further found that between 2005 and 2013, 2-bedroom fair market rents increased by 17 percent, while renters' median incomes increased by only 5 percent. Reducing barriers to all-electric multifamily housing supports low-income families and provides healthier and more comfortable homes with more reliable utility bills.

The two developers in this project assumed a risk by constructing all-electric zero net energy buildings that exceeded minimum standards through advanced technologies. Until these risks can be better managed, it will be difficult to scale up the advanced practices required by all-electric and zero net energy multifamily projects.

Project Purpose

The purpose of this project was to reduce barriers to all-electric zero-net-energy multifamily construction and its potential to lower construction and operational costs, provide greater electricity reliability, lower greenhouse gas emissions, and improve indoor air quality. The project provided greater understanding of water heating technologies and evaluated apartment energy use in high-performance housing as a pathway to more cost-effective zero net energy.

The project's overarching goal was to demonstrate the technical and economic potential of incorporating all-electric zero-net-energy construction practices into new multifamily buildings, which would reduce planning uncertainty and quantify savings. The research was guided by the following technical and policy goals:

1. Understanding the trade-offs of central-versus-individual heat pump systems
2. Evaluating central systems that serve both domestic hot water and space conditioning loads
3. Evaluate the potential for thermal storage to reduce peak energy demand and maximize the benefits of renewable energy sources.
4. Demonstrate that all-electric building systems with 100-percent offsets can be achieved for multifamily buildings.
5. Investigate both the consumption of other household loads such as cooking and plug loads, and each load's impact on zero net energy.
6. Identify opportunities to revise codes, technical standards, and software algorithms to support high-performing buildings and advance those technologies that support California's energy goals.
7. Research the interactions between building energy performance and health, comfort, and convenience, in a multifamily context.

The outcomes of this effort will advance all-electric zero-net-energy multifamily buildings through:

1. Evaluations of zero-net-energy feasibility for large multifamily projects using a combination of emerging technologies and standard integrated demand-side management measures.

2. Support for advancing codes and standards and their associated impacts on market acceptance and long-term savings.
3. Educational materials that support decision-making and advance adoption of those technologies and practices that move the multifamily market closer to zero net energy.

The research from this project is relevant for consultants, manufacturers, architects, engineers, multifamily building industry professionals, utilities, other researchers, and code development teams.

Project Approach

This project investigated and evaluated all-electric and zero-net-energy issues in depth in four demonstration projects. All four sought to achieve all-electric zero-net-energy construction by adopting breakthrough heat pump technologies that served the buildings' heating, ventilation, air conditioning and water-heating needs, augmented with solar photovoltaics. The projects, located in Calistoga and Cloverdale in California Energy Commission Climate Zone 2, along with Atascadero and Sunnyvale in Climate Zone 4, totaled 206 residences with individual heat pump water heaters, central heat pump water heaters, and combined central heat pump systems.

The research team worked with the four all-electric building projects to meet specific goals and educate the design team about new zero-net-energy technologies for all-electric, zero-net-energy projects. The team included the Association for Energy Affordability, Franklin Energy, Nexi, Redwood Energy, and Stone Energy Associates. The Corporation for Better Housing and Midpen Housing were the two developers who offered their developments for this project. The research team's main roles were to install and monitor the projects' performances and identify opportunities to optimize systems, achieve intended performances, and provide technical design assistance for the cities of Atascadero and Sunnyvale.

Significant technical assistance was required from architects, owners, engineers, and contractors to educate the design team on alternatives, help make decisions, solve problems, and build capacity within each of the design teams, enabling them to undertake electrification in future projects. Project designs were modeled using simulation software and alternative calculations for code compliance and zero-net-energy evaluations.

After the design phase, the team deployed monitoring equipment to document system performance, engage with management, collect tenant surveys, and discuss issues with both site personnel and tenants. During this period, the team completed experiments that evaluated opportunities to optimize systems, from recirculation system controls to load shifting with heat pump water heaters. The team balanced technical needs, accessibility, costs, and flexibility when selecting customized monitoring equipment for each site's domestic hot-water system, so was unable to use the same equipment at multiple sites.

Education of onsite management and tenants was another critical project component. During the monitoring period, particularly at Cloverdale and Calistoga, the team was not always notified when equipment adjustments were made. This communication gap made it difficult to fully understand performance implications. Over the project period, staff changes and unit turnovers resulted in further disconnects, though the research team worked with new management and maintenance staffs to educate them on both the project and equipment. COVID-19 and shelter-in-place orders converged at the project's end, which meant that priorities for many parties shifted; at one site the team was unable to access a complete data set.

Many technical challenges involved the functionality of monitoring equipment and connectivity. Solutions included adjusting database configurations, changing equipment out, making field visits to adjust settings to reconnect equipment, and relying on stored data rather than accessing real-time data. Without onsite data storage, the team would have lost a significant volume of data.

Throughout the project, the team evaluated system performance and shared its findings with both owners and contractors to help improve performance. This resulted in a more iterative rather than binary approach to performance evaluation. The research team also engaged a technical advisory committee to provide feedback on the monitoring and analysis of system performance.

Project Results

The research project was successful; all of the all-electric zero-net-energy multifamily projects were judged to be feasible, even though only one actually achieved the zero-net energy design goal. The research team was successful in gaining a better understanding of emerging technologies and identifying best practices and equipment choices that will support the success of future projects. Most importantly, the team identified issues that would not have been discovered without monitoring. The project did not shed much light on the behavioral aspects of tenants, though the two projects with significant tenant loads did allow monitoring prior to installation of tenant engagement interventions.

To meet local and state energy and climate goals, this type of development must significantly scale up. This project revealed that to do so will require technical support in the design and installation of new technologies, verification of installations, and system monitoring. For example, the team recommended against initial designs at Atascadero and Sunnyvale that used solar thermal water heating with gas backup. Contrary to owners' and engineers' expectations, economic and energy modeling clearly showed that heat pump water heating with solar photovoltaic panels would be less expensive to build and operate. The team also identified several conditions where systems were not installed as designed, from piping configurations to set points to modes of heat pump water heaters—demonstrating the value of verification. Monitoring specifically for photovoltaics was also needed to ensure system operations. The all-electric and zero-net-energy aspects of the projects were therefore considered separately.

Each development combined zero-net-energy goals with onsite generation to address reliability and affordability. Although only one project, Cloverdale, achieved zero net energy from an annual consumption standpoint, all the projects benefited from affordability. The other three were within 17 to 20 percent of achieving zero net energy, based on a 2019 calendar year evaluation, but it is possible that adjustments could bring each project closer to achieving its zero-net-energy goal. Even though Sunnyvale did not achieve this goal on an annual basis for common areas, it still netted an annual bill credit.

The team developed findings and recommendations that support advancement of all-electric buildings in the following areas for: domestic hot water (individual systems, central domestic hot water, and combined systems); heating, ventilation and air conditioning; electrical end uses; building modeling; and solar photovoltaics. Recommendations are explained extensively in this report.

Since domestic hot water is one of the largest electric loads in multifamily buildings, addressing all system types was critical. Specifically, modeling software must more adequately account for heat pump systems and incorporate design strategies used in the field (particularly for central heat pump water heaters), but also for the locations and set points that apply to all systems. Occupancy was an additional critical factor for both sizing systems and estimating draw schedules. Existing assumptions must be evaluated to more accurately reflect occupancies.

Because heat pump water heaters play a critical role in thermal storage and decarbonization, sizing methodologies must reflect more than heat pump recovery rates and peak demand; they must also reflect load shifting and reductions in electric resistance usage. This may be more acute for individual and clustered systems than for central heat pump water heater systems. To support this optimization, codes and standards must address controls such as recirculation and thermostatic mixing valves. Research into standards is required for manufacturers to develop settings that support the end goals of load shifting: reduced greenhouse gas emissions, energy use (minimized electric resistance), on-peak energy use, and utility costs for domestic hot water. For these systems, this project demonstrated a valuable potential for load shifting given the larger available storage and diversity in draw patterns from many different households. More research is required to determine approaches that best optimize load shifting.

Modular central domestic hot water heat pump systems are flexible applications that benefit both new and existing construction and require a significant shift from gas boiler designs. Absent the deep technical assistance and monitoring from this project, these systems would have underperformed. With new products coming into the market, it is critical to advance design and engineering specifications and commissioning practices to simplify a process that will ensure greater success. This research project shows that it will be critical to: develop best practices for system optimization for sizing, load calculations, and controls to distribution; require a level of system commissioning appropriate to system complexity; and define best practices for the recirculation system design for different system configurations.

Lastly, the combined space conditioning and water heating systems monitored in this project were generally better suited to projects with diverse loads rather than to multifamily projects with narrow profiles, even though those systems would benefit from simpler and more integrated systems and controls (with appropriate storage to minimize errors in engineering or installation).

The team studied other end uses, and for individual heating, ventilation, and air conditioning loads two key issues arose. First, there were baseloads that were neither understood nor accounted for, but which nevertheless affected overall energy use. These can be revealed and regulated through a variety of mechanisms from national testing and rating procedures in energy code regulations. Second, better education on the efficient operation of heat pump systems were critical in ensuring that both performance and comfort requirements were met.

While understanding that design and equipment are key parts of the story for efficient operations, occupant engagement was also critical. Although this was not a behavioral study, it did identify an opportunity to increase occupants' awareness of their energy usage through lighting displays. Based on self-reported data, nearly three-quarters of survey respondents became more aware of their energy use following installation of power-usage displays. This was an opportunity to build upon this awareness and engage occupants in both demand-response and peak-usage periods instead of just in pure energy savings.

In addition to all-electric technologies, zero net energy was a primary focus of these projects and tied to competitive funding. This project shined a light on several aspects of onsite photovoltaic systems critical to achieving defined zero-net-energy targets. For example, modeling tools that support zero-net-energy goals should be comprehensive. When a model fails to accurately estimate loads or systems, it is impossible to calculate optimal amounts of solar photovoltaic generation.

Photovoltaic system benefits can be maximized under four conditions:

1. Photovoltaic allocations for any net-metered configuration are reasonably allocated based on buildings, common areas, and tenant-metered loads.
2. Verification and inspections of photovoltaic systems are required to confirm operational settings and commissioning.
3. Standardized interconnection requirements across utilities streamline the process.
4. Photovoltaic installations must include monitoring systems that provide accessible information from inverter performance to system performance and production.

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

To realize maximum benefits from this research, the team developed a strategy to share its findings through different channels. The team developed digital technologies, design briefs, and case studies. Throughout the project, the team produced peer-reviewed papers and delivered conference presentations to engage other researchers and initiate conversations that advance design and research efforts.

The team discovered several potential improvement opportunities for the design, use, and integration of various technologies applicable to high-performance multifamily projects. To share these opportunities, the team created several technology briefs to ensure that energy consultants, manufacturers, architects, engineers, multifamily building owners, industry professionals, utilities, and code development teams understand them. The briefs explain the advantages of existing technologies, best practices for design and installation, integration of system elements, technological improvements, and recommendations for application of those technologies. The topics included: thermal storage and load shifting, monitoring of zero net energy, heating, ventilation, and air conditioning systems, photovoltaic systems, and other considerations for multifamily domestic hot water systems. The team will continue to evaluate how this research can best advance a pathway to market, and to determine which technologies, systems, and approaches to highlight in future briefs. The team additionally created case studies on two of the projects: Atascadero and Sunnyvale. All case studies and design guidelines, along with selected presentations, appear online.

Benefits to California

As the deadline for achieving California's zero-net-energy and carbon-neutral goals approaches, there is a growing need for more research and evaluation of multifamily design and construction practices. Lessons learned from each of this study's projects—which are typical of the multifamily building stock across the state—can be adapted to other projects, ultimately reducing pressure on California's electric grid and increasing the resiliency and reliability of all of the state's building stock. These benefits will together lead to lower costs for multifamily building owners (lower maintenance and utility costs), occupants (lower utility bills), and California utilities.

These projects demonstrated both the technical and economic feasibility of zero net energy for large multifamily projects and established design and installation best practices. These efforts will ensure that the potential benefits of zero net energy are fully realized. They do so by illuminating the trade-offs between capital costs, operating and maintenance costs, functional benefits, environmental and grid impacts, and physical limitations.

In summary, the advancement of all-electric and zero-net-energy buildings can achieve the following benefits:

Lower Costs: The project will help developers make more informed all-electric and zero-net-energy design decisions, reducing the risk of correcting unanticipated problems after the fact. In particular, the project increased understanding of the trade-offs involved in selecting central versus individual water heating systems, dedicated domestic hot water versus combined systems, electric versus natural gas equipment, and energy efficiency versus onsite renewable generation.

Greater Reliability: Electricity reliability will improve by quantifying the load shifting benefits of thermal storage and increasing the energy self-sufficiency of all-electric multifamily developments.

Environmental Benefits: Optimizing strategies for achieving zero-net-energy standards via 100-percent electric solutions will lower greenhouse gas emissions.

Public Health: Advancing all-electric systems will improve indoor air quality in buildings by eliminating natural gas from homes. Providing developers with cost benefits and tenant benefits such as comfort and improved air quality can also influence their decisions in favor of building all electric.

These projects represented different multifamily types: a 60-unit low-rise development with all individual systems and a 66-unit mid-rise development with a central heat pump water heater system with individual heating, ventilation, and air conditioning. These projects delivered savings of 70 percent and 68 percent, respectively. There has been significant advancement in electrification since this research was initiated, though the lessons learned would also complement current work to advance electrification and zero net energy for all Californians, regardless of income.

CHAPTER 1: Introduction

As California continues to explore ways to meet its ambitious energy and climate goals, the design and construction of buildings is emerging as a significant carbon reduction strategy, so under-researched areas like multifamily buildings are receiving new attention. This research project provides a comprehensive examination of apartment energy use in high-performance housing. It evaluated water heating and heating, ventilation, and air conditioning (HVAC) technologies as pathways to zero net energy (ZNE) and explored the complex, interdependent systems in multifamily buildings to determine how they can most effectively work together to achieve all-electric, cost-effective ZNE buildings. The project focused on four primary research questions:

1. How can costs for building multifamily developments to ZNE standards be reduced?
2. How much can greenhouse gas (GHG) emissions be reduced by making multifamily buildings all-electric?
3. Can water heating systems be used to shift building electrical loads to help electric grid reliability?
4. Can planning uncertainties be reduced by reconciling design and actual performance for advanced systems, and can methodologies for quantifying their benefits be improved?

The research was also guided by several technology and policy-research goals, to:

1. Understand the trade-offs between central heating versus individual heat pump (HP) systems.
2. Evaluate central systems that serve both domestic hot water (DHW) and space conditioning loads.
3. Evaluate the potential for thermal storage solutions that reduce electric loads during peak-demand periods and maximize the benefits of renewable resource generation.
4. Demonstrate that all-electric multifamily buildings with a 100-percent PV offset can be achieved.
5. Investigate "nonregulated" loads (e.g., plug loads, cooking) and their impacts on zero net energy.
6. Identify opportunities to revise codes, technical standards, and software algorithms to support high-performing buildings and advance technologies that support California's energy efficiency and climate goals.
7. Research the interactions between building energy performance, health, comfort, and convenience in the context of multifamily buildings.

These questions and goals guided the research team's discussions and actions throughout the research. This report describes the four projects, their approach and methodology for monitoring DHW systems and electrical end uses, the results from the analyses, and recommendations.

Descriptions of the Four Projects

The four research projects are located in the California cities of Calistoga, Cloverdale, Atascadero, and Sunnyvale (Table 1 and Appendix A, Development Profiles of Four Locations). All are deed-restricted low-income housing, and the first three had high-performance building envelopes and ventilation systems commissioned to verify compliance with by U.S. Environmental Protection Agency's ENERGY STAR for Homes program. The four projects offered the opportunity to study different DHW systems, from combined central systems for space and water heating to central domestic hot water (CDHW), to individual DHW (Table 2).

Table 1: Project Descriptions

Project Name	# of Buildings	# of Units	# of Stories	# of Bedrooms	California Climate Zone	Targeted Population (% AMI)
Calistoga	3	48	2	1, 2, 3	2	30–60
Cloverdale	1	32	3	2, 3	2	30–60
Atascadero	2	60	2 and 3	2, 3, 4	4	30–60
Sunnyvale	3	66	4	1, 2, 3	4	Low Income

AMI = area median income

Calistoga and Cloverdale have large central heat combined Armec pump systems that serve both DHW and space-conditioning needs. The system serves the tenants' space-conditioning needs by supplying hot and chilled water to individual fan coils units through a four-pipe hydronic system.

The Atascadero project has individual systems comprised of 50- and 80-gallon heat pump water heaters (HPWH) located on the roof, with recirculation system and ducted heat pumps for space conditioning.

The Sunnyvale project has two central modular Sanden heat pump water heating systems and individual ductless heat pumps for space conditioning. In the two front buildings, wings one and two (42 units), the system consists of 12 Sanden heat pumps, three 500-gallon storage tanks, and one Rheem HPWH for recirculation loads. The system in the other building, Wing 3 (24 units), consists of 4 Sanden heat pumps and one 500-gallon storage tank, with the same recirculation-system components as the other building.

Table 2: Project System Details

System	Calistoga	Cloverdale	Atascadero	Sunnyvale
Space Conditioning	Hydronic fan coil in ceiling	Hydronic fan coil in ceiling	Ducted split system, with a hydronic fan coil in ceiling	Ductless mini splits
Domestic Hot Water	Aermec: combined central DHW and heating and cooling	Aermec: combined central DHW and heating and cooling	Rheem Individual HPWH: 50 gal. (2 bedrooms) and 80 gal. (3 and 4 bedrooms)	Two central plants: modular Sanden HPWH with isolated recirculation loop

System	Calistoga	Cloverdale	Atascadero	Sunnyvale
DHW Distribution	Central	Central	Individual	Central
Storage	1,000 gallons hot water 500 gallons chilled water	500 gallons hot water 500 gallons chilled water	50–80 gallons	2,000 gallons hot water total

HPWH = heat pump water heater

Project Team Roles

The team's main role was to monitor the performance of the four projects and identify opportunities to optimize their systems. Team members functioned as consultants in the design phase of each project. The team consulted with developers and their respective construction teams during the design and construction of three of the projects and affected design changes at each site with the exception of Calistoga, which was completed just prior to grant period.

Approach

The team monitored electrical end uses and domestic hot water at both granular and comprehensive levels. Data collection was comprehensive for DHW systems and included temperatures, flow rates, and energy for appliances and pumps. Apartment-level electrical end uses were also monitored. Most of the data were accessible online, which allowed the team to identify connectivity issues and explore performance in real time.

The team additionally completed experiments to evaluate opportunities to optimize systems from recirculation system controls to load shifting with HPWHs. In general, the monitoring equipment was installed around initial occupancy of the projects except at Calistoga, where it was installed roughly one year following occupancy. Calistoga monitoring contributed to heat pump (HP) and solar-array sizing at Cloverdale. Overall, the team's monitoring identified issues that would likely have remained otherwise undiscovered.

The team monitored each project's apartments and central systems for a range of 1.5 to 3 years.

The team engaged with management, collected tenant surveys, and discussed issues with site personnel and tenants during site visits. Throughout this four-year endeavor, the team uncovered challenges and opportunities related to the design and specifications for all-electric multifamily buildings, their installation, and system operations.

The following chapters summarize the project:

- **Chapter Two**: The process from development and design, to better understand challenges, opportunities, and decision-making processes
- **Chapter Three**: Monitoring processes and installation issues, to understand the translation from design to installation and operation
- **Chapter Four**: The overall and system-specific performance at each site, to understand the achievement of ZNE goals and compare them to the design

- **Chapter Five**: The findings and recommendations, to understand the implications for design and development, engineering and construction, modeling, standards and codes, monitoring, and further research
- **Chapter Six** and **Chapter Seven**: The activities conducted to share the project's results and benefits, to understand how the industry can continue to move forward, and its impacts

CHAPTER 2: Project Design Approach

The research team worked with the four projects to meet specific design goals and educate the design team on new technologies during the design and development phases. Given the project's timing, in some cases (like with Calistoga), design assistance was provided pre-project kick-off by a member of the research team. This technical assistance helped the design team make informed decisions and solve problems on issues ranging from ZNE to compliance with installation specifications.

Significant technical assistance was required not only to educate the design team (architects, owner, engineers, and contractors) on alternatives, but to also build capacity within each of the design teams and enable them to undertake electrification in other projects.

Project designs were modeled using simulation software to demonstrate compliance with codes and programs and evaluate the ability to meet ZNE goals. Comparative whole-building computer simulation models were developed for each project using the latest energy code Title 24-approved software. Those models and other tools were employed as required to demonstrate the energy performance of different configurations and systems. Planning and design were undertaken in older code cycles that supported neither all-electric construction nor heat pump technologies. Each project completed workarounds approved by oversight agencies, not only for compliance with California Energy Commission (CEC) regulations, but also for design and program requirements such as the California Tax Credit Allocation Committee (CTCAC) and GreenPoint Rated. Modeling was completed using approved CEC compliance software and the California Utility Allowance Calculator (CUAC) for specific building end uses (e.g., lighting, cooking), and the CEC's photovoltaic (PV) calculator for solar sizing. While software for low-rise buildings was updated in the 2019 code to include an all-electric baseline, the gas baseline (a hurdle for the Sunnyvale project in 2016 that still exists today) for high-rise residential projects.

Over the past several years, the CEC has worked to address workarounds and functionality to model central heat pump water heaters and to minimize significant hurdles to show code compliance. This team contributed data from this project to assist in this effort.

Each project had unique design and development challenges and opportunities. The following sections discuss each development in the order of the development timeline: Calistoga and Cloverdale, Atascadero, and Sunnyvale. Calistoga and Cloverdale are discussed together throughout this document because they have the same central system. The discussion includes goals and drivers in the decision-making and unique modeling challenges in the design phase, which are compared with actual results in the Project Results chapter.

Calistoga and Cloverdale

Calistoga and Cloverdale, both permitted under 2008 Title 24 standards, were built sequentially by the developer; the design and installation experiences from one informed the other. Calistoga, a garden-style walk-up two-story development, is comprised of 16 one-bedroom apartments, 16 two-bedroom apartments, 16 three-bedroom apartments, a community room with kitchen and public bathrooms, a computer room, management offices, and a common laundry. Cloverdale is a three-story apartment building near downtown Cloverdale and is comprised of 16 two-bedroom apartments, 16 three-bedroom apartments, a manager's office, and computer, laundry, and community rooms with public bathrooms, as shown in Figure 1. Both developments were certified to the U.S. Department of Energy's Zero Energy Ready Home Program (ZERH) and Leadership in Energy and Environmental Design (LEED) Platinum standards, and both committed to a 100-percent offset of the site's annual energy demand (Appendix A, Calistoga and Cloverdale Energy Efficiency Measures).

Figure 1. Calistoga (top) and Cloverdale (Below) Projects

Calistoga

Calistoga was the first ZNE effort by the developer, the Corporation for Better Housing (CBH). The project design was constrained by local architectural considerations to blend into the neighborhood's historical housing. In other words, the site design was laid out to maximize the number of low-income apartments in the neighborhood style rather than for solar access.

CBH committed to several certifications, as well as to ZNE, to obtain competitive funding. The ambitious list of green commitments was of initial concern to the developer. While they focused on high-performance housing as a prerequisite for low-income financing, they were uncertain if they could afford to raise the bar to ZNE since it was less familiar to them than high-performing equipment, gas boilers, and building envelope measures. Value engineering to reduce construction costs was a significant part of initial design decisions for developers.

The commitment to the U.S. Department of Energy's (DOE) Zero Energy Ready Homes (ZERH) and ENERGY STAR for Homes programs meant that most shell measures were mandatory and could not be traded off in a California energy code (Title 24) compliance model. Therefore, the area of inquiry for the design process focused on the mechanical systems. During this process, the developer expressed an early interest in a central space conditioning and DHW system rather than distributed space conditioning and DHW systems to save construction costs—both labor and material—as well as valuable indoor floor space. So the design team and consultant worked together to find a central heat pump solution.

At that time, the most efficient household-sized tank-type HPWH on the market was GE's GeoSpring™, with a rated energy factor (EF) of 2.4 and an annual coefficient of performance (COP) of ~2.7. In contrast, Aermec, a central heat pump water heater (CHPWH) system, operated at least to the federal minimum of COP of 2.0, although ratings accepted in Europe and Canada showed performance at COP of 3.0 for normal operation and COP of between 5 and 8 during heat recovery mode or simultaneous operation. Given two basic choices with similar rated efficiencies, the developer chose to install the Aermec. This was the nation's first 4-pipe heat pump in a multifamily building and providing combined space conditioning and domestic water with one box of centrally located compressors and an underground distribution system to a campus of three apartment buildings. Cloverdale's was the second. Analysis of the design showed an estimated $2,000 first-cost savings per apartment, or about $100,000 for the project—enough to justify shifting to a central heat pump. The total project budget was $18.5 million, so this choice represented savings of only half of 1 percent. Avoiding redesign of the apartments' floor plans was the most significant factor, both politically and financially in the choice to not install individual heat pumps.

The Aermec, as a central combined system, is an air-to-water heat pump and chiller plant that feeds two distinct primary water loops: one providing chilled water to fan coils throughout the property and the other providing hot water for space heating to fan coils and domestic hot water. It uses R-410a refrigerant and has a series of compressors that heat and chill water to provide hydronic heating, cooling, DHW, and domestic chilled water. It was designed as a four-pipe system that does not require seasonal changeover and for situations of simultaneous demand for hot and cold water (e.g., summertime cooling and domestic hot water) and for facilities with large windows that cause heat loss in some spaces (e.g., north orientation) and heat gain in others (e.g., southeast orientation in the morning).

The control logic satisfies both heating and cooling loads while meeting DHW demand. The unit can operate in three modes: production of chilled water when a unit acts solely like a classic refrigerator; production of hot water where a unit acts only like a heat pump, using separate heat exchangers from chilled water production; and combined production where the system acts like a water heat pump controlling condensation and evaporation on two distinct plate heat exchangers. The hot water distribution system serves both the DHW fixtures and the space-heating fan coils. There is a single circulator on the secondary side of the heating loop that serves as both the space heating distribution pump and the recirculation pump (see Figure 2).

Figure 2. Aermec Installation at Calistoga

With the decision to use Aermec, the design team needed to see its modeled performance to understand this new system's ability to meet ZNE goals and code compliance. The central challenge of Title 24 modeling at Calistoga was determining the correct settings to accurately model a central heat pump. This applied to 2008, 2013, and 2016 compliance software. Given this lack of clarity, the energy consultant (who later joined the research team), eventually received guidance from the CEC on an approved methodology that demonstrated compliance with energy codes and other programs.

In addition to code modeling, comparative whole-building computer simulation models were developed using Energy Pro v.5.1 for residential space conditioning and DHW and nonresidential loads, and the California Utility Allowance Calculator (CUAC) for specific residential loads. The comparative modeling of a central system to individual systems showed an increase of 45 to 75 percent greater load for space conditioning and water heating. It is noteworthy that the underground piping from the central heat pump to the campus of three buildings may not have been accurately accounted for in the Title 24 modeling, yet the piping represents a significant amount of energy lost to the environment.

The first year of operation, in 2015, the Aermec and laundry room were monitored via metered data from a common utility meter that served both end uses in Building 2. The total consumption of 236,377 kilowatt-hours per year (kWh/yr) was roughly two-and-a-half times that of the modeled consumption of 89,864 kWh/yr. Issues with the Aermec were identified as the likely culprit of high electricity bills since more energy was used by the Aermec than the laundry. The recommended system modifications to overcome these performance issues is discussed in Chapter 3.

The performance of the Calistoga Aermec system was both far more energy intensive than initially estimated and consistent with central DHW research that demonstrated heat loss through recirculation and water-heating equipment (Zhang 2013; Oram 2017). The data were used to inform Cloverdale Aermec system energy-consumption estimates as well as solar PV sizing.

Cloverdale

The Cloverdale project was the third ZNE development by CBH, which was clear about how to build to ENERGY STAR for Homes and 100 percent ZNE with one exception: new ENERGY STAR R-5 thermal bridging insulation requirement.

The primary decision now facing the developer was whether and how to either install a central heat pump a second time after the performance challenges experienced at Calistoga or pursue instead a distributed approach to HVAC and DHW.

In 2015, while Cloverdale was under design development, individual heat pump efficiencies had improved and the most efficient tank-type HPWH on the market was the GE GeoSpring, with a rated EF of 3.1. For space conditioning, low-cost Fujitsu 9,000 to 18,000 British thermal units/hour (Btuh) ductless mini-splits were rated at a heating seasonal performance factor (HSPF) of 12 and seasonal energy efficiency ratio (SEER) of 25.[2]

These higher HVAC and DHW efficiencies did not move the decision-making dial. By staying with a lower-efficiency central system, an additional 19,000 kWh/year were required to feed the additional pump energy. It was determined that this could be met with an additional 13 kilowatts (kW) of PV on the roof. The developer self-installed the solar PV at $2,200/kW before rebates, so this lower efficiency central system cost $26,000 more in PV to accomplish ZNE, before incentives. This cost less in additional PV panels than it saved in mechanical system costs. They proceeded with the Aermec because it saved space in the tight design and saved money in equipment and installation. They also felt more confident that the Aermec design and installation process would be smoother the second time around since they were using the same engineering firm and design and construction teams that were used at Calistoga (see Figure 3).

A critical difference between Calistoga's and Cloverdale's design processes was the assistance of the research team during design development. With the additional support in Cloverdale, a variety of small measures was corrected: modifications to distribution systems, pump sizing, heat exchanger sizing, and fan coil valves. Interestingly, none of these corrective design measures could be modeled by the Title 24 software, though they impacted the system's energy use. Similarly, at Calistoga the hot water distribution system served both the DHW fixtures and the space heating fan coils. However, in this system there are separate circulators on the same loop. The larger of the two circulators acts as both the space heating circulator and the DHW recirculation pump and is controlled by a temperature relay that activates when the outdoor ambient temperature drops below 70°F (21°C). When the ambient temperature rises above 70°F (21°C) and it is assumed that space heating is no longer required), the larger

2 Efficiency ratings are used to evaluate heating and cooling systems. HSPF is a measure of heating efficiency of a heat pump. SEER is the standard of efficiency for air conditioning systems that is a ratio of cooling input in Btus divided by the energy in watt-hours that it consumes. For both metrics, the higher rating the more efficient the equipment.

pump turns off and a smaller dedicated DHW recirculation pump turns on to keep that loop primed.

Figure 3. Aermec Installation at Cloverdale

Similar to the Calistoga project, the project team developed comparative whole-building computer simulation models. The team used the 2008 and 2013 Code Title 24-approved software and CUAC to demonstrate both the energy performance of different configurations and how the building responded to changes in the energy systems.

The Title 24 compliance drop of 7 percent, from 44.5 percent for ductless mini-splits to 37.5 percent for the Aermec, was insufficient to sway the design one way or another though it still met all compliance requirements from the CTCAC and the U.S. Department of Energy (DOE) Zero Energy Ready Homes.

The CUAC simulations were a necessary part of the design process to estimate end uses for ZNE design and solar sizing. At ZNE-scale solar, all bills are the minimum monthly charge regardless of the modeled consumption. However, it is informative to see the relative amounts of energy consumed by each residential end use.

Cloverdale’s PV array completely filled the roof and carports wrapping around the building and adequately covered the project’s goals despite initial concerns that it would be inadequate. There are no combustion vents in the roof due to lack of combustion appliances, so the PV panels could be laid flat on four-foot racks safely above the plumbing and bathroom exhaust vents, maximizing the inexpensive installation on the roof. The horizontal orientation, hidden behind a parapet wall, provided the efficient PV layout with the additional required PV, which was placed on east- and south-facing carports.

The carport added an additional $800/kW to the self-installed cost of $2,200/kW, making the central system (with additional PV) pencil out at their bottom line. As a comparative, for CBH and its associated construction company, BLH Construction Company, central gas systems were 18 percent more expensive than central electric systems.

The design team for both Calistoga and Cloverdale worked through both the decision-making process and financial decisions to select the combined central systems and PV system sizing that achieved the design goals of ZNE, using available tools.

Atascadero

The Atascadero development was the fifth ZNE effort built by CBH. Like the previous ZNE developments, competitive scoring for U.S. Department of Agriculture Rural Development 514 farm worker housing loans led CBH to commit to 100 percent ZNE and 5 percent of the energy stored and used off grid. The Atascadero development consists of two buildings—one two-story building and one three-story building—and is comprised of 22 two-bedroom apartments, 24 three-bedroom apartments, 14 four-bedroom apartments, a manager's office, a computer room, two central laundry rooms, and a community room with kitchen and bathrooms (see Figure 4). It is certified to the DOE ZERH program LEED Platinum.

Figure 4. Atascadero Project

After working through the challenges of the central heat pumps in Calistoga and Cloverdale, the developer initially considered installing an Aermec, but decided it would be more cost-effective to install individual water heating and space conditioning at Atascadero in a well-ventilated rooftop shed (see Figure 5). Two previous ZNE single-family CBH developments used Rheem Prestige heat pump water heaters (HPWH), so the Rheem Gen4 product was chosen for Atascadero (EF of 3.5 for 50 gallons and EF of 3.7 for 80 gallons) (Appendix A Atascadero Energy Efficiency Measures).

The Atascadero project has individual systems comprised of 50-gallon (for two-bedroom units) and 80-gallon (for three- and four-bedroom units) HPWHs, with thermostatic mixing valves and ducted heat pumps for space conditioning. Each individual HPWH had a recirculation pump controlled by occupancy sensors located in each bathroom and kitchen of the apartments to meet WaterSense requirements for rapid hot water delivery. The HPWHs are all located on the roof in metal "sheds," and the outdoor condensing units are also on the roof.

The rooftop location introduced a new design challenge. The remote location led to significant plumbing runs to the first-floor apartments, making it a challenge to meet the WaterSense requirement limiting hot water flow to 0.6 gallons before water temperatures rise by 10°F

(5.5°C). After determining through modeling that a half-inch pipe could not meet this threshold, the only way to accomplish it was to install recirculating pumps (Taco Genie) with controls that met Title 24 requirements.

Figure 5. Rooftop Location for HVAC Outdoor Units and Heat Pump Water Heaters

CBH and the project team evaluated alternatives for meeting the 5-percent storage commitment. The initial strategy of using a central solar-thermal system to supply individual HPWH required additional infrastructure and competed with PV for rooftop space. At a cost of $10,000 per residence (as estimated by CBH's affiliated construction company), it was deemed unaffordable. With support from the research team, the strategy of thermal storage rose to the top. Thermal storage entails charging a hot water tank when renewable energy is available and minimizing hot water production when it is not. This off-grid storage of hot water makes a durable, inexpensive, nontoxic thermal "battery" of a hot water storage tank, with the following specifications:

- Tanks were set to Energy-Saver mode to maximize compressor power at EF of 3.7 and minimize use of the electric resistance element.
- To ensure adequate energy storage to meet peak loads, the temperature set point was raised from 125°F to 140°F (52°C to 60°C) and the tank size was increased from 50 gallons to 80 gallons for three- and four-bedrooms units. Two-bedroom units have 50-gallon tanks.
- Thermostatic mixing valves were installed per the building code and to ensure that DHW was delivered at the standard, safe 120°F (49°C), regardless of tank temperature.
- Ideally, a control mechanism is used to minimize operation during electric grid peak periods. This was discussed in the design phase, but not specified or adopted for the project because all the technologies available would negatively affect the manufacturer's warranty.

Through this process, the research team assisted the developer in moving from a central solar thermal system supplying individual HPWHs to the installed option of individual HPWHs with solar PV to offset costs and enable superheating water during solar peak, leveraging the planned PV system and simplifying its installation.

During the design phase the comparative whole-building computer simulation models included the Aermec and individual systems: a Maytag split heat pump (HSPF 10) for space conditioning and a Rheem Prestige HPWH for DHW.

The shift in technologies, from Aermec to the distributed systems, reduced the air conditioning load by 75 percent. The DHW time-dependent valuation (TDV) standard *increased* with the shift to individual systems, from 30.95 up to 34.19 (for the whole building), yet the COP of 2.0 modeled for the Aermec was less efficient with an EF of 3. 5 (for the individual systems). The origin of this modeling discrepancy is not clearly understood. Developers regularly face challenges with modeling variations and modifications between code cycles that affect compliance during planning and designing, prior to permitting. For example, the individual system modeled dropped 17 percent in compliance margin from the central system, which could affect code compliance or compliance with programs committed to for funding.

The final ZNE solar array sizing was completed with simulation models, using Energy Pro v.5.1 for residential HVAC and DHW, the 2016 CASE study for lighting, and monitored electrical end use (using data from the five previous ZNE CBH developments) to ensure that PV would meet all loads and achieve ZNE.

Only the later models incorporated shading from adjacent riparian forest and site trees. Consequently, the PV array was upsized shortly before completion of construction, to offset shading impacts. There is still space on site to add more solar should it be required for future electric vehicle charging loads.

In the final design, Atascadero met 5-percent storage through thermal storage with the heat pump waters and offset 100 percent of annual electrical end use with the specified PV systems, while undertaking a new individual system design.

Sunnyvale

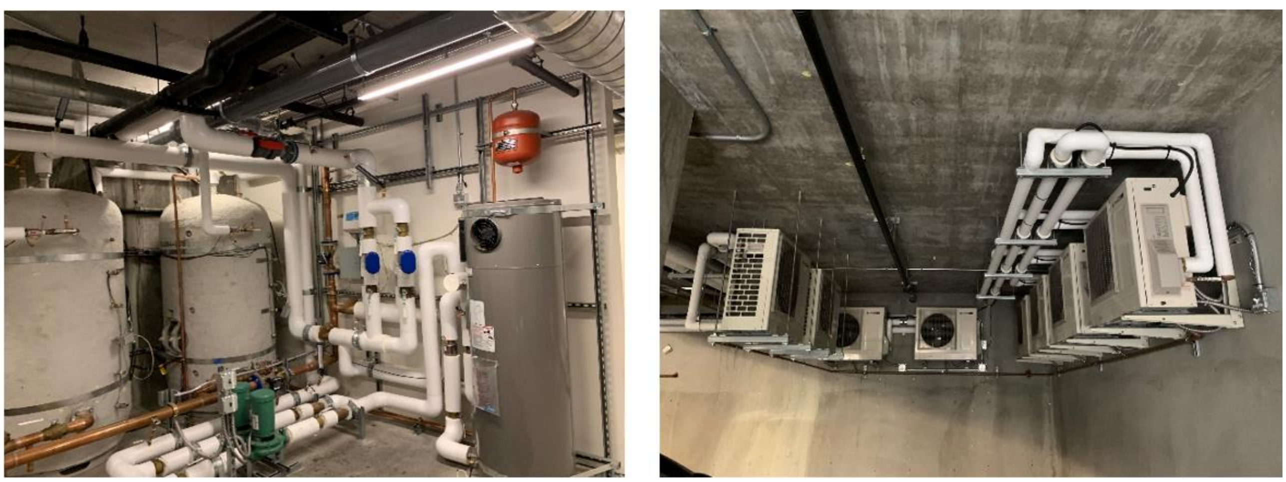
The Sunnyvale project is a four-story podium multifamily building with three wings. It is comprised of 66 units: 30 one-bedrooms, 18 two-bedrooms, and 18 three-bedrooms. Services include a community room, laundry services, social services, a play area, and a manager's office (see Figure 6). The project is GreenPoint Rated certified.

Figure 6. Sunnyvale Project

The Sunnyvale site was brought into the project after a central hot water plant had already been designed as a central tank-type condensing gas hot water plant, with solar thermal on the roof. That design changed significantly from a central boiler system to a central heat pump system with PV after it was incorporated into the research project.

The project is served by two central DHW systems: one serving wings 1 and 2 in Buildings 1 and 2 and the second serving Wing three in Building 3. The two central DHW systems are located in mechanical rooms on the first floor, along with services and parking. Wings 1 and 2 consist of 12 Sanden heat pumps and three 500-gallon storage tanks and one Rheem HPWH (see Figure 7); Wing 3 consists of 4 Sanden heat pumps and one 500-gallon storage tank with the same recirculation system. The dedicated recirculation heater effectively separated the recirculation system from the primary DHW system, allowing the primary hot water storage tanks to maintain a high degree of stratification, which in turn significantly improved the efficiency of the primary hot water heat pumps. There are two primary approaches to handling recirculated water in a heat pump system to avoid de-stratifying the main tanks. Both involved bringing warm, recirculated water back to its own dedicated heater, separate from the primary tank. One uses a recirculation heater and one uses a “swing” tank (see Appendix A for an overview of these recirculation approaches).

