



**CALIFORNIA  
ENERGY COMMISSION**



Energy Research and Development Division

## **DRAFT FINAL PROJECT REPORT**

# **Getting to All-Electric Multifamily ZNE Construction**

**Gavin Newsom, Governor**  
**March 2021 | CEC-500-XXXX-XXX**



**PREPARED BY:**

**Primary Authors:**

Amy Dryden, Andrew Brooks, Meghan Duff, Association for Energy Affordability  
Greg Pfothenauer, 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**

Laurie ten Hope

**Deputy Director**  
**ENERGY RESEARCH AND DEVELOPMENT DIVISION**

Drew Bohan

**Executive Director**

**DISCLAIMER**

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.





## **ACKNOWLEDGEMENTS**

The authors would like to 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 Associates, 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 \(www.energy.ca.gov/research/\)](http://www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

# ABSTRACT

Compared to single-family homes, relatively little empirical data have been gathered on the performance of water heating systems in multifamily buildings, and even less on the 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. Therefore, it is important to keep a focus on improving the efficiency and grid impacts of multifamily buildings if we are to achieve California's climate goals.

This project monitored second-by-second energy and one-minute interval water usage in four zero net energy-designed multifamily buildings, totaling 206 residences, with (a) individual heat pump water heaters, (b) central heat pump water heaters, and (c) 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 a 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 the intended performance, and (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 actually achieving zero net energy in multifamily construction. To scale and expand the market of all-electric and zero net energy projects, this study identified recommendations and findings related to design and construction activities, 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 Pfothenauer, Meghan Duff, Nehemiah Stone, and Sean Armstrong. 2021. *Getting to All-Electric Multifamily Zero Net Energy Construction*. California Energy Commission. Publication Number: [CEC-500-202X-XXX](#).

# TABLE OF CONTENTS

|   | Page |
|---|------|
| ACKNOWLEDGEMENTS.....   | i    |
| PREFACE .....   | ii   |
| ABSTRACT .....  | iii  |
| TABLE OF CONTENTS .....   | iv   |
| LIST OF FIGURES .....   | vii  |
| LIST OF TABLES .....  | x    |
| EXECUTIVE SUMMARY .....   | 1    |
| Introduction.....   | 1    |
| Project Purpose.....  | 2    |
| Project Approach.....   | 3    |
| Project Results.....  | 5    |
| Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)..... | 7    |
| Benefits to California .....  | 8    |
| CHAPTER 1: Introduction .....   | 11   |
| Descriptions of the Four Projects.....  | 12   |
| Team’s Roles in Projects .....  | 13   |
| Approach.....   | 13   |
| CHAPTER 2: Project Design Approach .....  | 15   |
| Calistoga and Cloverdale.....   | 16   |
| Calistoga.....  | 16   |
| Cloverdale.....   | 19   |
| Atascadero.....   | 21   |
| Sunnyvale.....  | 23   |
| From Gas to Heat Pumps .....  | 26   |
| Heat Pump System Selection and Sizing.....  | 27   |
| Other Systems .....   | 28   |
| CHAPTER 3: Monitoring Approach .....  | 30   |
| Domestic Hot Water Monitoring.....  | 30   |
| Electrical End Use Monitoring Approach .....  | 30   |
| Equipment Selection and Communications Protocol Considerations.....                   | 33   |



Calistoga and Cloverdale Projects.....33

    Behavior Research at Cloverdale and Calistoga.....35

Atascadero Project .....36

    Behavior Research at Atascadero.....37

Sunnyvale Project .....37

    Behavior Research at Sunnyvale.....38

CHAPTER 4: Project Results.....40

    Introduction.....40

    Summary of End Uses for the Four Projects .....40

    Calistoga and Cloverdale.....43

        Overall ZNE Performance .....43

        Electrical End Uses: Tenant Loads .....46

        Domestic Hot Water and HVAC (Combined System).....48

        HVAC.....50

        Cooking .....51

        MELs and Lighting .....52

        Nexi Evaluation .....53

        Planned, Actual and Modeling Evaluation .....53

    Atascadero.....55

        Overall ZNE Performance .....55

        Electrical End Uses: Tenant Metered Loads .....57

        Domestic Hot Water .....60

        Recirculation Systems .....67

        Thermal Storage.....68

        Heating, Ventilation, and Air Conditioning .....72

        Cooking .....74

        MELs, Lighting and Appliances .....75

        Nexi Evaluation .....76

        Planned, Actual and Modeling Evaluation .....76

        Hot Water Use: Planned vs. Actual .....77

    Sunnyvale.....79

        Overall ZNE Performance .....79

        Electrical End Uses - Tenant Metered Loads .....80

        Domestic Hot Water .....82

|   |     |
|---|-----|
| Sizing DHW .....  | 84  |
| DHW Consumption and Energy Use .....  | 85  |
| Recirculation System .....  | 88  |
| Thermal Storage and Load Shifting.....  | 90  |
| HVAC.....   | 92  |
| MELs and Lighting .....   | 94  |
| Nexi Evaluation .....   | 94  |
| Planned, Actual and Modeling Evaluation .....   | 95  |
| Operations and Maintenance .....  | 96  |
| Conclusion .....  | 97  |
| CHAPTER 5: Findings and Recommendations.....  | 98  |
| Domestic Hot Water .....  | 99  |
| Individual Heat Pump Water Heaters .....  | 99  |
| Central Modular DHW .....   | 103 |
| Combined Space Conditioning and DHW .....   | 106 |
| Heating, Ventilation, and Air Conditioning – (Split Heat Pump Systems and Ductless Mini-splits) ..... | 106 |
| Electrical End Uses .....   | 107 |
| Building Modeling .....   | 108 |
| Solar Photovoltaics .....   | 111 |
| CHAPTER 6: Knowledge Transfer Activities .....  | 113 |
| Technology Briefs.....  | 113 |
| Case Studies .....  | 113 |
| Conferences and Workshops .....   | 114 |
| CHAPTER 7: Benefits to Ratepayers .....   | 115 |
| GLOSSARY AND LIST OF ACRONYMS .....   | 117 |
| REFERENCES .....  | 120 |
| APPENDICES.....   | 121 |

# LIST OF FIGURES

|   | Page |
|---|------|
| Figure 1. Calistoga (top) and Cloverdale (Below) Projects .....   | 16   |
| Figure 2. Aermec Installation at Calistoga .....  | 18   |
| Figure 3. Aermec Installation at Cloverdale .....   | 20   |
| Figure 4. Atascadero Project .....  | 21   |
| Figure 5. Rooftop Location for HVAC Outdoor Units and Heat Pump Water Heaters.....  | 22   |
| Figure 6. Sunnyvale Project .....   | 24   |
| Figure 7. Central Heat Pump Water Heater Plant in Wings 1 and 2.....  | 25   |
| Figure 8. Ductless Minisplits Installed in Units .....  | 26   |
| Figure 9: The Nexi Light Display Device and Thresholds .....  | 32   |
| Figure 10: Comparison of PV Production to Actual Energy Consumption .....   | 41   |
| Figure 11: Calistoga Whole Site Energy Consumption and Solar PV Production – 2018 and 2019 Compared. Costs Are Aggregated from Portfolio Manager (PM). .....      | 44   |
| Figure 12: Cloverdale Whole Site Energy Consumption and Solar PV Production .....   | 45   |
| Figure 13: The Average Annual Demand Profile for Cloverdale and Calistoga Are Similar, with Cloverdale Having a Sharper Morning Peak.....                         | 48   |
| Figure 14: Heat Loss in the System Even When It Is Not Operating and Returning Warmer Water to the Aermec.....  | 50   |
| Figure 15: At Both the Cloverdale and Calistoga Sites, Cooling is the Dominant Use. ....  | 51   |
| Figure 16: Calistoga Modeled Versus Actual Usage and Production.....  | 54   |
| Figure 17: Cloverdale Modeled Versus Actual Usage and Production.....   | 55   |
| Figure 18: Atascadero Total Site Energy Consumption and Solar PV Production .....   | 56   |
| Figure 19: Atascadero Common Area: Building 1 and Building 2 Energy Consumption and Solar PV Production January–December 2019 .....                               | 57   |
| Figure 20: Seasonal Usage Is the Primary Driver of Consumption as It Relates to DHW and Space Conditioning. ....  | 58   |
| Figure 21: Daily Average End Uses Showing Distribution Variation by Month, with Space Conditioning and Water Heating Having the Greatest Seasonal Variation ..... | 59   |
| Figure 22: Space Conditioning and Water Heating Loads Drive the Seasonal Demand Profile. ....   | 59   |
| Figure 23: Average Daily Hot Water Consumption Gallons per Day by Occupancy and Bedroom Type Shows a Correlation with Occupancy.....                              | 62   |

|   |    |
|---|----|
| Figure 24: Average Gallons per Hour over a Nine-Month Period .....  | 62 |
| Figure 25: Average Daily Energy Use Showing Electric Resistance and Compressor Loads Across Months .....  | 64 |
| Figure 26: Summer and Winter HPWH Energy for All the Units in the Control Group Labeled by the Number of Occupants and Water Heater Size.....                       | 64 |
| Figure 27: The Difference in the Resistance Usage from 2018 with High Demand at 140°F (top graph) to Energy Saver at 125°F (bottom graphic).....                    | 65 |
| Figure 28: Recirculation Pump Energy and HPWH Energy Before and After Replacing Recirculation Controls the First Week in November 2019 .....                        | 67 |
| Figure 29: Daily Runtimes for Units, Including Baseload and Operational Load.....   | 73 |
| Figure 30: Contribution to Total Load (on Average) throughout the Monitoring Period   | 74 |
| Figure 31: Cooking Demand by Hour Showed a General Morning Peak and Strong Evening Peak.....  | 75 |
| Figure 32: Atascadero Modeled Versus Actual Energy Consumption and Solar PV Production Shows Lower Performing Solar PV and Underestimated Building Consumption..... | 77 |
| Figure 33: Average Daily Water Use Per Apartment Type (2, 3, and 4 Bedrooms), Comparing CBECC-Res vs. Field Data at Atascadero .....                                | 78 |
| Figure 34: Average Hourly Water Use in CBECC-Res and Atascadero by Unit Type .....  | 79 |
| Figure 35: Sunnyvale Common Area Energy Consumption and Solar PV Production (2019) .....  | 80 |
| Figure 36: Electrical End Use Consumption by Month Excludes Ranges and Therefore Does Not Represent Total Apartment Consumption.....                                | 81 |
| Figure 37: Demand Is Driven by HVAC Loads and Can Clearly Be Seen in Greater Demand in February.....  | 82 |
| Figure 38: Sunnyvale Monthly COP by System Component .....  | 82 |
| Figure 39: Sunnyvale CHPWH: Seasonal COP by System Component .....  | 83 |
| Figure 40: Sunnyvale Seasonal COP with Ambient Air Temperatures in Wings 1 and 2  | 84 |
| Figure 41: Sunnyvale Seasonal COP with Ambient Air Temperatures in Wing 3 .....   | 84 |
| Figure 42: Average Daily Plant and Total DHW Consumption per Month per Occupant over 14 Months.....   | 86 |
| Figure 43: Average Daily Plant and System DHW Seasonal Energy Consumption per Occupant .....  | 86 |
| Figure 44: Simultaneous Heat Pump Operation: Percent Runtime within Each Bank ...   | 87 |
| Figure 45: Heat Pump Bank 1 Load Shifting: Average Hourly COP Comparison May vs. June 2020 .....  | 91 |

Figure 46: Average Daily Consumption (Including Baseline Consumption) Is Overall Low for All Apartments.....93

Figure 47: Runtimes Are Generally Low with Clearly Higher Consumption in Winter. ...93

Figure 48: The HVAC Load Was Disaggregated by Compressor and Non-compressor (<250W) Runtime to Understand the Baseload. ....94

Figure 49: Sunnyvale Common Area: Modeled vs. Actual Consumption and Solar PV Production .....95

Figure 50: Monthly Operating Cost of Central Electric Heat Pump DHW (Sunnyvale Benner Project) vs. Central Gas DHW (Onizuka) .....96

# LIST OF TABLES

|   | Page |
|---|------|
| Table 1: Project Descriptions .....   | 12   |
| Table 2: Project System Details.....  | 13   |
| Table 3: Summary of Monitored Circuits at Each Site.....  | 32   |
| Table 4: Rheem Systems at Atascadero.....   | 36   |
| Table 5: Hot Water Plant and Service Metrics .....  | 38   |
| Table 6: Average Daily DHW Consumption per Unit for Each Project .....                              | 41   |
| Table 7: Average Occupancy for All Projects .....   | 41   |
| Table 8: Electrical End Use Comparison of Average Daily Usage.....                                  | 42   |
| Table 9: Daily Average Cooking Time and Energy Consumption Across Projects .....                    | 42   |
| Table 10: Comparison of Cloverdale and Calistoga PV Systems and Allocation .....                    | 45   |
| Table 11: Average COP of Plant by Season and Operational Mode .....                                 | 48   |
| Table 12: Gallons Hot Water During Time Period .....  | 63   |
| Table 13: Average Daily kWh.....  | 66   |
| Table 14: Apartment Parameters with Monitored Heat Pump Water Heaters.....                          | 68   |
| Table 15: Summary of Thermal Storage Experiments .....  | 69   |
| Table 16: The Percentage of Bedrooms at Various Occupancies at Atascadero and in CBECC-Res .....    | 78   |
| Table 17: 99th Percentile 3-Hour, and Daily Peak Demand for System Capacity Sizing.....             | 85   |
| Table 18: Comparison of Single Speed and Variable Speed Performance .....                           | 89   |
| Table 19: Recirculation Water Heater Runtimes (January 2019–August 2020).....                       | 90   |
| Table 20: Total kWh for Two-Week Pre- and Post-Load Shifting.....                                   | 91   |
| Table 21: Ductless Mini-Split Distribution by Bedroom Type.....                                     | 92   |
| Table 22: Multifamily Distribution of Occupancies over Time (%).....                                | 109  |
| Table 23: Occupants per Bedroom from 2009 RECS Data .....   | 109  |
| Table 24: Calculated Savings for Projects – 2019 Actual Compared to 2019 Energy Code Standard ..... | 116  |



# EXECUTIVE SUMMARY

## Introduction

As the carbon reduction opportunity of buildings is better understood, under-researched topics in multifamily buildings are receiving new attention. Compared to single-family homes, relatively little empirical data have been gathered on the performance of water heating systems in multifamily buildings, and even less on the 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.<sup>1</sup> Therefore it is important to focus on improving the efficiency and grid impacts of multifamily buildings to achieve California's climate goals.

California's electricity supply will become cleaner as the state advances towards its 2045 goal of 100 percent renewable energy. However, installing new gas-fired equipment today, such as gas boilers providing domestic hot water (DHW), will lock in greenhouse gas emission sources 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 (HPWHs) would greatly help to decarbonize this end use.

California legislative and regulatory efforts are moving to accelerate the electrification of the built environment. For example, the California Public Utilities Commission (CPUC) is in the process of implementing SB 1477<sup>2</sup>, which directs creation of two new programs to promote the use of highly efficient, low-carbon space heating and water heating appliances in new and existing construction. Also, the CPUC's Self-Generation Incentive Program recently allocated nearly \$45 million toward the expansion of HPWHs into the market. Moreover, several key regulatory barriers have been removed, so many energy efficiency programs are shifting towards replacing gas appliances with electric appliances. In addition, the compliance pathway for all-electric new construction projects is easier in the 2019 California Energy Code, and more jurisdictions have adopted local ordinances favoring—and in many cases requiring—all-electric new construction.

As a result, building electrical loads will increase dramatically, increasing the need to identify peak loads and loads that may be controlled to minimize impact on grid peak periods. Consumption of carbon-intensive generating sources must be minimized while maximizing solar production. Given these developments, it is imperative to understand the role for all-electric multifamily developments to support these goals.

While California's strategic goals are moving toward zero net energy (ZNE), the technologies and building performance of multifamily construction are also developing, but they need support to move this market segment toward the state's goals. Because multifamily buildings can be more complex to design and operate than single-family residences, there may be more

---

<sup>1</sup> 2019 was the first time in nine years that more single-family units were built in California than multifamily units.

<sup>2</sup> [https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill\\_id=201720180SB1477](https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1477)



challenges to achieving all-electric ZNE, so it is necessary to understand multifamily-specific issues.

These challenges include, but are not limited to:

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

Energy efficiency in multifamily buildings is also a social equity issue. The Benningfield Group found that “[a]pproximately 88 percent of multifamily households are renters, and renter-household incomes are roughly half those of owner-households.” The California Department of Housing and Community Development found that between 2005 and 2013, two-bedroom fair market rents increased by 17 percent, while renters’ median incomes increased by only 5 percent. As building electrification gains traction, it must be pursued equitably to ensure that environmental and social justice communities receive benefits. Reducing barriers for all-electric multifamily housing supports low-income families, providing healthier and more comfortable homes with more reliable utility bills.

The two developers in this project took the risk of constructing all-electric ZNE buildings that exceeded the minimum standards using advanced technologies. However, that risk poses barriers to further investment. Until these performance risks can be better managed, advanced practices leading to all-electric and ZNE multifamily projects cannot scale up.

## **Project Purpose**

The purpose of the project was to reduce barriers to all-electric ZNE multifamily construction, enabling benefits for lower construction and operational costs, greater electricity reliability, lower greenhouse gas emissions, and improved indoor air quality. The project focused on providing a comprehensive understanding of water heating technologies and evaluating apartment energy use in high performance housing as a pathway to cost-effective ZNE.

The overarching goal of this research project was to demonstrate the technical and economic potential for optimized all-electric ZNE construction practices in new multifamily buildings, reduced planning uncertainty, and quantified savings. More specifically, this research was guided by the following technology and policy research goals:

1. Understand the trade-offs of central versus individual heat pump systems.
2. Evaluate central systems that serve both domestic hot water and space conditioning loads.
3. Evaluate the potential for thermal storage to reduce energy demand at grid peak and maximize benefits of renewables.

4. Demonstrate that all-electric building systems with 100 percent offset can be achieved on multifamily buildings.
5. Investigate the consumption of other household loads, such as cooking and plug loads, and their impact on ZNE.
6. Identify opportunities to revise codes, technical standards, and software algorithms to support high performing buildings and advance technologies to support state goals.
7. Research the interactions between building energy performance, health, comfort, and convenience in a multifamily context.

The outcomes of this effort will advance all-electric ZNE multifamily buildings through:

1. Evaluations of ZNE 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 associated impacts on market acceptance and long-term savings.
3. Educational materials to support decision making and advance the adoption of technologies and practices to move the multifamily market to ZNE.

Research results are relevant to 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 ZNE issues in depth through four demonstration projects. All four sought to achieve all-electric ZNE construction, utilizing breakthrough heat pump technologies to serve the buildings' heating, ventilation, and air conditioning (HVAC) and/or water heating needs complemented with solar photovoltaics (PV)—as well as to provide affordable housing for low-income families. The projects, located in Calistoga and Cloverdale in CEC Climate Zone 2 and Atascadero and Sunnyvale in CEC Climate Zone 4, totaled 206 residences with (a) individual heat pump water heaters, (b) central heat pump water heaters, and (c) a central combined heat pump system.

The research team worked with the four all-electric building projects to meet specified goals and educate the design team on new technologies to achieve all-electric ZNE projects. The team was comprised of Association for Energy Affordability, Franklin Energy, Nexi, Redwood Energy, and Stone Energy Associates. 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 all the projects' performance and identify opportunities to optimize systems, achieve intended performance, and provide technical design assistance for Atascadero and Sunnyvale.

Significant technical assistance was required to educate the design team (architects, owner, engineers, and contractors) on alternatives, help make decisions and solve problems (from ZNE to compliance and installation specifications), and build capacity within each of the design teams so they could undertake electrification in other projects and portfolios. Given the project timing for Calistoga and Cloverdale, design assistance was provided by a single member of the research team prior to grant initiation. Project designs were modeled using simulation software

and alternative calculations for code compliance and ZNE evaluation. The team also completed iterative design calculations to demonstrate opportunities of different technologies and building practices.

After the design phase, the team deployed the monitoring equipment to document system performance, engaged with management, collected tenant surveys, and discussed issues with site personnel and tenants during site visits. During this period, the team 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 the initial occupancy of the projects, except at Calistoga, where it was installed roughly one year after occupancy.

The monitoring was both granular and comprehensive for domestic hot water and electrical end uses. The domestic hot water data included electricity usage for heat pumps and water pumps, water flow rates, water supply and return temperatures, tank temperatures, inlet and recirculating temperatures, and thermostatic set points. The team balanced technical needs, accessibility, costs, and flexibility in selecting monitoring equipment that was customized for each site's domestic hot water system. Ultimately, the team was not able to use the same equipment on multiple sites.

During the project, the team encountered several challenges.

Nontechnical aspects primarily involved capacity building, communication, and education on new technologies, engineering, and maintenance. A key aspect of this project was to provide technical assistance to the design teams to help them make choices for all-electric systems. To do this successfully, the team evaluated systems and researched conventional sizing approaches, monitored other projects to demonstrate loads, and identified modifications to incorporate heat pump technologies.

Education of onsite management and tenants was also a critical component. During the monitoring period, particularly at Cloverdale and Calistoga, adjustments were made to equipment, and the team was not always notified of the changes. This communication gap made it challenging to understand the performance implications. Over the project period, staff changes and unit turnovers resulted in a disconnect, yet the team engaged with new management and maintenance staff to educate them on equipment and the project, and utilized them as delivery channels to educate new tenants. COVID-19 and shelter-in-place orders converged at the project's end, which meant priorities for many parties shifted, and the team was unable to access a complete data set from one site.

The team also encountered technical challenges from monitoring to improper equipment installation. Many involved challenges with the functionality of monitoring equipment and connectivity. Solutions included adjusting database configurations, changing equipment out for alternatives better suited for the application, making field visits to adjust settings to reconnect equipment, and/or relying on stored data rather than accessing real-time data. Without data stored onsite, the team would have lost a significant volume of data.

In many cases, the team identified water heating equipment and installation issues through monitoring, which allowed for corrections to be made to address deficiencies. Unfortunately, this also prevented these data from being used as a baseline of standard operation for

comparison. Analysis of overall performance often was limited to post-correction periods, which also resulted in shorter time frames. Yet, the issues identified provided key learnings to apply for future successful projects.

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

## **Project Results**

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

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

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

The team developed findings and recommendations to support the advancement of all-electric buildings in the following areas: (1) domestic hot water: individual systems, central domestic hot water, and combined systems; (2) HVAC; (3) electrical end uses; (4) building modeling; and (5) photovoltaics.

The recommendations are detailed extensively in the report. Overall, they inform aspects of design and construction, codes and standards, and operations and maintenance. While this

study provided significant new information, most findings point to the need for further research to refine and/or hone recommendations.

With domestic hot water being one of the largest loads in multifamily buildings, addressing all system types is paramount. Specifically, modeling software must more adequately account for heat pump systems and incorporate design strategies being used in the field, particularly for central heat pump water heaters, but also locations and set points that apply to all systems. In addition, occupancy is a critical factor for sizing systems, as well as for estimating draw schedules. Therefore existing assumptions must be evaluated to reflect more accurate occupancies.

Because HPWHs can play a critical role for thermal storage and decarbonization, sizing methodologies need to reflect not only heat pump recovery rates and peak demand but also load shifting and reduction of electric resistance usage. This may be more acute for individual and clustered systems than central heat pump water heater systems (CHPWH). To support this optimization, codes and standards can address controls such as recirculation and thermostatic mixing valves. Research into standards is needed for manufacturers to develop settings to support the end goals of load shifting: reduced greenhouse gases, energy use (minimized electric resistance), on-peak energy use, and utility costs for DHW. For CHPWH systems, this project demonstrated 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.

Modular central DHW heat pump systems are a flexible application beneficial for both new and existing construction, and they require a significant shift from the gas boiler design. Without 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 the process and result in greater success. This research project has shown that it will be critical to: (1) develop best practices for system optimization from sizing, load calculations, and controls to distribution; (2) require a level of system commissioning appropriate to system complexity; and (3) define best practices for recirculation system design of different system configurations.

Lastly, the combined space conditioning and water heating systems monitored in this project are generally better suited for projects with diverse loads rather than multifamily projects with narrow profiles, yet these systems would benefit from simpler and more integrated systems and controls with appropriate storage to minimize errors in engineering and/or installation.

The team also looked at other end uses, and for the individual HVAC loads, two key issues arose. First, there are baseloads that are not understood or accounted for that affect overall energy use. These can be made transparent and/or regulated through a variety of mechanisms from national testing/rating procedures to energy code regulations. Second, better education on efficient operation of heat pump systems is necessary to ensure performance and comfort benefits are reaped. As DHW and HVAC systems become more efficient, miscellaneous electric loads and cooking are becoming a larger part of the load, and these are harder to shift and regulate. More research needs to be done to understand how to mitigate impacts on peak loads.

While knowing design and equipment are part of the story for efficient operations, occupant engagement is also critical. Although this was not a behavioral study, it did identify the opportunity to increase occupant 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 with the power usage display installed. There is an opportunity to build upon this awareness and understand the opportunity to engage occupants in demand response and peak usage periods, rather than just pure energy savings.

In addition to all-electric technologies, zero net energy was a primary focus of these projects and was tied to competitive funding. This project shed light on several aspects of onsite PV solar systems that are critical for achieving any defined zero net energy target. For example, modeling tools should be comprehensive to support zero net energy goals. When the model does not enable accurate estimates of loads or systems, it is impossible to accurately specify the necessary amount of PV.

The benefits of the PV system can be maximized under four conditions: (1) PV allocations for any net metered configuration are reasonably allocated based on building, common area, and tenant metered loads; (2) verification and inspections of PV systems are required to confirm operational settings and/or commissioning; (3) standardizing interconnection requirements across utilities streamline the process, and most important; (4) PV installations include monitoring systems that can provide accessible information, from inverter performance to system performance and production.

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

To provide the maximum benefit from the research, the team developed a strategy to share learnings through several different channels. The goal is to reach the largest possible audience through diverse media and advance adoption of heat pump technology and ZNE in multifamily buildings. The team developed digital technology and design briefs, as well as case studies. Throughout the project, the team wrote peer-reviewed papers and delivered conference presentations to influence other researchers and those involved in energy efficiency efforts and engaged in conversations to advance design and research efforts.

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. To share learnings, the team created several technology briefs to help energy consultants, manufacturers, architects, engineers, multifamily building owners, industry professionals, and utilities and code development teams understand the opportunities. The briefs 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. The topics include: thermal storage and load shifting, monitoring to achieve ZNE, HVAC systems, photovoltaic systems and ZNE, and considerations for multifamily domestic hot water systems. The team will continue to evaluate how this research can best advance the market and determine which technologies, systems, and approaches to highlight in future briefs. In addition, the team created case studies on two

projects: Atascadero and Sunnyvale. All case studies and design guidelines, and a selection of presentations, will be provided online.