Figure 7. Central Heat Pump Water Heater Plant in Wings 1 and 2



The more detailed design considerations were critical for both performance and identified installation issues. The designed system included three tanks connected to four heat pumps piped in a reverse return configuration for balanced flow between the storage tanks. The smaller plant has the same configuration, but with one tank and a four-heat-pump bank, as opposed to three of those modules. The hot water (HW) supply is piped through an electronic mixing valve that mixes the HW supply down to 120°F (49°C) before sending it out to the building. The plant also has a HW recirculation line maintained by a variable-speed, pressure-dependent recirculation pump that works in tandem with temperature-controlled balancing valves located on each hot water riser. As thermostatic valves close, pressure in the system increases, triggering the pump to reduce its speed. This system also includes a smaller HPWH (50-gallon Rheem) dedicated reheating the recirculated domestic hot water. The returning and reheated flows are remixed and added back into the cold-water inlet side of the mixing valve to mix with the hot water before it’s distributed to the building. The distribution network was balanced with Caleffi 116 thermal balancing valves installed on each riser and set to 110°F (43°C). These valves serve two purposes: to ensure that all branches of the recirculation loop are maintained at the same temperature and to serve as a control signal for the pressure-dependent variable speed pump. As each branch line reaches its set point, the thermal balancing valves begin to close, increasing pressure in the system and triggering the pump to reduce its speed. Fourteen balancing valves were installed in wings 1 and 2 and eight were installed in Wing 3. This dedicated recirculation heater effectively separates the recirculation system from the primary DHW system, allowing the primary hot water storage tanks to maintain a high degree of stratification which, in turn, significantly improves the efficiency of the primary hot water heat pumps.

For space conditioning, the apartment units are served by individual ductless mini-splits, a very efficient ZNE-ready system included in the design from the very beginning (see Appendix A Sunnyvale Energy Efficiency Measures).

Figure 8. Ductless Mini-Splits Installed in Units

The solar PV system was designed to maximize the usable roof space effectively. This resulted in a net energy metering (NEM) system that would produce roughly 20 percent more energy than the common area’s modeled load, with an excess on a net annual basis. This additional production was not enough to justify interconnecting the solar PV system as a virtual net energy metering (VNEM) system in order to provide solar credits to the tenants. A VNEM system with so few credits allocated across 66 households would do little to reduce tenants’ electricity bills; in fact, it could have potentially increased them, based on the forced change to a time-of-use rate. As a result, the solar PV system was tied directly into the house electric meter that served common area electric loads, offsetting those loads.

From Gas to Heat Pumps

Condensing gas water heaters have typically replaced less efficient atmospheric boilers and moving from gas plant to heat pump required significant changes in the design, installation, and infrastructure requirements that had to be navigated. Over numerous conference calls and dozens of emails between the owner (MidPen), architect, a mechanical, electrical, and plumbing (MEP) engineer,[3] a consultant and research team members, and the manufacturer's representatives for the heat pumps (Sanden) and storage tanks (Lochinvar), the team established the following alterations to the original design:

- Gas service was removed from the entire project. Since water heating and clothes drying were the only gas uses planned for building, removing gas service would not have yielded significant cost savings. The owner and joint-trench consultants estimated that cost savings from removing gas from the building were only $4,600 ($1,600 for trenching and piping and $3,000 for Pacific Gas and Electric Company's (PG&E) gas distribution and a service extension). This cost estimate varies based on end use, particularly if gas appliances are proposed in units.
- Electrical service was increased to accommodate loads for water heating and clothes drying.
- Solar thermal was replaced with additional solar PV on the roof. The HPWH manufacturer specifically recommended against using solar thermal with the Sanden units.
- The water heating plant was relocated due to the increased physical storage size and air circulation requirements for an HPWH system and cool-air exhaust. The small ground floor boiler room originally intended to house the gas water heaters did not meet system requirements. After considering options such as the rooftop (which competed with PV and a large mechanical room that required significant mechanical ventilation, increasing energy consumption), the ultimate solution was to install the heat pumps adjacent to the shared wall between the garage and the mechanical rooms in an open-air garage, suspended from the ceiling to prevent damage from vehicles. This split system allowed the storage tanks to remain in the mechanical rooms.
- Water heating loads were recalculated. In addition to splitting the single plant into two plants, the ratio of storage to recovery capacity was adjusted to increase storage and reduce the number of heat pumps.

Heat Pump System Selection and Sizing

It was decided that among the available options, the Sanden SANCO2™ would be the base system. The Sanden system was selected for several reasons:

- It uses carbon dioxide (CO_2) refrigerant and has a higher COP than other HPWHs on the market.
- The versatility of the CO_2 refrigerant eliminates the need for electric resistance backup, reducing load size and potentially increasing utility costs from electric resistance.
- The heat pump is separate from the tank, making it possible to design modular, larger systems.

3 An MEP engineer addresses mechanical, electrical, and plumbing issues.

- The team had experience with central Sanden systems installed in other locations and a good relationship with the manufacturer's representative.

The most contentious stage of the water heating redesign was determining the appropriate combination of heat pumps and storage tanks to meet the building's hot water loads. The design team went through four design iterations to arrive at a modular Sanden system for each wing (Appendix Table A-1).

- **Iteration 1: Condensing Gas:** This was a single-plant condensing system located in a small boiler room with solar thermal-based on the system design for a similarly sized multifamily building recently completed by the design team in the same city.
- **Iteration 2:** The engineer's design was based on load calculations for each wing and modules of two heat pumps connected to single 83-gallon tank at the request of the design and consultant teams. To meet the building loads and the engineer's rule of thumb that the first-hour storage ratio be no more than 50 percent, the project would require a total of 40 heat pumps and twenty 83-gallon tanks. This design was immediately deemed too expensive, so the research team set out to analyze how the loads could be met using fewer heat pumps and storage tanks.
- **Iteration 3: Four Sanden Heat Pumps and 400 Gallons of Storage:** This iteration was based on updating a few assumptions that underpinned the system sizing for Iteration 2. Temperature rise was adjusted to a climate-appropriate threshold of 75°F (24°C) rather than 100°F (38°C), and the first-hour storage ratio was increased to 75 percent to prioritize storage over heat pumps. The calculations with these adjustments suggested that a relatively simple base system of four heat pumps and a 400-gallon tank could be repeated four times for the whole building.
- **Iteration 4: Four Heat Pumps and 500 Gallons of Storage:** Based on research team input for the system configuration in Iteration 3, the consulting engineer agreed that the system would meet first-hour requirements but nevertheless increased the storage tank to 500 gallons for each heat pump module to ensure that the system could meet longer-demand events.

Other Systems

Other system considerations evaluated to support ZNE included mechanical ventilation requirements, building envelope treatments, and lighting (see Appendix Table A-2).

The project was required to meet the ventilation specifications included in the Conditions of Approval to mitigate elevated levels of air pollution from a nearby highway that could lead to health problems for building residents. The three recommendations were: filter all supply air at the minimum efficiency reporting value's (MERV) 13 levels, ensure that all dwelling units maintain one air change per hour (ACH) of outside air, and ensure that all dwelling units maintain 5 ACH of recirculated air (SFDPH, 2008).

With most of the focus on the hot water system, the research team was unaware of the implications of the air quality requirements until the MEP kickoff meeting. The 1-ACH requirement led to outside air supply rates 53 to 61 percent greater than the ASHRAE 62.1 standard required by the California Mechanical Code. Over-ventilating to this extent would have significant impacts on energy consumption and be difficult to deliver in a way that would not irritate occupants. Upon review, the team learned these requirements were no longer consistent with current San Francisco Health Code regulations: all supply air must be filtered to MERV 13, all makeup air must come through a filtered supply system, and the system must comply with California Code ventilation rates.[4] When presented with this information, Sunnyvale modified the requirement to align it with current regulations.

The research team provided a number of options to effectively meet this standard and ensure positive pressure in the units, which would in turn ensure that unfiltered makeup air is not inadvertently pulled in through the building envelope. The final design included a rooftop central fan on each building to supply filtered air to all the units, and continuous bathroom exhaust with a boost. This design provides positive pressure, except when the kitchen exhaust is turned on.

The research team evaluated other opportunities to minimize loads and maximize performance and modeled the effect of a few different envelope and lighting options early in the design process.

The team assessed several insulation options using compliance software. It was decided that the project would not have continuous insulation at the stick-framed walls, would have insulation under the concrete podium where there are conditioned spaces above, and would include at least one inch of interior rigid insulation (rock wool board) at the ground floor concrete and concrete masonry unit (CMU) walls.

The initial project design did not specify 100 percent light-emitting diode (LED) lighting but changed to 100 percent LED in the design process, with the exception of only a few fixtures (flush mount fluorescent access lighting in apartment units or the surface mounted exterior fixture in apartment unit's exterior patios).

The project modeled under the 2013 Energy Code had to meet several thresholds: code compliance, a 15-percent improvement above code requirements for GreenPoint Rated certification, and a 5 percent threshold basis boost for the CTCAC. Once again, the team was faced with modeling challenges since the compliance software could not model central heat pump systems. After eliminating the prescriptive approach as not viable given the lack of solar thermal and a noncompliant electric resistance system, a CEC-approved approach allowed the project to comply with energy codes while overcoming the solar-thermal penalty.

Similar to the CEC, Build It Green allowed an alternative compliance model that would reasonably accommodate both central heat pump systems and mini-split systems for GreenPoint Rated to overcome limitations in the Title 24 compliance software. The ultimate result was that the Sunnyvale project model became approximately 35 percent more efficient than the Title 24 2013 code.

The final critical step in modeling the Sunnyvale project was to show that the building would be 15 percent better than code to meet MidPen's stated commitment (on their mid-2016 CTCAC application) to receive a 5-percent threshold basis boost. The CTCAC made an exception to allow separate models for the residential and nonresidential spaces to illustrate

4 San Francisco Health Code, Article 38.

the 15-percent compliance margin, a departure from code compliance and CTCAC regulations. The result was that each separate space exceeded code by more than 30 percent, well exceeding the 15 percent required by the CTCAC.

The project goal was a 100 percent offset of common loads, which included the DHW system. The offset was estimated using the National Renewable Energy Laboratory's PVWatts® tool to determine the estimated annual generation (in kilowatt-hours) from the solar PV system. This was subtracted from the total kilowatt-hours calculated with the Savings by Design model used for GreenPoint Rated. The result was that the building became approximately 35-percent ZNE.

CHAPTER 3: Monitoring Approach

Following the design and specification for the four ZNE projects, the research team turned its attention to construction verification and monitoring to fully understand the performance of these projects.

The team completed onsite inspections to verify the efficiency of both systems and products, and those systems were installed as designed (with variations documented), and to inform recommendations and monitoring plans (see Appendix B Monitoring Plans and Equipment Lists). Overall, the monitoring periods were extended to monitor changes to the system to address issues only identified through monitoring. A monitoring equipment removal schedule coincided with shelter-in-place orders for the COVID-19 pandemic, limiting access to the sites. The team monitored each project's apartments and central systems for the following time periods—Calistoga: June 2017–June 2020; Cloverdale: June 2017–February 2020; Atascadero: April 2018–July 2020 and Sunnyvale: February 2019–July 2020.

The team used online data to identify data collection and connection issues and assess ongoing performance and coordinated with property developers and construction companies to address other issues. This also meant that lessons learned could inform other current projects. Throughout the monitoring process, the research team faced several challenges with connectivity of technology deployed for remote monitoring, which limited access to real-time data.

Domestic Hot Water Monitoring

Since the four sites had different DHW systems and configurations, the data monitoring details of each one required different monitoring equipment placed at differing locations. However, the team employed current transducers (CT) on all DHW system electrical components (e.g., pumps, compressors); flow meters on supply, return, and makeup pipes; and thermistors, thermocouples, or resistor temperature detectors (RTDs) on piping and tanks at strategic locations. Loggers connected to DHW system sensors logged data at one-minute intervals for all data points. Temperature sensors collected and logged data at one-minute intervals, while some CT and flow sensors collected data at a one-second scale and logged data as an average or a single value on a one-minute scale, depending on the sensor and output type. Monitoring to this degree exceeded typical monitoring plans.

This density and duration of data allowed the team to assess both the energy savings of these systems and their ability to coordinate with the electric grid.

Electrical End Use Monitoring Approach

For electrical end use monitoring the research team chose the Nexi monitoring system. The Nexi device had two primary functions:

- A data processing unit with five CTs installed in the electrical panel logged energy use at the circuit level.

- A light display (which was plugged into a standard outlet) had two light wings that displayed instant consumption on one side and daily consumption on the other to provide energy use feedback to residents on their household energy usage (Figure 9).

The Nexi device allowed the team to collect total household energy usage data while monitoring three individual circuits in Calistoga and Cloverdale and eight individual circuits in Atascadero and Sunnyvale. The Secure Digital SD cards storing the data were collected from each apartment, which allowed the team to check their thermostat set points and also allowed them to talk with tenants about any concerning issues. Given the type of thermostats installed, there was no other way to collect that data except in Sunnyvale, where the team installed Temp Sticks™ to log indoor temperatures. The Nexi data at Sunnyvale and Atascadero were reviewed remotely on a regular basis since the devices could connect to the internet, and wireless routers were installed in each apartment.[5] The data collected by the Nexi devices aided the team in:

1. Documenting and understanding the (partially) disaggregated, load-by-load, time-of-use profiles for low-income ZNE multifamily housing.
2. Mapping time-of-use for each monitored load type.

Nexi devices captured the time signature and current of the energy end uses. The main circuits utilized 50-amp CTs while all other circuits utilized 20-amp CTs. For all double pole circuits, usage was monitored using only one leg of the circuit. The electrical service to the panel was 120volt (V)/208 V. Given that, the amperage was multiplied by 1.73 to obtain total consumption for these loads rather than doubling as would have been appropriate for 120 V/240 V configurations. Because there are more than three circuits in each panel, the team had to choose which circuits to monitor at each apartment, yet each end use has a large enough sample size to identify trends and correlations. Table 3 shows monitored circuits for each site. Unlike other sites, Atascadero was metered in specific end-use sample groups that depended on the total number of circuits and the number of apartments available for each sample.

Functioning as a behavior feedback device, the Nexi devices provided residents with simple color signals instead of numbers, tables, and graphs (like other devices), which eliminated the need for more complex training for occupants. It allowed tenants to "see" their energy usage instantly via a changing light display plugged into a centrally located outlet. The thresholds at which the display color change was established as percentages of a total "allowance." The allowance (similar to an energy budget in Title 24 compliance software) was established based on a review of modeled energy usage for the site, a review of the electric utility's tier quantities, and monitored energy use at similar projects. The Nexi's color representation allowed residents to see green, which was shown to be an important color for tenant

5 PG&E provided funding that allowed the team to specify Nexi devices with more circuit connectors and Wi-Fi capability in exchange for access to the data.

satisfaction.[6] This promoted conservation by showing the estimated budget in red as a warning; 10 percent over budget was fuchsia (Figure 9).

Figure 9: The Nexi Light Display Device and Thresholds

Color Level	% of Budget
Green	<40%
Yellow	40%–70%
Orange	70%–95%
Red	95%–110%
Fuchsia	>110%

Table 3: Summary of Monitored Circuits at Each Site

Circuits	Atascadero			Calistoga	Cloverdale	Sunnyvale
	Kitchen	HVAC	Plug Loads			
Mains	X	X	X	X	X	X
General Receptacle			X			X
General Lighting		X		X	X	X
Bathroom Receptacle		X	X			X
Exterior Receptacle			X			
Fan Coil/ Mini-split		X		X	X	X
Condensing Unit		X				
Recirculating Pump	X	X	X			
Small Appliance 1	X		X			X
Small Appliance 2	X		X			X
Dishwasher	X					X
Refrigerator	X					
Electric Range	X	X		X	X	
Hood	X	X				X
Water Heater	X	X	X			
1 Bedroom					16	30
2 Bedrooms	8	6	8	16	16	18

6 In previous Nexi installations, occupant surveys indicated that residents with daily loads above their budget were not very happy with the devices when they were programmed so that they were only in the green mode for 25 percent of the energy budget. It made them feel as if they were doing something wrong.

Circuits	Atascadero			Calistoga	Cloverdale	Sunnyvale
	Kitchen	HVAC	Plug Loads			
3 Bedrooms	8	8	8	16	16	18
4 Bedrooms	4	7	3			
Central Laundry (washers and dryers)	X			X	X	X

Equipment Selection and Communications Protocol Considerations

The following primary factors were taken into consideration in determining the metering and logging equipment package selected for each site:

- Flexibility
- Ease of Installation
- Network Capability
- Accuracy
- Compatibility With the System and the Rest of the Monitoring Equipment
- Data Storage Method and Capacity of Onsite Loggers
- Battery Life and Power-Supply Options
- Communications Options (e.g., pulse, voltage, Modbus)
- Material Costs
- Installation Cost and Feasibility
- Ability to Use Equipment at Multiple Sites

The monitoring periods allowed for data collection over winter, summer, and the shoulder seasons. This is important since ambient temperature and incoming water temperature affect HPWH performance, particularly with regard to thermal storage potential.

The following sections describe specific variations from design and installation, as well as the monitoring approach and equipment used by the research team.

Calistoga and Cloverdale Projects

Cloverdale and Calistoga have different layouts and configurations but similar energy efficiency measures and central combined systems (Appendix A Calistoga and Cloverdale Energy Efficiency Measures).

The research team completed field inspections to verify that the project was installed as designed. For both Calistoga and Cloverdale, in-unit measures were installed as intended, except for the bathroom fan controls. The bathroom fans that provided mechanical ventilation were specified to run continuously at a low cubic feet per minute (cfm) and at a higher setting triggered by an occupancy sensor or humidistat. For Calistoga, the fan was always on, with no option for a higher flow rate, and it appeared that a standard switch was installed, then bypassed. For Cloverdale, humidistat switches were installed improperly, so the fan could only be controlled manually.

The central combined system, the Aermec, was not installed as designed at either project. The initial site visits to verify conditions for installation of monitoring equipment found several field variations from the plans.

For Calistoga, these variations included the following:

- The system was not piped as designed.
- The pump's pressure switch was not installed.
- Two-way valves were installed for fan coil units instead of three-way valves.
- A chilled water pump was not indicated on the plans.
- The installation of the hot water pumps (primary and secondary) differed from the plans.
- There was no dedicated recirculation pump.

For Cloverdale, these variations included the following:

- The secondary hot water pump (HWP) was supposed to be operating at variable speed, but it was running instead at constant speed.
- One of the two pumps, either the hot water or cold water, operated continuously.

The team also made operational suggestions that were incorporated into performance evaluations.

Based on the original plant design for both properties, the Aermec's internal single-speed circulating pump supplied chilled water to a 1,000-gallon storage tank, which turn supplied fan coil units within the apartments. The compressors cycled on and off based on return water temperature to maintain a set temperature within the tank. The mechanical plan set did not include a sequence of operations, or any other control strategy recommendations for the chilled water loop; the heat pump was controlled by Aermec proprietary controls. According to the manufacturer's representative, for the Aermec to read return water temperature the unit requires a constant flow, so the chilled water pumps were designed to operate continuously all year.[7]

A variety of changes had taken place to the chilled water side of each of the plants, resulting in changes to both the original monitoring equipment and the plan.

There is now a variable speed secondary chilled water pump that draws chilled water out of the tank and supplies it to the building. This pump modulates based on system pressure. A temperature-controlled relay recently added to that pump turns the pump off when outdoor air temperature drops below 70°F (24°C).

At Cloverdale, the HWP 2, a variable speed pump that circulates hot water to the building, was originally intended to modulate its speed based on temperature differential but was eventually switched to pressure-based modulation. At Calistoga, the HWP 2 was a single-speed pump that ran continuously all year; this diverged from what was designed and was an area of suggested improvement.

---

7 The team is exploring other options for sensing the temperature that should result in even greater energy efficiency.

Some of the key data points collected included the following:

- **Total Heating Energy Production and Consumption for DHW and Space Heating:** (measured in kW, kWh, and Btu): metering the electrical power and energy consumed, the thermal energy (Btu) used at the property, and pumping energy associated with moving useful heat around the property
- **Cooling Energy Production and Consumption** (measured in kW, kWh, and Btu): metering the electrical power and energy consumed, the chilled water thermal energy (Btu) used at the property, and pumping energy associated with moving useful heat around the property
- **Indoor Temperature Set Points** (from visual inspections)
- **DHW Energy Production and Consumption** (measured in kW, kWh, and Btu): metering cold water makeup (CWMU) because the heating loop provides both space heating and water heating. DHW Energy = Total Heating Energy (Btuh) - (gallons makeup water (gpm) X Delta T (°F) X 500)
- **Pumping Energy** (measured in kW and kWh): metering pump energy for all pumps (hot water pumps 1 and 2, recirculation pump, chilled water pump, and internal Aermec pumps)
- **Distribution Losses and Tank Losses (Standby)** (measured in Btu): Accurately determining losses in the field is difficult at best. The research team estimated that tank losses, using equipment runtime data and hot water supply temperatures, a significant amount of effort was not expended on this activity since tank loss is of minor importance to the overall project.
- **Total Hot Water Usage** (measured in gallons): Hot water determined by volume of makeup water supplied to Heating Hot Water Tank #2 was measured and logged, using an ultrasonic flow meter.

The purpose was to study these data and be able to compare DHW and HVAC loads to total loads to determine the relative contributions of each end use, understand the operating efficiency of the central plant, and identify and deploy optimization strategies to document savings. The plan then was to evaluate the systems and develop central plan recommendations, as well as to evaluate the balance of those loads to determine how to most readily achieve ZNE buildings (Table B-2 and Figure B-1, Appendix B).

Since the Aermec system's efficiency varies significantly based on how much heat recovery takes place at any given time, it is critical that the monitoring period captures the full range of seasonal events; in particular, shoulder seasons that may induce more or less coincident heating and cooling demand. It was critical to capture a statistically significant volume of data from the plant while it was operating in *heating only* and *cooling only* modes.

During the first year of monitoring, the research team analyzed data quarterly while simultaneously developing an improvement plan for both projects. Neither project executed full improvement plans but instead executed simpler, less extensive recommendations. Therefore, the team was not able to monitor the projects post-improvement measures to understand their impacts on performance.

Behavior Research at Cloverdale and Calistoga

Energy costs for fan coil use, along with other lighting, plug loads, and apartment level appliances, are paid by tenants who have individual electric utility accounts. One-, two-, and three-bedroom units at both Cloverdale and Calistoga were programmed with daily kWh allowances of 7.3 kWh/day, 8.8 kWh/day, and 10.4 kWh/day (Table B-1, Appendix B).

To analyze behavioral efficiency opportunities, deployment of the Nexi lighting displays were temporarily delayed following installation of the data-logging units. This provided the team with a comparison of before-and-after-display energy consumption, which illustrated the impact of providing tenants with energy use feedback. Yet, tenants were not responsible for the largest loads of space conditioning and water heating, which are more easily affected by behavior.

The team monitored indoor temperature in a sampling of units on each floor for a period of six to nine months; this monitoring captured seasonal variations and enabled evaluation of space conditioning demand and operation at a unit level, in conjunction with electrical end use consumption for the fan coil unit. The unit selection included units on each floor, as well as interior units and units with at least two exterior walls. These apartment level data were evaluated in conjunction with operation of the central combined system.

Atascadero Project

Onsite inspections were completed to confirm the following conditions for monitoring equipment selection and layout.

- Wire size of mains, to ensure that proper CTs were provided with the Nexi devices
- Layout of DHW cold water supply and hot water supply on the building roofs
- Location of condensing units and refrigerant lines
- Nameplate of the fan coil unit, condensing unit, and heat pump water heater

In general, the Atascadero project was built almost as designed. However, the following items were not installed as designed.

- **The Recirculation Pump**. It was specified to be controlled by a single occupancy sensor, but the installation included an infrared occupancy sensor in every bathroom and the kitchen to control the recirculation pump.
- **The Bathroom Fan**. As with Cloverdale and Calistoga, the fan providing mechanical ventilation was specified to run continuously at a low cfm, at a higher setting when triggered by an occupancy sensor with a timer. Instead, the fans were installed to run continuously at a low cfm, with a manual switch to raise air flow.

The Atascadero site utilizes 50- and 80-gallon individual Rheem Prestige Gen4 heat pump water heaters (Table 4: Rheem Systems at Atascadero), which can operate in three modes: high demand, energy saver, and heat pump only (see Glossary for operating mode definitions).

Table 4: Rheem Systems at Atascadero

Tank	Bedroom Type	EF	Number Installed	Number Monitored	Average Occupancy
50 gallons	2 bedrooms	3.50	24	8	2.73
80 gallons	3 and 4 bedrooms	3.7	36	14	4.25 and 5.14

The data collected was analyzed and used to:

- Understand the actual operating efficiency of a hybrid HPWH.
- Make recommendations for thermal storage for peak shaving and load shifting.
- Develop design and specification recommendations.
- Validate standard assumptions for water and hot-water usage.

The monitoring was limited to 22 of the 60 apartments, though the electrical end-use monitoring covered all 60. The remaining 38 HPWHs served as a control group whose tanks were in static mode and set points for the duration of the project, though both could have been adjusted by maintenance without our knowledge. Each of the 22 HPWHs had five temperature sensors and one flow meter installed on its piping (Figure B-2, Appendix B). The HPWHs were grouped in threes and connected to one Cloud-enabled and Wi-Fi-enabled Onset HOBO data logger that remotely transmitted data for access and analysis, allowing weekly dumps of data as well as on-demand, real-time data exports.

Behavior Research at Atascadero

The energy costs for the individual space conditioning and water heating equipment—along with all the other electrical end uses in the apartments—are paid by tenants through individual electric utility accounts.

Two-, three-, and four-bedroom units at Atascadero were programmed with daily kWh budget (allowances) of 12.7 kWh/day, 14.9 kWh/day, and 16.9 kWh/day, respectively (Table B-1, Appendix B). These tiers match tenants' likely daily usage (based on CUAC) and are below the baseline threshold of daily usage for all but the three-bedroom units, which were within 1 kWh/day of the baseline. With the ZNE scaled solar array, tenants will likely never meet net monthly usage above the baseline quantity.

Unfortunately, given the timing of installation and a shorter monitoring period, all the lighting displays were installed together with the data processing units. This prevented the team from evaluating the correlation of energy consumption with the impacts of the lighting display system with larger tenant loads.

Sunnyvale Project

At the unit level, the Sunnyvale development was built as planned, even though the central DHW system was not installed as designed.

Table 5 illustrates the configuration of the two plants.

The initial site visit to verify the conditions for installation of the monitoring equipment found several field variations from the plans:

- Single-speed pumps were installed instead of variable-speed pumps. One of the two single speed pumps was valved off at the start of system operation, so one single-speed pump was used for the majority of the monitoring period up to September 2019, when that pump was replaced with a right-sized variable-speed pump.
- The central system was not piped in reverse return, but was rather piped in direct return. A direct return configuration meant that one storage tank was supplied first, and then was darn from first to supply the rather than in reverse return, which is first in and last out.
- Several balancing valves were missing, and some of the installed balancing valves were set to 120°F (49°C) rather than to 110°F (43°C).
- The wrong HPWH was ordered for the recirculation system.
- The installed settings for the recirculation loop heat pump did not match specifications.

Table 5: Hot Water Plant and Service Metrics

DHW Plant	Number of Sandens in Plant	DHW Storage Tank Size (Gallons)	Recir-culation system?	Number of Units	Number of Bedrooms	Number of Occupants (as of 12/2019)
Wings 1 and 2	12	1,500	Yes	42	69	101
Wing 3	4	500	Yes	24	51	81
Total	**16**	**2,000**	**Yes**	**66**	**120**	**182**

The data collected were analyzed and used to:

- Understand the actual operating efficiency of modular HPWH systems.
- Make recommendations for using thermal storage for peak shaving and load shifting.
- Develop design and specification recommendations.
- Validate standard assumptions for hot water usage.

Monitoring equipment was installed for both central plants and in-unit monitoring (Table B-4 and figures B-3 and B-4, Appendix B). Flow meters were installed on the cold-water makeup, supply to the main tanks, recirculation return, recirculation to the dedicated heat pump, and on each tank loop. Temperature sensors were installed on the cold-water makeup, recirculation return, delivered water from the HPWH for recirculation, the main tank after the recirculation blend, supply water (after the mixing valve, supply, and return for each tank), and supply from the main tank to each individual tank. The sensors connected to an Onset HOBO data logger (which as Cloud-and Wi-Fi-enabled) transmitted data remotely for access and analysis. This allowed weekly dumps of data to the team's remote FTP site.

Behavior Research at Sunnyvale

The individual space conditioning equipment, along with all other electrical end uses in the apartments, was billed to tenants. The largest load of DHW was centrally metered at Sunnyvale.

One-, two-, and three-bedroom units at Sunnyvale were programmed with daily kilowatt-hour allowances of 10.2 kWh/day, 12.2 kWh/day, and 14.1 kWh/day, respectively (Table B-1, Appendix B). Similar to Atascadero, given the timing of the installation the team was unable to stagger the installation of lighting displays so therefore could not evaluate the correlation between energy consumption and the lighting display system. Due to impacts of COVID-19, the survey for Sunnyvale was delayed and administered in March 2021.

In addition, the team installed Temp Sticks at each thermostat in every apartment to monitor relative humidity and temperatures to provide insights into HVAC operation. Due to a drop in wireless signal and no local data storage, this data set was very limited.

CHAPTER 4: Project Results

Introduction

This chapter documents the performance of the four monitored ZNE projects.

The research team collected and analyzed the data described in Chapter 3 over the course of the monitoring periods (1.5 to 3 years, depending on project). Monitoring data were used to evaluate system performance and identify installation errors and opportunities to improve performance. Overall, this monitoring afforded the opportunity to identify performance issues with recirculation pumps, split heat pump systems, central system controls, and PV performance (which would otherwise have remained undiscovered). Qualitative data from surveys, conversations, and quantitative data were combined to understand the performance at each development.

Throughout the monitoring period there were changes in tenant occupancy. However, that occupancy (which was a variable in the analysis), was based on move-in schedules and did not reflect actual changes throughout the monitoring period. Unit turnovers and short-term vacancies throughout the time period may not have been consistently captured.

The performance results and findings for each project are described in subsequent sections, beginning with a summary of a selection of results across all projects, followed by a section for each site; Cloverdale and Calistoga were combined. The initial discussion focused on overall performance and ZNE analysis (Appendix C includes a summary of methodologies.) This is followed by a discussion of specific end uses and concludes with a discussion of planned (or modeled) results versus actual results. The analyses in this chapter set the foundation for the discussion in Chapter 5.

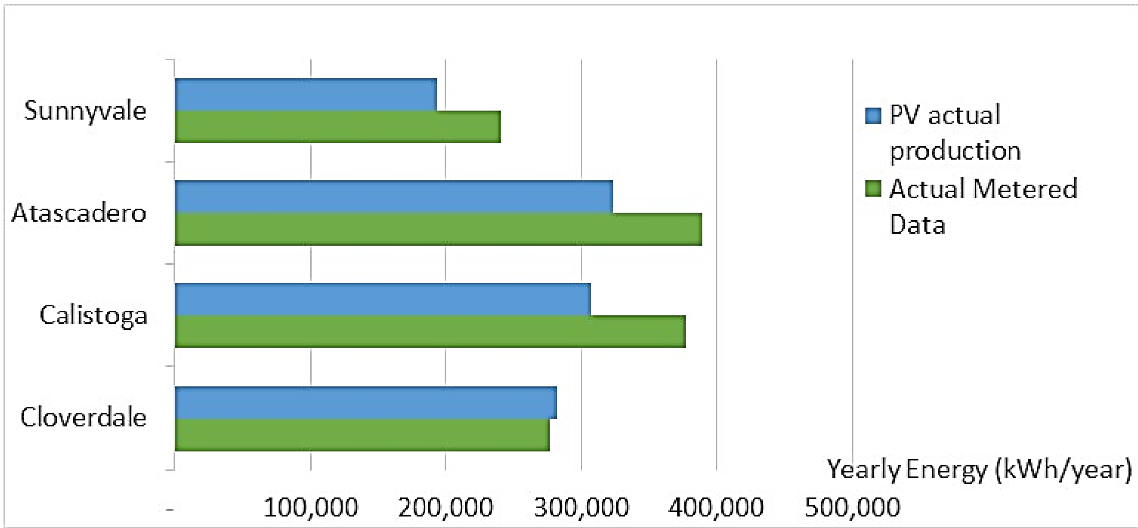
Summary of End Uses for the Four Projects

Given the varying configurations in the four projects, a few variables were worth extracting to examine show side by side. These include total ZNE performance, DHW, electrical end use, and cooking.

Each project targeted ZNE in some form. While only one of the four achieved its ZNE goal in the year 2019, all projects could have potentially achieved ZNE, which will be discussed in each section. The projects that did not achieve ZNE in 2019 were within 18 to 20 percent of achieving it (Figure 10 and Appendix C for the methodology). Atascadero and Sunnyvale[8] were close, and may well achieve it with additional modifications. Calistoga had the potential to achieve it even before making significant operational changes.

8 Sunnyvale is limited to common area consumption based on ZNE design goals.

Figure 10: Comparison of PV Production to Actual Energy Consumption



Given that this project's focus was on domestic hot water, it is informative to look at a comparison across all sites. Average hot water consumption per apartment was estimated per day and per person and calculated using cold-water makeup flow data, as shown in Table 6. The results represent actual usage normalized for behavior, draw patterns, or other variations across the sites. While the per-dwelling usage was higher than in other studies, the per-occupant values were fairly close to the ANSI/RESNET Home Energy Rating System (HERS) algorithms developed by Parker et al. (2015). Higher per-dwelling volumes were attributed to higher-occupancy apartments.

Table 6: Average Daily DHW Consumption per Unit for Each Project

	Atascadero (gal/unit/day)	**Calistoga (gal/unit/day)**	**Cloverdale (gal/unit/day)**	**Sunnyvale (gal/unit/day)**
Average daily/unit	56.1	64	67	57
Average daily/person	14.3	17.9	17.7	20.7

Average occupancy shown in Table 7 was higher than estimates using the number of bedrooms plus one algorithm. Note that each development includes a manager's unit, which is a single-occupant three-bedroom unit.

Table 7: Average Occupancy for all Projects

	Average Occupancy				
Project	**Total**	**1-BR**	**2-BR**	**3-BR**	**4-BR**
Calistoga	3.46	1.88	3.56	4.94	n/a
Cloverdale	4.19	n/a	3.50	4.88	n/a
Atascadero	3.90	n/a	2.73	4.25	5.14
Sunnyvale	2.85	1.67	2.72	4.94	n/a
TOTAL	3.50	1.71	2.96	4.65	5.14

Each development had different tenant end uses and panel configurations. Apartment end uses are summarized in Table 8 and show variation and similarities across the projects. Lighting and plug loads were aggregated due to electrical circuit wiring particular to each site, so quantifying those plug loads was not possible. In Table 8, Cloverdale and Calistoga loads included receptacles, lighting, refrigerator, dishwasher, and garbage disposal. Atascadero and Sunnyvale loads included bathroom, kitchen, and general receptacles and lighting loads. Given the different configurations, cooking and miscellaneous electric loads (MELs) were the dominant apartment loads identified for Cloverdale and Calistoga, and DHW and HVAC were the dominant loads for Atascadero. For Sunnyvale, HVAC and MELs were the dominant loads.

Table 8: Electrical End Use Comparison of Average Daily Usage

Average Daily	Cloverdale	Calistoga	Atascadero	Sunnyvale
Central Systems	Central HVAC and DHW	Central HVAC and DHW	None	Central DHW
Total Tenant Loads (kWh/day)	4.3–15.1	3.3–15.6	8.1–28.9	5.5–17.1
Nexi Estimated Loads (kWh/day)	7.3–10.4	7.3–10.4	12–16.9	10–14.1
Heating and Cooling (kWh/day)	0.3–2.1 (avg. 0.64)	0.2–1.9 (avg. 0.97)	2.5–6.4	4.8 (based on nine months)
MELs and Lighting (kWh/day)	1.9–11.8	1.9–11.8	4.9	5

Average cooking consumption on a per-occupant basis tracked reasonably well across apartment complexes with similar low-income demographics and was higher than model assumptions. Previous studies showed a high degree of demographic influence on range consumption, as well as individual variance, even within these demographically narrow populations. Daily average cooking time and consumption per apartment were similar across the three projects where ranges were monitored at the circuit level, as shown in Table 9. At all the study sites there were predictable spikes at holidays, and in general tenants cooked more in the winter, attributable to holidays, colder temperatures, and longer boiling times.

Table 9: Daily Average Cooking Times and Energy Consumption Across Projects

	Calistoga	Cloverdale	Atascadero
Average daily time (min)	110	97	103
Average kWh/day	2.2	1.9	1.9

Calistoga and Cloverdale

The team conducted in-depth monitoring for 2.75 years at Calistoga and 2 years at Cloverdale to understand central system performance and how each project performed relative to the goal of zero net energy. When the team began this project, it was discovered that Calistoga had been dealing with central plant performance issues.

The Aermec is an advanced system that requires a diverse set of skills in both the planning and installation phases. This complex system was new to the design and construction teams, resulting in multiple challenges from sizing to installation layout and configuration. Throughout two years of monitoring the property, the maintenance staff and Aermec-approved service contractors made changes to the Aermec system and replaced a variety of system components at both properties to mitigate performance issues. Significantly, even more changes were made at Calistoga. Throughout the monitoring process, many issues were identified and discussed with the developer. Despite a committed design team, a highly motivated construction company, and technical support and monitoring from the research team, the system proved to be impractical option for providing heating, cooling, and DWH services for these particular multifamily properties.

Overall ZNE Performance

Calistoga and Cloverdale had very different ZNE outcomes, despite having similar major mechanical systems, but a different building typology, Cloverdale was able to achieve ZNE, while Calistoga was not.

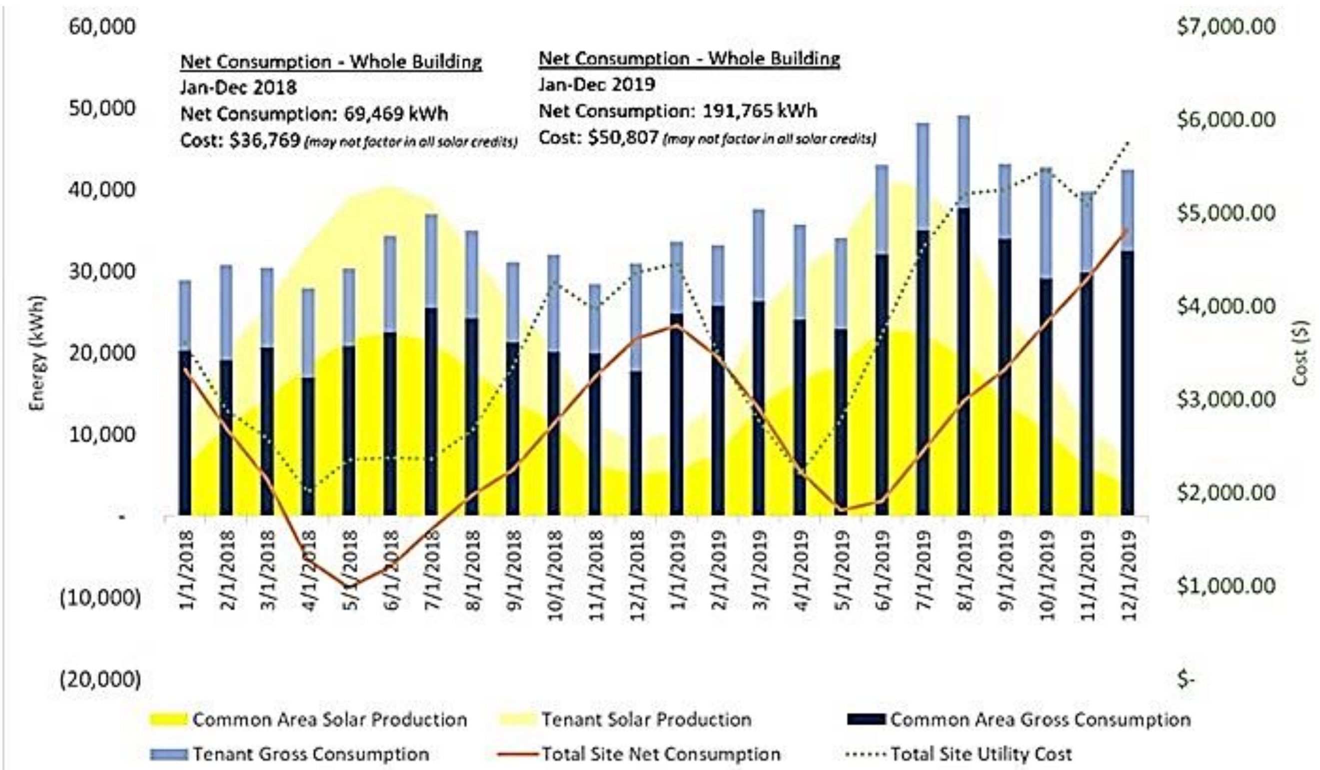
For Calistoga, at the time of the system's most optimal energy operations, the whole property was approximately 18 percent away from achieving ZNE. The central plant would have needed to achieve a 36 percent reduction in operational energy usage for the property to achieve ZNE (Figure D-1 in Appendix D). This seemed within reach with identified physical and operational changes.

Some of those changes included the following:

- Modifying the as-built piping to the storage tanks to match the original design drawings to achieve the intended stratification of the storage tanks.
- Reducing the primary loop flow rate to increase effective heat transfer and create greater temperature differential between supply and return; this is more optimal for a heat pump.
- Disabling the cooling mode operation in the winter instead of raising the cooling set point to 90°F (32°C) to prevent cooling operation. This not only required the primary chiller water pump to continue to operate, but also required the system to maintain 500 gallons of 90°F (32°C) stored water, which served no purpose and increased energy use.