## **Benefits to California**

As the time frame to achieve California's ZNE and carbon-neutral goals approaches, there is an increasing need for more research and evaluation of ZNE 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, greatly reducing dependence on the California 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), occupants (lower utility bills), and California utilities.

These projects demonstrated the technical and economic feasibility of ZNE for large multifamily projects and established design and installation best practices. These efforts will help ensure that all the potential benefits of ZNE are fully realized, especially persistent greenhouse gas-, energy-, and cost-savings. They do so by shedding light on the trade-offs between potential technology solutions in terms of capital costs, operating and maintenance costs, functional benefits, environmental and grid impacts, and physical limitations.

The advancement of all-electric and ZNE buildings can achieve the following benefits:

*Lower costs:* The project will help developers make more informed all-electric and ZNE design decisions, reducing the risk of unanticipated costs to correct problems. In particular, the project increased understanding of the trade-offs involved in selecting central versus individual water heating systems, dedicated DHW versus combined DHW and HVAC systems, electric versus natural gas equipment, and energy efficiency versus onsite renewables.

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

*Environmental benefits:* Optimizing strategies for achieving ZNE standards via 100 percent electric solutions will result in lower greenhouse gas emissions.

*Public health:* Advancing all-electric systems will improve indoor air quality in buildings through elimination of a natural gas from homes. Providing developers with cost benefits and tenant benefits such as comfort and improved air quality can inform decisions to build all-electric.

While these projects produced significant savings, over the energy code in place when the project was permitted, there are still savings to be had over the 2019 code even with the inclusion of minimum solar PV for low rise multifamily buildings in the code. With an easier path for electrification in the 2019 California Energy Code and the ordinances favoring electric construction, this work will help support developers adoption of these technologies while providing strategies to ensure greater consistency in performance with reduced risk.

The potential savings for two projects that included either individual heat pump water heaters or CHPWH systems are estimated to be approximately 460,000 kilowatt-hours annually. These

projects are representative of different multifamily types—a 60-unit low rise development with all individual systems and a 66-unit mid-rise development with a CHPWH system with individual HVAC. The projects has savings of 70 percent and 68 percent, respectively, over 2019 Building Energy Efficiency Standards (California Energy Code) when accounting for contributions of PV systems.

There has been significant advancement in electrification since this research was initiated four years ago, yet the lessons learned from this level of technical assistance and monitoring can be applied to current programs and policies. They also can be complemented by current work on equity to advance electrification and ZNE for all Californians, ensuring that low-income multifamily residents receive the benefits.





# 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. As a result, under-researched topics in multifamily buildings are receiving new attention. This research project provides a comprehensive understanding of apartment energy use in high performance housing. It evaluated water heating and heating, ventilation and air conditioning (HVAC) technologies as a pathway to zero net energy (ZNE) and explored the complex, interdependent systems in a multifamily building to determine how they can work together to achieve an all-electric, cost-effective ZNE building. 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 uncertainty be reduced by reconciling design and actual performance for advanced systems, and can methodologies for quantifying their benefits be improved?

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

1. Understand the trade-offs of 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 to reduce electrical demand at grid peak and maximize the benefits of renewables.
4. Demonstrate that an all-electric multifamily building with a 100 percent PV offset can be achieved.
5. Investigate “nonregulated” loads (i.e., plug loads, cooking) and their impact on zero net energy.
6. Identify opportunities to revise codes, technical standards, and software algorithms to support high performing buildings and advance technologies to support California’s efficiency and climate goals.
7. Research the interactions between building energy performance, health, comfort, and convenience in the context of a multifamily building.

These questions and goals guided the research team’s discussion and actions throughout the research. This report describes the four projects, the approach and methodology for monitoring DHW systems and electrical end uses, results and findings from the analysis, and recommendations.

## Descriptions of the Four Projects

The four research projects are located in Calistoga, Cloverdale, Atascadero, and Sunnyvale, California (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 the U.S. Environmental Protection Agency's ENERGY STAR for Homes program. The four projects offered an opportunity to study different DHW systems, from combined central systems for space heating 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 pump systems—Aremec 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 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 front two buildings, wings one and two (42 units), the system consists of 12 Sanden heat pumps, three 500-gallon storage tanks, and one Rheem heat pump water heater (for recirculation load). 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 |
| DHW Distribution   | Central  | Central  | Individual   | Central  |
| Storage            | 1,000 gallons hot water<br>500 gallons chilled water | 500 gallons hot water<br>500 gallons chilled water   | 50–80 gallons  | 2,000 gallons hot water total  |

HPWH = heat pump water heater

## Team's Roles in Projects

The team's main role was to monitor the performance of these four projects and identify opportunities to optimize systems to achieve the intended performance. Members of the research team were involved as consultants in the design phase of each project. The whole team consulted with the developers and their construction teams during the design and construction of all projects and was able to affect design changes at each, with the exception of Calistoga, which was already completed.

## Approach

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

In addition, the team completed experiments to evaluate opportunities to optimize systems from recirculation system controls to load shifting with heat pump water heaters. In general, the monitoring equipment was installed around the initial occupancy of the projects, except at Calistoga, where it was installed roughly one year after occupancy. Calistoga monitoring informed heat pump and solar array sizing at Cloverdale. Overall, the team's monitoring identified issues that would have otherwise gone 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 the challenges and opportunities related to designing and specifying all-electric multifamily buildings and installation and operation of systems.

The following chapters summarize the project:

- Chapter Two: The process from development and design, to understand the challenges, opportunities, and decision-making process
- Chapter Three: The monitoring process 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 comparison to the design intent
- 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 in this direction and the impact it can have

## CHAPTER 2: Project Design Approach

---

The research team worked with the four projects to meet specified design goals and educate the design team during design and development phase on new technologies to achieve all-electric ZNE projects. Given project timing, in some cases like with Calistoga and Cloverdale, design assistance was provided by a member of the research team prior to the grant award. The technical assistance helped the design team make decisions and solve problems on issues from ZNE to compliance to installation specifications.

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

Project designs were modeled using simulation software to demonstrate compliance with code and programs, as well as to 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 used as needed to demonstrate the energy performance of different configurations and systems to inform decision making. Planning and design were undertaken in older code cycles and versions of the software that did not readily support all-electric construction for compliance nor heat pump technologies. Each project had to complete workarounds approved by appropriate overseeing agencies, not only for compliance under California Energy Commission (CEC) purview, 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 2019 code to have an all-electric baseline, the gas baseline that was a hurdle for the Sunnyvale project in 2016 still exists today for high rise residential projects.

Over the past several years, the CEC has been working 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 its own design and development challenges and opportunities, and the following sections will discuss each development in order of development timeline: Calistoga and Cloverdale, Atascadero, and Sunnyvale. Calistoga and Cloverdale are discussed together throughout this document because they have the same central system, which was the primary focus of the design process. The discussion includes goals and drivers in the decision making, as well as the unique modeling challenges faced in the design phase, which will be compared to 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, with design and installation learnings from one informing 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, manager offices, and common laundry. Cloverdale is a three-story apartment building near downtown Cloverdale comprised of 16 two-bedroom apartments, 16 three-bedroom apartments, a manager's office, and computer, laundry, and community rooms with public bathrooms (see Figure 1). Both developments were certified to the U.S. Department of Energy's Zero Energy Ready Home Program (ZERH) and LEED Platinum, 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 zero net energy effort by the Corporation for Better Housing (CBH), the developer. The project design was constrained by local architectural considerations to blend into the neighborhood's historical housing. Therefore, the site design was laid out to maximize the number of low-income apartments in the neighborhood style, not solar access.

CBH committed to several certifications, as well as zero net energy, 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 zero net energy as this was less familiar than high performing equipment, gas boilers, and envelope measures. Value engineering to reduce construction costs was a significant part of the initial design decisions and typical foe to a majority of developers.

The commitment to the U.S. Department of Energy's (DOE's) 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 was 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 to find a central heat pump solution.

At that time, the most efficient household-size tank-type heat pump water heater 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, 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 5–8 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 four-pipe heat pump in a multifamily building, 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' floorplans was the most significant factor, both politically and financially, in the choice to avoid individual heat pumps.

The Aermec, as a central combined system, is an air-to-water heat pump/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 to plumbing fixtures. It uses R-410a refrigerant and has a series of compressors tasked with heating and chilling water to provide hydronic heating, cooling, domestic hot water, and domestic chilled water. It was designed as a four-pipe system that does not require seasonal changeover and for situations where simultaneous demand for hot and cold water exist (such as summertime cooling and domestic hot water) and 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 aims to satisfy heating and cooling loads while also meeting domestic hot water demand. The unit can operate in three modes: (1) production of chilled water only where the unit acts like a classic refrigerator, (2) production of hot water only where the unit acts like a heat pump using separate heat exchangers from chilled water production, and (3) 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 domestic hot water 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 domestic hot water recirculation pump (see Figure2).

**Figure 2. Aermec Installation at Calistoga**



With the decision to use the Aermec, the design team needed to see 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 for accurately modeling a central heat pump. This applied to 2008, 2013, and 2016 compliance software. Given the lack of clarity, the energy consultant, who later was a member of the research team, eventually received guidance from the CEC on an approved methodology to demonstrate compliance with the energy code and 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 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 large amount of energy lost to the environment.

The first year of operation (2015), the Aermec and laundry room were monitored via metered data from a common utility meter that serves these two 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, due to the order of magnitude more energy used by the Aermec than the laundry. The recommended system modifications to overcome the performance issues will be discussed in Chapter 3.

However, the performance of the Calistoga Aermec system has been far more energy intensive than estimated and is consistent with central DHW research demonstrating heat loss through recirculation and water heating equipment (Zhang 2013; Oram 2017). The data were used to inform the Cloverdale Aermec system energy consumption estimates as well as solar PV sizing.

## **Cloverdale**

The Cloverdale project was the third ZNE development by CBH, and by then that ambitious list of green commitments was no longer a concern to the developer. They were clear about how to build to ENERGY STAR for Homes and 100 percent ZNE with one exception: a 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 endured at Calistoga or pursue 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 heat pump water heater 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 Btu/hr ductless mini-splits were rated at a heating seasonal performance factor (HSPF) of 12 and seasonal energy efficiency ratio (SEER) of 25.<sup>3</sup>

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 was required, to serve the additional pump energy. It was determined that this could be met with an additional 13 kW of PV on the roof. The developer self-installed the solar 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 and aligned the second time around, resulting in a better performing system, considering 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 were corrected—modifications to distribution system, pump sizing, heat exchanger sizing, and fan coil valve. Interestingly, none of these corrective design measures can be modeled by the Title 24 software, yet they have an impact on the system's energy use. Similarly, to Calistoga the hot water distribution system serves both the domestic hot water 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 domestic hot water recirculation pump and is controlled by a

---

<sup>3</sup> 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 (number) the more efficient the equipment.

temperature relay that activates when the outdoor ambient temperature drops below 70°F. When the ambient temperature rises above 70°, and it is assumed that space heating is no longer required, that larger pump turns off and a smaller dedicated domestic hot water 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 the energy performance of different configurations and the way the building would respond 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—it still met all compliance requirements from the CTCAC and 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 used 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, the only penetrations, maximizing the inexpensive installation on the roof. The horizontal orientation, hidden by a parapet wall, provides efficient PV layout with additional PV needed placed on east- and south-facing carports.

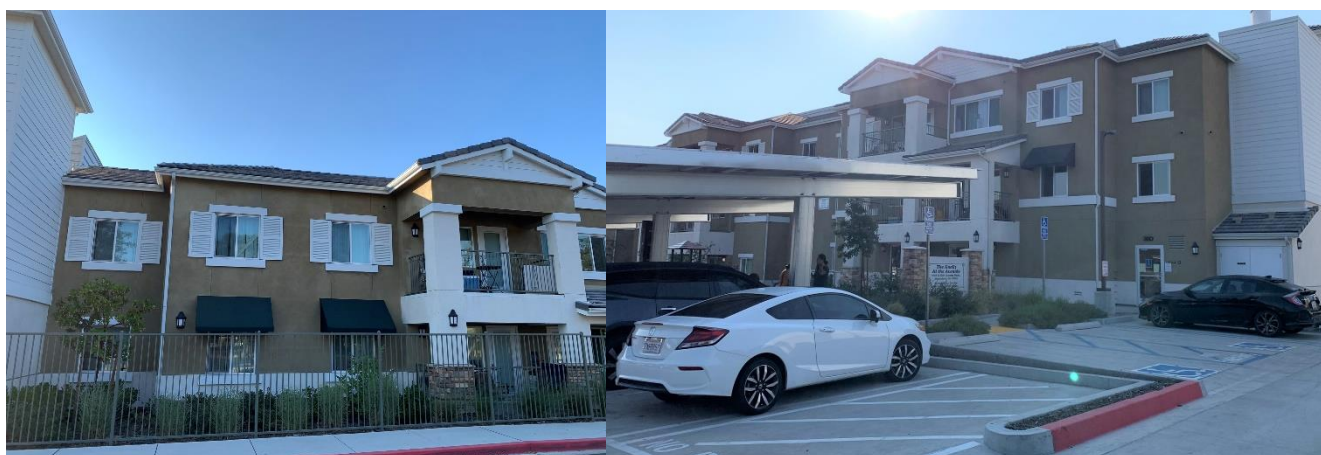
The carport was an additional \$800/kW to the self-installed cost of \$2,200/kW, making the central system with additional PV pencil out for their bottom line. As a comparative, for CBH and associated construction company BLH, central gas systems are 18 percent more expensive than electric central system.

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

## 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 farmworker 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 and LEED Platinum.

**Figure 4. Atascadero Project**



After having worked through the challenges of the central heat pumps in Calistoga and Cloverdale, the developer initially considered installing an Aermec, but determined it would be more cost-effective to install individual water heating and space conditioning at Atascadero in a well-ventilated rooftop shed for this project (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 has 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 the water temperature rises by 10°F. After determining through modeling that a half-inch pipe would not achieve 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/residence as estimated by CBH's affiliated construction company, it was determined 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 enough energy storage to meet peak loads, the temperature set point was raised from 125°F to 140°F, 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 domestic hot water is delivered at the standard, safe 120°F, regardless of tank temperature.
- Ideally, a control mechanism is used to minimize operation during 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 the installation.

During the design phase the comparative whole-building computer simulation models included the Aermec as an option and then the 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 is less efficient, not more, than an EF of 3.5 of the individual systems. The origin of this modeling discrepancy is not 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 and/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 zero net energy CBH developments) to ensure PV would meet all loads and the project would 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 the impact of shading. There is still space on site to add more solar should it be needed for future electric vehicle loads.

In the final design, Atascadero met the 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**

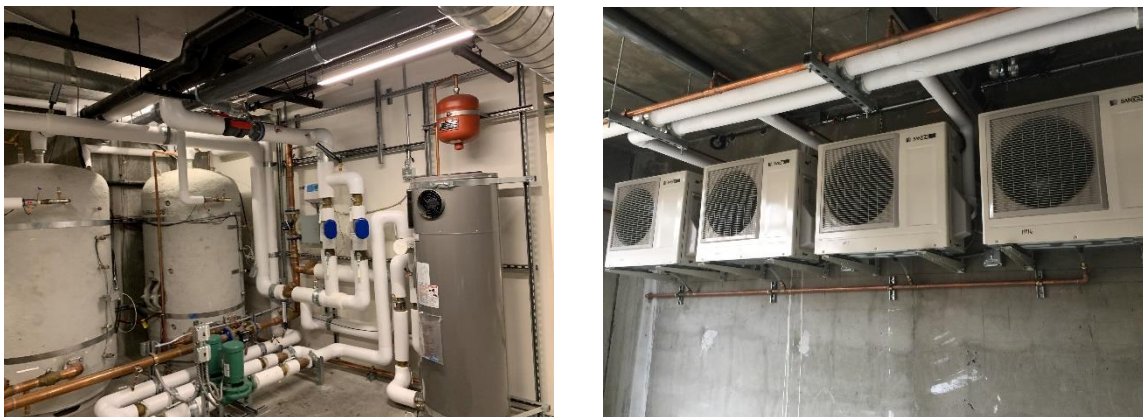
The Sunnyvale project is a four-story podium multifamily building with three wings. It is comprised of 66 units: 30 one-bedrooms, 18 two-bedrooms, and 18 three-bedrooms. Services include a community room, laundry services, social services, a play area, and a manager's office (see Figure 6). The project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

**Figure 6. Sunnyvale Project**



The Sunnyvale site was brought into the project after a central hot water plant already had 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 domestic hot water systems: one serving wings one and two in Buildings 1 and 2 and the second serving wing three in Building 3 of the project. The two central domestic hot water systems are located in mechanical rooms on the first floor, along with services and parking. wings one and two consists of 12 Sanden heat pumps and three 500-gallon storage tanks, and one Rheem heat pump water heater (see Figure 7) and wing 3 consists of 4 Sanden heat pumps and one 500-gallon storage tank, with the same recirculation system. The dedicated recirculation heater effectively separates the recirculation system from the primary DHW system, thereby allowing the primary hot water storage tanks to maintain a high degree of stratification, which in turns significantly improves 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 of which involve bringing the warm recirculated water back to its own dedicated heater, separate from the primary tank. One uses a recirculation heater and one use a “swing” tank (See Appendix A for overview of recirculation approaches).

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

The more detailed design considerations are critical for performance as well as identified installation issues. The designed system included three tanks connected to four heat pumps each, and all three tanks 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 four-heat pump bank as opposed to three of those modules. The HW supply is piped through an electronic mixing valve that mixes the HW supply down to 120°F to send out to the building. The plant also has a HW recirculation line maintained by a variable speed pressure-dependent variable speed 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) that is dedicated re-heating 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 being distributed to the building. The distribution network was balanced with Caleffi 116 thermal balancing valves installed on each riser and set to 110°F. These valves serve two purposes: (1) to ensure that all branches of the recirculation loop are maintained at the same temperature, and (2) 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, thereby increasing the pressure in the system, which in turn lets the pump know to reduce its speed. Fourteen balancing valves were installed in the wing 1 and 2 system and eight were installed in the wing 3 system. This dedicated recirculation heater effectively separates the recirculation system from the primary DHW system, thereby allowing the primary hot water storage tanks to maintain a high degree of stratification, which in turns 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 (Appendix A Sunnyvale Energy Efficiency Measures).



**Figure 8. Ductless Minisplits 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 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 being allocated across the 66 households would do little to reduce their electricity bills; in fact, it would have had the potential to increase them based on the forced change to time of use rate. As a result, the solar PV system was tied directly into the house electric meter serving common area loads, offsetting those electrical loads.

### **From Gas to Heat Pumps**

Condensing gas water heaters have been typical replacements for less efficient atmospheric boilers. Moving from gas plant to heat pump poses significant changes in design, installation requirements, and infrastructure that must be navigated. Over numerous conference calls and dozens of emails between the owner (MidPen), architect, MEP engineer,<sup>4</sup> consultant and research team members, and 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 deleted from the entire project. Since water heating and clothes drying were the only gas uses planned for building, removing gas service did not yield significant cost savings. The owner and joint trench consultants estimated the cost savings from removing gas from the building were only \$4,600 (\$1,600 for trenching and piping and \$3,000 for PG&E gas distribution and a service extension). This cost varies, based on end uses, 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.

---

<sup>4</sup> An MEP engineer addresses mechanical, electrical, and plumbing issues.

- The water heating plant was relocated due to the increased physical storage size and air circulation requirements of an HPWH system and the cool air exhaust. The small ground floor boiler room that was originally meant to house the gas water heaters did not meet the 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 final 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 for 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<sub>2</sub>) refrigerant and has a higher COP than other HPWHs on the market.
- The versatility of the CO<sub>2</sub> refrigerant eliminates the need for electric resistance backup, reducing load size and potential increased utility costs from electric resistance.
- The heat pump is separate from the tank, making it possible to design modular, larger systems.
- The team had experience with central Sanden systems being 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 the 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: Two Sanden heat pumps and 83-gallon storage:* 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 need a total of 40 heat pumps and twenty 83-gallon tanks. This design was immediately deemed too expensive, and the research team set about analyzing how the loads might 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

rather than 100°F, 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 of the system configuration in Iteration 3, the engineer agreed that the system would meet the *first* hour requirements but increased the storage tank to 500 gallons for each heat pump module to ensure the system met longer demand events.

## Other Systems

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

The project was required to meet the ventilation specifications included in the Conditions of Approval to mitigate the potential elevated levels of air pollution from a nearby highway that could lead to health problems for building residents. The three recommendations were: (1) filter all supply air at minimum efficiency reporting value (MERV) 13 levels; (2) ensure all dwelling units maintain 1 air change per hour (ACH) of outside air; and (3) ensure all dwelling units maintain 5 ACH of recirculated air (SFDPH, 2008).

With most of the focus was on the hot water system, the research team was not aware 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 be irritating to occupants. Upon review, the team learned these requirements were no longer consistent with the current San Francisco Health Code regulations, which are: (1) all supply air must be filtered to MERV 13, (2) all makeup air must come through a filtered supply system, and (3) the system must comply with California Code ventilation rates.<sup>5</sup> When presented with this information, Sunnyvale modified the requirement to align it with the current regulations.

The research team provided a number of options to effectively meet this standard and ensure positive pressure in the units, to 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

---

<sup>5</sup> San Francisco Health Code, Article 38.

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 two or three fixtures.

The project modeled under the 2013 Energy Code had several thresholds to meet: (1) code compliance, (2) 15 percent better than code for GreenPoint Rated certification, and (3) a 5 percent threshold basis boost for the CTCAC. 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 the Energy Code while still 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 of Title 24 compliance software. The result of this model was that the Sunnyvale project would be approximately 35 percent more efficient than Title 24 2013.

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 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 show the 15 percent compliance margin, which is 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 for 100 percent offset of common loads, which included the domestic hot water system. The offset was estimated using the National Renewable Energy Laboratory's PVWatts<sup>®</sup> 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 would be approximately 35 percent ZNE.

## CHAPTER 3:

# Monitoring Approach

---

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

The team completed on-site inspections to verify the efficiency of systems and products, and that systems were installed as designed and with variations documented, to inform recommendations and monitoring plans (Appendix B Monitoring Plans and Equipment Lists). Overall the monitoring periods were extended to monitor results of changes to the system to issues that were only identified through monitoring. In addition, a monitoring equipment removal schedule coincided with shelter in place orders of the COVID-19 pandemic, thereby 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 the online data to identify data collection and connection issues and assess performance on an ongoing basis, as well as to coordinate with property developers and construction companies to address any issues on an ongoing basis. This also meant any 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, limiting 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 required different monitoring equipment placed at differing locations. However, the team employed current transducer (CTs) 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 systems sensors logged data at a one-minute interval scale for all data points. Temperature sensors collected and logged data at a one-minute interval, whereas some of the 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 extent exceeds typical monitoring plans.

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

### **Electrical End Use Monitoring Approach**

For electrical end use monitoring the research team deployed the Nexi monitoring system. The Nexi device was deployed to make use of its two primary functions:

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

- A light display which is plugged into a standard outlet has two light wings to display instant consumption on one side and daily consumption on the other through color to provide energy use feedback to occupants on their household energy usage (Figure 9).

The Nexi device allowed the team to collect total household energy usage while also monitoring three individual circuits in Calistoga and Cloverdale and eight individual circuits in Atascadero and Sunnyvale. The SD cards storing the data were collected from each apartment, allowing tenants to visually check thermostat set points and allowing the team to unobtrusively talk with tenants about any issues they have noticed. Given the type of thermostats installed, there was no other way to collect that data, with the exception of Sunnyvale, where the team installed Temp Sticks™ to log indoor temperature. The Nexi data at Sunnyvale and Atascadero were reviewed remotely on a regular basis, since the Nexi devices were outfitted with the ability to connect to the internet, and wireless routers were installed in each apartment.<sup>6</sup> The data collected by the Nexi 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 the time of use of each monitored load type.

Nexi captures the time signature and current of energy end uses. The main circuits are utilizing 50 amp CTs, and all other circuits are utilizing 20 amp CTs. For all double pole circuits, usage is monitored using only one leg of the circuit. The electrical service to the panel is 120 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 dependent upon total number of circuits and the number of apartments available for each sample.

Functioning as a behavior feedback device, the Nexi provides occupants with simple color signals rather than numbers, tables, and graphs like other devices, avoiding the need to use different languages and more complex training for occupants. It lets occupants “see” their energy usage instantly and for the day via a changing light display plugged into a centrally located outlet. The thresholds at which the display color changes are established as percentages of a total “allowance.” The allowance (similar to an energy budget in Title 24 compliance software) is established based on (1) a review of modeled energy usage for the site, (2) a review of the electric utility’s tier quantities, and (3) monitored energy usage at similar projects. The Nexi’s color representation allows residents some chance to see green,

---

<sup>6</sup> 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.

which has been shown to be important for tenant satisfaction.<sup>7</sup> This promotes conservation by having the estimated budget be shown as red, as a warning, and 10 percent over budget is 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        |
| 3 Bedrooms                           | 8          | 8    | 8          | 16        | 16         | 18        |
| 4 Bedrooms                           | 4          | 7    | 3          |           |            |           |
| Central Laundry (washers and dryers) |            | X    |            | X         | X          | X         |

<sup>7</sup> 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 such 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.

## **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 any onsite loggers
- Battery life/power supply options
- Communications options (e.g., pulse, voltage, Modbus)
- Material cost
- Installation cost and feasibility
- Ability to use equipment in multiple sites

The monitoring periods allowed for data collection over winter, summer, and the shoulder seasons. This is important, as ambient temperature and incoming water temperature affect heat pump water heater performance, particularly in regard to thermal storage potential.

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

## **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 the project was installed as designed. For both Calistoga and Cloverdale, the in-unit measures were installed as intended, with the exception of the bathroom fan control. The bathroom fan providing the mechanical ventilation was 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 a standard switch was installed and 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 visit to verify conditions for installation of monitoring equipment found several field variations from the plans.

For Calistoga, these 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 included the following:

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

The team also made operational suggestions that informed performance evaluations.

Based on the original plant design for both properties, the Aermec's internal single speed circulating pump was intended to supply chilled water to a 1,000-gallon storage tank, which would in turn supply fan coil units within the apartments. The compressors would cycle 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, but rather indicated the heat pump to be controlled by Aermec proprietary controls. According to the manufacturer's representative, for the Aermec to read return water temperature the unit requires constant flow, and therefore the chilled water pumps were designed to operate continuously all year.<sup>8</sup>

A variety of changes had taken place to the chilled water side of each of the plants, resulting in changes in the original monitoring equipment and 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 is intended to modulate based on system pressure. Additionally, a temperature-controlled relay recently added to that pump turns the pump off when outdoor air temperature drops below 70°F.