In December 2018, in an effort to avoid compressor failures that occurred from short cycling, the newly contracted service technician made operational changes that effectively enabled the system to run its fans continuously. The Aermec has drawn power continuously since this change, which was made to optimize system reliability and minimize compressor burnouts but not optimize energy performance. The change increased the Aermec's energy consumption 45 percent in 2019, as compared to 2018 (see Figure 11 and figures D-1, D-2, and D-3, Appendix D). Because the Aermec consumed the majority of the energy when compared to other end uses at the property, Building 2's large positive net energy usage over the course of the year caused the whole property to be a net consumer rather than a net producer. Calistoga did not achieve ZNE even at its most optimized state; instead, with those changes made to the central plant, it became even more energy intensive and even farther from achieving ZNE, as shown in the profile of 2018 through 2019 in Figure 3.

Figure 11: Comparison of Calistoga's Whole-Site Energy Consumption and Solar PV Production From 2018 and 2019. Costs Were Aggregated From Portfolio Manager

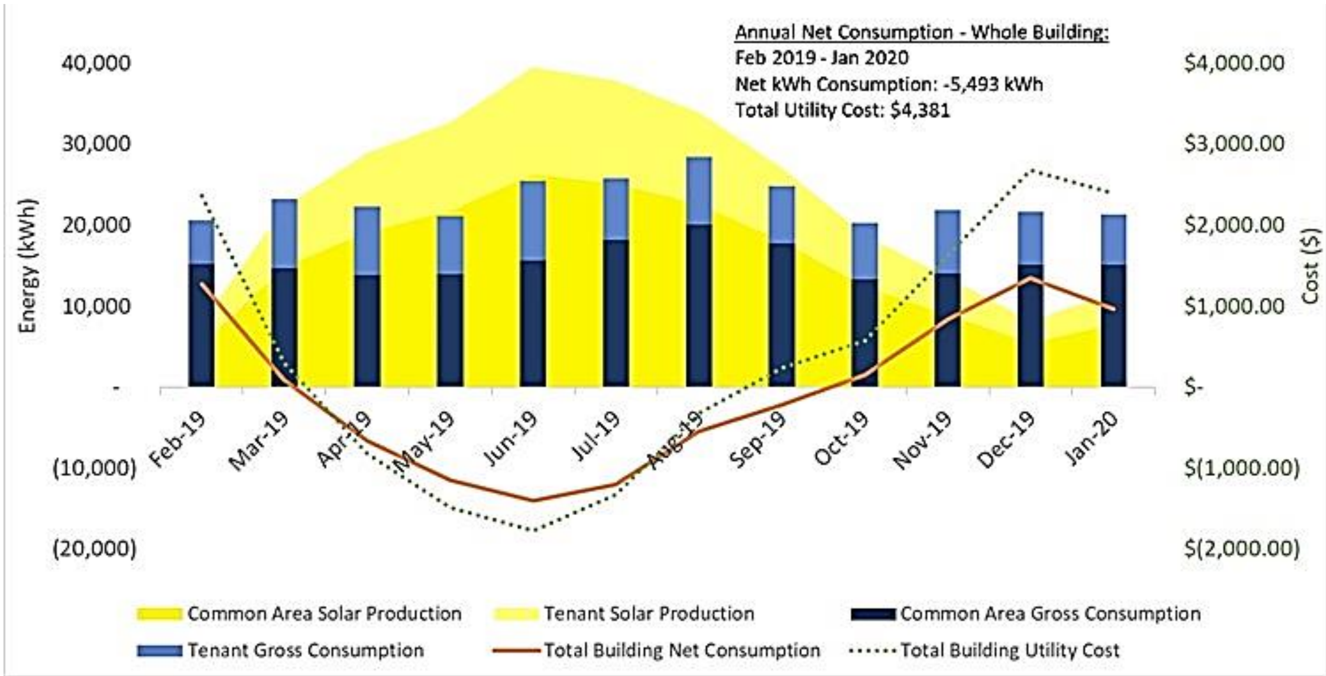


In contrast, Cloverdale was able to achieve ZNE for a 12-month period starting in 2020, in large part due to the better-optimized mechanical system and proportionally larger solar PV system. The property was not ZNE prior to 2020 because of compromised solar PV system production (see Figure 12). The Aermec system optimization measures included the addition of a small dedicated DHW recirculation pump, which operated in lieu of the larger space heating pump when there was no space heating demand and temperature controls on the hot water and cold-water secondary pumps to prevent continuous operation. That said, similar to Calistoga, the cooling set point was raised to 90°F (32°C) in winter, negatively affecting energy use. Aside from this change, the system was better optimized than the plant at Calistoga.

There were two issues with the solar system at Cloverdale: one related to billing and one related to inverter performance. The research team found that solar billing had not been configured properly since the VNEM solar PV system was interconnected and operating in November 2017. By summer 2018, nearly nine months after interconnection, the solar billing was corrected, with the property and tenants retroactively receiving bill credits.

The team also discovered a performance issue: a large monthly consumption and associated bill, but with very little electric production. After six months of discussion with the utility and with the building owner, in February 2019 the contractor and utility went onsite and discovered that half the inverters were turned down to 0 percent output. Once the inverters were properly configured, the solar PV system began producing at full capacity—nearly double what it had been previously. ZNE achievement was measured from March 2019 through February 2020 to capture a full calendar year of full capacity PV production.

Figure 12: Cloverdale Whole-Site Energy Consumption and Solar PV Production



Three primary factors affected Cloverdale's ZNE performance, relative to Calistoga: the sizing of the solar system, the allocation for virtual net metering, and modeling.

The solar PV system at Cloverdale is proportionally larger than that at Calistoga on the basis of kilowatts per square foot, per unit, per person, and the per Btu capacity of the Aermecs (Table 10). The Cloverdale system is larger than that at Calistoga. The most significant change in the approach at Cloverdale was the upsizing of the PV array (based on the Aermec performance at Calistoga instead of using the modeled projections.

Table 10: Comparison of Cloverdale and Calistoga PV Systems and Allocations

Property	Number of Units	W per Apt ft^2	kW per Unit Count	kW per Person	Annual kWh Production Allocated to Tenants per Unit (avg)	Annual kWh Production Allocated to Common Area per Unit (avg)	kW System Size
Calistoga	48	6.78	5.40	1.63	3,410	4,244	259
Cloverdale	32	8.10	7.42	1.96	3,448	6,896	209

Cloverdale's solar PV credits were allocated more favorably so that the common area with the Aermec load received the greater majority of the solar PV credits when compared with

Calistoga. The solar PV system at Cloverdale allocated 66 percent to the common area electric account and 33 percent to the tenants' electric accounts. The solar PV system at Calistoga—smaller on a per unit basis—allocated 55.5 percent to the three common area electric accounts, of which 48 percent was allocated to Building 2 with the Aermec system. The remaining 44.5 percent was allocated to the tenants' electric accounts across the 48 units.

At Calistoga, the allocation of credits resulted in Buildings 1 and 3 being net negative energy, with additional solar credits on the accounts, and Building 2 (with the Aermec) being net positive.[9]

Electrical End Uses: Tenant Loads

Common meter loads that served the tenants included space conditioning and water heating. Tenant loads on individual meters at Cloverdale and Calistoga included all general receptacles, kitchen and bath ground-fault circuit interrupters (GFCIs), refrigerators, ranges, lighting, bathroom fans, fan coil units, dishwashers, and garbage disposals. The tenant metered loads were monitored in aggregate, and the fan coil and range were directly monitored.

Due to central system DHW, heating and cooling, whole house consumption was largely sensitive to individual behavior rather than to seasonality, with the exception of limited fan coil operation for heating and cooling. There was little statistically significant difference between the two sites; for this reason, they were treated as a singular population with any clear differences explicitly noted. Average daily consumption ranged from 4.3 to 15.1 kWh (Cloverdale) and 3.3 to 15.6 kWh (Calistoga). Daily usage was relatively distributed across apartments, with no clear outliers (Figure D-6, Appendix D). Within apartments, however, daily variation was much more variable. This is typical of residential usage overall, but with generally less variance due to seasonal loads.

Consumption correlates better to occupancy rather than to bedroom type (Figures D-4 and D-5, Appendix D) though still driven by individual behavior. There was no significant difference in consumption between apartments with different numbers of bedrooms and an identical number of occupants. Variance can therefore be almost entirely explained by individual behavior. Between Cloverdale and Calistoga, there was remarkable agreement between both mean and median consumption.

Seasonal trends were less notable but still present in average data when fan coil unit energy was removed and trends were less predictable, with no clear trends within specific apartments (Figure D-7 in Appendix D). Weekly variance was relatively insignificant, though there was lower median usage on Fridays, a trend in other data sets. There were some differences between seasonal demand:

- Nighttime load was higher at both sites, driven largely by fan coil runtimes.
- Winter peaks were higher at Cloverdale, largely driven by cooking loads.

---

9 From a ZNE perspective, *net negative energy* means the building consumed less energy than the solar PV system produced over the course of the year and is therefore a net producer. By contrast, *net positive energy* means that the building consumed more energy than the PV system produced over the year, which makes it a net consumer.

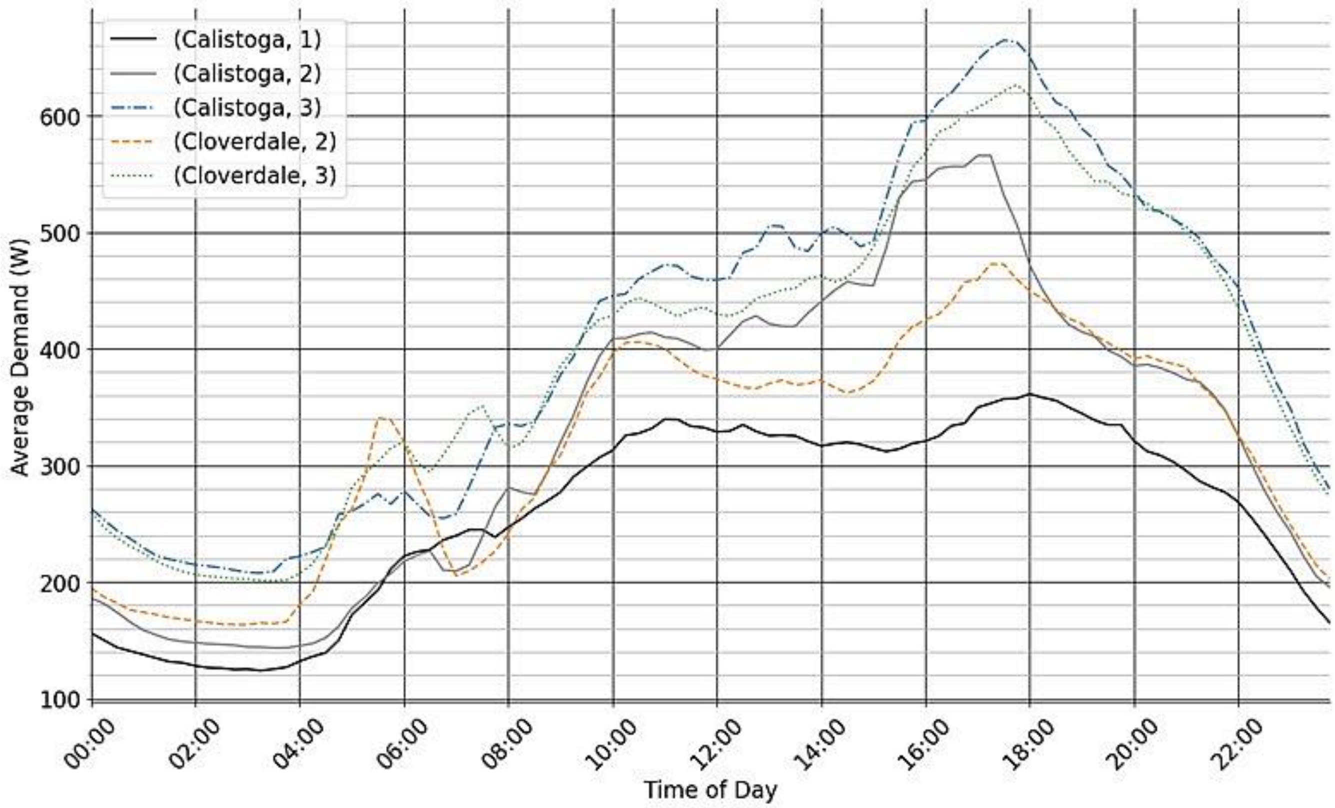
- Morning peaks were earlier in the summer, particularly at Cloverdale, due to normal seasonal solar influences on circadian rhythms and seasonal farm-worker schedules.

In terms of tenant loads, the kitchen range was the largest load—on average 24 percent (ranging from 6 to 40 percent) of the total annual tenant metered consumption. A small fraction of total usage was devoted to fan coil energy (11 percent, or 0.97 kWh/day at Cloverdale; 8 percent, or 0.64 kWh/day at Calistoga). Roughly half of this load at Cloverdale was baseload (20-watt [W], continuous). The remaining consumption was a mix of lighting, plug loads, refrigerator, garbage disposal, and bath fans, which comprised 50 to 85 percent of total annual consumption (average daily: 1.9 to 11.8 kWh, 5.4 kWh for Calistoga, and 5.9 kWh for Cloverdale). On average, the yearly demand pattern at Cloverdale and Calistoga (see Figure 13) showed site-wide demand peaks at about 5:45 pm. Evening peaks were reasonably consistent (80 percent of tenants' usage peaks between the hours of 4 to 7 pm). Significant daytime load was present in some apartments since many apartments were occupied by at least one person for much of the day, as indicated in survey results.

On average, demand shapes at Cloverdale were characterized by an abrupt but moderate morning peak at 6 a.m., driven almost exclusively by cooking, with a short dip in demand when cooking diminished. Then miscellaneous electric loads (MEL), lighting, and cooking increased steadily and peaked about 10 a.m. before plateauing until approximately 3 p.m. Cooking, MELs, and lighting loads increased thereafter and peaked again at 6 p.m. During the peak, cooking comprised 33 percent of total demand, which diminished throughout the evening. MELs and lighting showed significant amounts of activity throughout the day and comprised 60 percent of peak demand, and as much as 75 percent of evening demand, and remained consistent until 10 p.m. Drop-off continued until its minimum at 4 a.m.

Calistoga shares many of these characteristics but did not experience the same abrupt morning cooking peak. Instead, both cooking and plug loads gradually increased throughout the day. Cooking in general was also more spread out but still peaked at almost the exact same time it did in Cloverdale. Because of the central combined systems, cooking and plug loads were the largest tenant loads. Average demand profiles by bedroom types showed peaks for project and the variance of morning peaks between Cloverdale and Calistoga. The lower overall demand profiles of the one-bedroom units were also evident at Calistoga, with more similarities between two-bedroom and three-bedroom types at the projects. There is little variance in seasonal hourly demand (Figure D-8, in Appendix D).

Figure 13: The Average Annual Demand Profile for Cloverdale and Calistoga Is Similar, but With Cloverdale's Sharper Morning Peak



Domestic Hot Water and HVAC (Combined System)

Neither Aermec system performed as efficiently or as well as expected. Table 11 shows the average COP per season over the course of the monitoring period for both sites, which are well below the design COP of 3. Interestingly, in fall 2018, just prior to significant system changes, the plant at Calistoga achieved a COP of 3.01 under simultaneous-use conditions. The COPs were higher in simultaneous use (heating and cooling), as shown in Table 11, which indicates that projects with a high occurrence of simultaneous heating and cooling loads would be good candidates for the Aermec.

At Cloverdale, cooling operations performed much better than heating operations did; however, as with Calistoga, the adjustment of the cooling set point in the winter months resulted in very poor performance and produced hot water during this period, which therefore resulted in an overall negative COP.

Table 11: Average COP of Plant by Season and Operational Modes

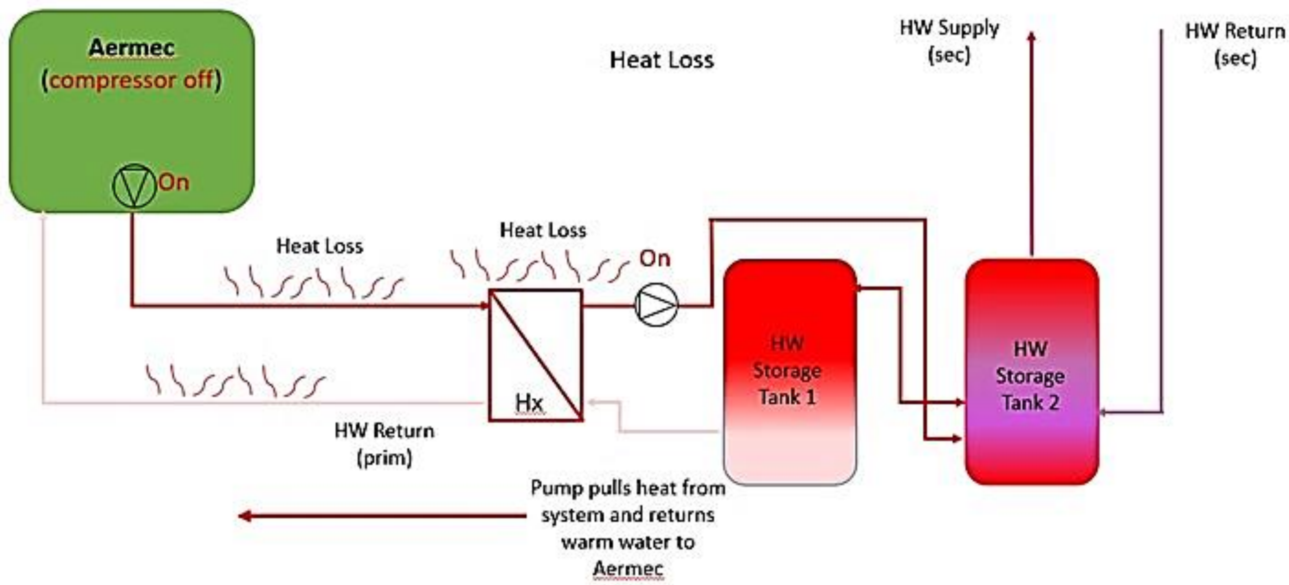
		Winter	Spring	Summer	Fall	Total
Calistoga (2-year total)	Heating	1.00	1.70	0.54	1.10	1.09
	Cooling	0.77	2.00	0.88	1.37	1.42

		Winter	Spring	Summer	Fall	Total
	Simultaneous	1.45	1.54	0.85	1.94	1.45
Calistoga ‘18	Heating	1.19	3.18	0.40	1.85	1.65
	Cooling	1.20	1.18	0.45	1.26	0.96
	Simultaneous	2.01	2.02	0.68	3.01	1.93
Calistoga ‘19	Heating	1.96	0.96	0.68	0.35	0.99
	Cooling	0.64	2.42	1.30	1.48	1.73
	Simultaneous	1.97	1.30	1.03	0.86	1.29
Cloverdale	Heating	1.29	1.31	1.32	1.21	1.28
	Cooling	-1.50	2.29	2.07	2.08	2.14
	Simultaneous	0.80	1.17	1.18	1.06	1.05

Understanding operating time of the Aermec in conjunction with COP provides more context for the impact of system performance. The units operated a small percentage of the time, aside from cooling in the summer months. Cloverdale showed little to no space heating demand, with an annual average of 10 percent operational time per season (three-month periods) and 17 percent for cooling time operation. Calistoga varied more; operational times in 2018 were more closely aligned with Cloverdale and increased significantly in 2019 (Table D-1, Appendix D) for percentage of time in each operation, by plant.

Short cycling of the compressors, which degraded their performance and lifespan and created inefficiencies in the large system, was prevalent at both properties. The data showed that during a two-week monitoring period the Calistoga Aermec power cycled 119 times, while the Cloverdale Aermec cycled 186 times—50 percent more than at Calistoga. Three compressors were replaced over the course of the monitoring period. The more the Aermec turned on and off, the more the primary loop pulled heat from the storage tanks. When there was a call for heating or cooling, the primary pump turned on and there was a several-minute lag before the compressor(s) turned on. During this delay, the water in the primary loop was pulling heat out of the storage tank through the heat exchanger and pipes, increasing heat loss from the system and also increasing the temperature of water returning to the Aermec (see Figure 14). Because heat pumps operate more efficiently with lower-temperature return water, this process further degraded performance once the compressor turned on.

Figure 14: System Heat Loss, Even When Not Operating and Returning Warmer Water to the Aermec



There were times when Cloverdale Aermec's compressors were not running, though the HW or chilled hot water (CHW) primary pumps were on and the associated loops exhibited flow. This happened for substantial amounts of time, in many cases for more than 10 minutes.

To better understand the operation of the Aermec plant, the research team applied a methodology (see the Appendix C for more detailed discussion) that disaggregated end uses to better understand total heating and total cooling inputs, space heating, and water heating loads. However, because this system was designed to provide space heat and DHW via a single distribution network, this calculation methodology proved challenging. The cold-water makeup flow data, which were the key piece of information used to disaggregate DHW and space heating, were deemed inaccurate because of the misalignment between the metering equipment's measurement range and the systems' very low flow rates. Because it was not possible to disaggregate the two end uses with data, the team determined it best to evaluate heating and water heating consumption together.

HVAC

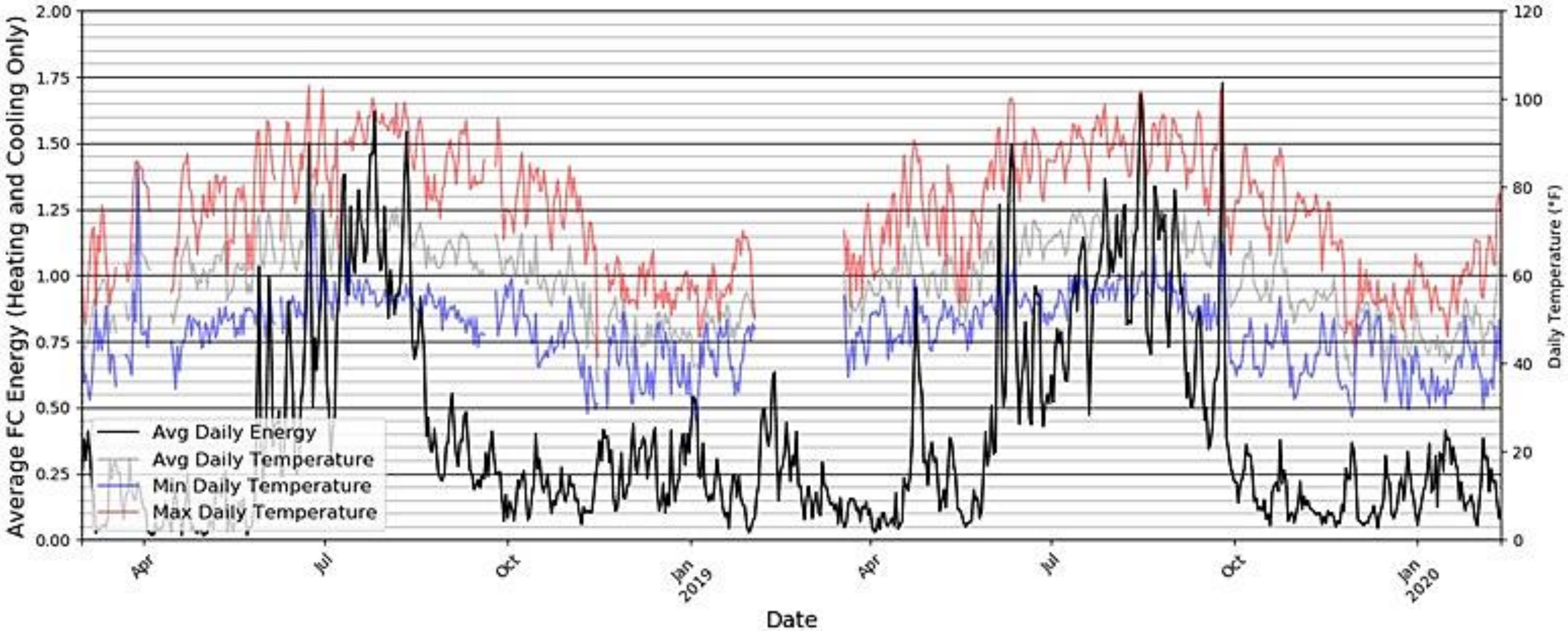
As shown in the Aermec performance, cooling constituted the dominant loads for tenant metered HVAC uses, comprising an estimated 82 percent and 73 percent of fan coil runtimes at Cloverdale and Calistoga, respectively.

Fan coil load was disaggregated into standby loads (roughly 10 W at Calistoga and 20 W at Cloverdale) and operational loads (from the fan coil motor). It was hypothesized that thermostat operations comprised the baseload. Total average daily usage ranged from 0.2 to 1.9 kWh at Calistoga and 0.3 to 2.1 kWh at Cloverdale. This translated to a daily average runtime of 18 to 728 minutes per day across apartments (Figure D-9, Appendix D).

At both sites, but particularly at Cloverdale, summer cooling demand made up the majority of annual usage, and runtimes varied significantly by apartment (Figure D-10, Appendix D).

There was little sensitivity to cool temperatures (Figure 15), with almost no change in winter fan coil demand throughout the day. Heating runtimes in the winter at Cloverdale were negligible. Summer cooling demand from May–September peaked at 6 p.m. At Calistoga, cooling functions ranged from less than optimal to nonfunctional; many tenants noted its inadequacy, although half reported no issues with it being too hot. Overall, few tenants reported issues with heating or cooling at either site, despite known issues (see Figure D-12, Appendix D, and Appendix G for survey results).

Figure 15: At Both the Cloverdale and Calistoga Sites, Cooling Was the Dominant Energy Use



In evaluating balancing points for heating and cooling, there was a broad range of temperatures where tenants utilized heating and cooling, and its relationship to outdoor temperatures and runtimes was not straightforward; for many apartments a heating balance point could not be calculated. Runtimes were more consistent on cooling, especially at 95°F (35°C) when units operated an average of six hours a day (Figure D-11, Appendix D). The survey revealed that many tenants use passive methods to cool and ventilate their homes, and site observations revealed that programmable thermostats were not used as intended. The research team documented that thermostat clock times did not match actual times at 75 percent and 93 percent of units at Calistoga and Cloverdale, respectively, and thermostats were not programmed in most apartments and instead were operated in on/off modes rather than being programmed and set to auto. On a May site visit, 14 of 15 apartments at Calistoga and 12 of 15 at Cloverdale had their thermostats turned off.

Therefore, response to temperature was more variable than if fan operations were controlled programmatically. It is also worth noting that solar exposure, floor level, and orientation of an apartment are all important to indoor temperature and may not align with onsite weather-station measurements.

Cooking

Cooking on average correlates with both occupancy and demographics, yet individual behavior creates variances. Average consumption ranged from 0.19 to 4.89 kWh/day, which translates to an average of 35 to 206 minutes per day of range cooking. Cloverdale's average and median daily usages were 1.9 kWh (97 minutes) and 1.9 kWh (84 minutes), respectively. At Calistoga, average and median daily usages were 2.2 kWh (110 minutes) and 2.0 kWh (112 minutes), respectively. Average occupancy correlated to average daily cooking energy (Figure D-13, Appendix D), with Cloverdale showing more individual variance.

Daily cooking demand was highly variable between 4 am and midnight, but on average followed the peak profile just discussed, with evening peaks at 5 p.m. and morning peaks at 5:30 a.m. (Figure D-14, Appendix D).

Seasonally, average daily cooking energy increased 25 percent at Cloverdale from summer to winter (mainly in the evening hours from 4 p.m. to 7 p.m.) which translated to roughly 0.5 kWh and actual usage of 1.68 kWh in June and 2.10kWh in January. This is a greater variation than in Calistoga, where daily average cooking energy ranged from 2.0 to 2.3 kWh month-to-month, with fewer straightforward seasonal trends (Figure D-15, Appendix D). Weekly trends showed consistently lower cooking energy consumption on weekends (Friday–Sunday).

One side note to actual usage: residents were not satisfied with the stoves and complained about lengthy heat-up times and nonfunctional burners. This may be attributed to appliance performance under lower voltage of 208 V rather than 240 V, where lower amperage and lower voltage resulted in longer cook times (e.g., eight minutes to boil water rather than six minutes).

Range hood use was reasonably high, and most tenants noted that if they did not use their range hood, it was because they did not need to for what they were cooking. (See Appendix G for survey results.)

MELs and Lighting

This analysis considered all receptacles lighting, refrigerators, dishwashers, and garbage disposals, and aggregated their usage at both sites. The average daily consumption ranged from 1.9 to 11.8 kWh/day (Figure D-16, Appendix D).

Seasonal variation was negligible, with an 8 percent decrease in the shoulder months compared to summer and winter. Weekly trends were largely due to significant baseload. Nighttime minimum load averaged 140 W at both complexes, with an estimated 30 percent from refrigerators. Throughout the course of the day, average demand roughly doubled from its nighttime low of 140 W to 300 W. The calculated parasitic and standby loads for each apartment ranged from 20 W to 180 W, with most apartments below 100 W. A large part of the baseload could be attributed to overall occupancy all day in homes, in addition to entertainment centers.

On-site laundry energy consumption was studied at all sites, but due to device failure full results were only obtained at Calistoga and Cloverdale. Data were collected from June 2017 to February 2020.

Total daily site washer and dryer energy was measured at 52.3 kWh (0.32 kWh/person) at Calistoga and 35.7 kWh (0.27 kWh/person) at Cloverdale (Figure D-17, Appendix D). On a per-dwelling-unit basis this ended up being 1.1 kWh per day for both complexes. There were some seasonal fluctuations, but they were inconsistent from year to year. Thursdays predictably showed the least consumption (0.9 kWh per dwelling) and Saturday the greatest (1.3 kWh per dwelling). At Calistoga and Cloverdale, 91.5 percent and 88.2 percent of total energy was consumed by dryers. Daily demand did not show significantly unique patterns across different seasons. Average demand peaks were at approximately 4.3 kW (4-kW dryer, 0.3-kW washer) at about 10 a.m. and 4.2 kW (3.8-kW dryer, 400-W washer) at 7 p.m. at Calistoga. Dryer load shapes at Cloverdale were proportionally similar to the number of occupants. Dryer peaks at Cloverdale were 2.6 kW at 1 p.m. and 2.7 kW at 7 p.m. However, total washer energy and peak demand were slightly greater at Cloverdale (Figure D-18, Appendix D).

Nexi Evaluation

A primary goal of end-use monitoring was to study behavioral changes possible with energy feedback displays. (See Appendix C for methodology). In many ways, these sites represented a well-controlled, demographically homogenous population to study the effects of energy-saving feedback displays like Nexi. However, there were challenges:

The sites have solar PV systems, and the apartments are virtually net metered, resulting in low bills. In fact, several tenants were surprised at how low their monthly bills were.

Despite tenants' overwhelming responses that Nexi made them more aware of both their energy use and their energy bills, no statistically significant usage change between pre- and post-Nexi installation was measurably distinguishable (p-values of 0.62 and 0.88 at Cloverdale and Calistoga, respectively). This could be attributed to the following:

- DHW and HVAC, except for fans, were not on tenant meters; if they had been, there would likely have been a stronger behavioral component since these are typically large loads when compared with cooking and plug loads.

- Overall loads on a tenant meter, such as cooking, were more challenging to reduce.

This statistical insignificance of this A|B analysis, does not necessarily imply that the devices had no impact. Residents indicated that after Nexi installation 67 percent at Cloverdale respondents and 83 percent at Calistoga respondents were very aware of their energy use. A third of Cloverdale respondents and three-quarters of Calistoga respondents checked the display at least three times a day. A comparison by unit for pre- and post-project was not completed. The team trusted tenant feedback that the devices had some effect on their awareness, but for these two projects there was no evidence that this translated into savings.

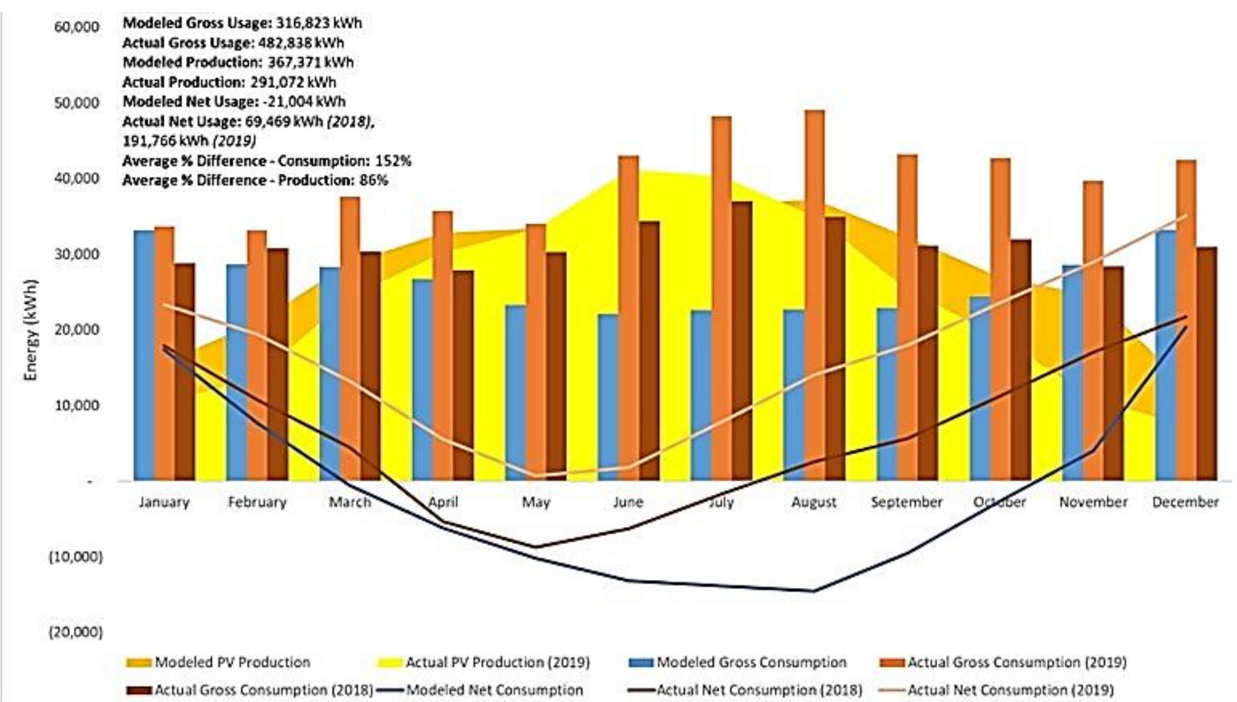
Planned, Actual, and Modeling Evaluation

Modeling estimated a building's energy use so that stakeholders could properly size a ZNE solar system. This study combined energy data from EnergyPro for building heating, cooling, and fan loads, and other tools (including the CUAC) to estimate the buildings' lighting, plug, equipment (e.g., elevator), and appliance loads.

Calistoga and Cloverdale were originally modeled in EnergyPro 5.1 for code compliance. A modeled-versus-actual comparison was based on using the current version of EnergyPro for the 2019 California Energy Code.

The actual building energy use at Calistoga was much higher than the model predicted, while the actual solar PV production was lower than predicted. Figure 16 shows both modeled-versus-actual energy usage and solar PV production at Calistoga.

Figure 16: Calistoga Modeled vs. Actual Usage and Production



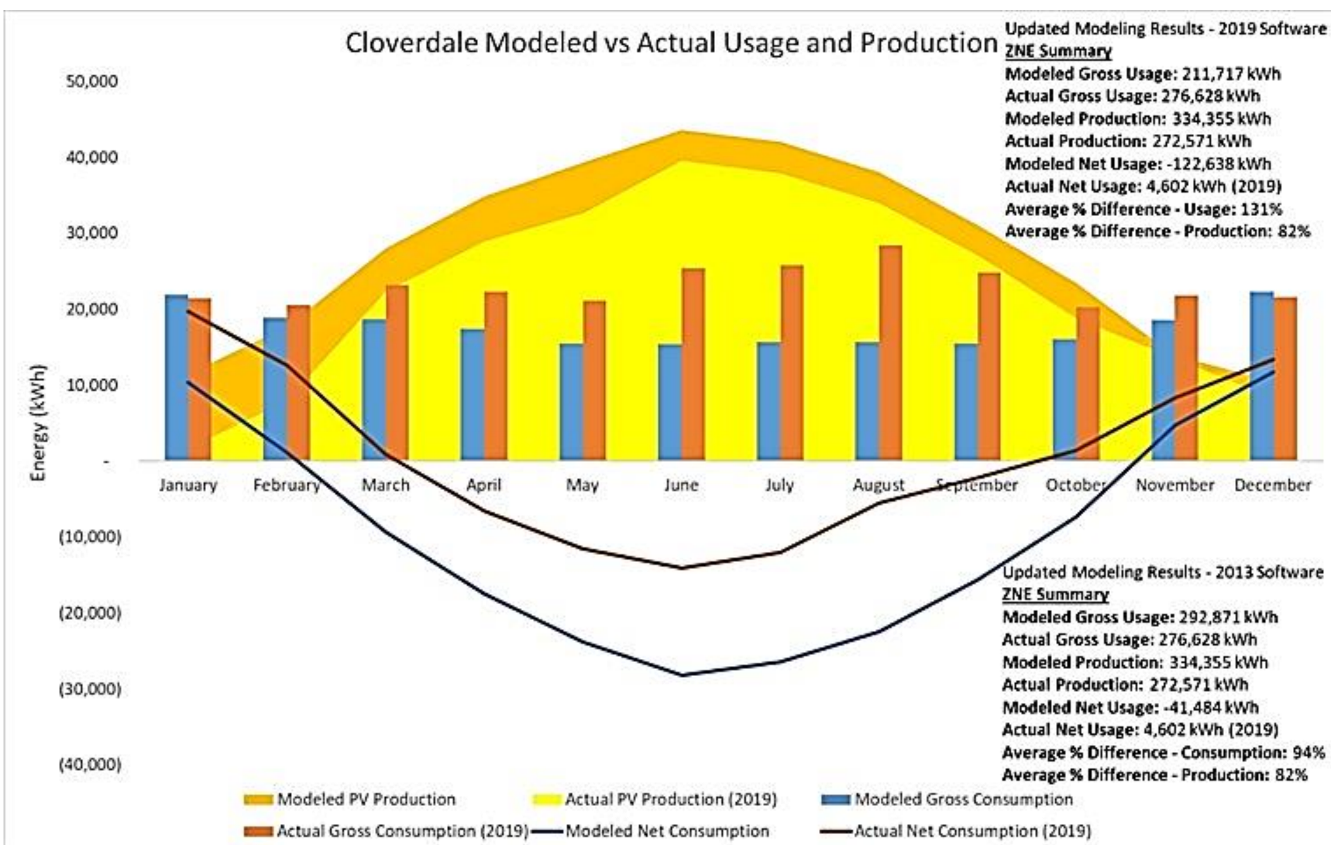
Calistoga consumed 119 percent of the energy the model predicted it would use in 2018, yet in 2019 the actual total building energy usage was 152 percent, or two-thirds more than what the model predicted the building would consume. The solar PV system produced 86 percent (in 2019) and 91 percent (in 2018) of what the model predicted it would produce.

Both tenant loads and common loads were underestimated in the models. The building model predicted that in-unit loads were 92 percent of what the aggregated in-unit loads were. The actual common area consumption in 2018 was over 40 percent more than modeled, and more than 200 percent higher than modeled in 2019. The model predicted fairly even whole building monthly energy usage, yet actual usage showed more energy consumed during the summer months than during the winter months.

Weather and external factors can account for discrepancies between actual performances between the two years; however, operational changes made to the Aermec can explain the increase in total annual energy usage of the building, as previously discussed.

In contrast, the property at Cloverdale consumed 94 percent of the energy that the original model (2013 code) predicted it would in 2019 (Figure 17). This may be due to a few factors: system improvements such as pump sizing, heat exchanger sizing and valves, and potentially the treatment of a central system with a single building vs. multiple buildings in the software. Interestingly, none of these design measures can be modeled by the Title 24 software, even though they had a dramatic impact on operating efficiencies of the systems. The efficiency measures may have brought the models more in line with actual usage, yet the 2019 version of the software resulted in an underestimation of central system energy consumption by more than 30 percent.

Figure 17: Cloverdale Modeled vs. Actual Usage and Production



The original model predicted that the building would consume more energy than it did. The Aermec was the largest end use, and because of lower heating loads at Cloverdale it was less of a driver than at Calistoga. Similar to Calistoga, the model underestimated summer usage and overestimated heating due to very low in-unit heating operation during those months.

To meet ZNE goals, the developer oversized the solar arrays in initial modeling. Figure 17 shows the estimated site consumption and solar production; Calistoga had a 117 percent solar offset, and Cloverdale, learning from Calistoga's underestimate, had a 130 percent solar offset. Cloverdale's model better accurately predicted the building's energy usage.

The prediction for energy production was also lower than the model assumed, and by a greater margin. The solar PV system produced 86 percent of what the model predicted in 2019 once the PV systems were operating correctly.