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 use pressure-based modulation. At Calistoga, the HWP 2 was a single speed pump that ran continuously all year long; this was divergent from what was designed and was an area of operation suggestion to improve.

Some of the key data points that were collected include 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.

---

<sup>8</sup> The team is exploring other options for sensing the temperature that should result in even greater energy efficiency.

- 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 inspection).
- 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.  $\text{DHW Energy} = \text{Total Heating Energy (Btu)} - (\text{Gallons Makeup Water (gpm)} \times \text{Delta T (}^\circ\text{F)} \times 500)$ .
- Pumping energy (measured in kW and kWh): metering pump energy for all pumps (hot water pump 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 tank losses using equipment runtime data and hot water supply temperatures, but 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 intent was to be able 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 load, understand the operating efficiency of the central plant, identify and deploy optimization strategies, and 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 in Appendix B).

Since the Aermec system's efficiency varies significantly based on how much heat recovery is taking 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 and, in parallel, began to develop an improvement plan for both projects. Neither project executed the full improvement plans but rather the simpler, less extensive recommendations. Therefore the team was not able to monitor the projects post improvement measures to understand the impact on performance.

### **Behavior Research at Cloverdale and Calistoga**

The fan coil use, along with all other lighting, plug loads, and apartment level appliances, were billed to tenants. One-, two-, and three-bedroom units at both Cloverdale and Calistoga were programmed with daily kWh budgets (allowances) of 7.3 kWh/day, 8.8 kWh/day, and 10.4 kWh/day (Table B-1 in Appendix B).

To analyze behavioral efficiency opportunities, deployment of the Nexi lighting displays were delayed for a time after installation of data logging units. This provided the team with a comparison of the before-and-after-display energy use, illustrating 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 can be 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 to capture seasonal variation and evaluate 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 those with at least two exterior walls. These apartment level data were evaluated in conjunction with operation of the central combined system.

## Atascadero Project

On-site inspections were completed to confirm the following conditions that would inform monitoring equipment selection and layout.

- Wire size of mains to ensure proper CTs were provided with the Nexi devices
- Layout of DHW cold water supply and hot water supply on roof
- 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 the mechanical ventilation was specified to run continuously at a low cfm and 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 the 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).

**Table 4: Rheem Systems at Atascadero**

| <b>Tank</b> | <b>Bedroom Type</b> | <b>EF</b> | <b>Number Installed</b> | <b>Number Monitored</b> | <b>Average Occupancy</b> |
|-------------|---------------------|-----------|-------------------------|-------------------------|--------------------------|
| 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 from this effort was analyzed and used to:

- Understand the actual operating efficiency of a hybrid heat pump water heater.
- 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, and the electrical end-use monitoring extended to all 60 units. The remaining 38 HPWHs remained as a control group whose tanks were in static mode and set point for the duration of our experimentation, to the best of our knowledge. Each of the 22 HPWHs has five temperature sensors and one flow meter installed on its piping (Figure B-2 in Appendix B). The HPWHs were grouped by threes and connected to one cloud-enabled and Wi-Fi-enabled Onset HOBO data logger that remotely transmitted data for access and analysis, allowing for weekly dumps of data as well as on-demand, real-time data export.

### **Behavior Research at Atascadero**

The individual space conditioning and water heating equipment—along with all the other electrical end uses in the apartments—are billed to the tenants.

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

Unfortunately, given the timing of the installation and shorter monitoring period, all the lighting displays were installed in conjunction with the data processing units, preventing the team from evaluating the correlation of energy consumption to the impact of the lighting display system at this development with larger tenant loads. Tenant surveys helped shed light on energy awareness.

### **Sunnyvale Project**

At the unit level, the Sunnyvale development was built as planned, but the central domestic hot water system was not installed as designed.

Table 5 details the configuration of the two plants.

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

- 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, and therefore one single speed pump was used for the majority of the monitoring period up until September 2019, at which point that pump was replaced with the right-sized variable speed pump.

- The central system was not piped in reverse return, but rather, piped in direct return. A direct return configuration means one storage tank is supplied first and drawn from first to supply the building, rather than reverse return, which is first in last out.
- Several balancing valves were missing. Some of the installed balancing valves were set to 120°F rather than 110°F.
- The wrong heat pump water heater was ordered for the recirculation system.
- The installed settings for the recirculation loop heat pump did not match the specifications.

**Table 5: Hot Water Plant and Service Metrics**

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

The data collected from this effort were analyzed and used to:

- Understand the actual operating efficiency of module heat pump water heater systems.
- Make optimization 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, as well as the in-unit monitoring (Table B-4 and Figures B-3 and B-4 in Appendix B). Flow meters were installed on the cold-water makeup, supply to main tanks, recirculation return, recirculation to a dedicated heat pump, and on each tank loop. Temperature sensors were installed on the cold-water makeup, recirculation return, delivered water from HPWH for recirculation, main tank after the recirculation blend, supply water after mixing valve, supply and return for each tank, and supply from main to each tank. The sensors connected to an Onset HOB0 data logger that was cloud- and Wi-Fi-enabled and remotely transmitted data for access and analysis. This allowed for 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, are billed to the tenants. The largest load of domestic hot water is centrally metered at Sunnyvale.

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

In addition, the team installed Temp Sticks at each thermostat in every apartment to monitor relative humidity and temperature to provide insight to 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 zero net energy 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 even PV performance, which would have otherwise been undiscovered. The qualitative data from surveys, conversations, and quantitative data were combined to understand the performance at each development.

Throughout the monitoring period there were variations in occupancy. However, occupancy, which is a variable used in the analysis, is based on move-in schedules, and does not reflect variations throughout the monitoring period. Unit turnovers or short-term vacancies that occurred throughout the time period may not always have been captured.

The performance results and findings for each project are described in the subsequent sections, beginning with a summary of a selection of results across all projects, followed by a section for each site, with Cloverdale and Calistoga combined. The initial discussion focuses on overall performance and zero net energy analysis (Appendix C includes summary of methodologies). This is followed by a discussion of specific end uses and concludes with a discussion on 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

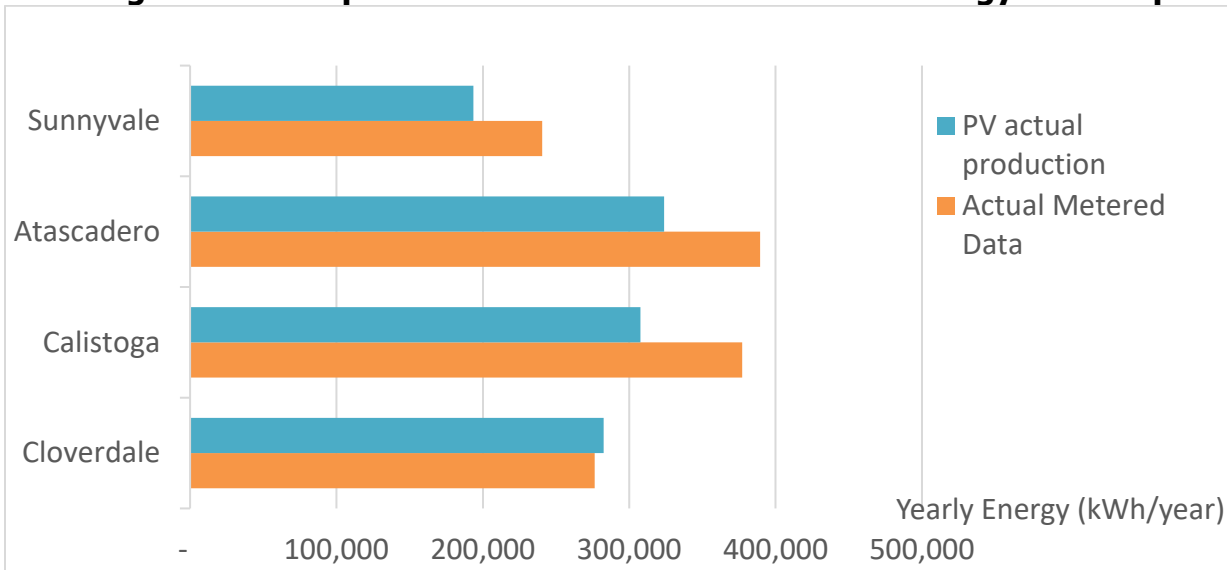
Given the varying configurations in all four projects, a few variables were worth extracting to show side by side. These include total ZNE performance, DHW, electrical end use, and cooking.

Each project targeted zero net energy in some form. While only one of the four achieved its ZNE goal in the year 2019, all projects have the potential to achieve ZNE, as 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<sup>9</sup> are close and may achieve it with some additional modifications. Calistoga had the potential to achieve it even prior to the significant operational changes.

---

<sup>9</sup> 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 domestic hot water, it is interesting to look at the comparison across the sites. Average hot water consumption per apartment per day and estimated per person usage were calculated using cold water makeup flow data, as shown in (Table 6). The results represent actual usage and normalized for behavior, draw patterns, or other variations across the sites. While the per-dwelling usage is higher than that found in other studies, the per-occupant values are fairly close to the ANSI/RESNET Home Energy Rating System (HERS) algorithms developed by Parker et al. (2015). Higher per-dwelling volumes are attributed to higher occupancy apartments.

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

|                      | Atascadero<br>(gal/unit/day) | Calistoga<br>(gal/unit/day) | Cloverdale<br>(gal/unit/day) | Sunnyvale<br>(gal/unit/day) |
|----------------------|------------------------------|-----------------------------|------------------------------|-----------------------------|
| Average daily/unit   | 56.1                         | 64                          | 67                           | 57                          |
| Average daily/person | 14.3                         | 17.9                        | 17.7                         | 20.7                        |

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

**Table 7: Average Occupancy for All Projects**

| Project    | Average Occupancy |      |      |      |      |
|------------|-------------------|------|------|------|------|
|            | 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, showing variation and similarities across the projects. Lighting and plug loads were aggregated due to electrical circuit wiring particular to each site, and therefore quantifying plug loads was not possible. In Table 8, Cloverdale and Calistoga loads include receptacles, lighting, refrigerator, dishwasher, and garbage disposal. Atascadero and Sunnyvale loads include 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<br>(avg. 0.64) | 0.2–1.9<br>(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 has been shown to track reasonably well across apartment complexes with similar demography (low-income) and is higher than model assumptions. Previous studies have shown 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 was similar across the three projects where ranges were monitored at the circuit level (Table 9). At all the sites in this study, predictable spikes at holidays were present, and in general tenants cooked more in the winter, which is attributable to holidays, colder temperatures, and longer boiling times.

**Table 9: Daily Average Cooking Time 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 intended goal of zero net energy. At the time the team engaged with these projects, it was discovered that Calistoga had been dealing with central plant performance issues since its installation.

The Aermec is an advanced system that requires a diverse set of skills at both the planning and installation phases. This is not typical for a multifamily development team; it may be more typical on a large commercial project. This complex system was new to the design and construction teams, resulting in multiple challenges from sizing to installation layout and configuration. Throughout the two years of monitoring the property, the maintenance staff, along with the Aermec-approved service contractors who were required to maintain the complex system (increasing the developer's maintenance costs), made myriad changes to the Aermec system and replaced a variety of system components at both properties to address performance issues. Significantly 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 has proven to be an 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 different building typologies. Cloverdale was able to achieve ZNE, whereas Calistoga was not.

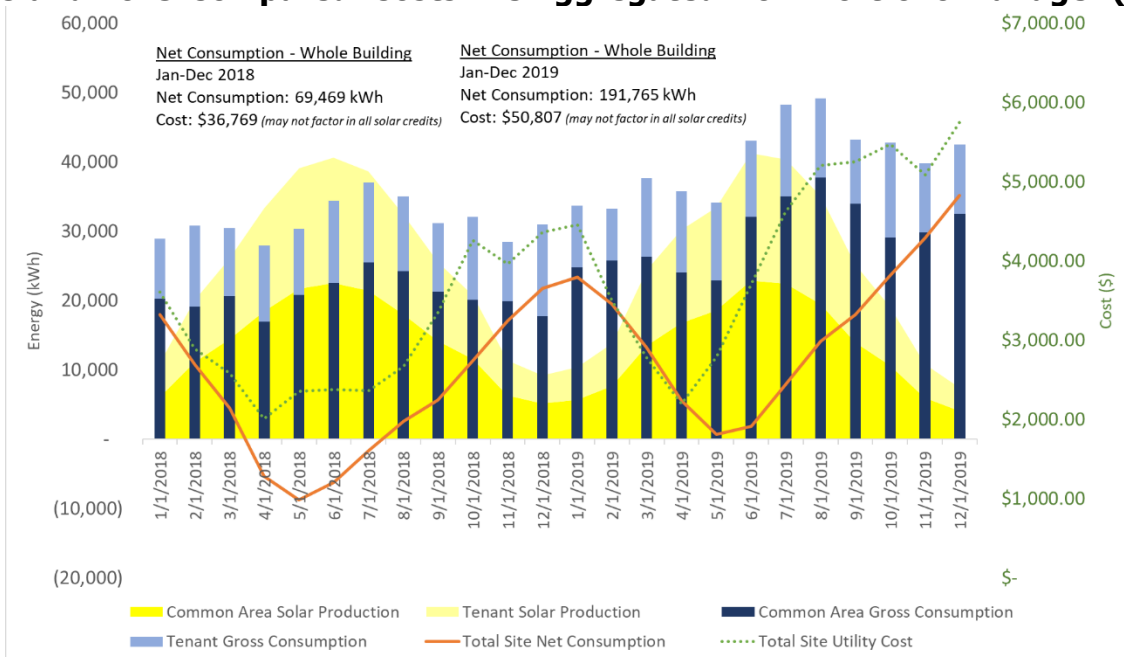
For Calistoga, at the time of the system's most optimal energy operations, the whole property was approximately 18 percent away from achieving zero net energy. The central plant would have needed to achieve a 36 percent reduction in operational energy usage for the property to achieve ZNE (Figure D-1 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 the effective heat transfer and create greater temperature differential between supply and return that is more optimal for a heat pump.
- Actually disabling the cooling mode operation in the winter, rather than raising the cooling set point to 90°F 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 stored water that served no purpose and increased energy use.

However, 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 in Appendix D). Because the Aermec consumes the majority of the energy 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; rather, with those changes made to the central plant, it became even more energy intensive and further from achieving ZNE, as shown in the profile of 2018 through 2019 in Figure 3.

**Figure 11: Calistoga Whole Site Energy Consumption and Solar PV Production – 2018 and 2019 Compared. Costs Are Aggregated from Portfolio Manager (PM).**



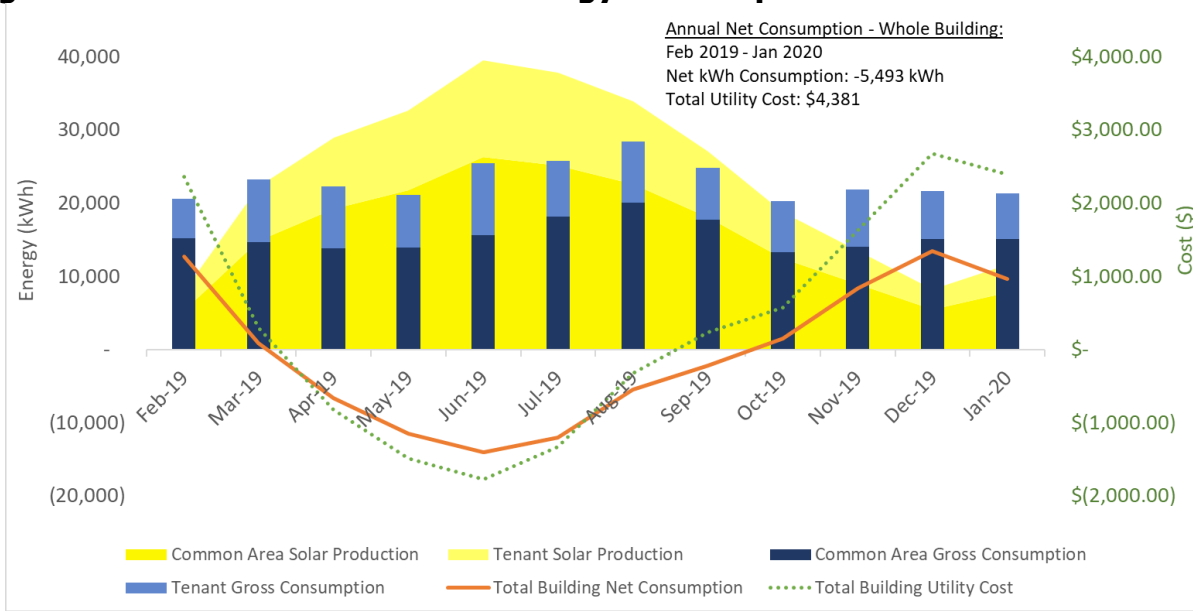
By contrast, Cloverdale was able to achieve ZNE for a 12-month period starting in 2020 in large part due to the better-optimized mechanical system and proportionally larger solar PV system. The property was not ZNE prior to 2020 because of compromised solar PV system production (see Figure 12). The Aermec system optimization measures included the addition of a small dedicated DHW recirculation pump that operates in lieu of the larger space heating pump when there is 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 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 very large monthly consumption and associated bill, but with very little electric production from the system. After six months of discussion with the utility and 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, rather than using the modeled projections.

**Table 10: Comparison of Cloverdale and Calistoga PV Systems and Allocation**

| Property   | Number of Units | W per Apt ft <sup>2</sup> | 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 are allocated more favorably so that the common area with the Aermec load receives a greater majority of the solar PV credits as compared to 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.<sup>10</sup>

### **Electrical End Uses: Tenant Loads**

Common meter loads that serve tenants include space conditioning and water heating. Tenant loads on individual meters at Cloverdale and Calistoga included all receptacles (general receptacles, kitchen and bath GFIs, and refrigerators), range, lighting, bathroom fans, fan coil unit, dishwasher, and garbage disposal. The tenant metered loads were monitored in aggregate, and the fan coil and range were monitored directly.

Due to central system DHW, heating, and cooling, whole house consumption is largely sensitive to individual behavior rather than seasonality, with exception of the limited fan coil operation for heating and/or cooling. Relatively little statistically significant difference between the two sites is present; for this reason they are treated as a singular population with any clear differences noted explicitly. Average daily consumption ranges from 4.3 to 15.1 kWh (Cloverdale) and 3.3 to 15.6 kWh (Calistoga). Daily usage is relatively distributed across apartments, with no clear outliers (Figure D-6 in Appendix D). Within apartments, however, daily variation is 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 bedroom type (Figures D-4 and D-5 in Appendix D), while still being driven by individual behavior. There is no significant difference in consumption between apartments with different numbers of bedrooms and identical number of occupants. Therefore, variance can be almost entirely explained by occupancy and individual behavior. Between Cloverdale and Calistoga, there is remarkable agreement between the mean and median consumption.

Seasonal trends are less notable but still present in average data when fan coil unit energy is removed and trends are less predictable with no clear trends within specific apartments (Figure D-7 in Appendix D). Weekly variance is relatively insignificant, though there is lower

---

10 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.

median usage on Fridays, a trend present in other data sets. There are some differences between seasonal demand:

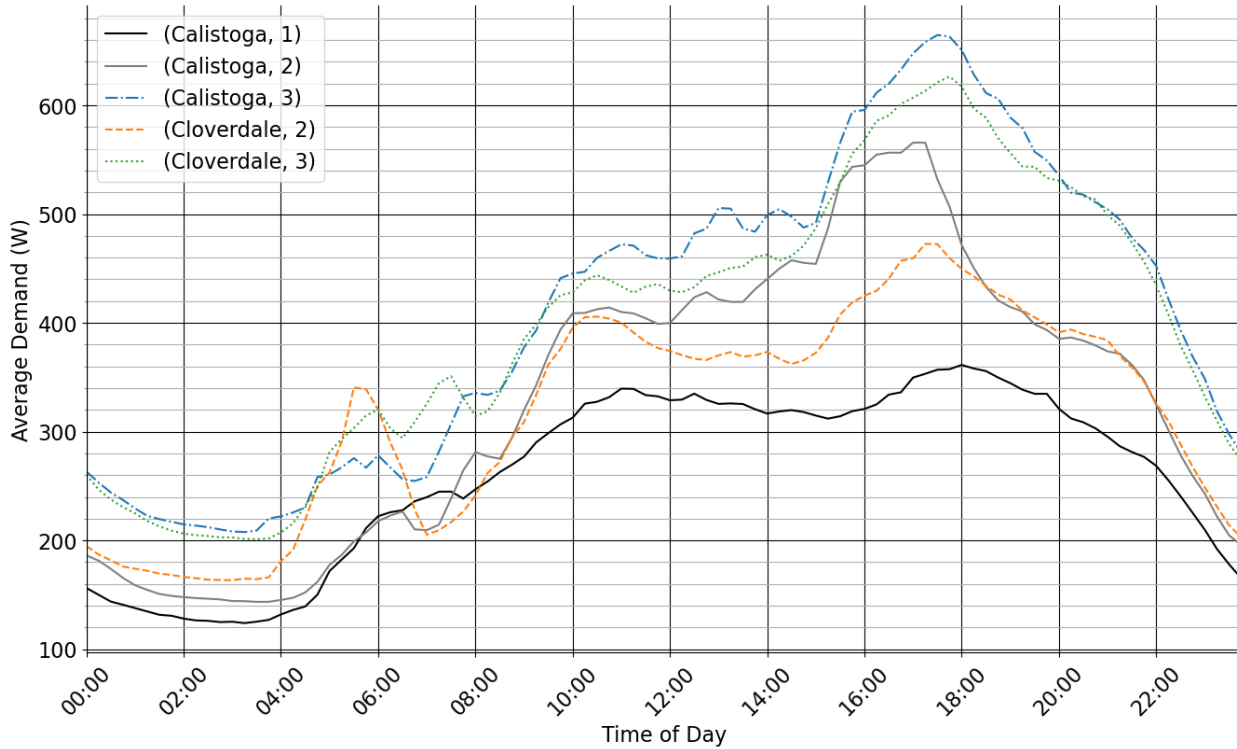
- Nighttime load was higher at both sites, driven largely by fan coil runtimes.
- Winter peaks were higher at Cloverdale, largely driven by cooking loads.
- Morning peaks were earlier in the summer particularly at Cloverdale, due to normal seasonal solar influences on circadian rhythms and/or seasonal farmworker schedules.

In terms of tenant loads, the kitchen range is 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 is 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 noted to be baseload (20 W continuous). The remaining consumption is a mix of lighting, plug loads, refrigerator, garbage disposal, and bath fans, comprising 50 to 85 percent of total annual consumption (1.9 to 11.8 kWh, 5.4 kWh for Calistoga, and 5.9 kWh for Cloverdale average daily). On average, the yearly demand pattern at Cloverdale and Calistoga (see Figure 13) shows site-wide demand peaks at about 5:45 pm. Evening peaks are reasonably consistent (80 percent of tenants' usage peaks between the hours of 4 to 7 pm). Significant daytime load is present in some apartments, as many apartments are occupied by at least one person for much of the day, as indicated in survey results.

On average, demand shapes at Cloverdale can be characterized by an abrupt but moderate morning peak at 6 am, driven almost exclusively by cooking, with a short dip in demand when cooking diminishes. Then MELs/lighting and cooking increase steadily and peak at about 10 am, then plateau until approximately 3 pm. Cooking and MELs/lighting loads increase thereafter and peak at 6 pm. During the peak, cooking makes up 33 percent of total demand, which diminishes throughout the evening. MELs/lighting show a significant amount of activity throughout the day and comprise 60 percent of peak demand, and as much as 75 percent of evening demand, and remain consistent until 10 pm. Drop-off continues until its minimum at 4 am.

Calistoga shares many of these characteristics, but does not experience the same abrupt morning cooking peak. Instead, both cooking and plug loads gradually increase throughout the day. Cooking in general is also more spread out, but peaks at almost the exact same time as it does in Cloverdale. Because of the central combined systems, cooking and plug loads are the largest tenant loads. Average demand profile by bedroom types below shows peaks for project and variance of morning peaks between Cloverdale and Calistoga. The lower overall demand profiles of the one-bedroom units is 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 Are Similar, with Cloverdale Having a 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 are higher in simultaneous use (heating and cooling), as shown in Table 11, which indicates projects with a high occurrence of simultaneous heating and cooling loads would be good candidates for the Aermec.

At Cloverdale, the cooling operation performed much better than the heating operation 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 Mode**

|                             |              | Winter | Spring | Summer | Fall | Total |
|-----------------------------|--------------|--------|--------|--------|------|-------|
| Calistoga<br>(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  |
|                             | Simultaneous | 1.45   | 1.54   | 0.85   | 1.94 | 1.45  |
| Calistoga '18               | Heating      | 1.19   | 3.18   | 0.40   | 1.85 | 1.65  |

Draft Final Report

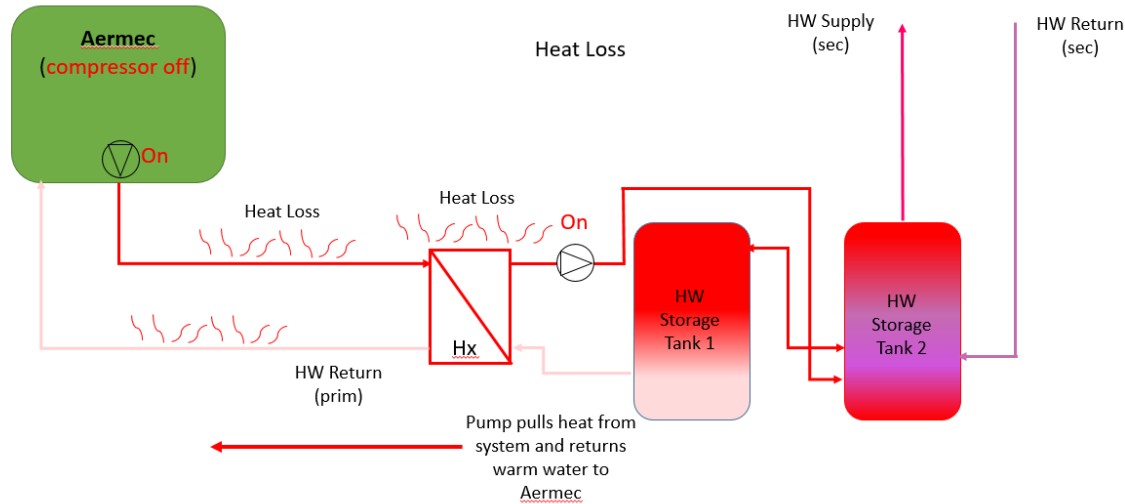
|               |              |       |      |      |      |      |
|---------------|--------------|-------|------|------|------|------|
|               | Cooling      | 1.20  | 1.18 | 0.45 | 1.26 | 0.96 |
|               | Simultaneous | 2.01  | 2.02 | 0.68 | 3.01 | 1.93 |
| Calistoga '19 | Heating      | 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 operate 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 varies more; operational times in 2018 were more closely aligned with Cloverdale and increased significantly in 2019 (Table D-1 in Appendix D for percentage of time in each operation by plant).