Atascadero

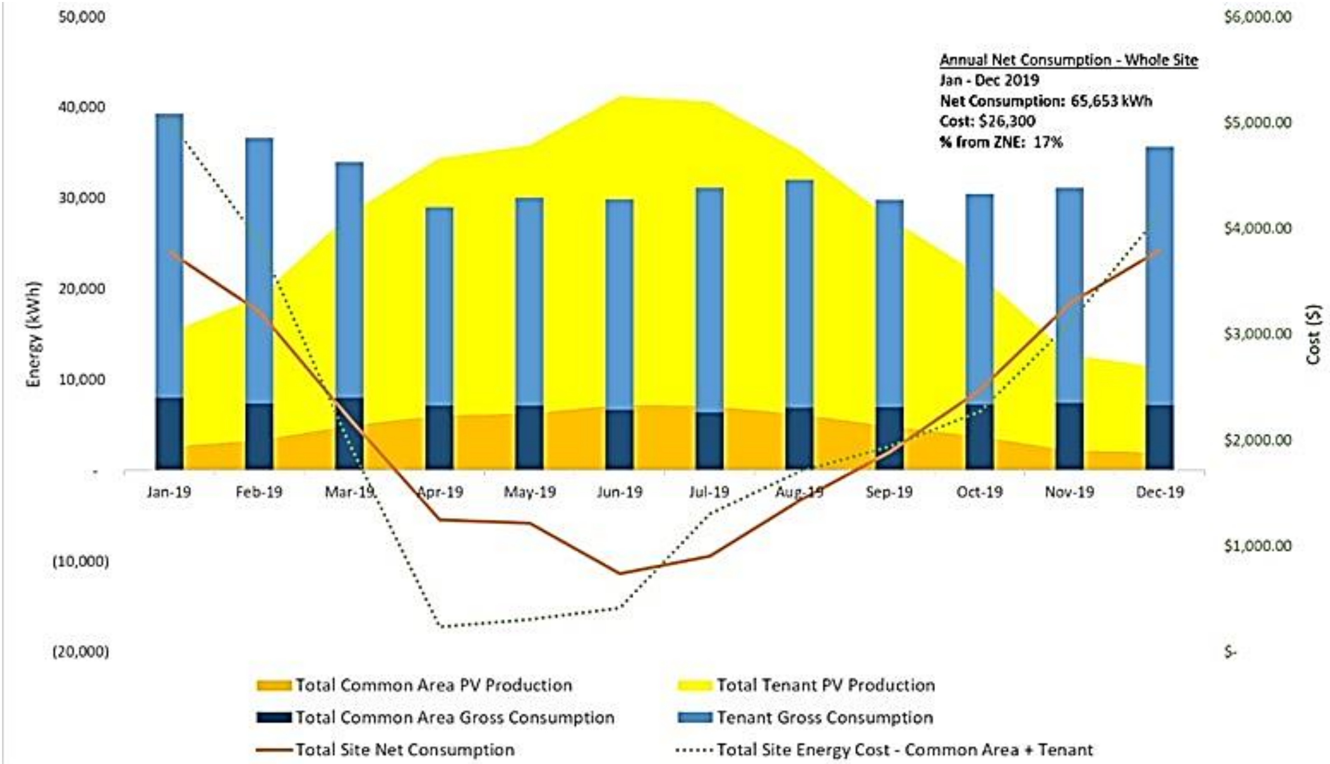
The project was monitored from June 2018 to June 2020. Unlike Cloverdale and Calistoga, Atascadero has individual systems and therefore greater tenant-metered end uses. Surprisingly, there were issues with the systems that prevented the project from achieving ZNE.

Overall ZNE Performance

Atascadero did not achieve ZNE usage for the 2019 calendar year. Approximately 83 percent of its energy usage was offset by solar PV, leaving a total of 65,000 kWh in annual positive consumption, as shown in Figure 18. Neither the tenant loads nor the common area loads were completely offset by the onsite solar PV system, though tenant loads were very close to being offset.

As will be discussed later in the HVAC section, if the contribution of the HVAC baseload could be mitigated, then the tenant loads would be ZNE and the project as a whole would have estimated consumption at approximately17,000 kWh more than produced. Furthermore, if the solar production was closer to designed and estimated production, the project would have been closer to achieving ZNE.

Figure 18: Atascadero Total-Site Energy Consumption and Solar PV Production

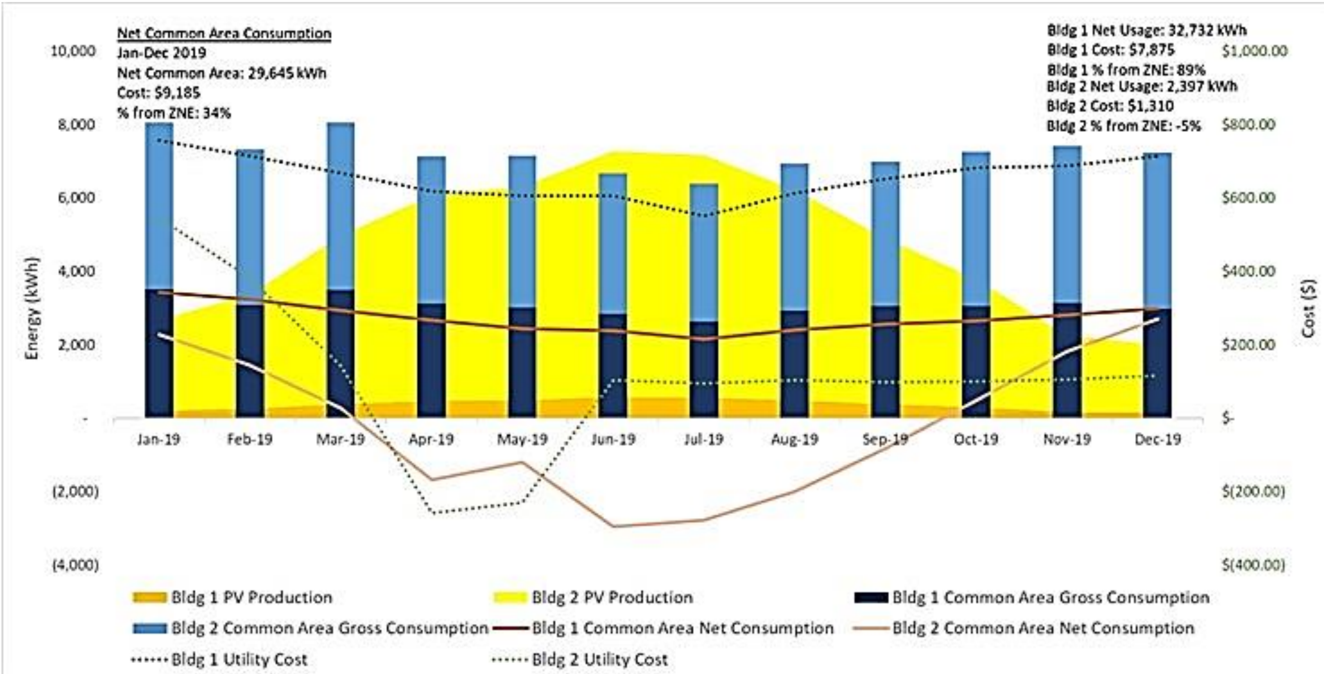


In addition to whole building consumption, ZNE was be evaluated for both common area load for each building and for aggregated tenant meters.

For virtual net metering configurations, which allocate solar credits by meter, it was critical to evaluate the loads by meter to understand ZNE performance from a utility perspective. This evaluation would also shed light on utility costs in a ZNE-designed property.

The aggregated common metered loads for Buildings 1 and 2 missed achieving ZNE by 34 percent (Figure 19). Common meter loads for Building 1, which were smaller than for those in Building 2, included laundry equipment, elevators, and interior and exterior common lighting. In addition to those end uses, Building 2 included lighting and loads for the office, computer room, community room, and public bathrooms. Building 1, despite fewer loads, did not achieve ZNE, and in fact consumed 89 percent more energy than its allocated solar PV generated. By contrast, the Building 2 common meter did achieve ZNE consumption, with about 2,400 kWh (5 percent) in excess energy produced (Figure 11). The solar PV credit allocation heavily favored Building 2 even though it was not proportional to each of the building's loads. The common meters accounted for 17.62 percent of the entire system's credits, with only 1.41 percent of the credits allocated to offset Building 1's common-area consumption, while 16.21 percent of the solar credits were allocated to offset Building 2 common-area consumption. This credit distribution resulted in overallocation to Building 2 and under allocation to Building 1.

Figure 19: Atascadero Common Area: Building 1 and Building 2 Energy Consumption and Solar PV Production January–December 2019



The in-unit load energy consumption was far closer to achieving ZNE than the common-area metered loads, but still resulted in a net-positive energy load. The net in-unit energy consumption was 9 percent away from achieving ZNE (Figure E-1, Appendix E). This was a significant offset because most of the major systems (DHW and HVAC) are on individual apartment meters. With system optimization (e.g., load shifting HPWHs, reduced HVAC baseload, and increased solar PV production) the in-unit loads would move closer to or achieve ZNE. Because in-unit loads constituted the largest fraction of property energy consumption, the property as a whole could be driven further toward ZNE.

Electrical End Uses: Tenant-Metered Loads

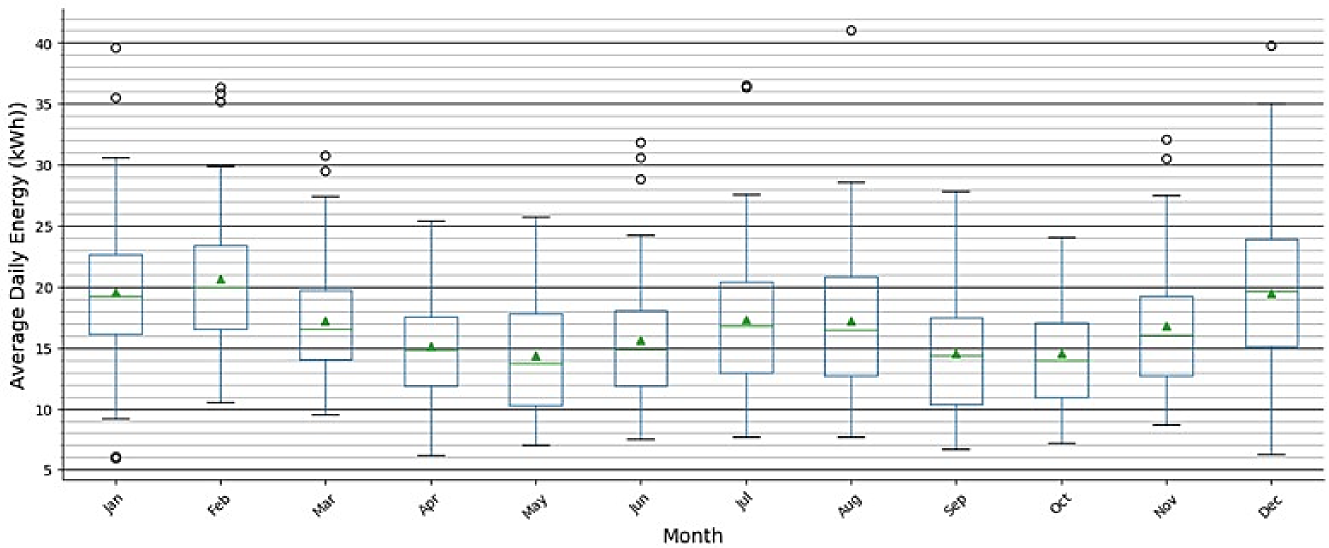
All apartment-level end uses were individually metered, so those were monitored. These loads included domestic hot water, space conditioning, ranges, lighting, plug loads (general plugs and bath GFIs), refrigerators, kitchen circuits, dishwashers, and garbage disposals. All loads except garbage disposals were monitored in at least two-thirds of units, as discussed in Chapter 3.

Whole house consumption was largely sensitive to occupancy, individual behavior, and seasonality. Average daily consumption ranged from 8.1 to 28.9 kWh over the course of a two-year monitoring period (with an average of 16.7 kWh) and was relatively normally distributed across apartments, with no clear outliers (Figure E-2, Appendix E).

Consumption was sensitive to occupancy (Figure E-3), as seen in Cloverdale and Calistoga, with individual behavior also driving energy consumption. Differences in consumption between bedroom sizes were also present, but occupancy was a much better predictor of consumption (Figure E-4, Appendix E).

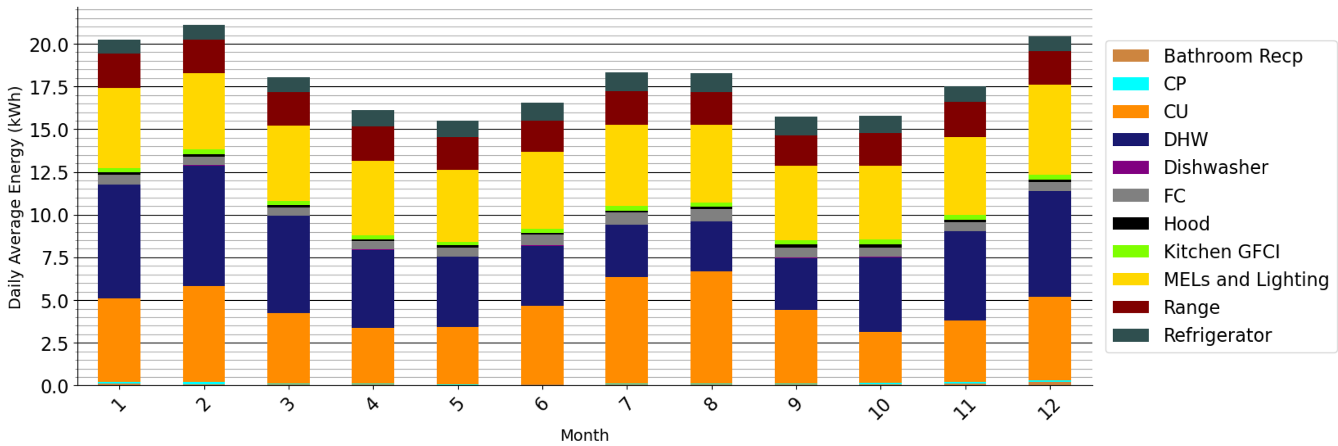
Seasonality was a primary driver of whole house usage, largely driven by DWH and HVAC (Figure 20). Trends followed annual and seasonal weather patterns, as seen in variations between the winters of 2018/2019 and 2019/2020 (Figure E-5, Appendix E). Across the entire monitoring time frame, data peaks in February were 20.5 kWh/day, on average, with an annual minimum in May of 14.5 kWh/day, on average. Weekly variance was relatively insignificant, though lower median usage on Fridays was present both here and in other data sets.

Figure 20: Seasonal Usage Was the Primary Driver of Consumption of DHW and Space Conditioning



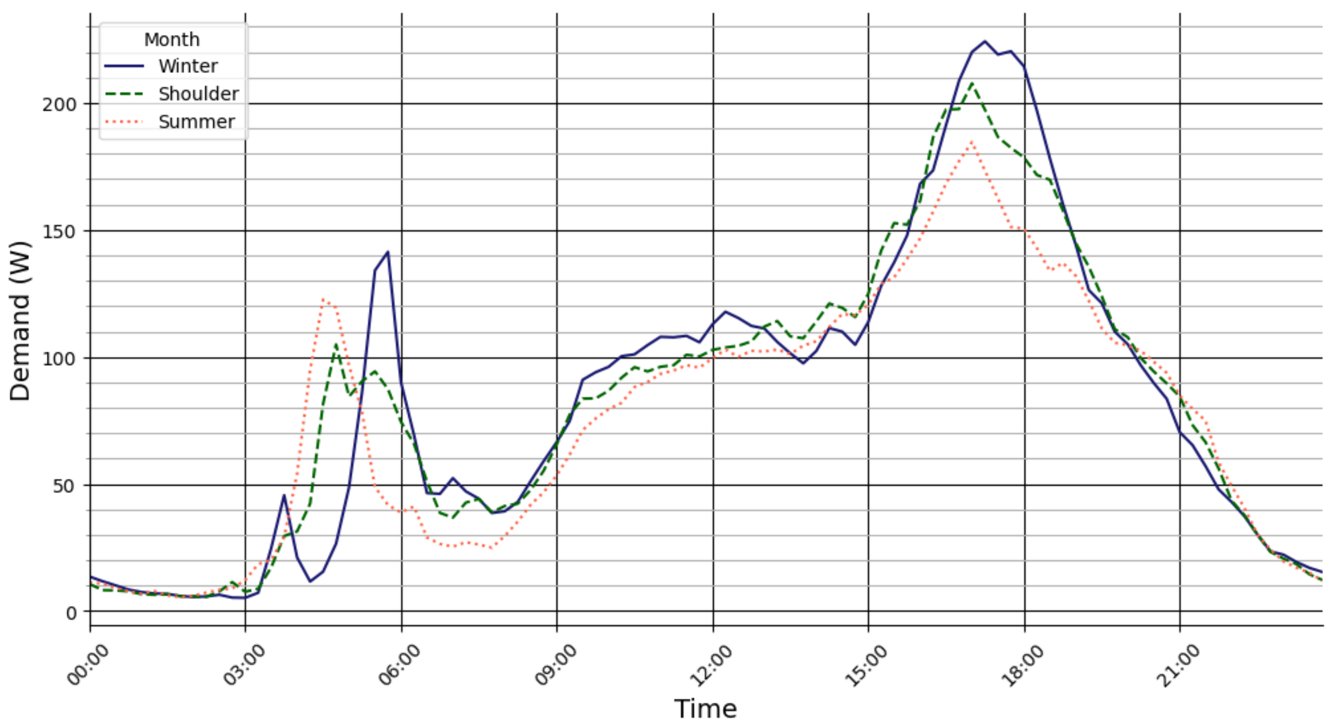
DHW, HVAC, and MELs made up the majority of total energy consumption by far, with each accounting for between 3 to 6 kWh/day, depending on season and apartment size. On an individual apartment basis, DHW accounted for 15 to 38 percent of annual consumption, with HVAC between 25 to 45 percent. On average, MELs (plugs, lighting, and bathroom and kitchen ground-fault circuit interrupters [GFCIs]) accounted for approximately 30 percent of total annual load. At its seasonal peaks, HVAC comprised, on average, 40 percent of total consumption in July and 30 percent in February. These contributions were only marginally sensitive to apartment size. MELs fluctuated throughout the year and were highly variable across all bedroom sizes. DHW accounted for approximately 10 to 15 percent throughout the summer months and 25 to 30 percent in the winter for both two- and three-bedroom apartments. Four-bedroom apartments had a significantly larger annual DHW consumption of 20 percent and 40 percent of total energy in summer and winter, respectively. Figure 21 shows averaged contributions across all apartments, by month (Table E-1, Appendix E).

Figure 21: Daily Average End Uses Showing Distribution Variation by Month, With Space Conditioning and Water Heating Showing the Greatest Seasonal Variation



HVAC and DHW had highly variable demand shapes, across months, to seasonal impacts. (See Figure 22 and figures E-6, E-7, and E-8, Appendix E, for seasonal profiles.) In general, peaks were much stronger in the winter, especially in the morning, and occurred later and without much of a midday lull. The average peak occurred at about 5 p.m. in the summer and 9 p.m. in the winter.

Figure 22: Space Conditioning and Water Heating Loads Drove the Seasonal Demand Profile



Summer: The variance was highest around late afternoon, largely from behaviorally driven cooling and cooking. Variance increased again during the second peak (roughly 9 p.m.), when many HPWHs recovered from hot water consumption earlier in the evening.

Winter: Winter demand was distinguished from other months by relatively high daily variances. This was largely due to variability in the performance of HPWHs since there was higher sustained demand throughout the day and more aggressive, earlier, and longer-lasting evening peaks driven by hot water demand.

Shoulder: In general, shoulder demand patterns were reasonably flat. Both behavioral and seasonal influences were significantly reduced. Higher spring DHW drove late peaks and fall heat waves drove midday afternoon ramp-ups.

Annual: During all seasons, the earliest contribution to morning peak was from cooking (5 a.m. to 6 a.m.), followed by a similarly sized increase in demand from HPWH operation (at roughly 7 a.m.) as tanks recovered from early morning water use. Cooking diminished shortly after the morning peak but increased steadily until evening, when its peak preceded large increases in DHW demand and, to a lesser extent, MELs. Demand from MELs, on average, remained at least 150 W and steadily increased throughout the day. Its peak (250 W) coincided with DHW demand at about 9 p.m. MELs contributed a significant amount of variance to consumption throughout the day. Demand from dishwashers, hoods, and circulating pumps was negligible, and low fan coil baseloads were constant. Small increases in refrigerator and kitchen GFCI energy were also present around peak times. Finally, a significant amount of baseload consumption from heat pump crankcase heaters (see the Heating, Ventilation and Air Conditioning section and Figure 22) was present throughout the year.

Domestic Hot Water

With DHW a key research focus, the research team delved into individual HPWHs and performed a series of experiments to evaluate the potential for thermal storage, as discussed in Chapter 3. The high-level discussion of energy usage and baseline performance utilized data from the control group. Unless otherwise noted, data analyses were restricted to November 2019 through July 2020 after recirculation pump controls were changed.

The seasonal performance of HPWHs is sensitive to both ambient air temperatures and incoming water temperatures (Figure E-9, Appendix E). The HPWHs are located in unconditioned sheds on the roof which are affected by both ambient air and incoming water temperatures, which in turn affect HPWH performance.

Ambient air temperatures and temperatures within the HPWH shed were monitored throughout the period. Ambient air temperatures have a number of effects on overall heat pump performance in unconditioned space, including performance swings from COP of 2 to 6 (Figure E-10, Appendix E).

Temperatures inside the HPWH shed (where HPWH air is sourced) were subject to significant solar gain and colder-than-ambient nighttime temperatures (0°F to 3°F (0°C to 1.7°C) colder than outdoor air). Anecdotally, during winter site visits, the shed felt much colder than the outdoor ambient air; this could be a result of the temperature sensor placement in the shed. Even with the HPWHs venting cooling air in the shed, the solar heat gain had a greater effect, resulting in an average hourly temperature 4°F–8°F (2°C to 4.4°C) greater than the outdoor air temperature (OAT) in the afternoon (Figure E-11, Appendix E). During the middle of the day, especially in summer, solar gain warmed the shed; in the absence of sun and exposure to ambient temperatures and cold air vented from HPWHs, the shed was like a refrigerator.

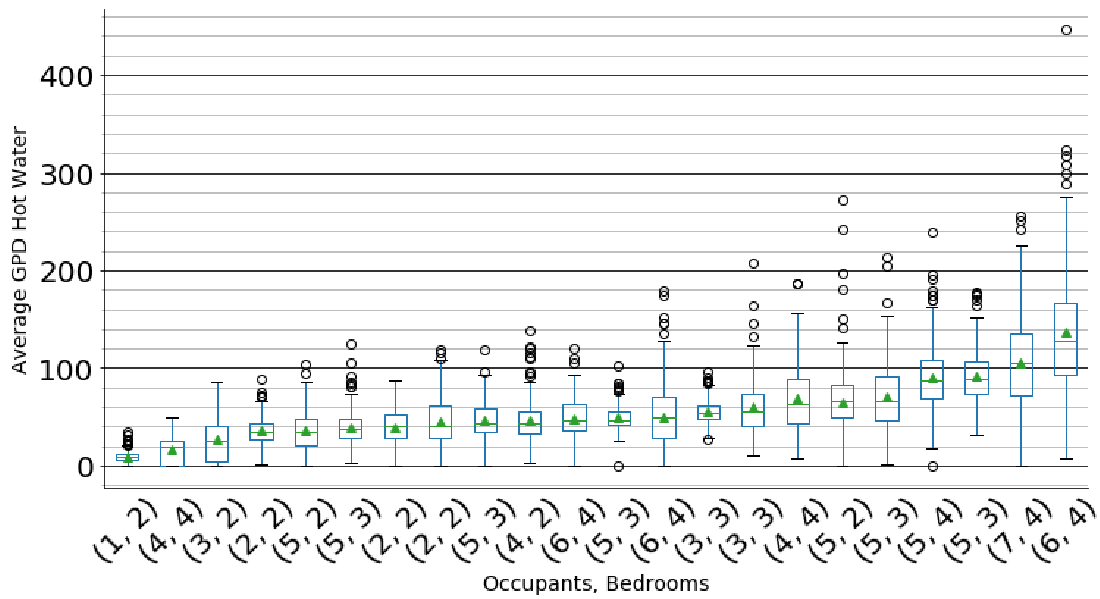
Colder incoming water temperatures fluctuated more seasonally due to location and were exacerbated in the winter; they therefore required greater amounts of heat to bring the water to temperature. Incoming water temperatures were affected by the length of time the incoming water was exposed to colder ambient air. Incoming water temperatures directly correlated with shed temperatures due to the location of piping in the shed (Figure E-12, Appendix E). For 2018 and 2019, milder than modeled or average weather conditions generally resulted in better performance in the summer and worse performance in the winter, with a few exceptions. It was impossible to unpack the exact effect this had on performance due to other variables (Table E-2, Appendix E).

In addition to reduced efficiency from cold incoming water temperatures, these HPWHs had an operating range of 37°F–145°F (3°C to 63°C), so during large-flow events lower tank temperatures approached incoming water temperatures. This can lead to large spikes in resistance energy even when the tank was reasonably full since the compressor does not operate below 40°F (4°C).

Due to colder temperatures, rates of heat loss in the tank were greater in the winter and lesser in the summer. This was initially noticed due to a few pieces of anecdotal evidence: incoming water temperatures got warmer during periods of "no hot water" demand due to conduction at the tank's cold-water inlet, and there was higher-than-expected electrical (compressor) demand during periods of no hot water demand in the winter, when the shed temperature was lower than the ambient air. Calculated rates of heat loss for periods when there was no demand and average tank temperatures were 135°F (57°C) showed higher rates of heat loss when compared with modeled assumptions, especially at lower ambient temperatures (figures E-13 and E-14, Appendix E).

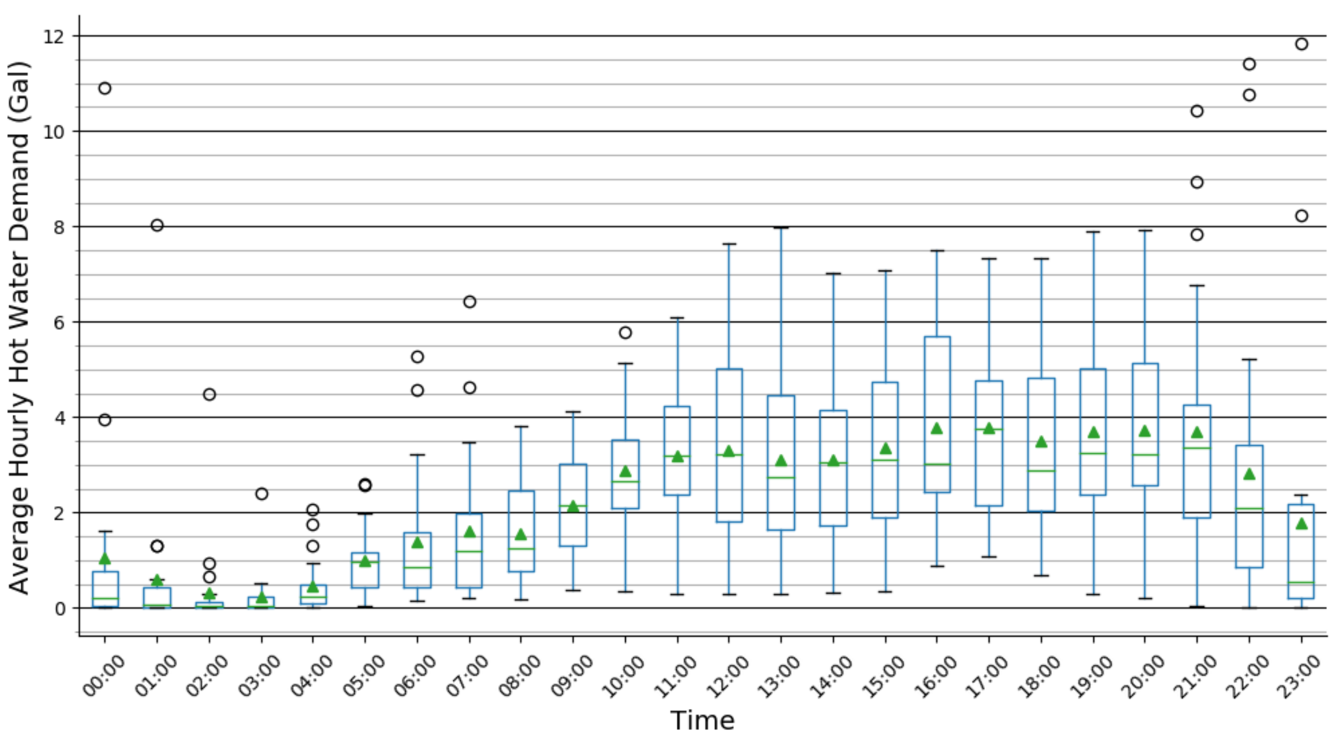
Water consumption on average was relatively constant across long time periods, but variance was high, due primarily to occupancy and secondarily to behavior. Generally, greater occupancy resulted in greater hot water demand and variance (Figure 23). Average daily hot water demand by apartment ranged from 9.5 to 137.5 GPD to 56.1 GPD. For the highest-consuming apartment, there were still days of near-zero demand, but more than 25 percent of daily flows exceeded 160 GPD.

Figure 23: Average Daily Hot Water Consumption Gallons per Day by Occupancy and Bedroom Type Showed a Correlation with Occupancy



Higher-occupancy apartments generally had an increased likelihood of both coincident and consecutive draws. Coincident demand and the drawdown of tank storage resulted in longer recovery times. Hours of subsequent demand compounded this problem. Daily demand by hour over the course of nine months (November 2019 to July 2020) is shown in Figure 24. With so many different profiles, the hot water demand overall was still relatively constant from 12 p.m. to 9 p.m.

Figure 24: Average Gallons per Hour Over a 9-Month Period



The most common hour at which hot water demand peaked, by apartment, ranged from 6 a.m. to 12 a.m. Sixty percent of apartments commonly peaked during the late afternoon or evening, 22 percent in the morning, with the remaining 18 percent during midday or after 10 p.m. Hourly peaks can be isolated (especially in the morning), however, and broader plateaus were common, with steady demand over a period of many hours. Table 12 shows the demand trends for each time period for the lowest-consuming (approximately less than the 25th percentile), highest-consuming (approximately 75th percentile), average-consuming, and median-consuming apartments, which demonstrate sustained demand throughout all hours of the day. The HPWH sizing met the demands of the household, on average, but not without a great deal of resistance usage.

Table 12: Gallons of Hot Water, by Time Period

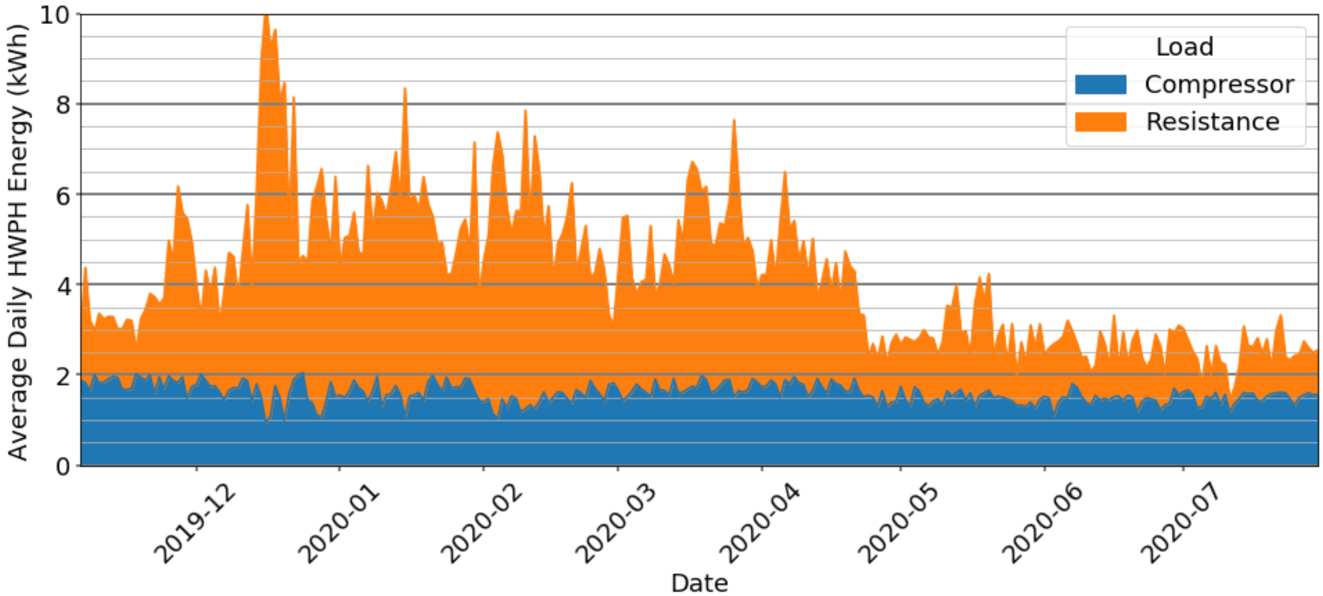
	Lowest-Consuming	Highest-Consuming	Average-Consuming	Median-Consuming
Night (12 am–5 am)	0.1	27.6	2.6	1.2
Morning (5 am–11 am)	2.6	21.6	10.6	11.6
Midday (11 am–4 pm)	1.6	33.2	16.1	15.8
Peak (4 pm–9 pm)	4.0	36.7	18.5	17.9
Post-Peak (9 pm–12 am)	0.1	33.7	8.3	7.1

Demand shapes varied less seasonally than they did simply due to tenant behavior, but there was a decrease in total consumption from winter to summer, coincident with warming temperatures. From November to mid-April, average hot water demand was 58.7 GPD per apartment, and from April through the end of July average hot water demand was 52.5 GPD per apartment (a 10.5-percent decrease) (Figure E-15, Appendix E).

It was difficult to isolate impacts from interactive seasonal variables, but the net effect on seasonal performance was very noticeable and evaluated using a control group.

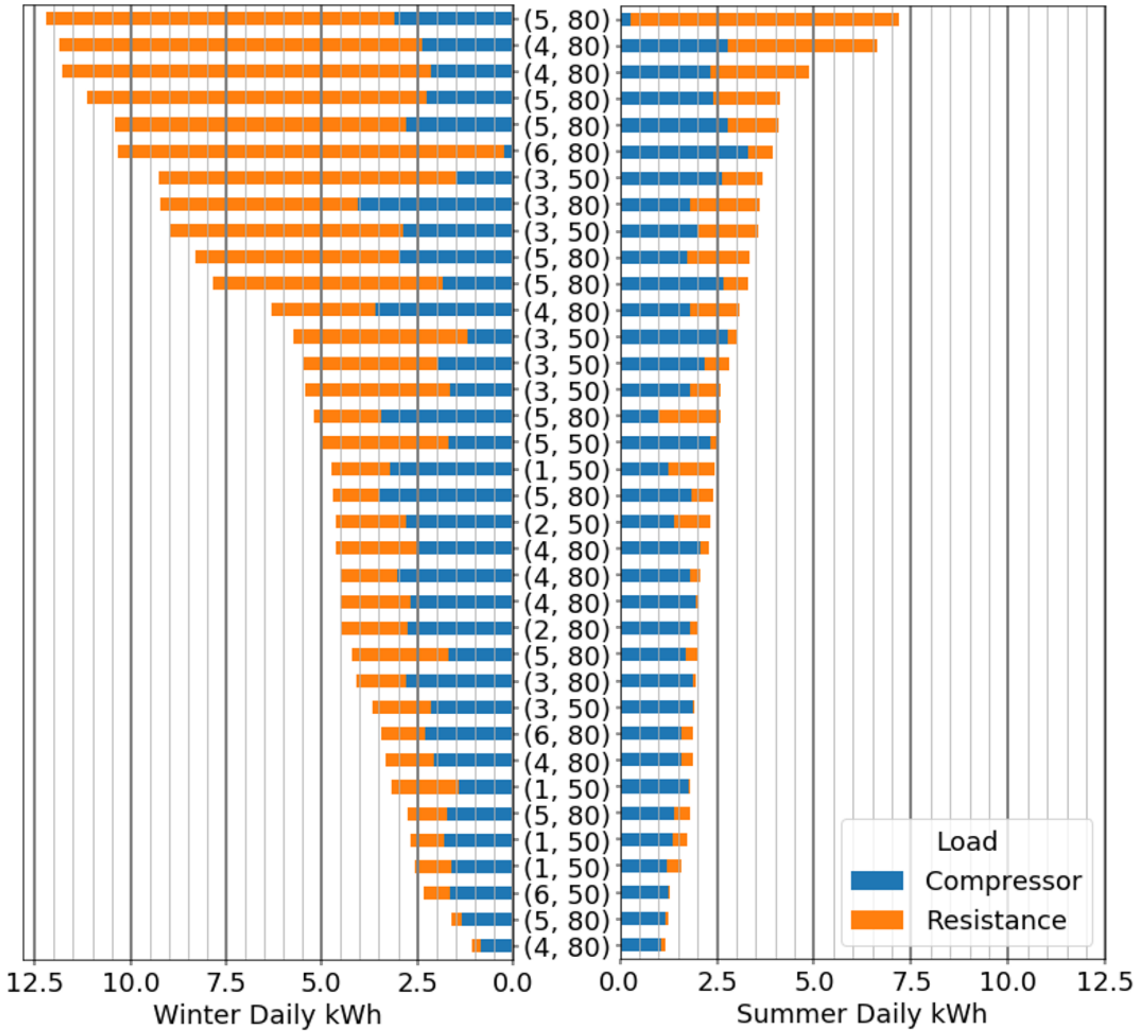
Figure 25 shows average energy usage for a nine-month period for all apartments in the control group. These units were set to 125°F (52°C), in Energy Saver mode, which represents a typical configuration. Compressor usage was reasonably constant, and with few exceptions both compressor and resistance energy were greater in the winter (Figure 26). Resistance backup was more prevalent during periods with greater hot water demand, especially with greater temperature differentials. Short-term weather patterns also affected usage (high usage in mid-December and an overall decrease in a relatively warm and dry late February). Winter (November–March) average daily energy consumption was 5.1 kWh (69-percent resistance) and summer (June–July) averaged daily energy consumption of 2.6 kWh (42-percent resistance) (Figure 18).

Figure 25: Average Daily Energy Use Showing Electric Resistance and Compressor Loads Across Months



In winter, lower morning hot water demand with colder incoming water resulted in a 200 W increase in electrical resistance, though it was negligible in summer. Yet even in the summer there was significant resistance usage (figures E-16 and E-17, Appendix E), including a few average-consuming units where more than 50 percent of total summer usage was resistance energy. This suggests that the vast majority of hot water demand occurred within a narrow time frame, and that factory settings (125°F (52°C), Energy Saver mode) were inadequate to meet demand regularly without significant electric resistance elements.

Figure 26: Summer and Winter HPWH Energy for all Units in the Control Group, Labeled by Number of Occupants and Water Heater Size



June 2018 marked the beginning of monitoring for HPWHs, which were installed with a set point of 140°F (60°C) in High Demand mode, the most aggressive configuration most reliant on electric resistance elements that ensure customer satisfaction. The design specified 140°F (60°C) in Energy Saver mode. After this was identified, all HPWHs were switched to 125°F (52°C), Energy Saver. This improved performance with less resistance.

Overall, this change did reduce energy use. Average daily energy usage was reduced by approximately 37 percent (3.58 to 2.25 kWh), and average peak demand was reduced by 40 percent (250 W to 150 W) across the control group from summer 2018 (High Demand, 140°F (60°C)) to summer 2019 (Energy Saver, 125°F (52°C)) (Figure 27). However, the fraction of resistance energy actually increased from 2018 to 2019 despite the less aggressive mode. A lower set point temperature increased chances that the tank would be depleted of hot water. When resistance is called for, it charges the tank to its set point before switching back to compressor-only heating. Therefore, a lower set point with less aggressive logic can result in more resistance than a more aggressive setting, depending on draws and tank sizes.