Short cycling of the compressors, which degrades their performance and lifespan and creates inefficiencies in the large system, was very 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 turns on and off, the more times the primary loop pulls heat from the storage tanks. When there is a call for heating or cooling, the primary pump turns on, and there is a several-minute lag before the compressor(s) turn(s) on. During this delay, the water in the primary loop is 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 the water returning to the Aermec (see Figure 14). Because heat pumps operate more efficiently with lower temperature return water, this process further degrades performance once the compressor turns on.



**Figure 14: Heat Loss in the System Even When It Is Not Operating and Returning Warmer Water to the Aermec**



There are also times in which Cloverdale Aermec’s compressors are not running, but the HW or CHW primary pumps are on and the associated loops are exhibiting flow. This was seen to happen for substantial amounts of time, in many cases for more than 10 minutes at a time.

To better understand the operation of the Aermec plant, the research team applied a methodology (see the Appendix C for more discussion) to disaggregate the end uses to understand total heating and total cooling input, as well as space heating and water heating loads. However, because this system was designed to provide space heat and domestic hot water via a single distribution network, this calculation methodology proved challenging. The cold-water makeup flow data, which was the key piece of information used to disaggregate DHW and space heating, were deemed inaccurate, due to the misalignment of 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

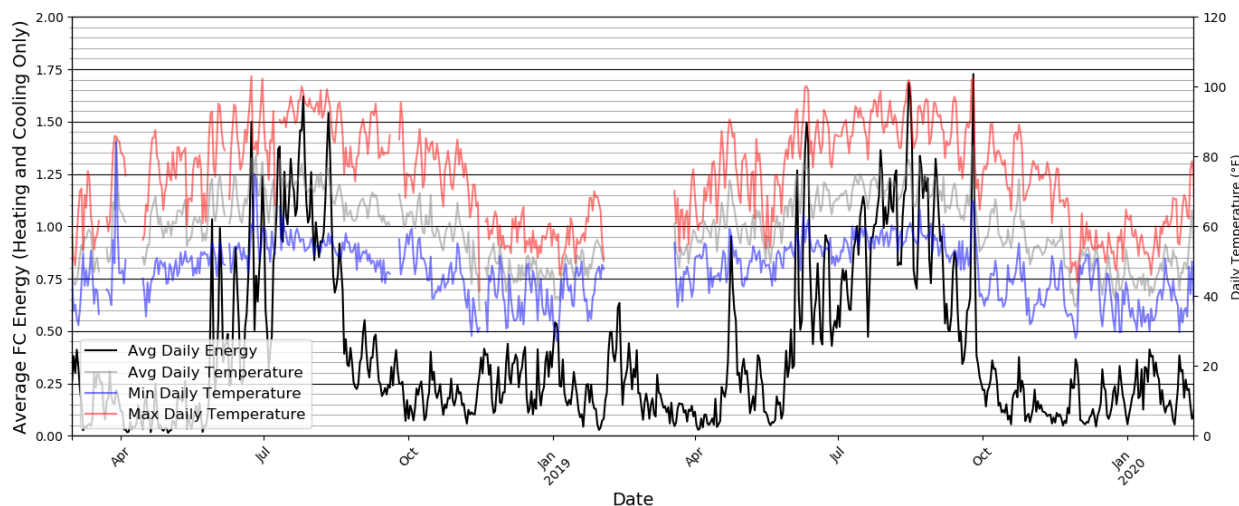
As shown in the Aermec performance, cooling constitutes the dominant loads for tenant metered HVAC uses, comprising an estimated 82 percent and 73 percent of fan coil runtimes at Cloverdale and Calistoga, respectively.

Fan coil load was disaggregated into standby load (roughly 10 W at Calistoga and 20 W at Cloverdale) and operational load (from the fan coil motor). It is hypothesized that the thermostat operations comprise 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 translates to a daily average runtime of 18 to 728 minutes per day across apartments (Figure D-9 in 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 in Appendix D). There is 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 pm. At Calistoga, cooling function ranged from less than optimal to nonfunctional, with many tenants noting its inadequacy, although half reported never encountering issues with it being too hot. Overall, few tenants reported having issues with the heating/cooling at either site, despite known issues (see Figure D-12 in Appendix D and Appendix G for survey results).

**Figure 15: At Both the Cloverdale and Calistoga Sites, Cooling is the Dominant Use.**



In evaluating balancing points for heating and cooling, there is a large range of temperatures at which tenants utilize heating and cooling, and the relationship to outdoor temperature 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 when units were operated on average six hours a day (Figure D-11 in Appendix D). The survey revealed that many tenants use passive methods to cool and ventilate their homes, and site observations revealed programmable thermostats were not used as intended. The research team documented that (1) thermostat clock times did not match the actual time at 75 percent and 93 percent of units at Calistoga and Cloverdale, respectively, and (2) thermostats were not programmed in most apartments and were used as *on/off* rather than programmed and set to auto. In a May site visit, 14 of 15 apartments at Calistoga and 12 of 15 at Cloverdale had their thermostats set to *off*.

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

## Cooking

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

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

Seasonally, average daily cooking energy increased 25 percent at Cloverdale from summer to winter, mainly in the evening hours from 4 to 7 pm, roughly by 0.5 kWh (June, 1.68 kWh; January, 2.10 kWh). 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 less straightforward seasonal trends (Figure D-15 in Appendix D). Weekly trends were also present, with consistently lower cooking energy on weekends (Friday–Sunday).

One side note to actual usage: residents were not satisfied with the stoves, with complaints over lengthy heat up times or 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 (Appendix G for survey results).

## **MELs and Lighting**

This analysis includes all receptacles, lighting, refrigerator, dishwasher, and garbage disposal use aggregated for both sites. The average daily consumption ranged from 1.9 to 11.8 kWh/day (Figure D-16 in Appendix D).

Seasonal variation is negligible, with an 8 percent decrease in the shoulder months compared to summer and winter. Weekly trends are even less present, largely due to the significant baseload present. Nighttime minimum load averaged 140 W at both complexes, of which an estimated 30 percent was 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/standby load for each apartment ranged from 20 W to 180 W, with most apartments falling below 100 W. Observationally, 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 to be 52.3 kWh (0.32 kWh/person) at Calistoga and 35.7 kWh (0.27 kWh/person) at Cloverdale (Figure D-17 in Appendix D). On a per-dwelling-unit basis this ends up being 1.1 kWh per day for both complexes. There are some seasonal fluctuations, but they are inconsistent from year to year. Thursdays predictably show consistently 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, respectively, of total energy is represented by dryers. Daily demand does not show significantly unique patterns across different seasons. Average demand peaks at approximately 4.3 kW (4 kW dryer, 0.3 kW washer) at about 10 am and 4.2 kW (3.8 kW dryer, 400 W washer) at 7 pm at Calistoga. Dryer load shapes at Cloverdale are proportionally similar to the

number of occupants. Dryer peaks at Cloverdale were 2.6 kW at 1 pm and 2.7 kW at 7 pm. However, total washer energy and peak demand were slightly greater at Cloverdale (Figure D-18 in Appendix D).

## **Nexi Evaluation**

A primary goal of our end use monitoring was to study the behavioral change possible with energy feedback displays (see Appendix C on methodology). In many ways, these sites represent a very well-controlled, demographically homogenous population to study the effect of energy-saving feedback displays like Nexi. However, certain challenges are present.

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 responding overwhelmingly that the Nexi made them more aware of their energy use and bill, no statistically significant change of usage between pre- and post-Nexi installation was identifiable, and practically they were indistinguishable (p-values of 0.62 and 0.88 at Cloverdale and Calistoga, respectively). This may be attributed to the following:

- DHW and HVAC (except fans) are not on a tenant meter; if they were, there would likely be a stronger behavioral component as these are typically large loads, compared to cooking and plug loads.
- Overall loads on a tenant meter, such as cooking, are more challenging to reduce.

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

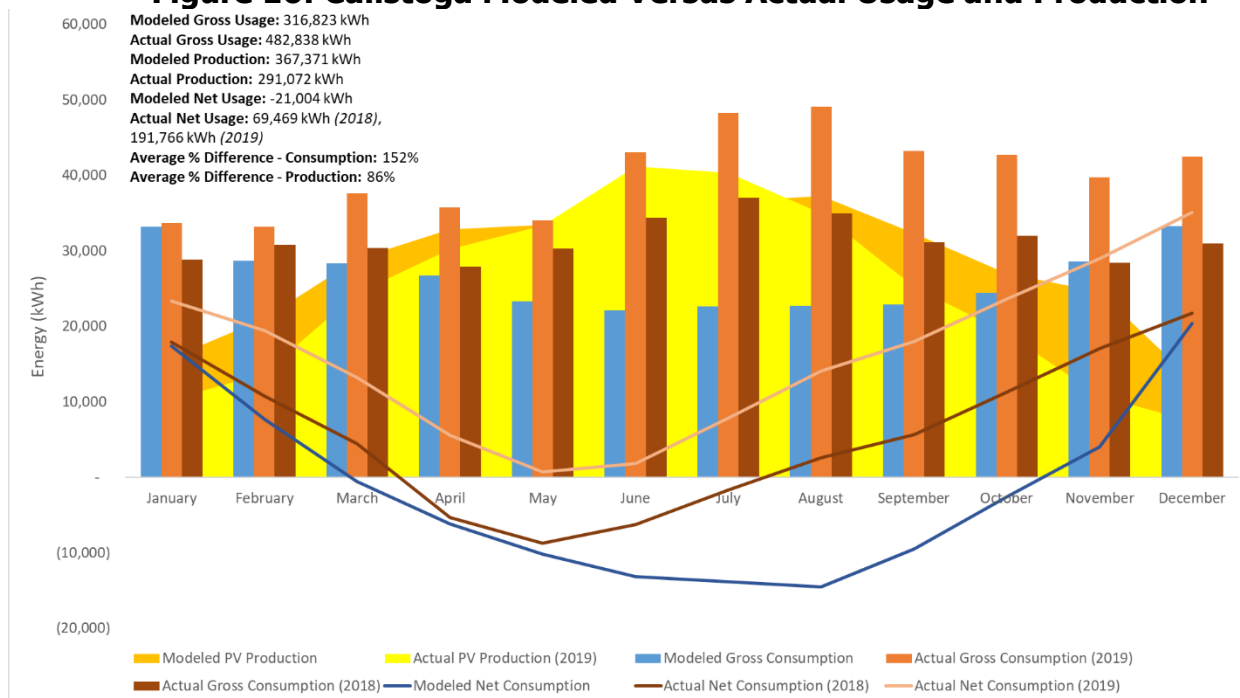
## **Planned, Actual and Modeling Evaluation**

Modeling estimates a building's energy use so stakeholders can properly size a zero net energy solar system. This study combined energy estimates from EnergyPro for a building's heating, cooling, and fan loads and other tools, including the CUAC, to estimate the building's lighting, plug, equipment (i.e., elevator), and appliance loads.

Calistoga and Cloverdale were originally modeled in EnergyPro 5.1, for code compliance. The modeled versus actual comparison below 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 was predicted. Figure 16 shows the modeled versus actual energy usage and solar PV production at Calistoga.

**Figure 16: Calistoga Modeled Versus Actual Usage and Production**



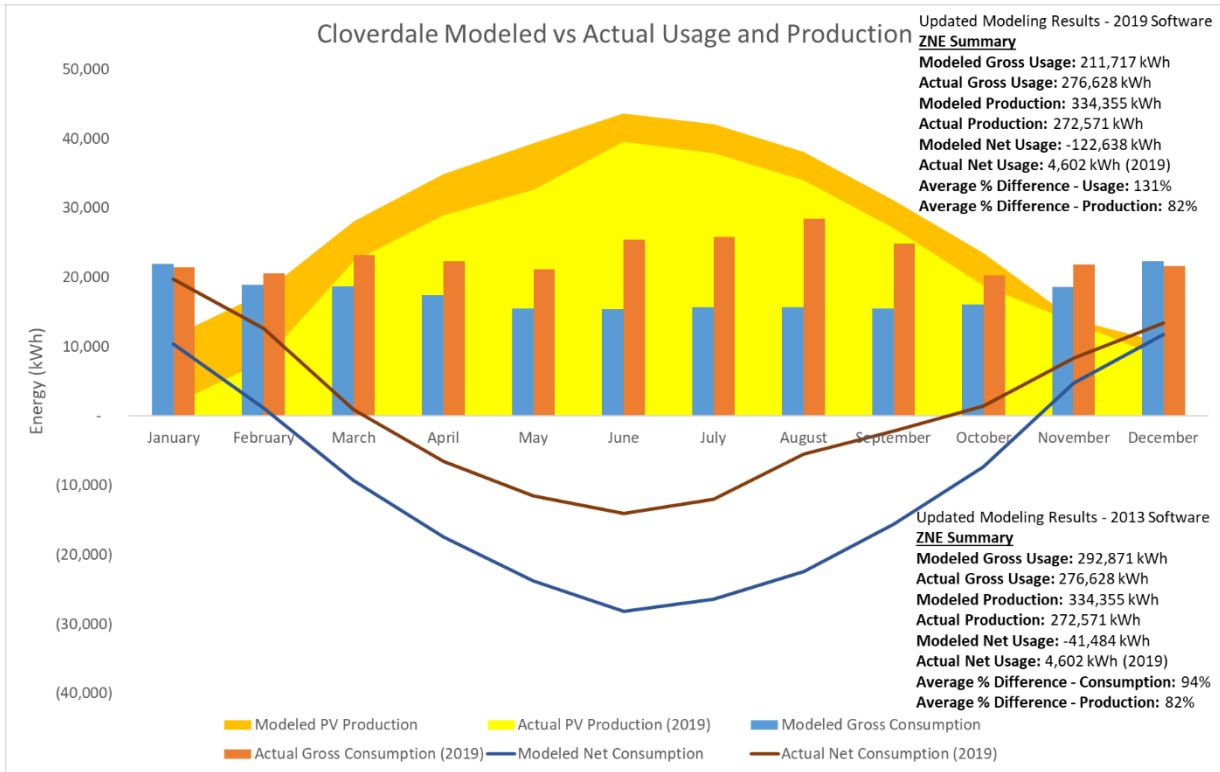
Calistoga consumed 119 percent of the energy the model predicted it would use in 2018, yet in 2019 the actual total building energy usage was 152 percent: two-thirds more than what the model predicted the building would consume. The solar PV system produced 86 percent (in 2019) and 91 percent (in 2018)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

Both tenant loads and common loads were underestimated in the models. The building model predicted that the 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 the discrepancy 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.