Figure 27: The Difference in the Resistance Usage From 2018 With High Demand at 140°F (60°C) (top Graph) to Energy Saver at 125°F (52°C) (Bottom Graph)

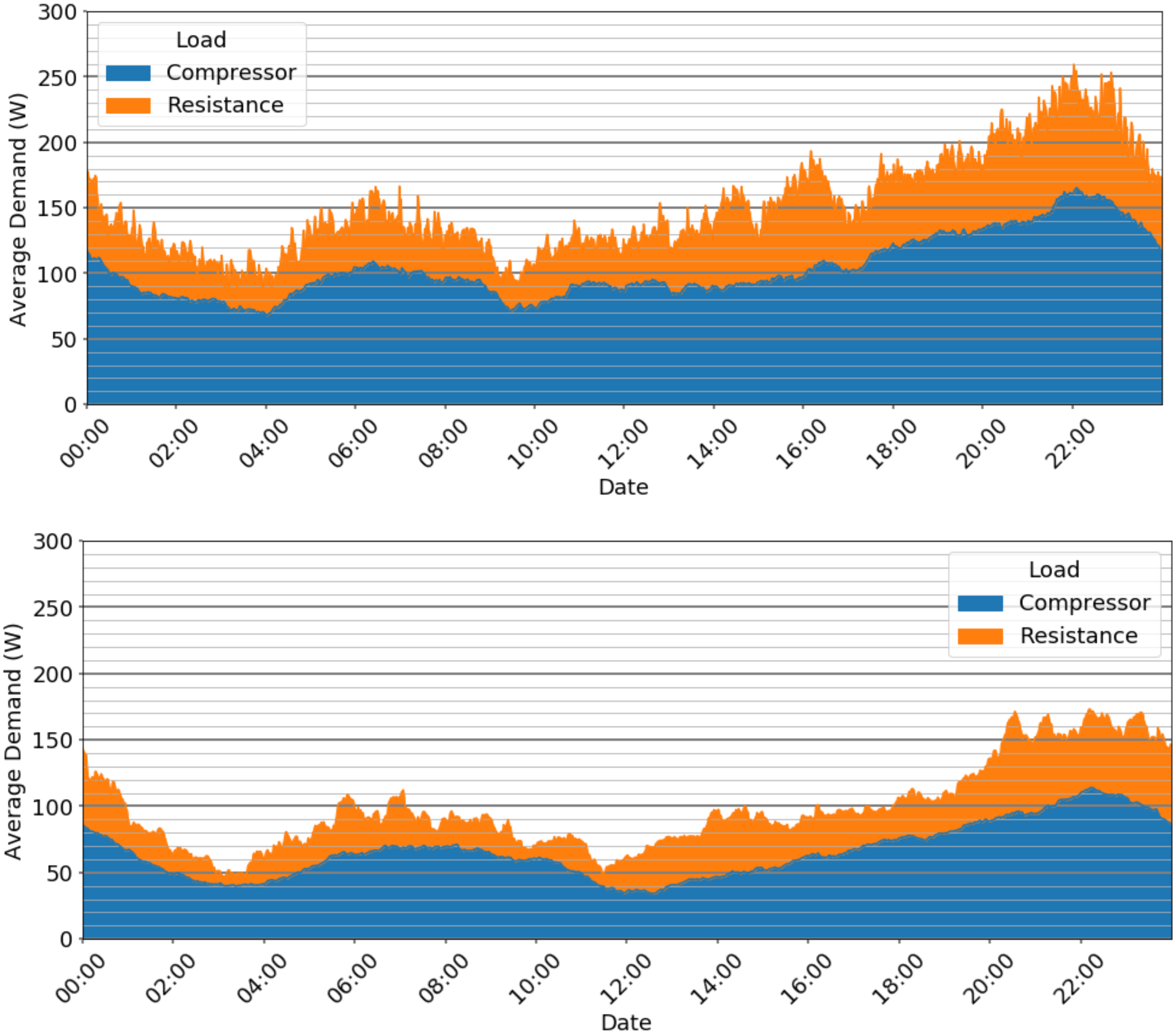


Table 13 compares compressor and resistance use as a function of occupancy. Higher-occupancy units actually showed a decrease in compressor energy from 2018 to 2019 from decreased thermal storage, reinforcing that 125°F (52°C) was not enough storage for many units to prevent using electric resistance. Mixed results are representative of the highly variable demand within apartments of similar occupancy. Unfortunately, a 140°F (60°C) Energy Saver mode experiment was not undertaken during the summer.

Table 13: Average Daily kWh

	Summer 2018, 140°F (60°C) High Demand			Summer 2019, 120°F (49°C) Energy Saver		
Occupants	**Total**	**Compressor**	**Resistance**	**Total**	**Compressor**	**Resistance**
1	1.87	1.63	0.24	1.76	1.74	0.02
2	2.70	2.45	0.25	1.99	1.95	0.04
3	2.74	2.06	0.69	2.66	1.51	1.16
4	4.07	2.78	1.29	1.67	1.30	0.37
5	3.72	2.98	0.74	2.91	2.02	0.88
6	6.35	1.91	4.44	2.24	0.37	1.87

In considering recommended sizing, the research team compared sizing recommendations from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the plumbing code, with field data from Atascadero. The team compared the field data with ASHRAE sizing, which was more favorable for 3-hour peaks and incoming water temperatures (Table E-3, Appendix E). While average demand was lower than the 31 gallons in ASHRAE calculations, sustained draws across all hours affected hot water availability. Assessing 3-hour demand in Atascadero draw data, in 30 percent of the days the water heater did not meet demand when 3-hour demand exceeded 31 gallons for 2-bedroom units.

Secondly, the research team used actual draws from Atascadero in a model to determine the frequency that the HPWH would be unable to deliver hot water. Each of the 22 dwelling units' hot water draw profiles was evaluated in the model, based on the HPWH installed for the study: 50-gal RHEEM ProTerra for 2 and 3 bedrooms and 80-gal RHEEM ProTerra for 4 bedrooms. These profiles were also evaluated using "code-sized" HPWHs based on Table 501.1(2) in the 2019 California Plumbing Code[10] for sizing residential hot water heaters according to the number of bedrooms and bathrooms served. Both HPWH sizes were evaluated in hybrid (compressor and resistance heating both available) and heat pump only (compressor heating available) modes. As the number of bedrooms increased, the likelihood that the HPWH could not provide adequate hot water also increased (Table E-3, Appendix E). This indicated that the 2019 California Plumbing Code sizing methodology became less accurate as the number of bedrooms increased, based on draw profiles at this specific site. The likelihood that the HPWH could not provide sufficient hot water was increased when running in Heat Pump Only" mode for all bedroom types and both HPWH sizes.

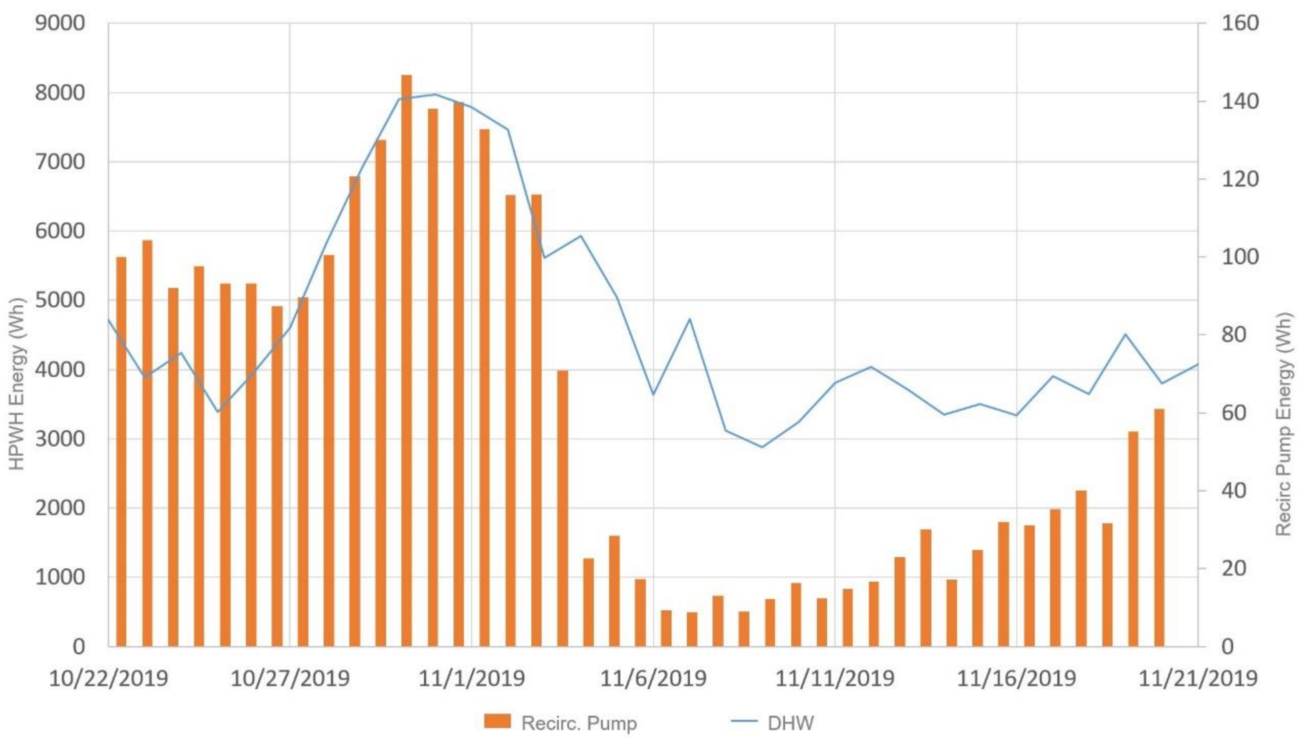
Recirculation Systems

Total electrical usage for individual water heaters included the HPWH usage and recirculation systems. Each apartment's recirculation pump was controlled by two or three infrared occupancy sensors installed at the kitchen sink and in each bathroom across from the mirror. Monitoring data showed the sensitivity of infrared occupancy controls, which would frequently trigger unnecessary operation, as demonstrated by both the lack of hot water demand after activation and activation in unoccupied apartments. The recirculation pumps operated more

[10] Plumbing Code: https://up.codes/viewer/california/ca-plumbing-code-2019/chapter/5/water-heaters#5

than 100 times a day in 3-second cycles, and in some units more than 300 times a day. This unnecessary energy usage was not large, but it significantly increased the energy use of the HPWHs, especially in winter's lower ambient temperatures and greater pipe losses. Frequent runtimes also circulated warm water into the tanks throughout the day, decreasing stratification of stored water and wasting energy through heat loss during unnecessary recirculation. Occupancy sensors were replaced with push-button demand controls in early November 2019, which reduced both pumping and water heating energy use (Figure 28). After control replacements, recirculation pumps operated less than once per day, on average.

Figure 28: Recirculation Pump Energy and HPWH Energy Before and After Replacing Recirculation Controls the First Week in November 2019



Thermal Storage

Peak demand reduction strategies were tested on 22 HPWHs (Table 14) binned into three groups, with staggered scheduling[11] changes for the HPWHs by 15 minutes across the groups.

Initial load-shifting strategies were developed with draw patterns during the load-up (charge) period from 1 p.m. to 4 p.m., as well as during the peak (shed) period from 4 p.m. to 9 p.m. This strategy reduced the risk of negatively affecting tenants' hot water delivery temperatures. The results discussed were from November 2019 through June 2020 and represent 8 of the 19 experiments. The others were omitted due to misoperation of the recirculation pump controls, bad data, or incorrectly programmed schedules. Table 15 summarizes the eight selected

11 The research team initially leveraged the third-party app Wink to schedule and control the set point and mode of the HPWHs until Econet, Rheem's proprietary app, was updated to support scheduling.

experiments. The team utilized results from one experiment to inform the subsequent experiment to better understand opportunities for thermal storage for this property, using Rheem HPWHs.

Table 14: Apartment Parameters with Monitored Heat Pump Water Heaters

Number of Bedrooms	Number of Units	Average Square Footage	HPWH Size (gallons)	Average Occupancy (at move-in)
2	8	793	50	3.00
3	7	1,048	80	4.43
4	7	1,284	80	5.43

Appendix E (figures E-18 through E-25 and tables E-5 through E-12) includes descriptions of each experiment including scheduling, temperature set points, and mode parameters, as well as each experiment's intent and results. The results graphically show average demand for electric resistance and compressor energy, with an accompanying box plot of average daily draws that show outliers.

A single metric cannot represent the thermal storage capacity for any single experiment. The set of metrics was selected to demonstrate the complexity of the experiments and the need to understand trade-offs from various changes. For example, low resistance energy usage during the shed periods can increase the energy burden during subsequent time periods and negatively impact costs.[12] Overall, the results of the experiments can be categorized under seasonal performance, storage capacity, and monitoring.

Table 15: Summary of Thermal Storage Experiments

	Experiment							
Metric	**1e**	**1h**	**1i**	**1j**	**1k**	**1o**	**1p**	**1q**
Time Frame	12/2/19-1/10/20	2/7-2/14/20	2/14-21/20	2/21 - 2/28/20	2/28-3/9/20	5/22-6/12/20	6/12-6/22/20	6/22-7/10/20
Average Ambient Temperature (°F/°C) (inside water heater enclosure)	46.78 8.2°	48.49 9.2°	52.22 11.2°	56.06 13.4	53.02 11.7	71.00 21.7	69.65 20.9	72.48 22.5
Average Incoming Water Temperature (°F/°C)	52.81 11.6	52.56 11.4	55.34 13	58.34 14.6	56.66 13.7	57.37 14.1	69.04 20.6	70.83 21.6
Average Tank Delivery Temperature (°F/°C) (at top of tank when there is demand)	131.1 55.1	132.9 56.1	119.3 48.5	133.9 56.6	133.9 56.6	135.1 57.2	134.2 56.7	136.5 58.1

12 The cost and the marginal GHGs were quantified based on the operation of the HPWHs on a daily basis during the time period during which the experiment was undertaken. Costs do not include the tier usage or any fixed fees. For the E1 rate, it assumes all apartments remained in Tier 1 regardless of other load usage. The daily cost reflects the winter pricing schedule. The winter average pricing from the time period was used for experiments 1e–1k, and a May/June average pricing for experiments 1o and 1q.

	Experiment							
Metric	**1e**	**1h**	**1i**	**1j**	**1k**	**1o**	**1p**	**1q**
Percentage of Time Delivery Temperatures <105°F (41°C)	1.7	0.32	3.4	4.1	5.8	0.77	2.3	2.9
Daily DHW Energy (kWh)	7.01	7.27	5.72	4.37	5.40	2.85	3.04	2.3
Daily DHW Energy (kWh) During Grid Peak, (Fraction of Total Daily Energy), 4–8 pm	0.92 (13%)	1.32 (18%)	0.82 (14%)	0.79 (18%)	0.73 (14%)	0.10 (4%)	0.11 (4%)	0.48 (21%)
Daily Resistance Energy Fraction (%)	59	60	52	15	42	5	12	1
Daily Compressor Energy Fraction (%)	41	40	49	85	58	95	88	99
Avg. Daily COP	1.6	1.5	1.8	2.4	2.1	2.8	2.6	2.6
Daily Cost – E1 ($)	1.53	1.77	1.40	1.06	1.28	0.65	0.76	0.87
Daily Cost – TOU3 ($)	1.87	2.15	1.70	1.29	1.56	0.86	1.04	0.87
Daily GHGs (kg CO_2e)	2.67	2.9	2.23	1.77	2.00	0.52	0.52	0.53

Because mode configuration impacts heat pump operation and energy consumption, experiments were conducted to understand performance under the Heat Pump Only and Energy Saver modes to meet both load shifting goals and hot water delivery demand.

Several experiments used Energy Saver mode to avoid unsatisfactory low-temperature hot water delivery for residents. Yet, in general, Energy Saver mode appeared to trigger unrequired electric resistance, making strategies ineffective due to operation of the resistance element, whose operation hinges on differentials between upper and lower tank temperatures and/or incoming water temperatures. This was most obvious in the winter, when colder incoming water temperatures (40°F–60°F (4°C-16°C)) triggered resistance operation even when upper tank temperatures were much higher. In addition, because electric resistance was used to bring the tank up to temperature, experiments with lower set points and Energy Saver mode had higher electric resistance as the tank was drawn down more frequently. The black-box proprietary nature of the internal logic led to unexpected results and made it challenging to create optimized schedules.

With regard to the Heat Pump Only mode, the main concern was water delivery temperature, particularly in the winter. Going to Heat Pump Only mode with only a 400 W compressor meant it was not always possible to recover quickly enough from large or coincident demands. In the winter, COPs hovered between about 2–4, depending on ambient temperatures, so a heat pump recovery time for an 80-gallon tank could take anywhere from 4 to 8 hours, depending on tank stratification. Although low delivery temperatures were more common (4.1 percent of delivery temperatures were below 105°F (41°C)) during winter Heat Pump Only operation, they were concentrated among a couple apartments with very unusual high-demand patterns (more than 100 gallons of hot water per day). For the average user, hot water delivery needs were met. In fact, the average delivered temperature was the highest of any experiment, since the set point was 140°F (60°C). Except for a few extremely high-water-usage outliers, experiment 1j delivery temperatures were favorable, and peak demand (including during peak hours), costs, GHG emissions, and overall energy usage were the lowest of any experiment, as shown in Table 15.

To support load shifting and shedding, set point temperatures were increased in charge periods and decreased in shed periods in several experiments. In addition, several experiments maintained constant set point temperatures to create a baseline reference.

Dropping to low set point temperatures during the shed period often resulted in unintended post-peak demand and usage of resistance energy. Much of this may be attributed to the operational logic of the Energy Saver mode.

In addition, the proprietary logic of the Rheem water heaters required that mode changes be made prior to temperature changes to avoid unintended electric resistance in meeting set point temperatures.

Maintaining a set point of 140°F (60°C) for all hours, either in Energy Saver mode or Heat Pump Only mode resulted in:

1. Minimal thermal storage depletion due to large coincident demands.
2. Smoothed-out variable demand, especially in apartments with outlying usage patterns including very late peaks or unusually high peaks.
3. Mitigated very low delivery temperatures.
4. Lowered COPs that elevated tank temperatures and reduced heat pump efficiency, but not enough to offset the gains from reducing the frequency of resistance energy.

In summary, when ambient conditions were unfavorable for keeping up with demand, it was better to take a conservative approach and keep temperatures as warm as possible with the heat pump instead of risking resistance-driven recovery by eliminating energy consumption entirely during peak hours. This point is particularly salient when considering populations of unpredictable and highly variable hot water users.

Initial winter experiments attempted to load shift using load-up and shed approaches that were less successful than hypothesized. For these experiments, the most successful winter schedule involved less load shifting and greater load reduction. Within the limitations of field experimentation, the best approach for winter to limit both total energy and demand during peak hours was to operate the water heaters in Heat Pump Only mode at a 140°F (60°C) set point at all times. This approach also had the lowest overall daily energy consumption and the lowest overall costs when compared with other winter experiments. This setting resulted in greater average peak demand than some of the other winter experiments, yet without high demand post peak. As mentioned, increased storage at 140°F (60°C) more than offset thermal losses and the probability of incurring resistance heating. This was especially true when compared with the experiments that involved actual load shifting during peak hours; load shifting efficacy often suffered toward the end of the peak period when tank storage was depleted.

Summer performance was predictably much better and load shifting much easier. Experiments undertaken during the summer, which were nearly identical to winter schemes, proved to be highly effective. Charging tanks to 140°F (60°C) enabled the team to eliminate peak load almost entirely from 4 p.m. to 9 p.m. A second experiment to extend the shift to 10 p.m. was slightly less effective on average, but still broadly effective for most apartments. Only one apartment with significant hot water demand was unable to consistently shift load during this time period. In many cases, only a small fraction of the total hot water stored was used. Even in the summer, a conservative approach (hotter tanks) was the most effective way to reduce demand and overall energy, as well as increase the quality of delivery.

Given the significant influence of proprietary mode logic, the research team utilized a similar methodology for code compliance sizing to evaluate both thermal storage potential and HPWH sizing. The model was used to evaluate the effect of load shifting between the hours of 5 p.m. and 9 p.m. for each bedroom type and each HPWH heating mode (hybrid and heat pump only). The analysis was completed for 50-gallon, 65-gallon, and 80-gallon RHEEM ProTerras. The load shifting analysis results indicate that an 80-gallon HPWH for this specific site should adequately provide hot water with load shifting logic applied for the two- and three-bedroom units. The majority of the two- and three-bedroom units would allow the HPWH to run in Heat Pump Only mode and load shift during the 5 p.m.–9 p.m. peak period with insignificant hot water interruptions. For the selected two- and three-bedroom units with larger draw profiles, the HPWH successfully shifted load when set to Hybrid mode. For the 4-bedroom units, an 80-gallon HPWH did not provide enough hot-water storage when load shifting, based on draw profiles of this specific site (Table E-13, in Appendix E). Note that all installations must include a mixing valve to enable higher set point temperatures.

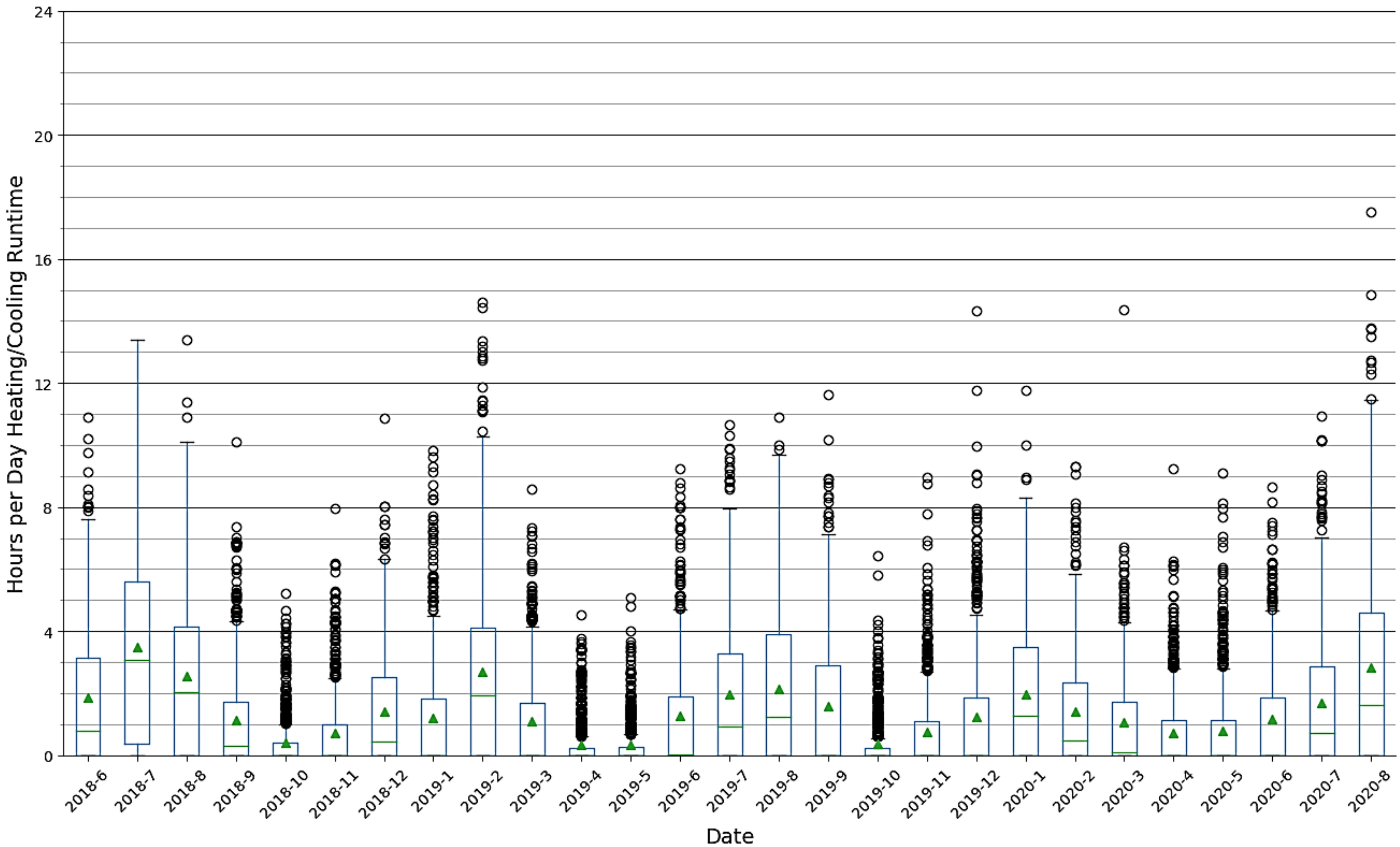
Heating, Ventilation, and Air Conditioning

Ducted heat pumps were monitored on 20 of the 60 units, and electrical energy was disaggregated into heating and cooling energy, comprised of compressor and fan energy for operational times and baseload energy.

In general, runtimes were somewhat lower than expected for heating and cooling. The heat pumps operated an average 33 percent of all days (121 days per year). This varied by apartment (6 percent to 43 percent of total days) and seemed to be largely behaviorally driven (rather than driven by orientation, building floor, or conditioned floor area). With the exception of a few outliers, cooling was the dominant load and was used 7 percent to 50 percent of days (a mean of 37 percent). Winter usage was similar at 8 percent to 50 percent of all days (a mean of 33 percent), and shoulder seasons significantly less at 2 percent to 40 percent of days (a mean of 23 percent). Generally, there was a strong correlation between consumption throughout seasons, by apartment; apartments that cooled more aggressively in the summer also heated more in the winter.

Daily runtimes for all apartments over the course of monitoring were generally low. They were longer in the summer and varied more in the winter (Figure 29), even in apartments that consistently conditioned their space. In July 2018 (the highest-consuming month for HVAC at this site during the monitoring period), 75 percent of all days in all units remained below six hours of runtime. Similarly, during the cold February of 2019, 75 percent of all days in all apartments had daily runtimes below four hours. Average runtimes across all apartments responded to short-term weather patterns (Figure E-26, Appendix E). There was little demand for heating or cooling below an average daily temperature of 60°F (16°C), although balance points (the average temperature a household will call for heating or cooling) varied. Cooling balance points across all apartments ranged from an average daily temperature of 55°F to 83°F (13°C to 28°C), and heating balance points ranged from 44°F to 68°F (7°C to 20°C). In three apartments, there was no significant heating load at all.

Figure 29: Daily Runtimes for Units, Including Baseload and Operational Loads



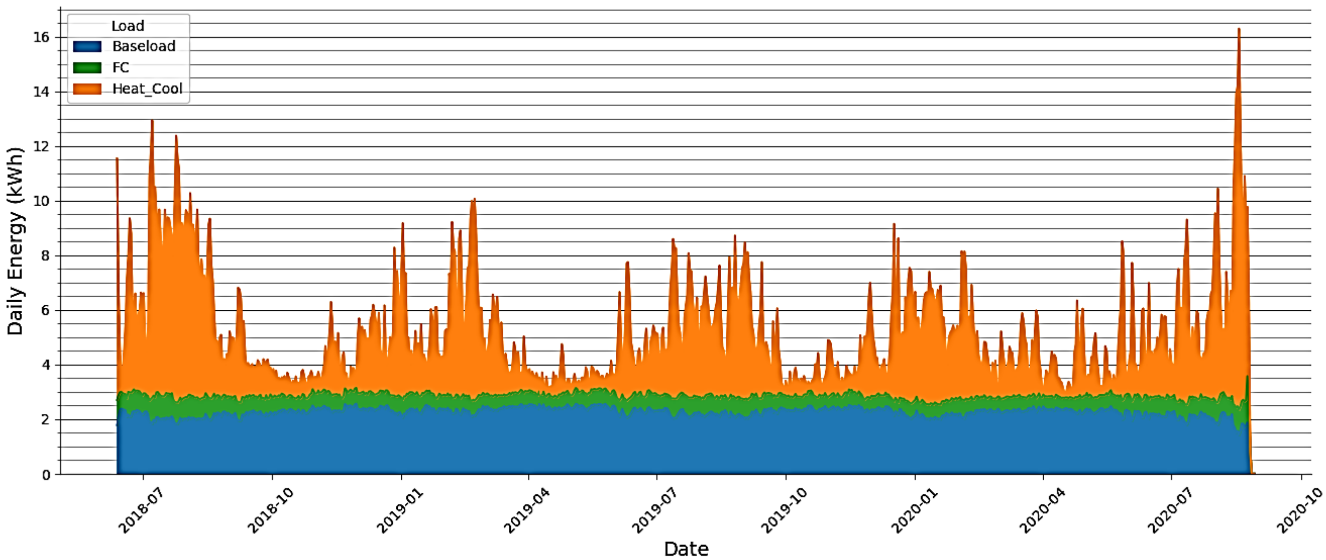
Total annual energy for heating, cooling, and parasitic loads averaged between 2.5 and 6.4 kWh/day, by apartment (figures E-27 and E-28, Appendix E). Cooling and heating energy consumed roughly 24 percent and 20 percent of the totals, respectively, and baseloads of crankcase heaters, control boards, and reversing valves accounted for 45 percent of the total HVAC load, on an annual basis (50 percent of heat pump energy).[13] Due to proprietary engineering calculations, it was not possible to identify the actual distribution of baseload consumption between the crankcase, inverter controls, and the reversing valve.

Seasonal demand patterns were as expected (Figures E-29 and E-30, Appendix E). Shoulder months (October, April, and even November and March) were, on average, flat due to weather pattern changes on shorter time frames, which resulted in a mix of heating and cooling. Summer months peaked in mid-afternoon. Winter heating was much more persistent but did not experience a real peak, with decreased demand between 10 a.m. and 4 p.m. Both anecdotal and survey data suggest that tenants used their thermostats manually rather than taking a "set it and forget it" approach, which accounted for large variances across apartments and perhaps some of the aggressive ramping up and down present in some months of the year.

Despite many tenants rarely heating or cooling their homes, heat pump space heating and cooling represented the largest load for many apartments and was on average the same magnitude as total HPWH and MELs, primarily due to baseload. HVAC consumption was also significantly more than projected by building-energy models. The crankcase heater for the high-performance condensing unit operated 24/7, even when there was no call for space conditioning. The total baseload used approximately 2.5 kWh a day, even though the primary need for a crankcase heater in these units was when air temperatures dropped below 40°F (4°C), less than 10 percent of annual operating hours (Figure E-31, Appendix E). These baseloads constituted about half the tenants' space conditioning energy usage annually and approximately 800 kWh of unaccounted-for and potentially unnecessary consumption, per apartment. Figure 30 shows this baseload contribution to total load (on average) throughout monitoring, along with the fan coil unit and actual heating and cooling energy. Baseload energy per apartment varied based on space conditioning operation times.

[13] Monitoring equipment may overestimate baseload consumption due to small inductive loads. Unfortunately, due to COVID, the research team was not able to access occupied units to complete additional verification. The evaluation of baseload consumption and crankcase heater loads is ongoing.

Figure 30: Contribution to Total Load (Average) Throughout the Monitoring Period



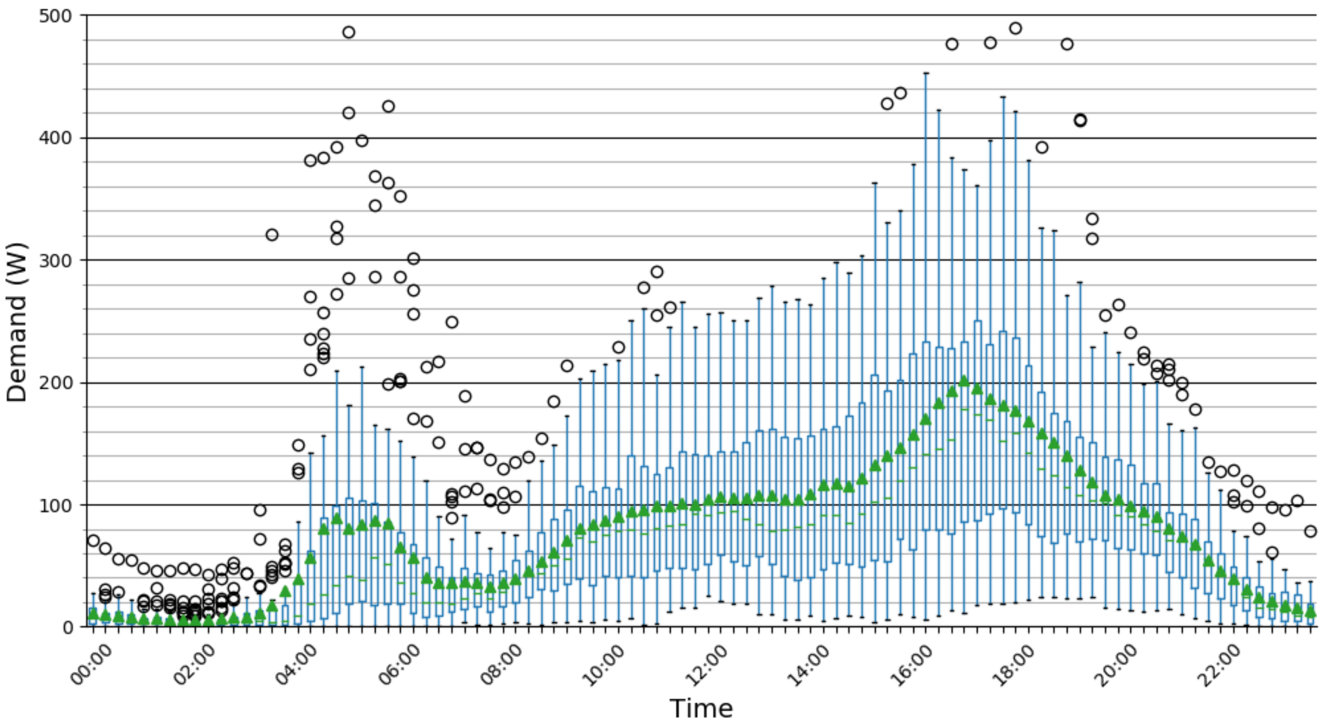
Cooking

Cooking usage tracked with occupancy, as shown in other studies (Figure E-32, Appendix E), yet here the presence of a few high- and low-consuming outliers was notable. Average consumption ranged from 0.25 to 4.87 kWh/day, which translated to an average of 25 to 204 minutes per day of cooking. This agrees with sites of similar demographics.

Seasonally, daily cooking energy (averaged across all apartments) varied by roughly 0.25 kWh (June, 1.78 kWh; December, 2.03 kWh), which was less than at similar complexes studied (Figure E-33 in Appendix E). Cooking demand increased by 12 percent from summer to winter and manifested between the hours of 4 p.m. to 7 p.m. There was a shift in peak demand in the morning between summer and winter seasons (Figure E-34, Appendix E). Weekly trends also were present, with consistently lower cooking energy on weekends (Friday–Sunday) (Figure E-35, Appendix E).

Daily cooking demand was highly variable across apartments, except between 12 to 4 a.m., where it was virtually nonexistent. Most apartments followed a similar pattern presented in Figure 31, which shows a late evening peak (5 p.m.) and often an early morning peak (5 a.m.).

Figure 31: Cooking Demand by Hour Showed General Morning Peaks and Strong Evening Peaks



The range hood use was minor compared to other loads, representing only 47 kWh on average across apartments. In general, hood use paralleled cooking demand. Average daily runtime for range hood fans was only six minutes, with a maximum average of 19 minutes (Figure E-36 in Appendix E). Simultaneous cooking range and range hood runtimes (Figure E-37 in Appendix E) have an average 14.5 percent (ranging from 1.9 percent to 33.2 percent) of total time that cooking takes place. This did not align completely with the survey results, wherein most tenants reported always or usually using the hood while cooking.

MELs, Lighting and Appliances

The research team completed additional analysis on miscellaneous electric loads, dishwashers, and refrigerators.

Energy demand of the MELs (comprised of bathroom, kitchen, general receptacles, and lighting loads in Atascadero) was relatively higher than at other sites, with an average daily consumption of 4.9 kWh/day. Loads did not correlate to the number of bedrooms or occupancy. General receptacles and lighting comprised on average of over 90 percent of the load. These loads included observed appliances such as hot and cold water dispensers, electric scooters, and entertainment and gaming systems. Parasitic loads averaged 80 W, but ranged from 0 W to 200 W, and were primarily associated with general receptacle and lighting circuits. Loads showed moderate increase on weekends and winter, similar to other end uses.

The dishwashers were underutilized, with almost zero energy consumption, translating to 0 uses to 1 cycle per week over the course of two years.

Refrigerator total energy was more variable than expected (Figure E-38, Appendix E) in the 20 units metered. There was a positive correlation between average daily consumption and occupancy, likely due to increased frequency of opening and closing the refrigerator door. Total average daily energy ranged from 0.6 to 1.2 kWh per day (an average of 340 kWh/yr), representing a 5.5 percent decrease from expected consumption (360 kWh/year). Strong seasonal correlation showed a 25 percent decrease from summer to winter (roughly 1 kWh in July to 0.75 kWh in January) (Figure E-39, Appendix E).

Nexi Evaluation

A primary goal of end-use monitoring was to study behavioral changes possible with energy feedback displays, but this was not possible at Atascadero. Survey results (58-percent response rate) produced the following results: 28 percent of respondents indicated they were aware of energy use prior to installation of the lighting display and 54 percent were aware after the installation, with 46 percent of respondents checking the monitor at least three times a day.

Planned, Actual, and Modeling Evaluation

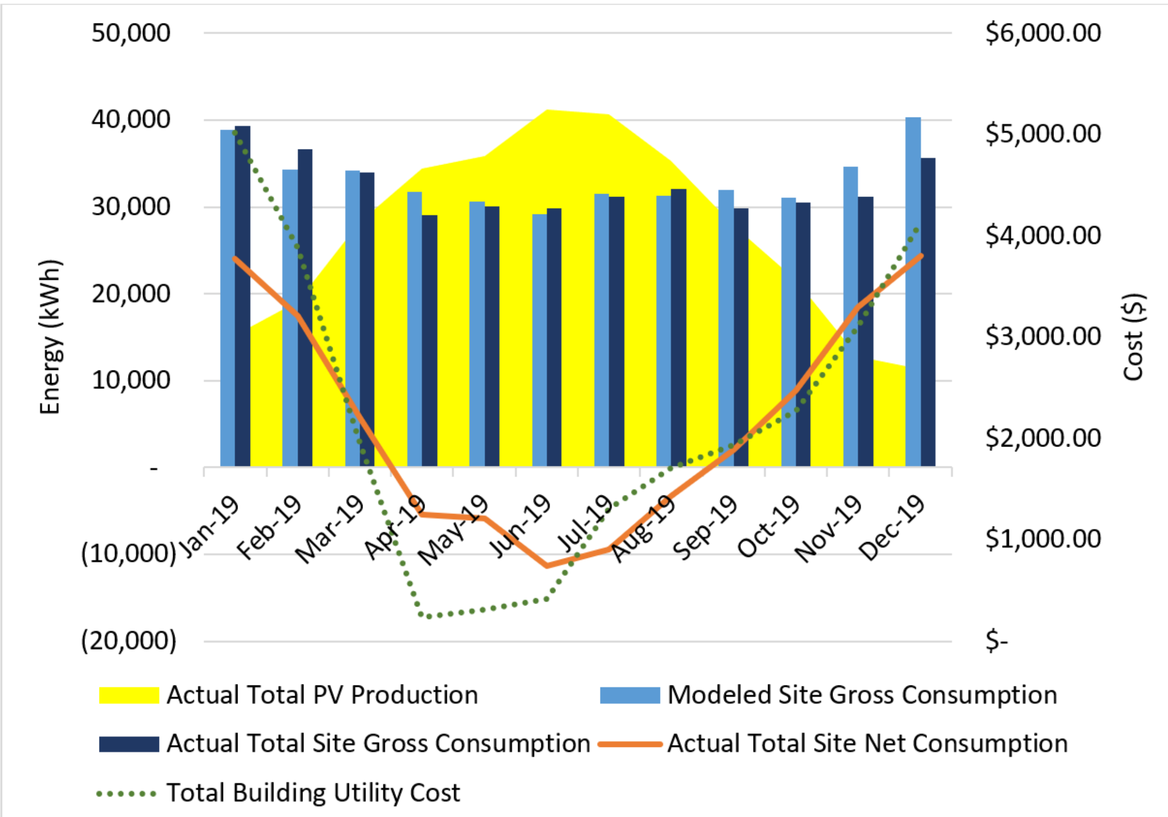
Solely for the Atascadero project, the research team undertook the ZNE and building modeling evaluation with the other projects, but also completed an analysis of code compliance modeling for the hot water draws and consumption.

To properly size a ZNE solar system, the property's energy usage was calculated by combining energy estimates from EnergyPro for a building's heating, cooling, and fan loads and the CUAC to estimate the building's lighting, plug loads, and appliance loads.

Atascadero was originally modeled in EnergyPro 5.1 for code compliance, which showed a 50-percent compliance margin over code for the residential portion and 75 percent above code for the common area spaces. The modeled versus actual comparison was based on using the current version of EnergyPro for the 2019 Energy Code, under which the model showed a compliance margin of 21 percent. When combining both these estimates (2019 software and CUAC), the total annual energy usage was estimated to be 366,000 kWh/year. Additional custom calculations were performed external to the model, and those were informed by past building design, data monitoring, and research studies to estimate certain loads like elevator or laundry loads to more accurately reflect expected loads. The combined load of all three methods produced a project consumption estimate of 404,000 kWh per year. The solar array was designed to offset 119 percent of the original model produced during design and was estimated to produce 376,000 kWh/year. Interestingly, using the compliance software for all plug loads, appliances, exterior lighting, and elevators resulted in 410,979 kWh per year, a greater consumption estimate.

The actual building energy usage at Atascadero was lower than predicted for both the common area buildings and lower for the tenants' end uses. The actual solar PV production was also lower than predicted (Figure 32). The graph below shows the modeled versus actual energy usage and solar PV production at Atascadero. Overall, the variations from modeled to actual energy usage were primarily for DHW, HVAC, and MELs and lighting. The source of the discrepancy of the PV model's output to its actual output was unclear and could not be identified because the PV system does not have a PV monitoring system, and the modeled monthly PV production was not available. The installed system matched the intended design, so the discrepancy may be attributed to shading, equipment performance, panel maintenance needs, system configuration, and/or yearly weather variance. The impact was probably from a combination of these factors.

Figure 32: Atascadero Modeled vs. Actual Energy Consumption and Solar PV Production Shows Lower Performing Solar PV and Underestimated Building Consumption



	Modeled kWh	Actual kWh	Variance
Gross Consumption	399,873	389,453	97%
PV Production	346,494	323,800	93%
Net Consumption	34,214	65,653	

Modeling weather assumptions use an average over multiple years and may not reflect actual weather patterns for specific years.

Hot Water Use: Planned vs. Actual

Given the ability to model individual HPWH systems in compliance software, the research team was interested in how the California Simulation Engine (CSE), the engine under California Building Energy Code Compliance for Residential (CBECC-Res) that contains model assumptions that predict water use versus actual water use for this project.

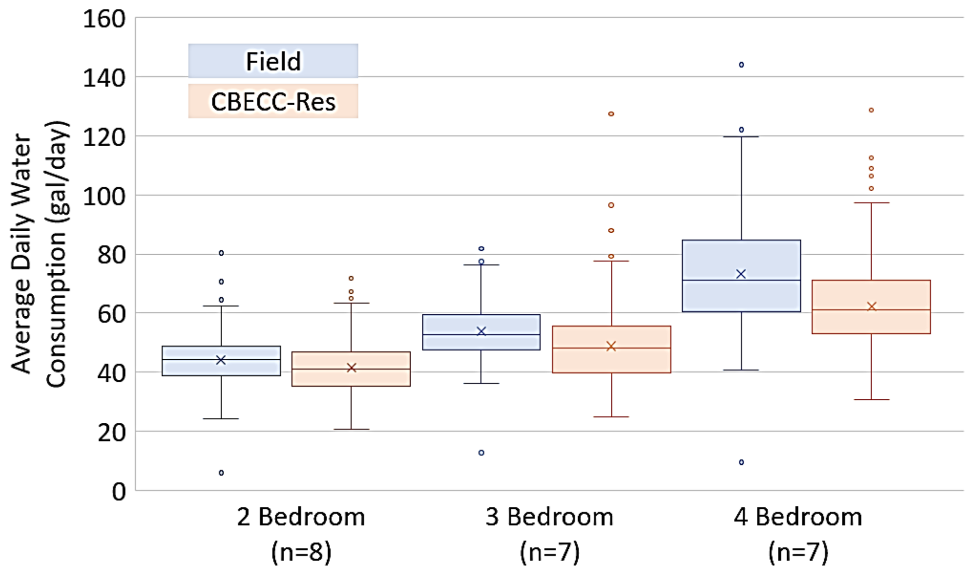
This evaluation compared daily water use on a per-apartment basis by the number of bedrooms. On average the field water use was higher per unit and closer to the modeled assumptions on average for the smaller units and higher by 13 GPD for the 4-bedroom units. This can be attributed to Atascadero's higher occupancies than what CBECC-Res predicted (see Table 16). Average occupancy in CBECC-Res is based on market rate apartments with lower occupancy than observed at these demonstration sites. At Atascadero the 3- and 4-bedroom units mostly had five occupants, whereas CBECC-Res assumes that 3-bedroom units mostly had three occupants, with mostly four occupants in the 4-bedroom units.

Table 16: The Percentage of Bedrooms at Various Occupancies at Atascadero and in CBECC-Res

	Atascadero Occupancy			CBECC-Res Occupancy for Multi Family Homes					
Occupancy	**2 Bedroom (n=21)**	**3 Bedroom (n=23)**	**4 Bedroom (n=14)**	**Studio**	**1 Bedroom**	**2 Bedroom**	**3 Bedroom**	**4 Bedroom**	**5+ Bedroom**
Average	2.8	4.3	5.1	1.4	1.7	2.6	3.1	4.2	3.8
1	19%	0%	0%	73.5%	56.4%	25.3%	9.7%	2.0%	0.2%
2	19%	4%	0%	19.4%	27.8%	31.6%	27.3%	16.8%	35.1%
3	33%	13%	7%	4.1%	7.8%	18.7%	28.5%	6.0%	1.6%
4	5%	35%	14%	2.5%	4.0%	14.7%	15.8%	35.3%	35.9%
5	14%	43%	43%	0.2%	1.4%	4.9%	13.7%	11.1%	5.7%
6	5%	4%	29%	0.3%	2.6%	4.8%	4.9%	28.7%	21.6%
7	0%	0%	7%	-	-	-	-	-	-

The spread of daily draws was similar between the field and CBECC-Res for the 2- and 3-bedroom units, but for the 4-bedroom units there was more variation of daily draws in the field data. Generally, the average daily water usage was higher than in the model assumptions, as summarized in Figure 33 (Figure E-40, Appendix E).

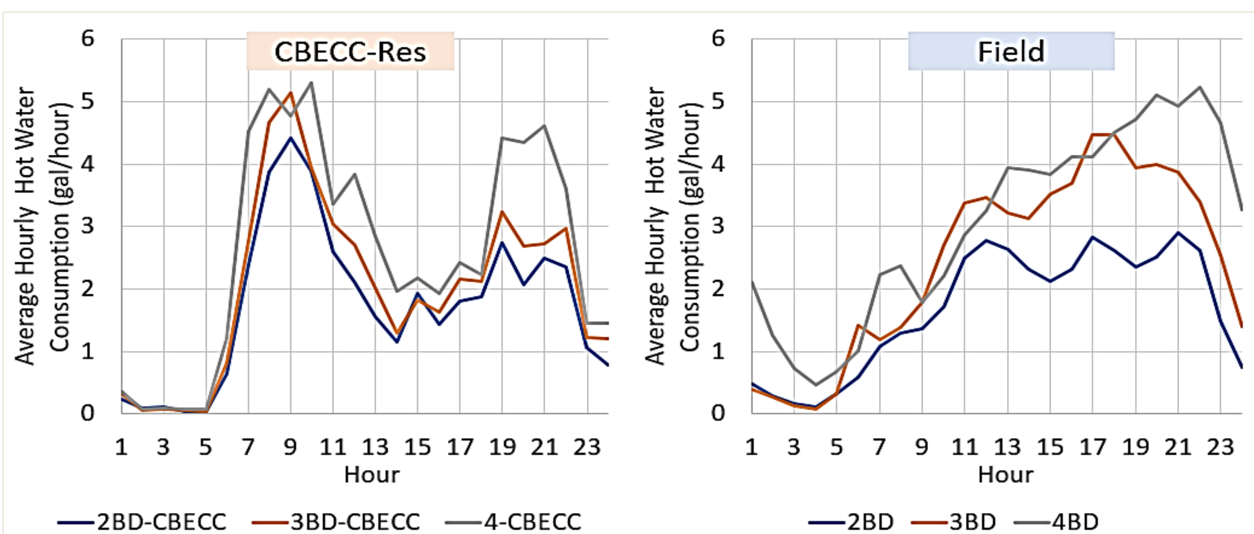
Figure 33: Average Daily Water Use per Apartment Type (2, 3, and 4 Bedrooms), Comparing CBECC-Res vs. Field Data at Atascadero



	2BD-Field	2BD- CBECC	3BD- Field	3BD- CBECC	4BD- Field	4BD- CBECC
Daily Average	47	42	51	49	75	62

Average hourly use also varied between field and CBECC-Res data. There was a much stronger evening peak at Atascadero while CBECC-Res has a larger and later morning peak and a later, smaller evening peak (Figure 34). Time of use has implications for time-dependent valuation (TDV) energy use and grid impacts. Because Atascadero had higher evening peaks, it could see more benefits to load shifting than those predicted by CBECC-Res.

Figure 34: Average Hourly Water Use in CBECC-Res and Atascadero, by Unit Type



For Atascadero overall there were variations between the modeling and actual end uses, as discussed in the performance of HVAC and HPWHs. The evaluation of hot water draws and modeling informed findings.

Sunnyvale

The Sunnyvale project was monitored from February 2019 to July 2020. While the whole-building central heat pump system performed well, this was attributed to extensive technical assistance, installation support, and corrected performance issues that were only identified through data monitoring. The team also took the opportunity to test the potential for thermal storage.

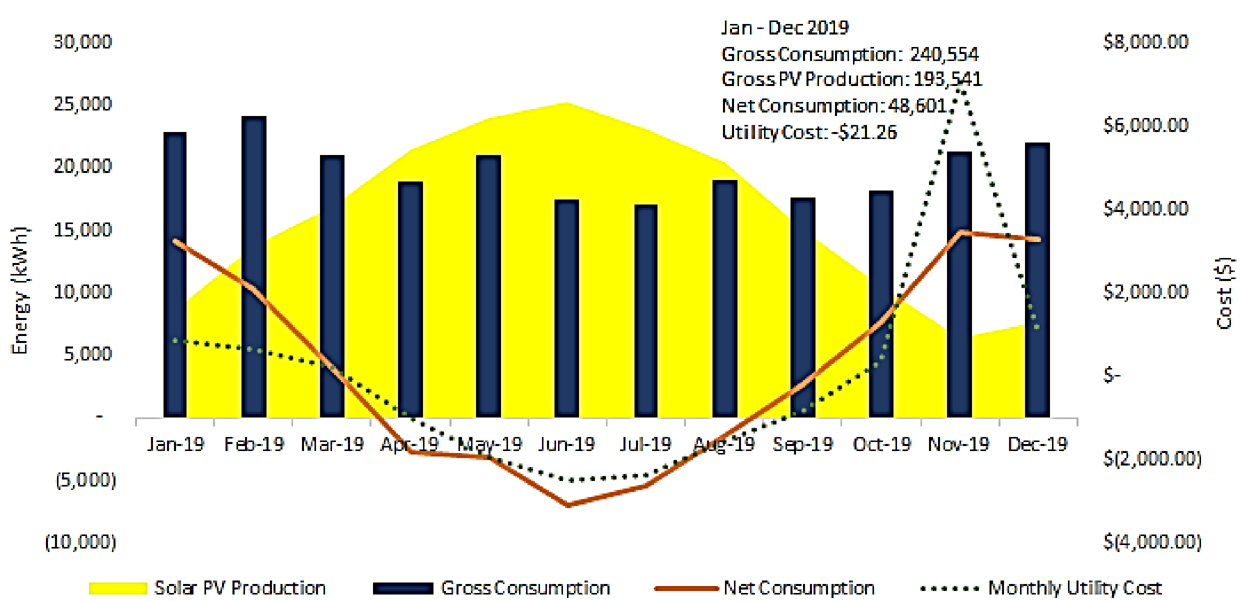
Overall ZNE Performance

Overall, the Sunnyvale project did not meet the goal for common-area ZNE goals defined in the design stages.

As discussed, the solar PV system was designed to produce roughly 20 percent more energy than the common-area modeled load.

Over the 2019 calendar year, Sunnyvale's common area did not achieve ZNE and consumed about 20 percent more energy than the solar PV system produced. The central DHW plant is the largest load on the common area electric meter, which also includes laundry, whole-building and apartment-level mechanical ventilation, community rooms, an office, social services, an elevator, and common area and exterior site lighting. Each of the DHW plants performed well; however, they were commissioned and optimized during the ZNE measuring period so their performance improved from the beginning of 2019 when compared with the end of the year. The building was also not fully occupied until January 30, 2019.The resulting downward trend in energy consumption coincided with the more favorable spring conditions shown in Figure 35.

Figure 35: Sunnyvale Common Area Energy Consumption and Solar PV Production (2019)



Despite not achieving ZNE over the course of a year, the common area net utility cost for the year was actually negative (-$21.26), which included the annual true up. This was possible because the common area meteris on the NEM A-6 rate with Silicon Valley Clean Energy

(SVCE), the local Community Choice Aggregator (CCA). This utility rate is structured with time-of-use (TOU), meaning that the price for electricity (and therefore the solar credit value) is higher during the afternoon and evening with peak consumption, as well as higher in the summer. This aligns with solar production and creates a greater cost offset than a production offset.

In terms of missing the ZNE mark, the discrepancy came from the energy consumption instead of the energy production (see the Planned Actual and Modeling section). The solar PV system performed as expected; in fact, in 2019, it exceeded modeled production by 2 percent, a very small margin of variance. Opportunities to achieve ZNE would come from increased solar production through higher performing panels or additional panels. Given the bill credit with the current sized system, it was hard to promote investment in larger or more productive PV solar system.

Electrical End Uses – Tenant-Metered Loads

As discussed in Chapter 3, the study monitored most apartment electrical end uses—space conditioning, lighting, plug loads, kitchen circuits, dishwasher, and range hoods—but not the ranges due to prioritization of end uses to monitor with a limited number of CTs. The following sections describe consumption and demand at the apartment level with some comparative analysis of end uses, followed by a deeper dive into specific end uses. Extreme connectivity issues in the building resulted in a data set representing 50 percent of the units for six months rather than a complete year of data, resulting in limited resolution. Due to COVID-19 restrictions since March 2020, the team has not been able to retrieve the SD cards with the stored data.

Whole apartment consumption was largely sensitive to occupancy, individual behavior, and seasonality (Figure F-1, Appendix F). That said, since the tenant loads did not include DHW, there was less seasonal representation of seasonality and occupancy impacts than at Atascadero. Figure 36 shows total daily energy for the whole monitoring period. Average daily consumption ranged from 5.5 to 17.1 kWh/day (an average of 10.1 kWh) and was normally distributed across apartments (Figure F-3, Appendix F). Overall, averages aligned with the other projects, assuming exclusion of DHW.

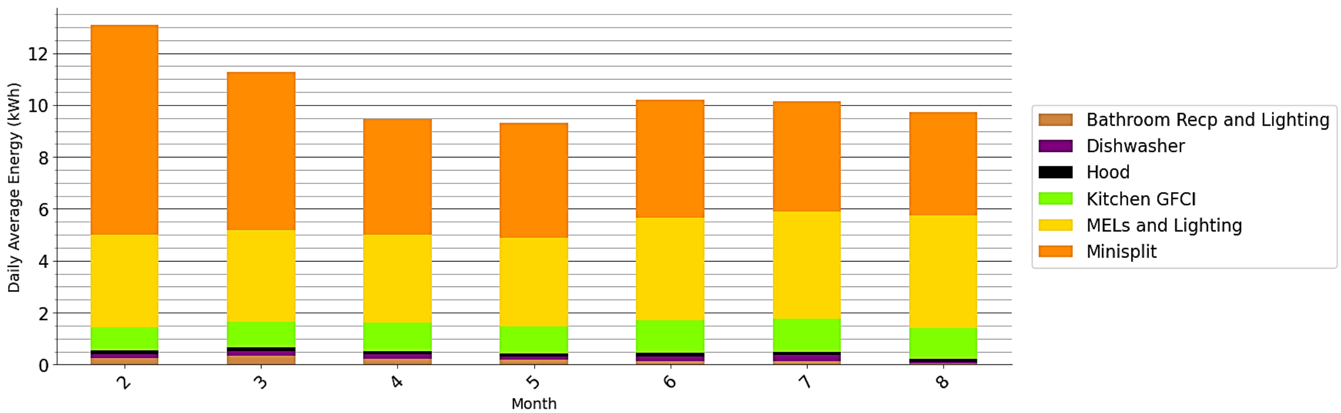
The ductless mini-split system was designed to have a head unit in each bedroom, as well as in the living space, so total usage may therefore be more sensitive to the number of bedrooms. Differences in consumption between bedroom sizes (Figure F-2, Appendix F) were also present, but occupancy was a much better predictor of consumption.

There was some seasonality to consumption, mainly due to hot and cold fronts that significantly influenced short-term spikes. Average consumption was otherwise reasonably flat across the six months, with less long-term seasonal sensitivity since there was no DHW load (Figure F-4, Appendix F). Weekly variance was relatively insignificant though there was higher consumption on weekends, which differed from the other three sites.

HVAC, MELs, and lighting made up the vast majority of consumption, as shown in Figure 36. On an individual apartment basis, HVAC accounted for between 29 to 76 percent of annual consumption, with MELs (plugs, including kitchen and bathroom) and lighting accounting for approximately 15 to 70 percent. At its seasonal peaks, HVAC made up an average of 44 to

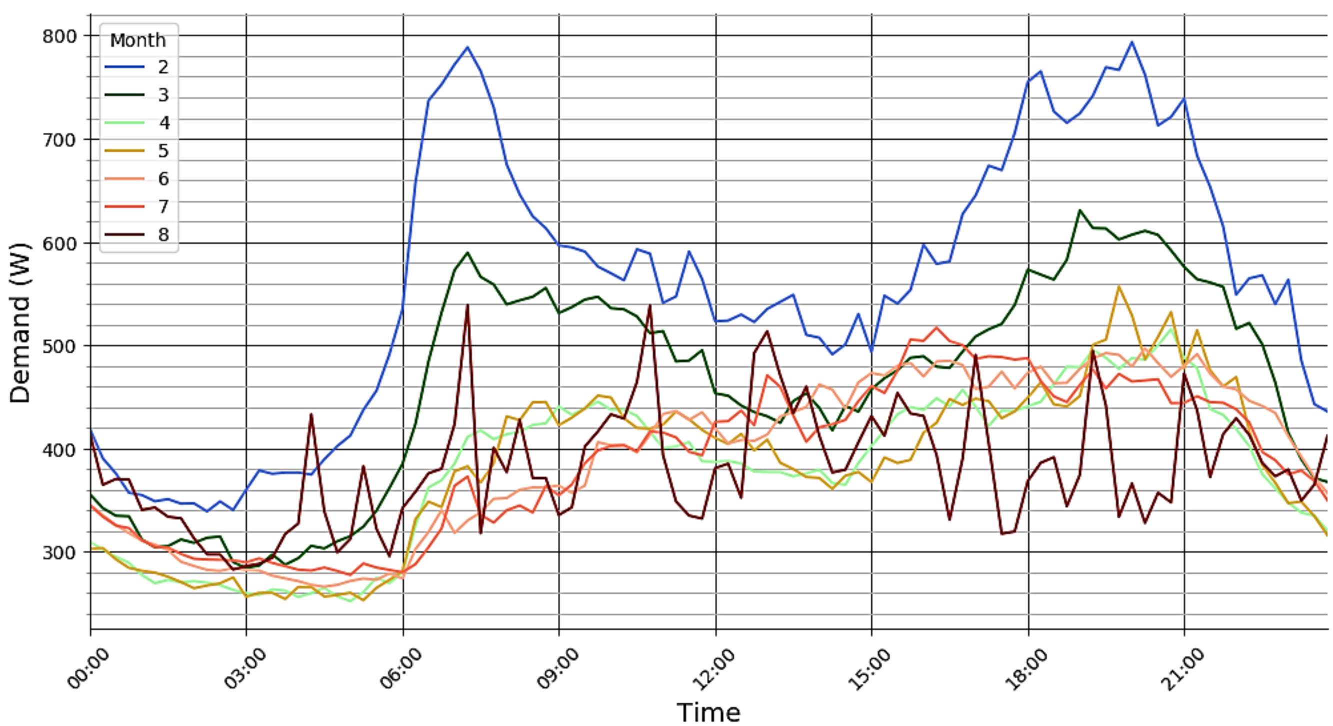
80 percent of total consumption in July, and 27 to 82 percent in February. In shoulder seasons, HVAC was slightly lower, ranging from 25 to 70 percent.

Figure 36: Electrical End Use Consumption by Month Excludes Ranges and Therefore Does Not Represent Total Apartment Consumption



Average demand shapes were very different from February to July (Figure 37). In general, baseline demand stayed about 250 W on average across all apartments. Average peaks in February were about 750 W (and much higher for many apartments) for both morning and evening compared with less than 500 W in the evening in summer. Morning peaks in the summer were almost nonexistent. The peaks shown were largely driven by HVAC.

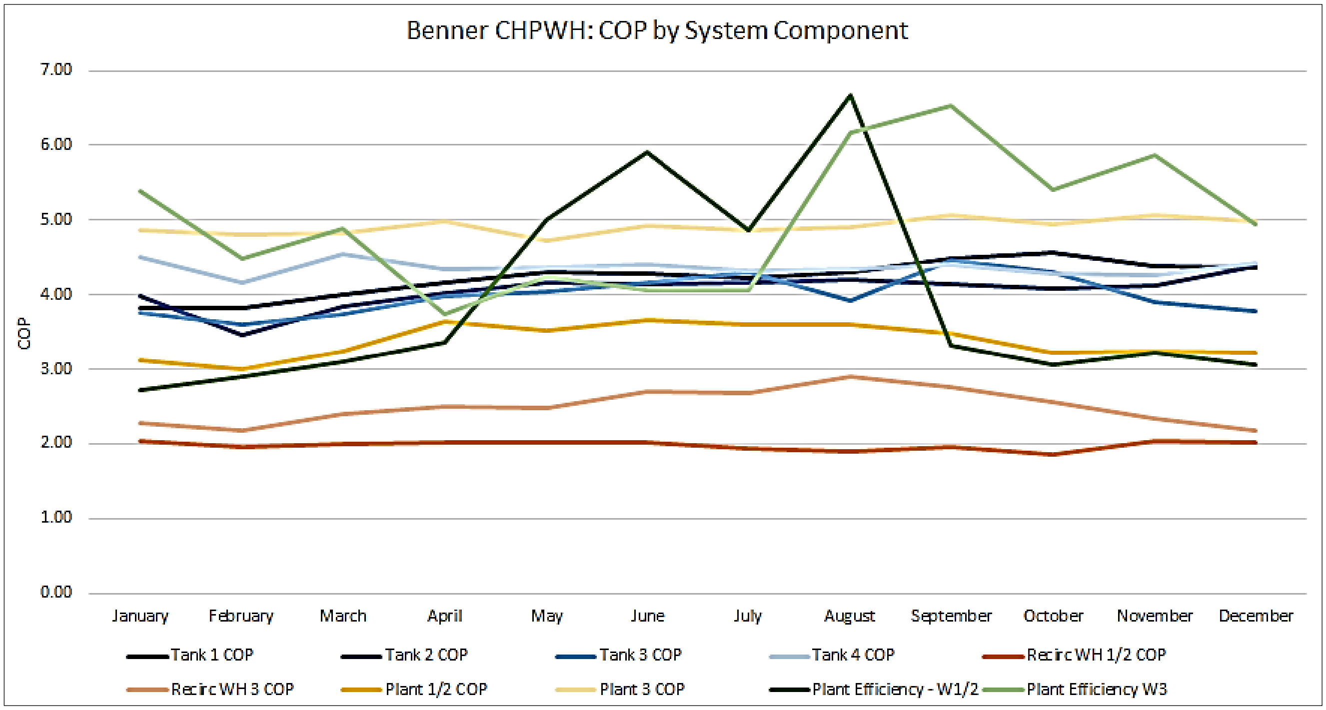
Figure 37: Demand Was Driven by HVAC Loads, Seen in February's Greater Demand



Domestic Hot Water

Both of the CHPWH plants at Sunnyvale performed well. The COP of the individual Sanden heat pumps, the recirculation system water heater, and the overall plant efficiency were all calculated to better understand the true performance and success of the design. Figure 38 (Table F-1, Appendix F) shows the calculated COP of the plants and plant components, as well as the efficiency of the plants.

Figure 38: Sunnyvale Monthly COP by System Component



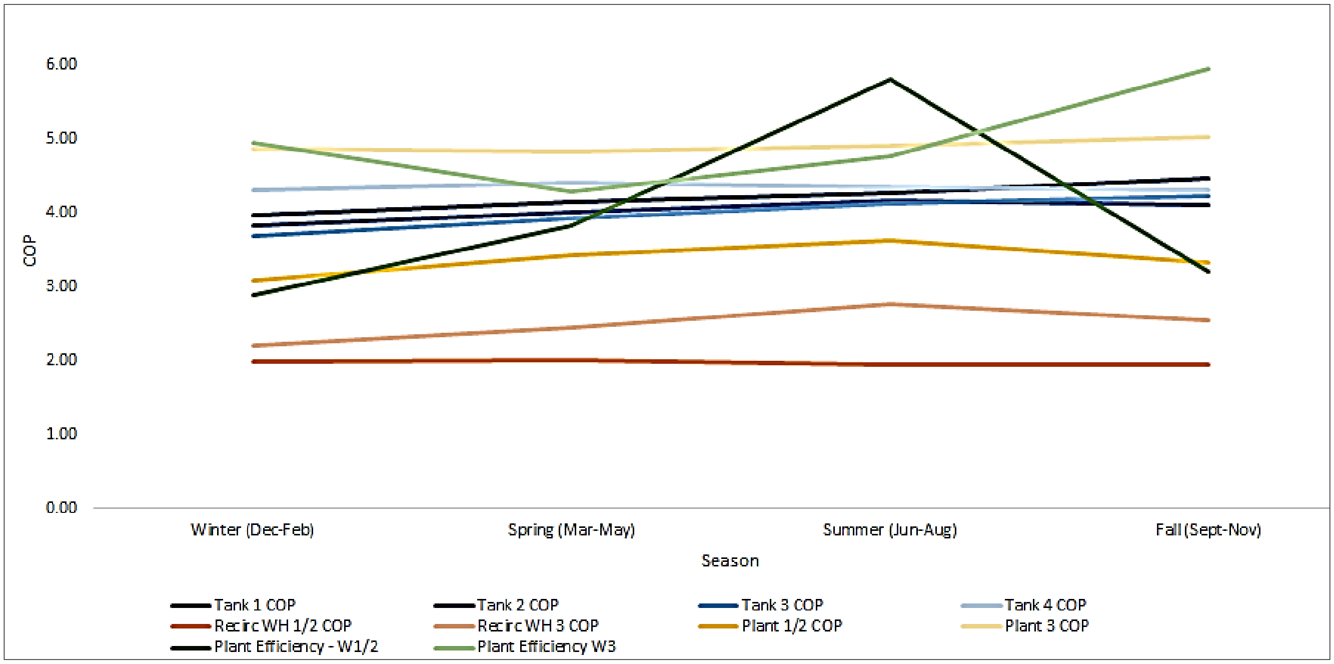
The Sanden heat pumps generally performed around or slightly below the specified COP of 4.5,[14] with an annual average COP ranging from 4.00 to 4.36 across the four banks of heat pumps. The bank of four Sanden heat pumps in Wing 3 performed better than those in the three banks of wings 1 and 2, with a higher system COP for almost every month of the year. Within wings 1 and 2, the third bank of Sanden heat pumps performed the worst on average for most months of the year. Bank 2 performed second best, and Bank 1 performed the best, in terms of both average monthly and annual COPs. It is important to note that Bank 3 and Tank 3 carried the largest portion of the DHW production load for the plant for wings 1 and 2, Bank 2 carried the second most, and Bank 1 the least. This was because of the way the system was piped (as noted in the design section, the installed system plumbing diverged from what was specified in the plans). Because the system was piped in direct return instead of reverse return, Tank 1 experienced the least flow so therefore contributed the least to the DHW load. COPs for each bank of heat pumps varied based on the volume of incoming water and runtime in wings 1 and 2, whereas in Wing 3, where loads were more evenly distirbuted, the COPs were more consistent. The reverse return configuration would have resulted in a more distributed load across the banks.

The system's efficiency and performance fluctuated across various seasonal weather conditions. Generally, the seasonal COPs, aggregated from monthly COPs, showed optimal

14 Referencing COP @60°F (16°C), as shown in the Sanden technical manual

performance during the summer and fall. On average, air temperatures in the summer and fall were warmer than those in the winter and spring; fall was typically warmer than spring when comparing shoulder seasons (Figure 39). This was generally reflected in average COP data since the COP followed air temperatures. Variations to this trend were limited and marginal.

Figure 39: Sunnyvale CHPWH: Seasonal COP by System Component



One of the driving factors of the heat pumps' performance was outdoor ambient air temperature; the warmer the surrounding air temperature, the more optimal the heat pump performance. For Sunnyvale, Figure 40 and Figure 41 show the average monthly temperature of the location of the heat pumps. The garage, where the Sanden heat pumps are mounted, and the inside of the mechanical rooms had warmer temperatures.

Figure 40: Sunnyvale Seasonal COP With Ambient Air Temperatures in Wings 1 and 2

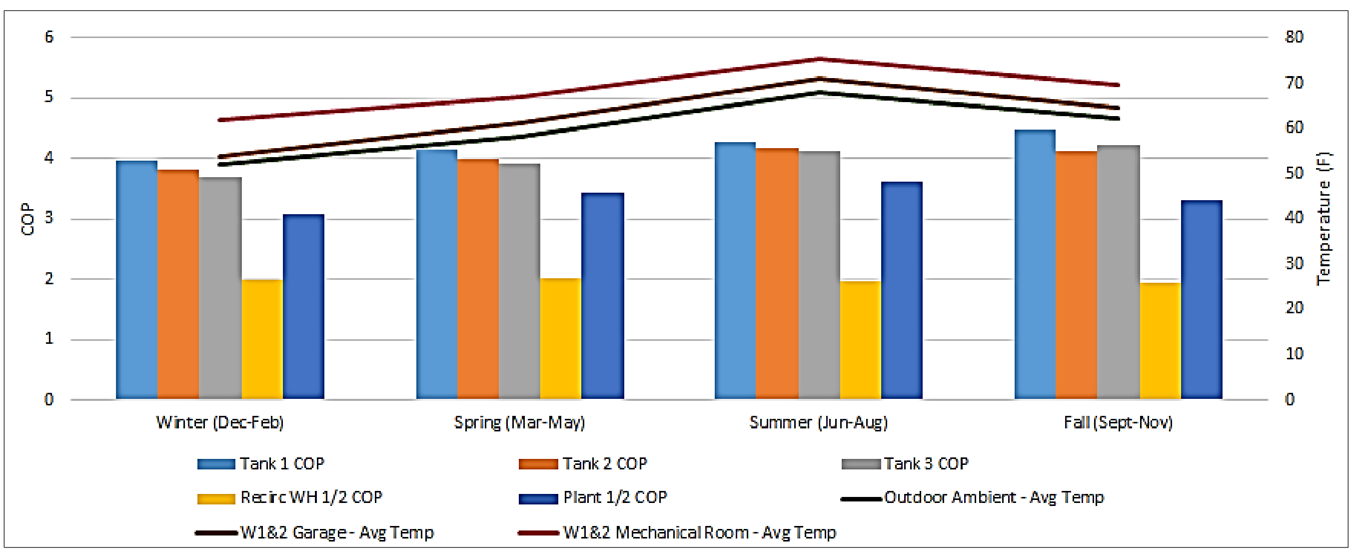
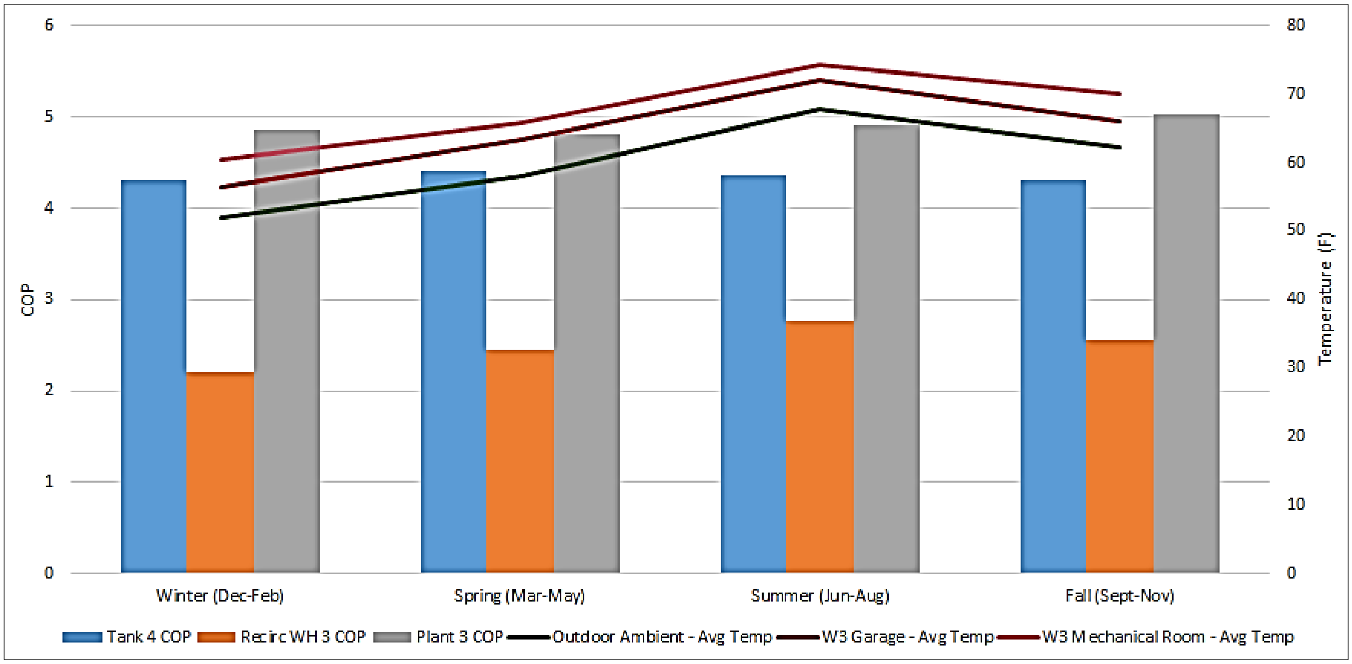


Figure 41: Sunnyvale Seasonal COP With Ambient Air Temperatures in Wing 3



Sizing DHW

Monitoring and collected data were used to evaluate sizing and to inform HPWH-sizing best practices. DHW demand, by way of the cold-water makeup flow, was analyzed from both plants to determine the 99th percentile for specific intervals (excluding the 1 percent characterized by outlier events). Peak 1-hour, 2-hour, and 3-hour intervals were used to determine continued demand events versus short, and large events that would affect the needed recovery capacity. Twenty-four-hour demand was included for comparison to understand if the demand event was a one-time event during otherwise low or normal usage, or sustained usage throughout the days. Table 17 includes 3-hour results. (See Table F-2 in Appendix F for all intervals.) The results provided the worst-case number of gallons of hot water consumed at this property over time intervals to determine the output and storage capacity of the DHW system. These values were then compared with two hypothetical systems of DHW plants that were sized according to the Ecotope Ecosizer.[15] Based on the 99-percent peaks for the 16-month monitoring period (April 2019 to August 2020), the ASHRAE Low Demand profile was the closest match to the actual Sunnyvale demand, but it provided no additional safety factor (or buffer). The Low-Medium profile provided a 24-percent safety factor across all demand intervals, while the Medium profile resulted in a system with a 127-percent safety factor. In addition, actual and Low and Low-Medium design estimates indicated that the original design of 400-gallon storage tanks (for an effective storage of 960 gallons) met the actual 3-hour peaks at Sunnyvale, which serves 42 units. Wing 3 performed well, with 400 gallons of effective storage with a 500-gallon tank. Taking into consideration equipment and installation costs, and system size with a buffer for hot water demand, the Low-Medium

15 Ecotope's Ecosizer sizing is based on the number of units and unit layouts (e.g., 1 bed/1 bath, 2 bed/1 bath) using ASHRAE Low- and Medium-demand profiles, as well as a Low-Medium demand in between the two (e.g., peak gallons/day/person: Low = 20, Low-Medium = 25, and Medium = 49).

demand, based on 25 gallons per person per day, appeared to be the most reasonable choice for sizing future DHW systems.

Table 17: 99th Percentile 3-Hour and Daily Peak Demands for System Capacity Sizing

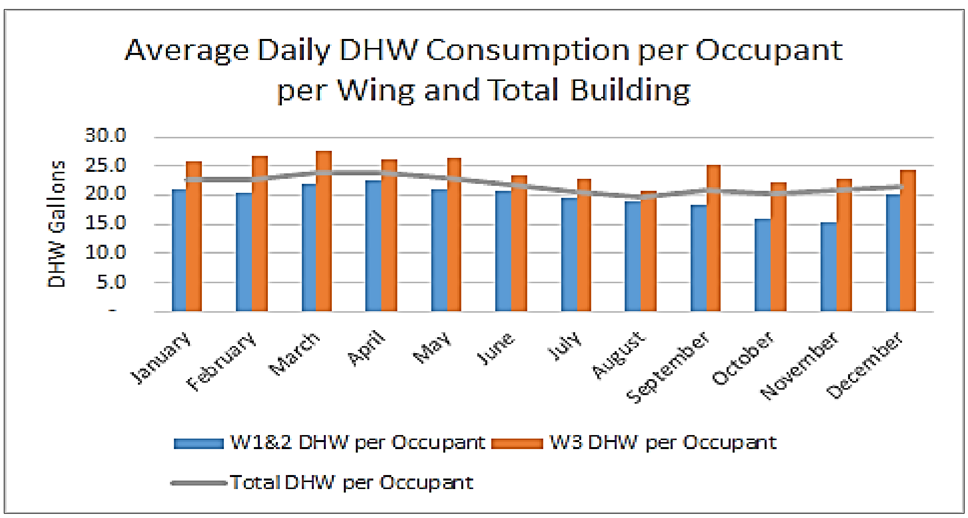
System Peak	Measured 15-month 99% Peak (Gallons)	Ecosizer-Based – Sunnyvale DHW System Capacity					
		Demand Profiles					
		Low		Low-Medium		Medium	
		Peak Rating (Gallon)	Safety Factor	Peak Rating (Gallons)	Safety Factor	Peak Rating (Gallons)	Safety Factor
Wings 1 and 2 3 hr	774	931	1.20	1,171	1.51	2,351	3.04
Wing 3 3 hr	650	643	0.99	803	1.24	1,473	2.27

DHW Consumption and Energy Use

Because occupancy, rather than unit count, was the main driver of DHW consumption, it was the most fitting normalizer for quantifying both DHW and energy consumption.

The average daily DHW consumption was 21.8 gallons per occupant, which was reasonably stable over the course of the year (Figure 42), with an insignificant increase of 1 to 2 gallons (4.5 to 9 percent) in the months of March, April, and May (Figure F-5, Appendix F).

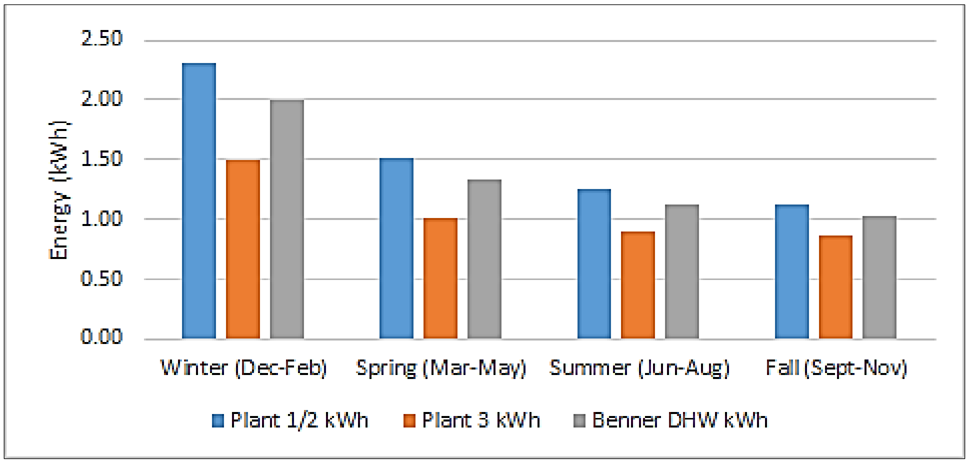
Figure 42: Average Daily Plant and Total DHW Consumption per Month per Occupant Over 14 Months



The mid-morning peak tapers off a bit but continues throughout the day and leads to an even larger evening peak. The evening DHW peak is highest during the 8 p.m. hour and then begins to decline. On average, there was reasonably steady hot water consumption throughout the day, as indicated by the relative absence of a trough between the morning and evening peaks. The average hourly per-occupant hot water profile at the property was unique because of its continuous consumption when compared with other properties, and was likely indicative of the demographics. Generally, based on survey data, apartments were occupied for much of the day.

Both DHW plants were designed with high-efficiency equipment and optimized design and engineering. Figure 43 (Table F-3 and Figure F-6, Appendix F) quantifies seasonal energy consumption of the DHW plants on a per-occupant basis, showing higher energy consumption in winter, as expected.

Figure 43: Average Daily Plant and System DHW Seasonal Energy Consumption per Occupant



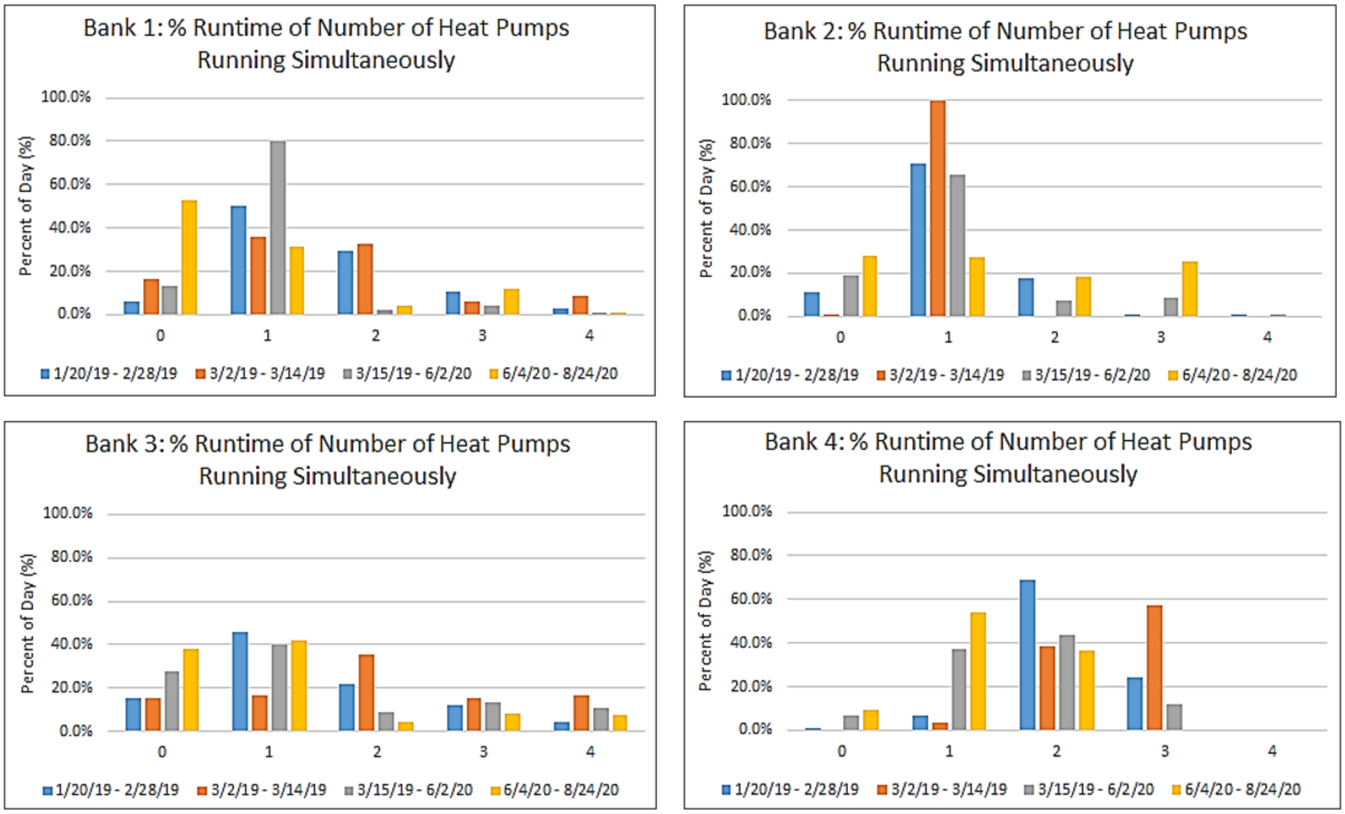
Consistent with system performance and efficiency, both DHW plants consumed less energy during the summer and fall months and highest average daily consumption in the winter months. The Sanden heat pumps do not operate as efficiently in colder ambient air temperatures as they do in warmer temperatures, so they have to consume more energy to yield the same output.

As designed, the Sanden heat pumps in each bank were designed in reverse return to provide an equal flow, with the load equally distributed. Their thermistor controls were all installed within the same thermal well in the HW storage tank and at the same depth to read the same temperature, with the assumption that they would operate simultaneously. Yet, the runtimes and operation times were not equivalent, and on average were dominated by one heat pump in the bank, presumably related to the variable thermistor installation and temperature readings for each heat pump.

In theory, the runtimes should have been more evenly distributed after correcting the thermistors, yet it was challenging to isolate that impact. See Table F-4 in Appendix F, which includes detailed runtimes for specific time periods.

There were also unequal runtimes between multiple banks of heat pumps in wings 1 and 2 due to the direct return piping configuration. This configuration resulted in an increased flow to Tank 3, allowing more balanced operation and longer runtimes for the heat pumps serving that tank. Figure 44 shows the percentage of the average daily time that each heat pump operated in each bank (Table F-4 in Appendix F shows tabular data).

Figure 44: Simultaneous Heat Pump Operation: Percent Runtimes Within Each Bank



The bucketed date ranges within the graphs represent time periods with different conditions; the following list describes each:

- **1/20/2019–2/28/2019**: Start of the clean data collection period. In this period, the data revealed that the heat pumps were not turning on in unison, which in turn led to the discovery that the thermistors were not uniformly installed in the thermal well.
- **3/1/2019–3/14/2019**: Thermistor controls were addressed and performance improved, but some control issues persisted. On March 14, 2019, using more thermal paste, the placement of all thermistors in the wells was further adjusted and secured.
- **3/15/2019–6/2/2020**: The thermistor issue was resolved.
- **6/4/2020–8/24/2020**: Thermal load shifting experimentation on heat pump Bank 1 in wings 1 and 2 was implemented midday on June 3, 2020. This date range encapsulates normal operation on heat pump banks 2, 3, and 4, and 4 p.m. to 9 p.m. peak load shifting experimentation on heat pump Bank 1 through the end of the monitoring (described further in the Thermal Storage and Load Shifting section.

These events and associated performance shed light on several topics:

- Using the standard/default manufacturer's control strategy, it proved difficult to ensure that all of the heat pumps in a bank operated simultaneously.
- Changes to thermistor placement affected banks differently in terms of how simultaneous heat pump operation did or did not change.

- Analyzing simultaneous heat pump operation within a bank may expose potential issues with control strategies, shed light on the accuracy of system sizing, and help to identify system balancing issues.

Because both DHW systems are meeting the building loads, the unequal distribution of load among the heat pumps within a bank or among the banks of heat pumps was not necessarily problematic from an energy or performance perspective. It was still too soon to know if it will negatively affect the expected useful life of the equipment, though. Years of operation and time until compressor failure will therefore be the best determinant of the impact of heat pump runtime.

Recirculation System

As described earlier, each of the DHW plants had a recirculation system served by a dedicated HPWH that was tied into the larger distribution network at the mixing valve.

The average recirculation load (pump energy, recirculation heater, losses) at Sunnyvale, after improvements, was lower than the design standards for 100 watts per apartment (Table F-5, Appendix F).

Through monitoring, the research team identified several issues that affected system performance: recirculation pumps, balancing valves, and the HPWH itself. First, each system was initially installed with two oversized single-speed pumps until they were replaced with the right-sized variable-speed pump about 10 months after occupancy. The impact on energy consumption and recirculation flow was significant (Table 18). Wings 1 and 2 system saw a 99-percent reduction in average daily pump energy and an 89-percent reduction in average recirculation flow. Similarly, the Wing 3 system had a 98-percent reduction in average daily pump energy and a 44-percent reduction in average recirculation flow.

Table 18: Comparison of Single Speed and Variable-Speed Performances

	Single Speed	Variable Speed
Average gpm	30.2 gpm (W1 and 2) 2.2 gpm (W3)	3.5 gpm (W1 and 2) 1.5 gpm (W3)
Average kWh/Day	28.0 kWh (W1 and 2) 14.8 kWh (W3)	2.4 kWh (W1 and 2, W3)

In early 2019, the missing Caleffi 116 balancing valves were installed and the set point corrected, resulting in improved recirculation system performance by maintaining adequate loop temperatures in all of the recirculation lines, and by allowing the recirculation pump to operate at a very low flow rate.

Testing was conducted in both plants to find the best operating modes and set points for the recirculation water heaters. Starting in High Demand mode at 140°F (60°C), the mode and set point adjustments were intended to reduce energy consumption and maintain service delivery. When switched to Energy Saver mode, the unit could not keep up with the recirculation load and hot water supply temperatures fell. The set point was incrementally adjusted downward to 125°F (52°C), at which temperature the units maintained recirculation load.

Though it could not be definitively determined why the Rheem HPWH unit could not maintain recirculation loop temperature in any mode other than High Demand, it was hypothesized that it was largely attributable to the operating algorithms for the Energy Saver mode. As seen at Atascadero, there was more electric resistance to achieving the set point, in addition to intermittent periods when the unit was totally off, as tank temperatures dropped below the set point. Once the unit was switched to High Demand mode, it responded quickly to temperature drops and maintained the set point. The optimal setting was High Demand mode at 135°F (57°C).

A HPWH was used as the recirculation loop heater because of its higher efficiency over a standard electric resistance water heater. Even though it operated in High Demand mode, the HPWH exhibited an average annual COP of 1.98 in the wings 1 and 2 plant and a COP of 2.50 in the Wing 3 plant, both far above the COP of 1 for an electric resistance heater. Seasonal differences in COPs were negligible and fairly stable throughout the year, with little impact on efficiency because of consistent water temperatures (compared with the Sanden heat pumps which receive variable temperatures of incoming water.

The HPWH in wings 1 and 2 had significantly longer operating times and electric resistance usage, shown in Table 19. The lower flow rates (1.5 gpm in Wing 3) and lower loads resulted in more efficient operation when compared with wings 1 and 2. The higher DHW load and reduced stratification caused by the higher recirculation flow rate together increased energy consumption in the HPWH that served recirculation in wings 1 and 2.

Table 19: Recirculation Water Heater Runtimes (January 2019–August 2020)

	Wings 1 and 2 (%)	Wing 3 (%)
On	98	64
Compressor (% of operating time)	20	87
Electric Resistance (% of operating time)	80	13

One aspect that was not evaluated in this research project was the distribution system, since thermistors were not installed on each riser to capture this data. A limited sample of tenant satisfaction surveys indicated a range of satisfaction with DHW that does not readily correspond to either floor or plant. While understanding plant and recirculation system performance was critical, this warrants additional research into tenant satisfaction and distribution performance to provide best practices.

Thermal Storage and Load Shifting

Thermal load shifting was carried out in the Wings 1 and 2 plant by cutting power to one bank during the peak demand period defined by the utility rates. Based on the measured average and peak loads on the specific bank of heat pumps, Bank 1 heat pumps, which carried the lowest load, were selected for the test. This was the safest option—in the event of failed load shifting, the availability of hot water to the tenants would not be heavily compromised. Insteon load controllers with remote capability were installed to control the four heat pumps in Bank 1. The load controllers were scheduled to cut power to the four heat pumps at 4 p.m. each day and then restore power at 9 p.m. With this methodology, the load that would have been accrued during this 5-hour peak time period was shifted to 9 p.m. onward.

Using this relatively lightly loaded group of heat pumps for the thermal load shift experiment greatly limited the energy reduction potential of the experiment and was intended simply to demonstrate the viability of this load shifting strategy for a central heat pump water heating system. The results presented below show that this type of load shifting with this methodology was effective and feasible.

Energy savings of 20 percent for Bank 1 (4 percent for entire plant) were achieved despite the already low load. There was no discernible impact on either the quantity or temperature of the hot water delivered to the building. Table 20 compares the performance of the two-week thermal load shifting experiment initiated June 3, 2020, to performance in the two weeks prior.

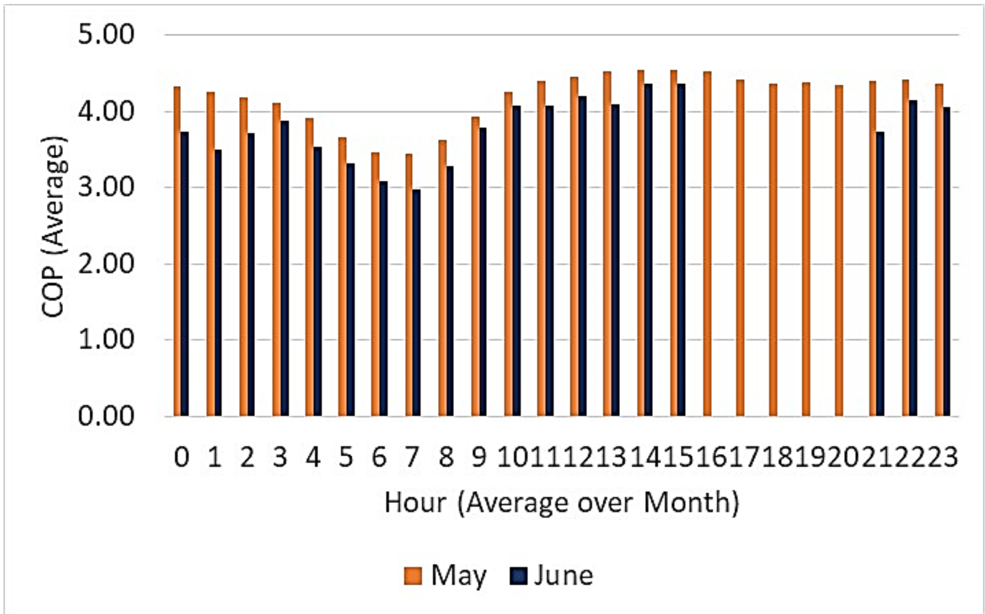
Table 20: Total kWh for 2-Week Pre- and Post-Load Shifting

Time Period (2020)	HP1-1 (kWh)	HP1-2 (kWh)	HP1-3 (kWh)	HP1-4 (kWh)	Total HP Bank - 1 (kWh)	Plant (W1 and W2) (kWh)
5/17–6/2 (pre-load shifting)	19.06	56.64	2.18	334.33	**412.20**	2,462
6/4–6/20 (load shifting)	68.10	73.27	0.02	201.18	**342.56**	2,371

Despite energy consumption being reduced, there was also an approximately 4 percent reduction in COP for both Bank 1 and the overall plant (Table F-6 in Appendix F). This reduction in average COP per heat pump bank and DHW plant was somewhat surprising given the coincident energy reduction during the same time period. The average daily DHW consumption was 53 gallons (2.1 percent) lower during the load shifting experiment. Due to these differences, it is difficult to discern the reason for the reduction in COP, although at least a portion of the energy savings can be attributed to decreased demand.

Digging further into the change in COP, the average hourly COP of Bank 1 heat pumps in May 2020 was compared to those in June 2020 once thermal load shifting had begun (Figure 45).

Figure 45: Heat Pump Bank 1 Load Shifting: Average Hourly COP Comparison May vs. June 2020



On an average hourly basis, the COPs in May were higher in every hour than they were in June, as shown in Figure 45. The second greatest variation occurred during the 9 p.m. to 10 p.m. hour following conclusion of load shift periods. Because of this, it was that much more difficult to understand how much impact the thermal load shifting had on COP, as other factors could include ambient temperature and draw volume. During the pre-load shifting period, the OAT was 62.7°F (17.1°C), which was 6.3°F (3.5°C) degrees lower than the average outdoor temperature during the load shifting time frame, a 9 percent temperature increase.

An additional benefit was that load was better balanced for this bank of heat pumps. Over the same two-week periods of pre-load shifting and post-load shifting commencement, the four heat pumps in the bank went from one heat pump dominating more than 80 percent of the load to a much more equitable split of about 20 percent, 21.5 percent, and just under 60 percent for three of the four heat pumps in the bank. The third heat pump barely operated during the four-week snapshot of this experiment.

HVAC

The ductless mini-splits were monitored in every apartment, and electrical energy was disaggregated into heating and cooling energy (represented mostly by compressors and fans) and baseloads.

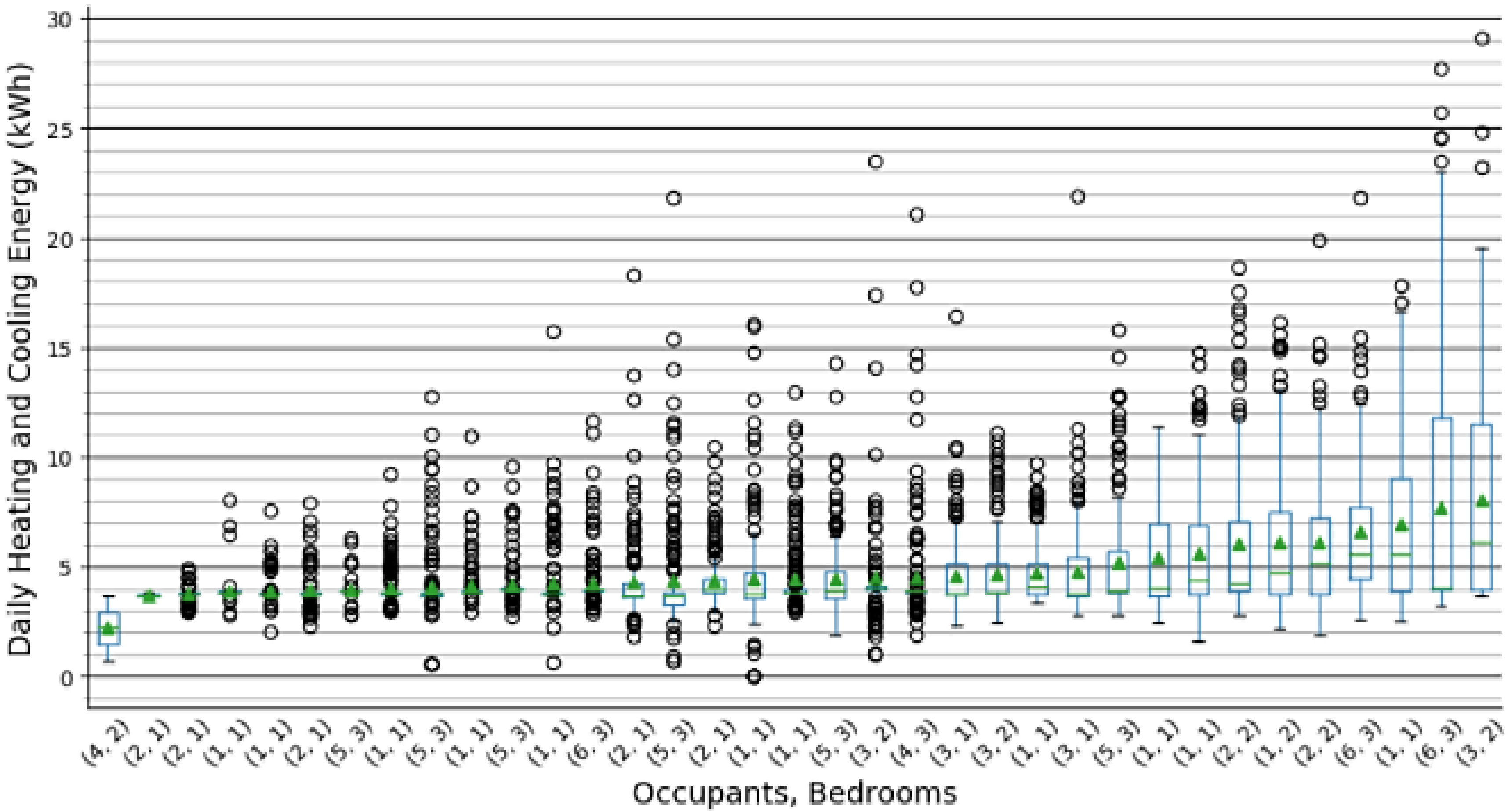
The space conditioning is provided by Mitsubishi ductless mini-splits with two to four heads in each unit, depending on the number of bedrooms per apartment, as shown in Table 21.

Table 21: Ductless Mini-Split Distribution by Bedroom Type

Bedrooms	Number of Heads per Bedroom Type	Monitored Mini-Splits (annual kWh)
1	2	1,812
2	3	2,408
3	4	2,155

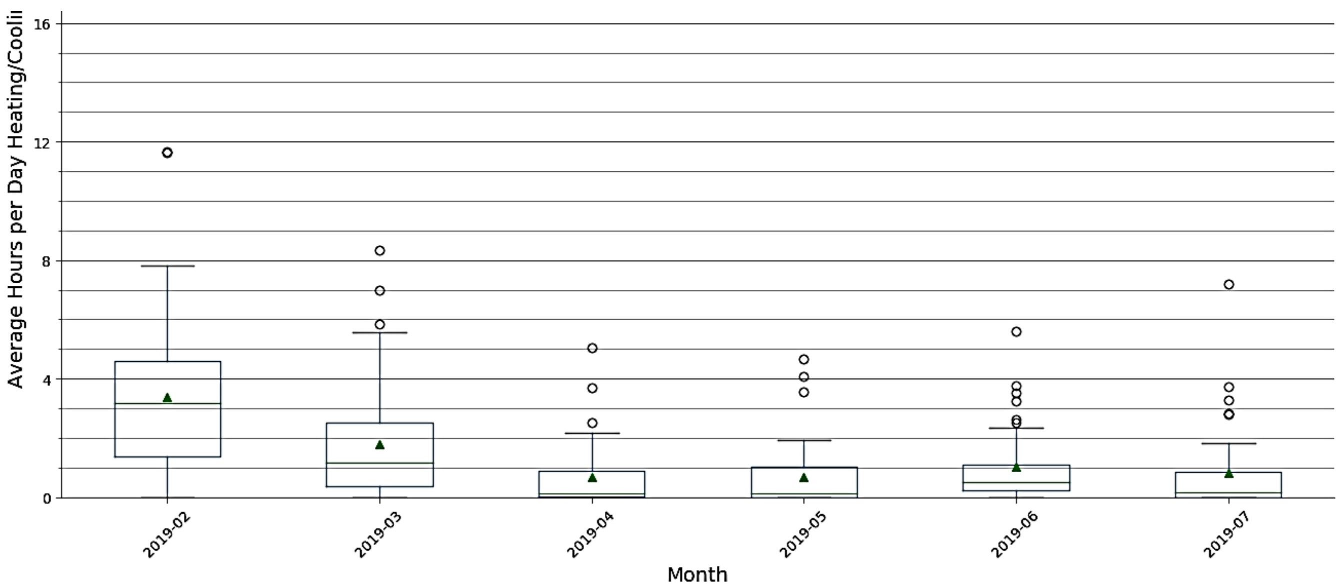
Overall heating and cooling loads were low, with heating being the dominant load. Summer loads were mainly driven by non-compressor loads (or baseloads) defined as 250 W or less, identified through monitoring (Figure 46) (Figure F-7, Appendix F).

Figure 46: Average Daily Consumption (Including Baseline Consumption) Is Overall Low for all Apartments



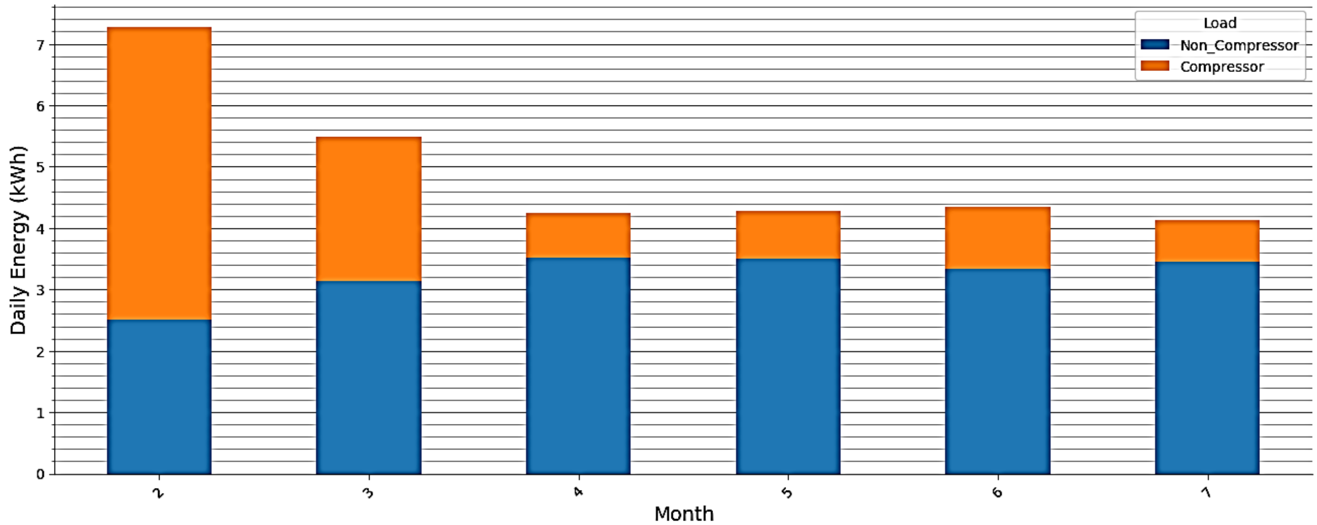
In general, runtimes are somewhat lower than expected for heating and cooling energy. Even for apartments that consistently heat or cool daily, daily runtimes are low, although generally longer in the winter (Figure 47). Runtimes on average for the whole six-month period range from 0 to 274 minutes per day. Winter runtimes averaged as much as six hours per day across all apartments, and most average summer runtimes were less than one hour but approached six hours during one peak in mid-June. A small sample of tenants (16-percent response rate) responded to maintain lower set point temperatures than data showed. Averages and variances in runtimes across apartments were greater in the winter, but varied greatly in response to short-term weather patterns (Figure F-8, Appendix F). Even with these low HVAC loads, tenants identified challenges with meeting comfort needs, indicating potential improper operation of the ductless mini-splits, a newer technology.

Figure 47: Runtimes Are Generally Low, With Higher Consumption in Winter



The research team identified the high baseloads associated with the ductless mini-splits through the monitoring data. In every month except February, the non-compressor load made up a larger portion of the HVAC load than either the heating or cooling loads themselves did, as shown in Figure 48. The load was relatively evenly distributed across apartments (Figure F-9, Appendix F).

Figure 48: The HVAC Load Was Disaggregated by Compressor and Non-Compressor (Less than 250 W) Runtimes to Understand Baseload



To investigate this HVAC baseload, electrical performance testing was conducted on a Mitsubishi ductless mini-split heat pump unit in one of the Sunnyvale apartments and one installed in a different building. The testing of current draw in different modes of operation and without power as a baseline at both locations indicates that there was a baseload present at all times when the unit was not operating. At Sunnyvale, this load accounted for, on average, 71 percent of a household's total HVAC load. Investigation into the cause of this load is ongoing, so the manufacturer was engaged to provide insight and additional investigation resources.

MELs and Lighting

The MELs comprised of bathroom, kitchen, and general receptacles and lighting loads were comparable with Atascadero, with an average daily consumption of 5 kWh/day. General receptacles and lighting comprised on average 75 percent of the load. The refrigerator contributed an average of 1 kWh/day. Loads were driven by individual behavior and did not correlate with the number of bedrooms. That said, there was a large increase in the three-bedroom units. Limited observations show parasitic loads averaged 70 W but ranged from 0 W to 200 W and were primarily associated with general receptacle and lighting circuits. Loads showed a moderate increase on weekends. There was more seasonal variability than at other sites, yet some of this variability may be due to a more limited data set, both in terms of number of units and duration.

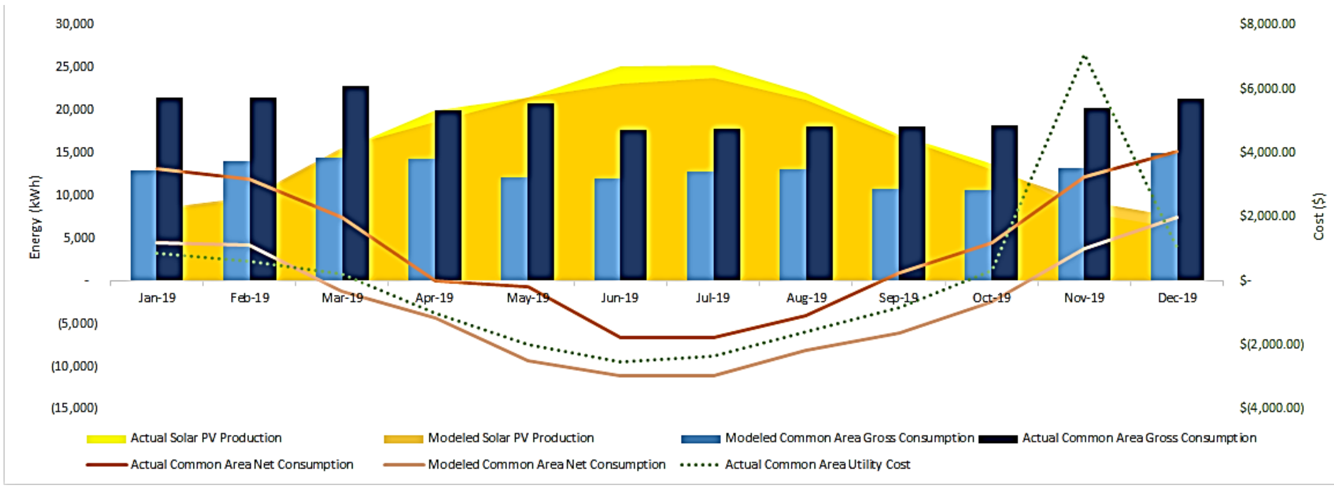
Nexi Evaluation

Similar to Atascadero, Nexi evaluation at Sunnyvale was limited to surveys with a 33-percent response rate; 54 percent of survey residents noticed the Nexi display at least three times a day. The lighting displays were installed at move-in so at this development, there was not a period without lighting displays. It was therefore hard to evaluate energy awareness pre- and post-installation of the lighting displays. Yet, 45 percent indicated that Nexi influenced their behavior (rating of 6 or greater on scale of 1–9), and 80 percent did if the metric includes "somewhat" influenced (rating of 5 or greater). Given the installation sequence this qualitative data cannot be paired with any quantitative data.

Planned, Actual and Modeling Evaluation

As addressed in the ZNE section, the Sunnyvale common area did not achieve ZNE for the year; it fell 20 percent short. Figure 49 shows the modeled versus actual energy consumption and solar PV production for the common-area loads attached to the house meter, including the DHW system. Tenant loads were excluded from this graph because they did not receive PV credits.

Figure 49: Sunnyvale Common Area: Modeled vs. Actual Consumption and Solar PV Production



The solar PV production modeling was very accurate. The model, using PV watts[16], predicted production within 2 percent of actual 2019 production. The model slightly underestimated production during the summer, which can be attributed to regular fluctuations in a given year's weather and incoming solar radiation as compared with the average. The building model underestimated energy consumption for both the total building and common area loads. The modeled energy consumption of the common area loads, including for the DHW system, was much lower than the actual measured consumption; missing the ZNE target therefore does not necessarily indicate poor performance, but rather highlights the discrepancy of the modeling tools. The actual total gross building consumption was 20 percent higher than modeled, and the actual total gross common area consumption was 53 percent higher than modeled. The CHPWH modeling, and the inability to model this major end use accurately, resulted in a 40 percent discrepancy between modeled and actual consumption. The remaining variation was attributed to other modeled loads, but our monitoring did not support evaluation of all common end uses disaggregated.

16 The PV Watts tool has a far smaller chance of a shading calculation error for a system installed on a high rise building in a dense urban environment without neighboring tall buildings.

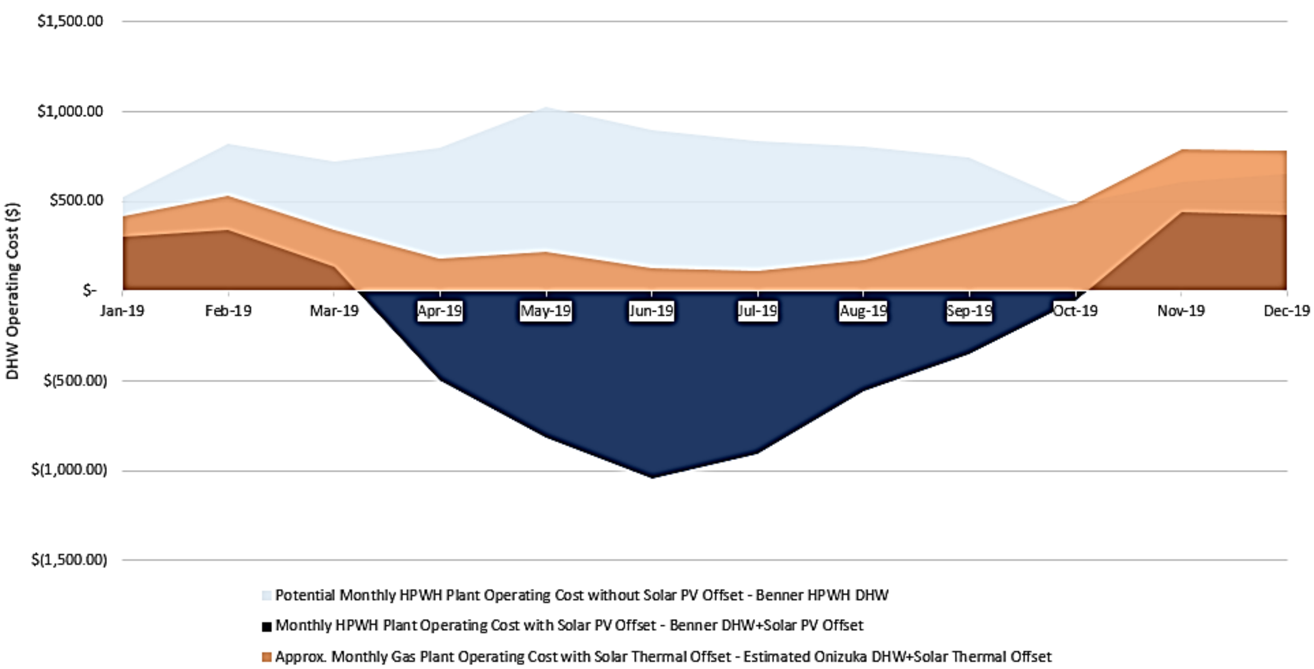
The model predicted the solar PV system would produce almost 20 percent in excess of what the common area meter needed, so it was estimated there would be a negative energy balance on this meter, and that it would be well below 0 kWh for annual net consumption.

Operations and Maintenance

Understanding the operation and maintenance of an all-electric system was critical to informed decision making.

CHPWH plant operational costs were estimated for both the Sunnyvale all-electric project and a mixed-fuel building by the same owner, also in Sunnyvale. The other project was of similar size (58 units), had solar PV offsetting the common area meter, solar thermal offsetting the gas DHW boiler, and gas dryers. There were many assumptions embedded in this calculation, and the data used were far less granular than those of the research all-electric project. Figure 50 shows the all-electric Sunnyvale CHPWH loads with and without solar PV contributions, compared with a gas boiler central system where costs are never offset by renewables (though load was reduced by the solar thermal). The findings demonstrate the cost-effectiveness of all-electric central heat pump systems when paired with PV, and that ZNE cannot be achieved in a mixed fuel building.

Figure 50: Monthly Operating Cost of Central Electric Heat Pump DHW (Sunnyvale Benner Project) vs. Central Gas DHW (Onizuka)



In addition to significant performance and energy consulting during project design and installation, this study supplied support and training provisions for the maintenance and property staff. An operations and maintenance manual were prepared, along with maintenance and upkeep training exclusively focused on operating and maintaining the CHPWH system and its components. This training included routine steps that should be taken to maintain the system so that it extends its useful life as long as possible. It recommends actions to take, such as cleaning the filter in the heat pumps' compressors and unclogging the condensate lines and identifies at what frequency to take recommended actions.

Finally, support was provided to building staff to effectively utilize utility data and solar PV monitoring data to track operations and operational costs of the new building once fully occupied. This provided useful insights into the project's design success. The utility data can also indicate specific system performance, depending on operational conditions; if there was an egregious issue with a large end use like the CHPWH system on the owner-paid house electric meter, it would show up as a change in the energy consumption data provided by the electric utility. Utility data are very powerful and informative for tracking a building's performance without investing a lot of time and money in a separate building management system.

Conclusion

This stage of the project allowed the research team to process and analyze the data collected over the monitoring period. Its purpose was to understand the performance of both the projects and individual systems, as well as the impacts of electrical loads, and to understand opportunities and challenges to achieving ZNE for each of these projects. The data analysis has informed findings and recommendations that advance all-electric ZNE multifamily buildings. These will be discussed in Chapter 5.

CHAPTER 5: Findings and Recommendations

This research demonstrated that all-electric ZNE multifamily projects are possible and that they require technical support, particularly with new technologies. To meet local and state energy and climate goals, this type of development must scale up.

The all-electric and ZNE aspects of the projects must be considered separately. Each project was able to demonstrate the cost effectiveness of building all-electric projects, notwithstanding recommendations and findings to improve and scale this effort. From an emissions perspective, these developments can be served by 100 percent clean energy, resulting in reduced building emissions. In addition, the developments incorporated ZNE goals with on-site generation to address reliability and affordability for both lower tenant bills and owner utility bills. While only one project achieved ZNE from an annual consumption standpoint in 2019, each project benefited from greater affordability of utility costs. Each of the projects was within 17 to 20 percent of achieving ZNE in 2019. Yet, with some adjustment, each project could be closer to achieving its ZNE goal, as discussed in Chapter 4. For Atascadero the reduced PV production and high HVAC loads hampered the project. Poor modeling for a central heat pump system negatively affected Calistoga and Sunnyvale; yet Sunnyvale still had a bill credit. Optimization efforts at Calistoga to reduce Aermec usage could have brought the project closer to ZNE.

From a development-cost perspective, CBH completed a material economic analysis which showed that the material costs of central gas boilers and chillers were 18 percent higher than for electric central heat pump systems. The central MEP systems, in turn, are 38 percent more expensive (gas) and 17 percent more expensive (electric) than individual MEP systems for each apartment. However, lacking Labor costs, we cannot conclude that individual systems are actually less expensive than central systems, only that gas-fired central systems are more 18 percent expensive than electric central systems.

Based on the results from this research project on four all-electric multifamily projects, the research team developed findings and recommendations that support advancement of all-electric buildings. Based on four years of research that resulted in an extensive data set, there are a number of considerations and perspectives to share. The project team has honed in on the following issues as the most valuable ones to advance all-electric ZNE multifamily buildings.

The findings are organized under the following topic headings:

- Domestic Hot Water: Individual Systems, Central DHW, and Combined Systems
- Heating, Ventilation, and Air Conditioning
- Electrical End Uses
- Building Modeling
- Solar Photovoltaics

Within those topic areas the findings and recommendations largely fall into these three categories:

1. **Design and Construction:** This includes the architectural design, engineering, and specification of a project and onsite inspections. The findings may inform aspects at this stage from project layout, equipment specifications, installation and engineering sizing calculations to commissioning.
2. **Codes and Standards:** This includes standards referenced in building codes and appliances standards, manufacturing standards, and algorithms and logic in compliance software and inspections.
3. **Operations and Maintenance:** This includes elements such as monitoring and maintenance activities from occupants and property owners and building maintenance personnel.

Each finding below will identify which of these categories it applies to. Many of the findings fall into multiple categories.

Domestic Hot Water

Individual Heat Pump Water Heaters

Several best practices for individual HPWHs are already known to benefit performance. These include locating them in well-vented spaces with warmer air, properly insulating all pipes and fittings, and following manufacturer's recommendations for piping of recirculation systems. In addition to standard best practices, the research team identified a number of practices and considerations to aid in optimizing the performance of individual HPWHs.

DHW Demand: This finding applies to conditions in Design and Construction.

The hot water consumption per occupant estimates used for sizing the water heaters at Atascadero were derived from the American Society for Plumbing Engineers (ASPE) and ASHRAE industry standard calculations for DHW consumption and water heater sizing. However, there is some question as to whether the assumed apartment occupancies in that calculation is correct. According to these design standards a two-bedroom unit with an assumed occupancy of three people had a three-hour hot water demand of 35.1 gallons per hour (GPH) according to the ASHRAE method and 33 GPH according to the ASPE medium demand method. Evaluating actual hot water consumption at Atascadero from the perspective of number of *bedrooms* found that the two-bedroom apartments exceeded this three-hour demand 32 percent of days. However, evaluating consumption from the perspective of number of *occupants* found that three occupant apartments only exceeded that three-hour demand 19 percent of days. Additionally, these standards assume a three-hour morning and evening peak, yet in reality, the actual peaks were longer and evening peaks started prior to the grid peak at 5 p.m. This indicates that the number of bedrooms plus one occupancy assumption is not adequate for all housing types, and that the methodology needs to be reevaluated for higher-occupancy households and potentially for longer evening peak periods.

Sizing: This finding applies to conditions in Design and Construction and Operations and Maintenance.

Sizing needs to be considered from two perspectives: standard operation (availability of hot water while minimizing energy consumption) and load shifting operation (minimizing electricity us during discrete times of day). Ultimately the amount of demand that an HPWH can keep up with is dependent upon the tank temperature at the beginning of a period of demand, the recovery efficiency (which is strongly dependent on ambient conditions and heat source), and the amount of hot water demand sustained. This constantly moving target increases the difficulty of adequately sizing HPWHs to limit auxiliary resistance backup and makes it even more difficult to consistently reduce electrical demand and shift thermal load without draining the tank. In addition, recovery time also should include considerations for 240 V versus 208 V. An HPWH supplied with 208 V will incur longer recovery times, as the heating element is devalued 75.11 percent (Rheem, no date). This can be a 7 GPH difference in recovery. Higher occupancy increases the amount of random variation in daily draw profiles, making both sizing and optimization for thermal storage and reduced energy consumption challenging.

For standard operation, increase the tank size to better correlate with expected occupancy. The four research projects undertaken for this study had higher occupancy than traditional estimates. As discussed, HPWHs have longer recovery times, and generally higher occupancy residences have higher loads and higher potential for coincident or consecutive draws. Since HPWH performance was significantly influenced by incoming water temperature and ambient air temperature, sizing for winter loads would represent a worst-case scenario. In addition, the sizing can be approached to minimize the use of electric resistance elements, regardless of intention to load shift or not. In the comparison of High Demand 140°F (60°C) to Energy Saver 125°F (52°C) (both scenarios have mixing valves installed and set to 120°F (49°C)), there was an overall decrease in energy consumption while in Energy Saver mode at 125°F (52°C), but an increase in the fraction of electric resistance usage. This was in part due to the fact that the smaller volume of available hot water that exists when storing at lower temperatures (125°F (52°C) in this case and mixing down to 120°F (49°C)) compared with storing water at 140°F (60°C) mixed down to 120°F (49°C). This lower volume of available hot water meant that the water heater required more time to recover. The algorithms governing the electric resistance operation for these particular HPWH's may also have played a role in the frequency of electric resistance operation. With larger storage volumes, a higher set point, and a mixing valve, electric resistance will be minimized, as shown in the comparison of a 140°F (60°C) set point to a 125°F (52°C) set point at Atascadero. As previously discussed, the control group data set only included energy consumption and not flow data, electric resistance for this group on average comprises 64 percent of consumption in Energy Saver mode. Therefore, to ensure hot water delivery and minimize resistance, this limited study demonstrated the need to increase stored water at higher temperatures with a mixing valve installed.

Using California Plumbing Code sizing guidance, as the number of bedrooms increase, the occurrence that the HPWH could not provide hot water also increased. This indicates that the 2019 California Plumbing Code sizing methodology becomes less accurate as the number of bedrooms increase based on the draw profiles of this specific site. The events where HPWH could not provide sufficient hot water increased when running in heat pump only mode for all bedroom types and both HPWH sizes. If the intention was to avoid running the HPWH with the electric resistance element to maximize its efficiency, it is recommended that HPWHs are sized based on the First Hour Rating of the heat pump only mode. This would require manufacturers to provide first-hour ratings based on the different heating modes (hybrid and heat pump only) to ensure the HPWHs can provide adequate hot water in more efficient modes.

With higher occupancy units, a two-bedroom apartment should have a 65-gallon tank and a three- and four-bedroom apartment should have an 80-gallon tank, both with a mixing valve to support a higher temperature set point.

For load shifting operation**,** typical sizing assumes 80 percent available water at the beginning of the peak period (shed period). Yet if the tank was drawn down below 80% prior to the shed event, this will negatively impact usage during the shed period. With individual water heaters, optimizing control schedules (load up and shed modes, times and temperatures, recovery temperatures and modes) has the potential to help relieve the worst aspects of greater peak grid demand and lower solar production. Using the modeling analysis with Atascadero draw profiles to evaluate load shifting from 5 p.m. to 9 p.m. eliminated the proprietary logic of the HPWH mode operation. This load shifting analysis result indicate that an 80-gallon HPWH for these draws should adequately provide hot water with load shifting logic applied for the 2- and 3-bedroom units, allowing the HPWH to be run in heat pump only mode during the shed event without significant interruptions. For larger draw (higher occupancy units), the HPWH would need to be run in hybrid mode during the shed event to ensure available hot water. To adequately provide hot water for 4-bedroom higher occupancy units while load shifting, it is recommended to install HPWHs with storage volumes greater than 80 gallons to provide adequate amounts of hot water.

With longer and higher hot water usage periods that start prior to the "grid peak," apartments are not entering the shed period with a full tank. This indicates (1) more gradual ramp may be needed, (2) smart learning or artificial intelligence is needed to better regulate operation, (3) larger tanks with higher set points are needed, and (4) mode logic for HPWHs should be configured to efficiently achieve set points, minimizing electric resistance usage. In this limited research, raising set points prior to switching mode increased electric resistance usage. Therefore, set points must be adjusted incrementally to minimize electric resistance.

HPWH Modes: This finding applies to conditions in all three categories: Design and Construction, Codes and standards, and Operations and Maintenance.

Logic embedded in HPWH controls are treated by most manufacturers as proprietary information. Literature from the manufacturers does not explain the operational logic of temperature readings within the tank that controls compressor and resistance operation under the various modes, making it challenging to optimize the system. Manufacturers should provide clear definitions of modes and explanations on how they operate so residents and/or facility managers can make informed decisions. The defined modes in the manufacturer's literature did not align with field study findings. There are reminders that state "Energy Saver mode is most cost-effective," yet this research proved that this is not always the case.

Manufacturers should provide more detailed information about how each of the operational modes of their equipment differ from one another to enable informed decisions about scheduling. In reality, this is too detailed for most end users, but the information should still be accessible regardless. Manufacturers should create a load shift mode with two to four options and explain the pros and cons for each, to enable decision-making. For example, one load shift option could be "Load Shift Option One" and configured to operate in Heat Pump Only mode with a set point of 140°F (60°C) from 9 p.m. to 4 p.m. and then switch to Energy Saver Mode with a set point of 115° (46°C) from 4 p.m. to 9 p.m. The manual would describe how it worked, when it made the switch, and what the trade-offs and considerations might be (i.e., the difficulty of keeping up with unusually large usage periods outside of the evening peak hour, or possibly slightly lower temperature hot water during the peak hours) in an accessible manner for designers, installers, consumers, and maintenance staff.

Recirculation Controls: This finding applies to conditions in Codes and Standards.

The poor operations of the infrared occupancy controls at Atascadero increased pump energy and reduced HPWH performance. Code requires sensors to be installed in a location and any point of use at least 20 feet away from the water heaters to ensure controls at all end uses, to maximize savings. On-demand push-button control eliminated the issue. If the use of infrared occupancy sensors for recirculation pump control device will continue to be allowed under Title 24, the approved use must include installation requirements to minimize false triggers. These may include addressing installation in relation to reflective materials (i.e., mirrors) and movement in proximity to the water fixture but unrelated to the end use that would trigger the sensor (e.g., installation in an open kitchen, as in Atascadero). They also could include angle and distance of activation to inform the most effective installations.

In addition, manufacturers have different guidance on installing recirculation systems with their products due to the potential to disrupt stratification and impact performance in specific modes. Rheem, for example, released a technical brief in 2019 indicating that recirculation systems can be installed with Rheem HPWHs but can affect performance, particularly in Energy Saver mode. Because recirculation controls affect performance of HPWHs, manufacturers need to provide clear guidance on the effects of recirculation systems on HPWH performance, suggested application, and include specifications such as acceptable flow rate.

Thermostatic Mixing Valves: This finding applies to conditions in Codes and Standards.

HPWHs should always include a mixing valve to have

1. The flexibility to expand available hot water for any given tank size.
2. The flexibility for load shifting.
3. The ability to ensure safe hot water delivery temperatures.
4. The ability to minimize overall energy usage.

A thermostatic mixing valve would enable setting a HPWH in Heat Pump only mode with a higher set point, reducing electric resistance or auxiliary heat that would increase energy consumption. This could be addressed in the energy code, the building code, or appliance standards. The energy savings aspect for HPWHs with auxiliary heat would support energy efficiency goals of the energy code. It could be installed externally to the HPWH, or manufacturers could include a mixing valve that was integral to the HPWH. To meet compliance with the plumbing code and accommodate various sizes of HPWHs, especially in multifamily residences, it would be helpful to consider an amendment to the California Plumbing Code that clearly allows for a first-hour delivery based on a higher set point, with a mixing valve in addition to the manufacturer's first-hour rating (FHR). Additionally, manufacturers should provide FHR at higher set point temperatures and mode, such as 140°F (60°C).

Monitoring: These findings apply to Operations and Maintenance.

Systems may be monitored for either research or operational performance. Either way the most important data points are: CWMU flow, HW supply temperature, HW supply post-mixing valve temperature, recirculation return temperature, CWMU temperature, and HPWH electrical consumption.

In multifamily projects with individual water heaters there is no easy way to centrally monitor and control HPWHs. Alarms, scheduling, and programming need to be packaged and centralized enabling multifamily site management to receive alarms and manage the HPWHs as a group.

Further Research

- **Load Shifting Sizing and Benefits:** The concept of load shifting using HPWHs is relatively new. Additional research on sizing HPWHS for load shifting would be beneficial as well as how load shifting should be addressed in models.

Central Modular Domestic Hot Water

Sanden currently makes the only commercially available low-global warming potential (GWP) heat pump water heating product that uses CO_2 as a refrigerant, which can effectively be employ central water heating applications. Mitsubishi introduced its larger capacity QAHV CO_2-based central HPWH to the U.S. market in 2021, but for the time being Sanden remains the only commercially available low-GWP option for these applications. Even when other systems built for central system applications become more widely available, there will still be a market and a need for these types of modular systems because of their flexible sizing options. In many situations the QAHV may be too large, both physically and by capacity, to use in many smaller multifamily central system applications. It is therefore critical that best practices be developed for the effective design and installation of these modular Sanden systems, and that some degree of standardization also be developed. While this project has demonstrated that these systems can be deployed effectively and achieve high efficiencies, it was also revealed that it can be quite difficult to do and requires careful planning and commissioning. Developing standardized approaches to design and installation will mitigate issues of system complexity and become critical for achieving market adoption. The recommendations and findings discussed here are based on evaluation of the Sunnyvale project.

Central Domestic Heat Pump Water Heating System Verification. This finding applies to conditions in Design and Construction.

Regardless of who designs a system, a requirement for relatively simple verification and testing of each system is necessary. Development of system verification protocols should align with system complexity. The eventual goal should be simple post-installation Home Energy Rating System (HERS) verification once design and installation of HPWH products become routine and are designed and installed by ever-more experienced professionals. In the interim, there may be a need for more detailed verification. A qualified and knowledgeable professional should perform an onsite inspection to verify that all equipment is installed as specified and controls are set up appropriately. While these systems are still new to the market, it is recommended that each system undergo a formal startup and commissioning process performed by a qualified manufacturer's representative. At a minimum the following functions and operational parameters should be checked and confirmed at startup:

- Equipment installed matches specifications for the heat pump, recirculation heaters, pumps and balancing valves, and pipe and storage-tank insulation.
- Desired delivery temperature from the heat pumps to the tanks is achieved.
- Supply temperatures to buildings after the mixing valve meet mixing valve set points.
- Heat pump, circulators, recirculation heaters, and other ancillary equipment control logic and sequence of operations meet the design intent
- Plant operation is observed long enough to determine whether short cycling occurs.
- Recirculation temperatures are maintained as specified.

System Design: This finding applies to conditions in Design and Construction.

The design approach must be adjusted from the "boiler approach" and must include larger space for storage and an accessible and safe location for outdoor units, with access to adequate makeup air. Practices to optimize a system with a recirculation heater include: tanks or heat pumps are piped in parallel a reverse return piping configuration for equal flow within the heat pump banks and between multiple storage tanks, use of an electronic mixing valve for finer tempering and control, and a distribution system that includes thermostatic balancing valves on every riser.

Recirculation System: This finding applies to conditions in Design and Construction.

In the Sunnyvale scenario, an isolated recirculation loop with a variable speed pressure-dependent pump was optimal for system performance. For a comparable design, consider isolating the recirculation loop with a HPWH to optimize performance.

When utilizing a HPWH and aiming to maximize the efficiency benefits from it, the recirculation heater must be properly sized for the load. In the Sunnyvale project, the recirculation water heater was better sized for the recirculation load in Wing 3, which had a lower load and flow rate. For a higher flow rate and larger systems, other approaches to recirculation re-heat, such as a swing tank, may be a better option. Determining the best practices for the recirculation loop design warrants additional research.

Based on the performance of the recirculation load at this one project, the standard design estimate of 100 W per apartment appears to be a safe assumption as used in the Ecosizer. The recirculation load in Wing 3 was only 50 W per apartment, about half of the standard assumption. Therefore, if it is possible to complete a more accurate assessment, such as monitoring an existing building prior to retrofit, the recirculation heater size could be reduced.

Sizing for DHW Load: This finding applies to conditions in Design and Construction.

Balancing the need for safety factor with installation and maintenance costs, the Low-Medium sizing tier of DHW demand—based on an assumption of 25 gallons of DHW consumed per person per day—is appropriate for central heat pump water heating plants. This approach should result in systems that can meet building demand while ensuring that owner entities do not purchase or maintain hot water systems that are larger than required.

Monitoring: This finding applies to conditions in Operations and Maintenance.

In monitoring operations of a system to ensure performance, the following minimum data points should be collected: supply temperatures into and out of each storage tank, supply post-mixing valve to building temperature, recirculation return temperature, supply from recirculation heater temperature (if applicable), supply and return temperatures to and from each group of heat pumps, HP electrical, and CWMU flow. This monitoring can supplement routine maintenance and evaluations conducted on the system and its components to ensure proper functionality and system durability. Maintenance activities and checks are specific to the system and should be defined in an operation and maintenance manual, in tandem with system installations.

Further Study

- **Recirculation Losses:** Additional research is needed to quantify recirculation loop losses, especially for combination systems.
- **Modular Heat Pump System Controls:** Using the standard/default manufacturer's control strategy proved difficult to ensure that all the heat pumps in a bank operated simultaneously with equal runtime. A more reliable control system is needed to ensure this operation. As more modular systems enter the market it would be useful to quantify the pros and cons of different control strategies. This can inform sizing (i.e., number and output of heat pumps to storage-tank capacity). In addition, quantifying the energy impacts of multiple units running simultaneously for shorter durations (versus fewer units running for longer durations to minimize short cycling), would be beneficial for informing control strategies.
- **Load Shifting:** The load shifting results in this report demonstrate the feasibility of its methodology and benefits. For central systems, there is great potential for load shifting given the larger available storage and the diversity in draw patterns of many different households. More research is needed to determine the best approach to optimize load shifting. For example, in a central modular Sanden system, is it best to turn off individual heat pumps using simple on/off controls or is it better to manage set points and heat pump operation using more sophisticated controls?
- **Modular Systems:** With current performance curves and calculations, these modular systems are evaluated on a component basis rather than at a system level. A consistent methodology for whole system performance evaluations would be valuable.
- **Recirculation Heater vs. Swing Tank:** Central heat pump system operation is optimized with dedicated recirculation heaters or swing tanks. More research is needed to understand the best application for each strategy, as well as installation requirements.

Combined Space Conditioning and Domestic Hot Water

The complexity of the combined systems monitored in this project proved to be barriers to realizing the manufacturers' stated energy performances. These systems are generally better suited to commercial projects with highly trained maintenance staff and typically involve commercial mechanical contractors during installation. These systems are also better suited for projects with high potential for simultaneous heating and cooling loads.

System Design and Engineering: This finding applies to conditions in Design and Construction and Codes and Standards.

Manufacturers should provide simpler, more integrated systems with appropriate storage to minimize errors or mistakes during engineering and installation.

DHW and space heating water should be provided in separate hot water loops for the two uses. Sharing a distribution network complicates controls and prevents optimization of each load. Ideally, the building code should prohibit providing both DHW and space heating water through the same distribution piping, making it mandatory rather than voluntary. At a minimum, design and engineering teams can apply this practice at the system level.

Technology Application: This finding applies to conditions in Design and Construction.

With newer products in the market and the complexity of combined space conditioning and water heating systems, there is a need for increased engineering and design support to determine if a project is a good fit for the technology. Resources should be made available by the manufacturer and the design community that support successful implementation. One of the primary benefits of combined systems is the opportunity to take advantage of heat recovery. This additional benefit generally comes at the expense of a far more complicated system; each project should therefore be thoroughly assessed prior to system design to determine whether the climatic conditions and use cases are well suited for heat recovery. High cooling loads coincident with DHW demand are primary indicators for heat recovery opportunities in multifamily buildings. Larger properties with the right mix of draw profiles, a high probability of simultaneous heating and cooling loads, and a full-time maintenance staff with some experience with larger more complicated mechanical systems would be promising fits for this type of system.

Heating, Ventilation, and Air Conditioning – (Split Heat Pump Systems and Ductless Mini-Splits)

Energy Consumption for HVAC Systems. This finding applies to conditions in all three categories: Design and Construction, Codes and Standards, and Operations and Maintenance.

This research project identified baseloads in both split and ductless mini-split systems that were neither anticipated nor accounted for in design or energy usage calculations for ZNE. Baseloads can be addressed through codes and standards and manufacturing, but they must also be factored in design and installation. Baseloads of interest could include crankcase heaters or preheaters, reversing valves, and inverter controls. At least one manufacturer indicated that information on these baseloads is proprietary.

For split systems, specify equipment that either has a crankcase heater with controls that limit operation to temperature bands, or does not have a crankcase heater. This requires the design team to look closely at the technical specifications and engage with the manufacturer since they are inconsistent across product types and not included in energy data. For an existing condensing unit, a temperature relay may be an option to control crankcase operation. For ductless mini-splits, installation specifications should ensure preheating, fan operation, and air temperature sampling to minimize baseload operation. The research team is studying this operation in order to make clearer recommendations as to whether this is manufacturer-specific or generalizable to system type.

These baseloads for the operation of the systems should be accounted for in models to enable users to reasonably estimate end uses and size PV systems. This requires that the usage be transparent. Crankcase heaters and other similar baseloads are not part of the federally rated SEER, EER, or HSPF efficiencies for heat pumps, so are not consistently documented as additional energy load within the technical documents. This can be addressed in several different ways: through revision of national testing protocols to include these operational loads; through disclosure requirements for crankcase, preheater loads, or other baseloads associated with outdoor units; and through modifications to codes and standards to account for additional load. Overall, crankcase heater and other baseloads should be addressed at the manufacturer's level, but in the interim, it is important to understand the impacts of these baseloads on projected consumption and PV sizing.

HVAC Operation: This finding applies to conditions in Operations and Maintenance.

As with HPWH operations, residents and property managers need to be informed on how to operate heat pump space conditioning systems efficiently. Providing instructions on how to program a thermostat does not meet this requirement. First, it has been documented that thermostats are generally not programmed. Second, it is necessary for users to understand conditions for optimal performance so that they can apply them to their own circumstances. Providing additional information on optimized schedules is also necessary since these systems do not respond to short ramp-up periods like gas furnaces. One tenant indicated that he thought operating the equipment would be expensive since it provided a lot more air than the system in his previous residence.

Further Study

- **HVAC Preheat and Crankcase Heater Operations:** Future large-scale research of baseloads for HVAC systems, including crankcase heaters and preheaters, implications for testing protocols, and other issues, is necessary to advance heat pump use. Given the focus on expanding the market for heat pumps, it is important to understand more of the baseloads that may not be accounted for in Air-Conditioning, Heating, and Refrigeration Institute (AHRI) testing protocols. Research can inform appliance standards and testing protocols, as well as algorithms in compliance software.

Electrical End Uses

Energy Management: This finding applies to conditions in Operations and Maintenance.

Engagement with occupants is key. Through this study, the team learned tenants are more aware of energy use with an in-unit device such as the Nexi; but because of limited tenant loads it was not possible to link this awareness to energy savings.

Further Study

- **MELs Peak Load Shapes:** These sites show similar shapes and magnitudes, on average, to loads studied in other complexes with similar demography, and that their significant contribution toward peak (and off-peak) total demand cannot be addressed by load shifting. With limited tenant loads, behavioral changes have limited potential to impact consumption. Lighting and plug loads are often combined on the same circuits, making it difficult to isolate different loads. With plug loads becoming a larger piece of household energy consumption, there needs to be further research on the extent of plug loads and how to best manage them.
- **Energy Awareness:** Based on self-reported data, nearly three-quarters of survey respondents were more aware of their energy usage with the lighting displays. There is an opportunity to build off this awareness to better understand opportunities that engage occupants in demand response and peak usage periods instead of just pure energy savings. Ideally this would result in energy savings. More research should be done on simpler ways to make occupants aware of their energy usage so that all occupants (not just an adult with an app) have an opportunity to contribute to savings.

Building Modeling

Each of the four projects had challenges with modeling, for both compliance and overall building performance. Modeling is a critical component in determining performance, meeting ZNE design and goals, and funding. Recognizing that models are imperfect, it is imperative to continue to improve these tools to better serve these goals. The discussion following includes findings and recommendations, both cross-cutting and specific end-use applications.

All these findings apply to conditions in Codes and Standards.

Nonresidential Baseline: It is paramount that the nonresidential baseline for DHW include an electric baseline. Higher performing buildings, like those presented in this study, needed workarounds to comply with codes because systems were compared with gas DHW systems.

Occupancy Assumptions: Evaluate the best fit for multifamily occupancy assumptions. CBECC-Res uses occupancy in current algorithms to estimate loads such as mechanical ventilation. The CBECC-Res software uses the number of bedrooms as a proxy to inform occupancy using an algorithm of the number of bedrooms plus 1.[17] This algorithm may underestimate occupancy (and therefore the loads) for higher occupancy homes and apartments. Consider revising the algorithms to include both the number of bedrooms and square footage. Another approach could be to consider an option that shows higher

17 The 2019 California Energy Code states that single-family and multifamily dwellings must provide mechanical ventilation in accordance with ASHRAE 2.2:4.1.1. The total required ventilation rate is calculated using Equation 150.0-BQtot = 0.03Afloor + 7.5(Nbr + 1) (Equation 150.0-B).

occupancy, along with guidance on eligibility or the ability to select this criterion through some other proxy.

For hot water draws, occupancy is based on a randomized changing occupancy that simulates the lifetime occupancy of a given home or apartment. Table 22 summarizes the multifamily distribution of occupancies over time. For low-income multifamily or potentially low-income residences, these percentages may need to be adjusted to reflect less time with lower occupancy and more time with higher occupancy, based on data sets evaluated to date where overall occupancies are higher per bedroom type. The algorithm for occupancy that determines hot water use was created from market-rate housing data (see Table 23 for RECCS 2009), which resulted in lower occupancy rates than what was observed at project sites. This method underestimates DHW load in most cases, so the development of higher occupancy households will improve DHW load estimates. This issue is exacerbated in apartments with more bedrooms (e.g., four or more bedrooms).

Table 22: Multifamily Distribution of Occupancies Over Time (%)

	Studio	1 Bedroom	2 Bedrooms	3 Bedrooms	4 Bedrooms	5+ Bedrooms
1 Person	73.5	56.4	25.3	9.7	2.0	0.2
2 People	19.4	27.8	31.6	27.3	16.8	35.1
3 People	4.1	7.8	18.7	28.5	6.0	1.6
4 People	2.5	4.0	14.7	15.8	35.3	35.9
5 People	0.2	1.4	4.9	13.7	11.1	5.7
6+ People	0.3	2.6	4.8	4.9	28.7	21.6

Table 23: Occupants per Bedroom From 2009 RECS Data

Bedrooms	Average Occupants
2	2.17
3	2.71
4	3.25
5	3.79

DHW Draw Schedules: Create draw schedules based on multifamily research data instead of single-family data. Multifamily occupancy differs as described, which affects draw schedules as well as the potential for consecutive draws. Neither the 100th percentile draws of 80 to 135 gallons per day are predicted by CBECC-Res, nor their impact on electric resistance usage during high draw periods. High draw periods may lead to unsatisfactory delivery temperatures, triggering the need to switch controls to the High Demand mode, with increased resistance. One-hundredth percentile use can affect tank sizing, GHG emissions, spikes of electric resistance, solar system sizing, and utility bill predictions.

Set Point: Consider a methodology to support operational scheduling and set points in compliance software. Because this mode is specific to each manufacturer, it is difficult to include this in modeling and standards with any clarity. The set point temperature can be an input in CBECC-Res for individual tank HPWHs only if a mixing valve is installed, consider how to deploy this particularly since there can be changes made to set points and schedules after install.

MELs Load Estimates: Develop better-fit algorithms for MELs. In an all-electric multifamily setting, miscellaneous electric loads are becoming the largest loads. It is important for building modeling programs to adequately account for these loads and to correctly model their determinants. Most software, including California's CBECC-Res, bases MELs on a dwelling's square footage. Our data showed that the number of occupants is a more accurate determinant. Because using occupancy is not reasonable for code compliance, a good surrogate for occupancy is to factor in both square footage and number of bedrooms. Total MELs may be generally close, but the distribution of the loads should be evaluated since better distribution could inform algorithms and management of hourly uses.

DHW Recirculation Operation: The Sunnyvale project aided in identification of one of the most successful recirculation strategies: variable speed pressure-controlled recirculation pumps paired with TBV's on the distribution risers. This cannot be currently modeled in the software but should be added as an option. Currently, the software is limited to four recirculation configurations: recirculation with temperature modulation, recirculation with no control (continuous pumps), recirculation demand control, and recirculation with temperature modulation and monitoring.

Accounting for Unconditioned Spaces: The model needs to accommodate more than one unconditioned space. With this limitation, building characteristics were misapplied in the model. For example, in the case of Atascadero, the model would not allow for isolation of the heat pump rooftop shed ("exterior closet") with many tanks inside from the rest of the site's unconditioned spaces like hallways. The software could model the impact of shed volume on heat pump operation, but that eliminated the ability to model other unconditioned spaces.

Further Study

- **Domestic Hot Water Draws:** The limited data set from this research project indicates the need to further investigate hot-water draw patterns for multifamily and higher occupancy households to better inform peak periods and their potential for consecutive draws.
- **Heat Pump Water Heater Locations:** Additional research into the impacts of location and pipe runs would be valuable to inform not only software algorithms but also best practices for design and installation. For example, at one site the heat pumps were placed in metal "sheds" on top of the buildings. This resulted in hotter than expected ambient temperatures in the summer and colder than expected temperatures in the winter. If HPWHs were installed in the conditioned space, the model should provide an option to vent the water heater to the outside to prevent negative impacts on heating loads. In addition, tank heat loss was significant during colder periods and calculated losses were greater, especially in low ambient temperatures (when compared with modeled losses with R-16 insulation).
- **Compact Hot Water Distribution:** Create a stronger incentive for more compact distribution. This can be accomplished in the building code or in an algorithm in compliance software to provide greater benefits in performance or to devalue a system

that does not meet compact hot water distribution requirements. Recognizing that recirculation systems may have some limited applications for specific HPWHs, there is an opportunity to increase the benefit of compact distribution for more efficient hot water delivery.

- **DHW Recirculation Operation:** Further research should be undertaken to validate the algorithms currently included in the software. The energy consumption associated with each of these methods appears to be counter to performance.

Solar Photovoltaics

Zero Net Energy Modeling: This finding applies to conditions in Design and Construction and Codes and Standards.

Modeling tools should comprehensively support ZNE goals. Each project utilized multiple tools to estimate whole building loads and PV sizing. Cooking and plug loads were underestimated in the modeling, however, creating a gap between predicted energy usage and actual usage. When the model does not allow an accurate estimate of loads or systems to be modeled, it is impossible to accurately specify the necessary amount of PV. Many end uses did not appear to be well accounted for in system design. For example, gyms or exercise rooms, elevators, electric vehicle (EV) chargers, and others were not included in calculations so were unaccounted for in ZNE estimates.

PV Allocations: This finding applies to conditions in Operations and Maintenance.

Both PV and building consumption modeling inform credit allocations for VNEM PV systems. Special care should be taken to ensure that the PV credit allocation is set accurately to offset the expected loads of credited meters. The VNEM allocation can only be altered with certain regularity depending on the utility, and this can greatly dictate a building's ability to achieve ZNE and zero net utility costs.

Verification of Installation: This finding applies to conditions in Design and Construction.

Verification and inspections of PV systems should be required to confirm operational settings and commissioning. Currently, PV installations require minimal verification. In multifamily projects with larger systems, consider verification requirements for operations/commissioning, including elements such as inverter settings in the field beyond installer-confirmation) of installation. In one of the projects, the inverter settings were not configured properly, resulting in reduced system production for at least six months. Convoluted billing can obscure this issue, so owners may not discover it.

Interconnection and Billing: This finding applies to conditions in Operations and Maintenance.

Consider opportunities to inform best practices or requirements from utilities for grid tied solar systems. Standardizing interconnection processes and requirements across utilities is one way of streamlining the PV installation process to make it more accessible. This would primarily benefit solar contractors but would also have a trickle-down effect for building owners. Streamlining the post-interconnection process on the utility end could also alleviate many issues, particularly billing-related issues that arise after systems begin operating. This is an especially important billing issue for VNEM systems, which rely solely on utilities to receive solar PV credits. The billing process also needs to be more streamlined, standardized, and rapid; automation would be beneficial and potentially critical. A utility has an incentive to manage each individual system to accurately pinpoint how much energy is flowing into the electric grid from each project. Increased utility surveillance of VNEM systems would help alleviate billing issues or missed billing setups and would allow electric grid management to benefit everyone.

Solar PV Monitoring: This finding applies to conditions in Operations and Maintenance.

All PV systems should have monitoring systems that provide accessible information to operation managers ─ from inverter performance to system performance to production. To sharpen visibility into a solar PV system's operation and output, a third-party PV-monitoring system should be installed to provide information on system components and production. Maintenance personnel or property owners will then be able to actively use the monitoring system to perform regular system checks, which could then inform the frequency of regular maintenance.

CHAPTER 6: Knowledge Transfer Activities

To provide maximum benefits from the research, the team developed a strategy to share its findings through several channels. The goal is to reach the largest possible audience through diverse media, and to advance both heat pump technology and ZNE in multifamily buildings. The team is developing technology and design briefs, as well as case studies, in downloadable print format.[18] To broadly influence other researchers and those heavily involved in energy efficiency efforts, the team is also writing peer-reviewed papers and creating conference presentations. The plan is to make all resources available online.

Technology Briefs

During this project, the team discovered several potential improvement opportunities for the design, use, and integration of various technologies that can be used in high-performance multifamily projects. The team is creating several technology briefs to help energy consultants, manufacturers, architects, engineers, multifamily building industry professionals, utilities, and code development teams understand the opportunities. The briefs will cover the advantageous use of existing technologies, best practices for design and installation, integration of system elements, technological improvements, and recommendations for application of the technologies. Potential topics include:

1. Thermal storage.
2. Monitoring to achieve ZNE.
3. HVAC systems.
4. Photovoltaic systems.
5. Considerations for multifamily DHW systems.
6. Modeling to achieve ZNE.
7. Comparing modeled and field findings. The team will evaluate how this research can best advance the market and determine which technologies, systems, and approaches to highlight in these briefs.

Each brief will be a stand-alone document and be available online. Other organizations will be able to share them with their members. These briefs are intended to spur the use of advanced technologies, provide insights into best practices, and allow interested parties to gauge the advantages and disadvantages of the technologies. They should also be useful to the CEC as it considers potential building code and appliance standards updates.

Case Studies

Since a case study is specific to a particular building, it is not particularly flexible in providing design assistance for other projects. However, case studies do provide demonstrated proof and prompt potentially interested parties to trust that an option is feasible for them. The team

18 All knowledge transfer documents, including the technical briefs and case studies, will be available at www.aea.us.org/research.

created two case studies of the demonstration sites—one on Atascadero and one on Sunnyvale. These concise two-page documents will present the most salient elements of each project, including the parties involved, the project's general characteristics, specific equipment that contributed to success, essential processes (such as integrated design, commissioning, and monitoring), costs (where available), and both expected and actual performances. They also cover the energy using-, energy managing-, and energy producing-equipment used in the projects.

To ensure readability and clear understanding, the text will be interspersed with pictures, graphs, and tables. The target audience for the case studies is design professionals, including architects, engineers, developers, builders, and energy consultants. The case studies should also be useful to the CEC, utilities, and others working on future code improvements.

Conferences and Workshops

In the energy efficiency world, an effective way to share knowledge is through conferences and workshops. The team will look for future opportunities to present this data at conferences and workshops. In addition, findings will be worked into trainings to support knowledge transfer. Throughout the grant period, the team presented highlights of the research approach and findings at appropriate venues, including the American Council for an Energy Efficient Economy (ACEEE) Summer Study on Building Efficiency (where two papers were accepted for the 2020 ACEEE Summer Study), the ACEEE Hot Water Forum, the California Association of Building Energy Consultants' semi-annual Conference, and the Forum on Dry Climate Home Performance.

The papers accepted for the 2020 ACEEE Summer Study cover (1) the project design and results generally and (2) a description and results of experiments to optimize control of HPWHs for grid harmonization. In 2019 at the ACEEE Hot Water Forum, the team presented on the design and initial performance of the central HPWH system operating at one of the four projects in this research. Also in 2019, at Redwood Energy's ZNE Retreat, the team presented the project's findings to date about the households' electrical end use patterns. In 2020, at the Forum on Dry Climate Home Performance, the team presented monitored data on performance of the HPWHs and HVAC systems in the projects. The team is planning to deliver at least one more presentation once the final data have been analyzed.

The audiences at these conferences are well-positioned to advance these efficient technologies both technically and in the market. At the ACEEE Summer study, they include primarily researchers, efficiency program designers, implementers, and evaluators, building code and appliance standards developers, and energy utility regulators. The audience at the Hot Water Forum includes mostly manufacturers, researchers, and program implementers. The Dry Climate Forum draws home performance contractors, researchers, and consultants to state and local agencies concerned with home performance.

Presentations will also be delivered to property owners and contractors to build the knowledge base of those implementer groups.

CHAPTER 7: Benefits to Ratepayers

As the goal for achieving California's ZNE and carbon-neutral targets approaches, there is a critical need for more research and evaluations of ZNE multifamily design and construction practices. Multifamily construction is more complex than single-family construction, and it presents additional barriers to achieving ZNE. A host of key design and building science issues remains poorly understood by multifamily developers. Lessons learned from each of the four projects in this study—which are typical of multifamily building stock across the state—can be adapted to other projects, greatly reducing dependence on California's electric grid and increasing the resiliency and reliability of all California building stock. This decreased dependence leads to lower costs for multifamily building owners (lower maintenance and utility costs), building occupants (lower utility bills), and California utilities.

The four multifamily demonstration projects provided timely opportunities to investigate ZNE issues in depth. These projects share a goal of all-electric ZNE construction with a 100-percent renewable offset and utilized breakthrough heat pump technologies that served the buildings' HVAC and water heating needs. These projects provided insights into optimizing technology but are still only the beginning of ongoing research into how energy is consumed in multifamily buildings and how complex, interdependent systems (e.g., envelope, mechanical systems) can best work together to effectively achieve ZNE.

These projects demonstrated the technical and economic feasibility of ZNE for large multifamily projects and established design and installation best practices that minimized risks for developers and accelerated the market path to ZNE. These efforts will help ensure that all of the potential benefits of ZNE are fully realized, especially persistent GHG-, energy- and cost-savings, which together shed light on the trade-offs between technology solutions and capital costs, operating and maintenance costs, functional benefits, environmental and grid impacts, and physical limitations. This research produced the following ratepayer benefits:

- **Lower Costs:** Better understanding of the economic and performance trade-offs for various technologies will ultimately lower costs for building multifamily ZNE developments. This research project is helping developers understand ZNE design decisions and how to reduce the risk of unanticipated costs for future developments. This project also increased understanding of trade-offs for central-versus-individual mechanical systems, combined DHW-space heating and cooling technologies versus separate systems, electric versus natural gas, and energy efficiency versus onsite renewable investments. This improved understanding can lead to lower costs and more reliable utility costs for tenants.
- **Environmental Benefits:** Optimizing strategies for achieving ZNE new constriction standards through 100 percent electric solutions will result in lower greenhouse gas emissions.
- **Greater Reliability:** Electricity reliability will be improved by quantifying load-shifting benefits of thermal storage systems and increasing energy self-sufficiency in multifamily

ZNE developments. Reconciling design and actual performance for emerging systems and developing new methodologies for quantifying benefits from thermal storage for code compliance purposes will together reduce planning uncertainties.

- **Public Health:** Optimizing systems for ZNE will improve indoor air quality.

The savings shown in Table 24 represents savings over baseline 2019 California Energy Code to demonstrate the benefits had these projects been built today.[19] The savings for each project over the permitted code baseline would be greater than shown because natural gas usage was included in baseline for low rise, and there was no requirement for PV systems for low rise prior to the 2019 California Energy Code. Savings are based on net consumption using actual usage from meter data and PV production compared with 2019 modeled standard design from the model for each of the projects. Calistoga, Cloverdale, and Atascadero, as low-rise buildings, included the minimum required PV in the standard design used for the savings baseline. Sunnyvale as a mid-rise building had the mixed-fuel standard design as its baseline for savings. GHG savings were based on a flat rate of 0.131 metric tons of CO_2e per megawatt-hour. The consumption used in the calculation was based on the 2019 calendar year, though that consumption did not include the potential benefits of load shifting since the research evaluated potential instead of capturing a year's worth of load-shifting performance. Therefore, if load shifting were undertaken, savings for the project (including load shifting) would result in overall greater savings for both emissions and total energy savings.

Given the outcomes of the projects and the applicability of the technology, savings in future projects should be based on the Atascadero and Sunnyvale scenarios since these two projects are most representative of typical multifamily developments. These developments will therefore reap greater savings.

Table 24: Calculated Savings for Projects – 2019 Actual Compared to 2019 Energy Code Standard

	Calistoga	Cloverdale	Atascadero	Sunnyvale	**Total**
Reduced kWh	74,320	105,086	150,759	511,130	**841,295**
Equivalent GHG emissions ($MTCO_2e$)	9.73	13.7	19.74	66.9	**110.2**

$MTCO_2e$ = million tons of carbon dioxide equivalent

[19] PV estimates for the 2019 Energy Code baseline use an assumed 1 kW per conditioned floor area.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ACEEE	American Council for an Energy Efficient Economy
ACH	air changes per hour
API	application program interface
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BLH	BLH Construction Company
Btu	British thermal unit
Btuh	British thermal unit per hour
°C	Celsius
CBECC-Res	California Building Energy Code Compliance for Residential
CBH	Corporation for Better Housing
CDHW	central domestic hot water
CEC	California Energy Commission
cfm	cubic feet per minute
CHPWH	central heat pump water heater system
CHW	Chilled Hot Water
CO_2	carbon dioxide
COP	coefficient of performance
CT	current transducer
CTCAC	California Tax Credit Allocation Committee
CUAC	California Utility Allowance Calculator
CWMU	Cold Water Make Up
DHW	domestic hot water
DNS	domain name system
DOE	U.S. Department of Energy
EF	energy factor
Rheem Energy Saver Mode	Relies primarily on the heat pump, but still uses electric resistance elements to ensure faster recovery. Compressor and electric resistance element may function simultaneously.
GFCI	Ground-fault circuit interrupter
°F	Fahrenheit
FCU	fan coil unit
FHR	first hour rating
FTP	file transfer protocol
GFCI	ground-fault circuit interrupter

Term	Definition
GHG	greenhouse gas
GPD	gallons per day
GPM	gallons per minute
Rheem Heat Pump Only Mode	Relies almost exclusively on the heat pump and minimizes the use of the resistance elements. Compressor only (heat pump only) unless freezing based on the upper tank temperature. The compressor and element can turn on simultaneously but only one element at a time.
HERS	Home Energy Rating System
Rheem Heat Pump High Demand Mode	The most aggressive configuration which prioritizes fast recovery over efficiency and thus relies heavily on the electric resistance elements to ensure customer satisfaction Thermistors measure stratification in the tank and operate based on this setting. The electric resistance will turn on sooner based on a lower differential.
HP	heat pump
HPWH	heat pump water heater
HSPF	heating seasonal performance factor
HW	Hot Water
HWP	hot water pump
HVAC	heating, ventilation and air conditioning
Hx	heat exchanger
kW	kilowatt
kWh/yr	kilowatt-hour per year
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
MEL	miscellaneous electric load
MEP	mechanical, electrical, and plumbing
MERV	minimum efficiency reporting value
NEM	net energy metering
Nexi	An energy monitoring unit with occupant engagement device
NSHP	New Solar Homes Partnership
OAT	outdoor air temperature
PG&E	Pacific Gas and Electric
PV	Photovoltaic
rH	relative humidity
RTD	resistor temperature detector
SD Card	Secure Digital Card
SEER	seasonal energy efficiency ratio

Term	Definition
TOU	time-of-use
TDV	time-dependent valuation
VFD	variable frequency drive
VNEM	virtual net energy metering
ZNE	zero net energy
ZERH	Zero Energy Ready Homes

REFERENCES

Oram, Shawn. 2017. Hot Water Temperature Maintenance Pilot Study. Presentation to the ACEEE Hot Water Forum.

Parker, Danny. Philip Fairey, Jim Lutz. 2015. Estimating Daily Domestic Hot Water Use in North American Homes. FSEC-PF-464-15. 2015 ASHRAE Conference. ASHRAE Transactions, Volume 121, Part 2.

Rheem. No date. Technical Service Bulletin: Statement of down-rating electrical heating elements. 1306.doc. https://globalimageserver.com/FetchDocument.aspx?ID=74bd7266-e7da-48a4-97da-ea59c11d4c67.

San Francisco Department of Public Health. 2008. Assessment and Mitigation of Air Pollutant Health Effects from Intra-Urban Roadways: Guidance for Land Use Planning and Environmental Review. May.

Zhang, Yanda. 2013. *Multifamily Central Domestic Hot Water Distribution Systems.* California Energy Commission. Heschong Mahone Group.

APPENDICES

Appendix A: Development Profiles

Appendix B: Monitoring Plans and Equipment Lists

Appendix C: Methodology

Appendix D: Calistoga and Cloverdale Data

Appendix E: Atascadero Data

Appendix F: Sunnyvale Performance Data

Appendix G: Customer Satisfaction Survey Results

Appendix H: Team Members