By 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 versus multiple buildings in the software. Interestingly, none of these design measures can be modeled by the Title 24 software, yet they have a dramatic impact on the operating efficiencies of the systems. The efficiency measures may have brought the models more inline 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 Versus Actual Usage and Production**



The original model actually predicted that the building would consume *more* than it did. The Aermec is the largest end use, and because of the lower heating loads at Cloverdale it is 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 zero net energy goals, the developer was motivated to oversize the solar arrays in the 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 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 after 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.

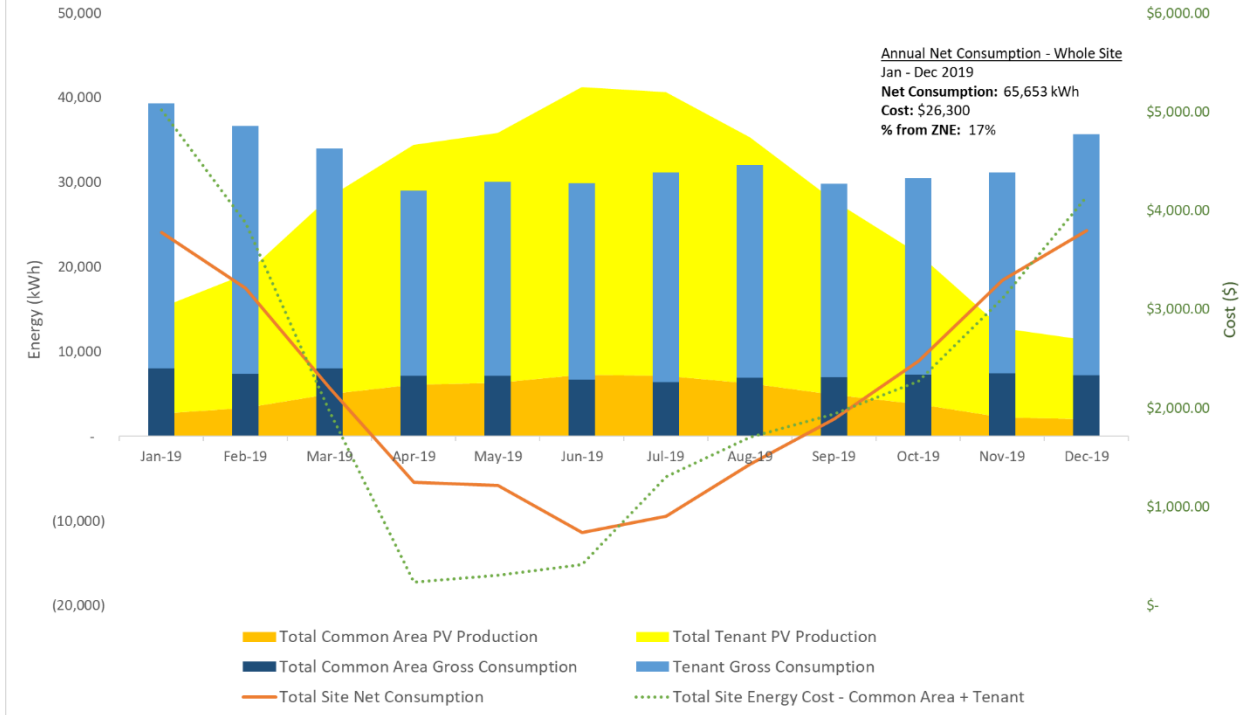
## Overall ZNE Performance

Atascadero did not achieve zero net energy 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 annual

positive consumption as shown in Figure 18. Neither the tenant loads nor the common area loads have been completely offset by the onsite solar PV system, yet 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 zero net energy, and the project as a whole is estimated to consume approximately 17,000 kWh more than produced. Furthermore, if the solar production was closer to the designed and estimated production, the project would have been closer to achieving ZNE.

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



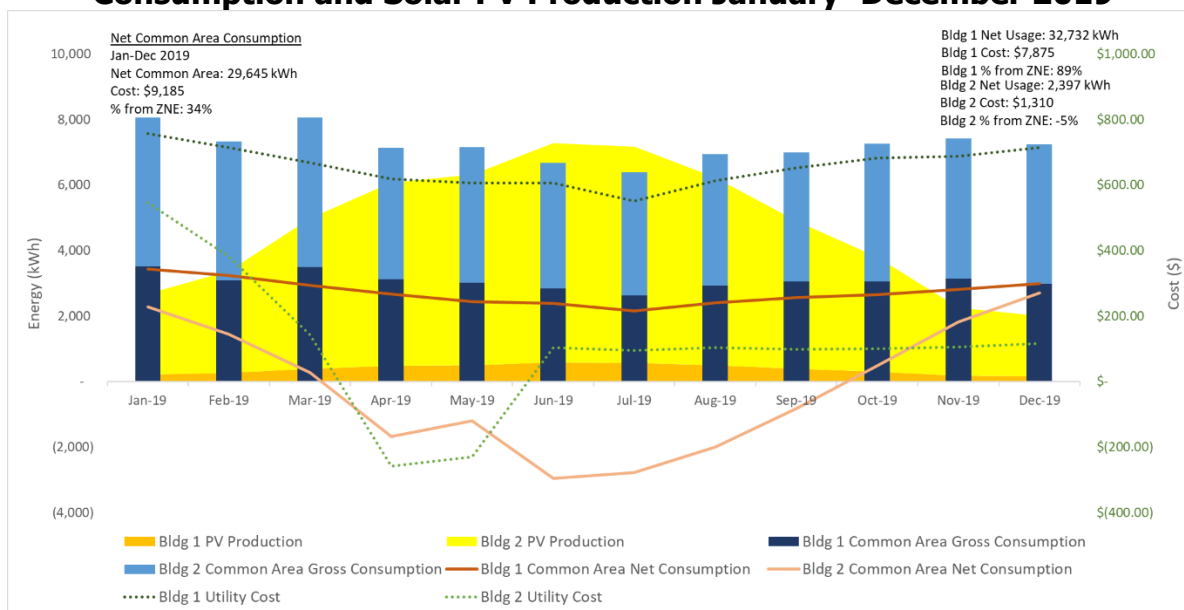
In addition to whole building consumption, ZNE can be evaluated for the common area load for each building and aggregated tenant meters.

For virtual net metering configurations, which allocate solar credits by meter, it is critical to evaluate the loads by meter to understand zero net energy 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 are smaller than those in Building 2, include laundry equipment, elevator, and interior and exterior common lighting. In addition to those end uses, Building 2 includes lighting and loads for the office, computer room, community room, and public bathrooms. Building 1, despite fewer loads, did not achieve zero net energy, and in fact consumed 89 percent more energy than its allocated solar PV generated. By contrast, the Building 2 common meter did achieve zero net energy 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 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 underallocation 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 it still resulted in a net-positive energy load. The net in-unit energy consumption was 9 percent away from achieving ZNE (Figure E-1 in Appendix E). This is 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/or increased solar PV production) the in-unit loads would move closer to or achieve ZNE. And because the in-unit loads constitute the largest fraction of property energy consumption, the property as a whole would be driven further toward ZNE.

### Electrical End Uses: Tenant Metered Loads

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

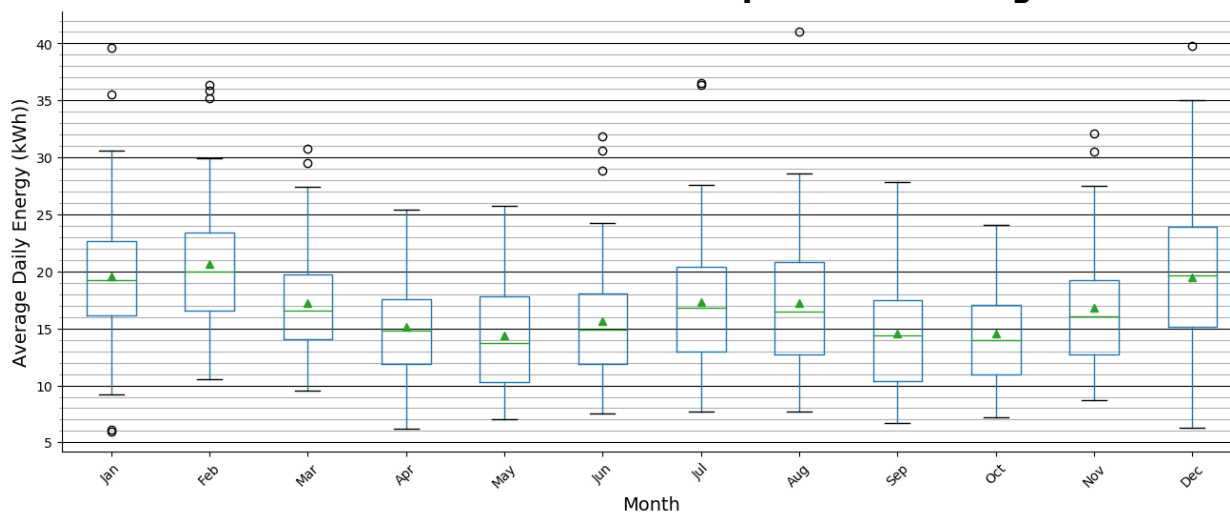
Whole house consumption is largely sensitive to occupancy, individual behavior, and seasonality. Average daily consumption ranged from 8.1 to 28.9 kWh over the course of a two-year monitoring period (with an average of 16.7 kWh) and is relatively normally distributed across apartments, with no clear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

Consumption is 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 are also present, but occupancy is a much better predictor of consumption (Figure E-4 in Appendix E).



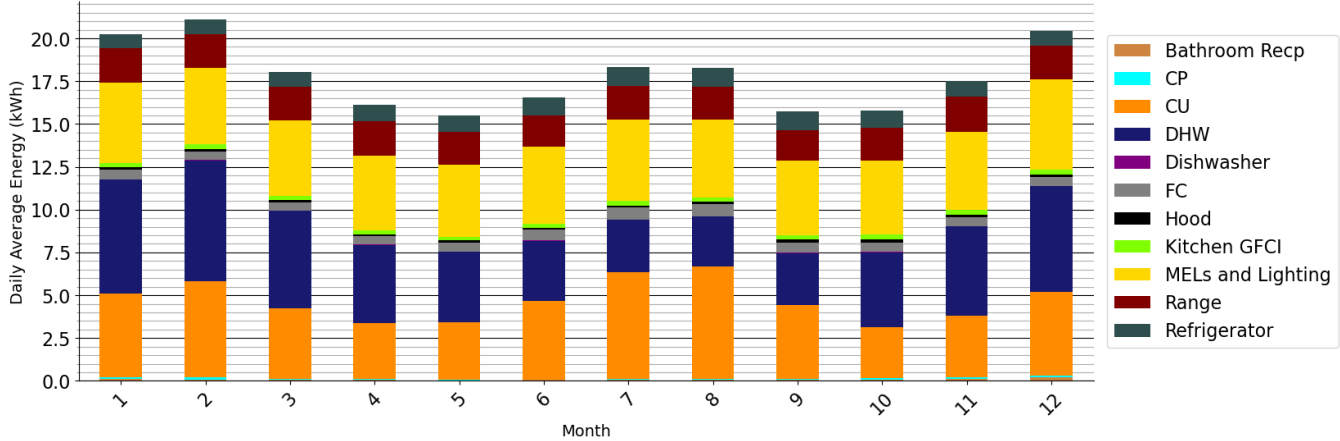
Seasonality is a primary driver of whole house usage, largely driven by DHW and HVAC (Figure 20). Trends follow annual and seasonal weather patterns, as seen in variations between the winters of 2018/2019 and 2019/2020 (Figure E-5 in Appendix E). Across the entire monitoring time frame, data peaks in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

**Figure 20: Seasonal Usage Is the Primary Driver of Consumption as It Relates to DHW and Space Conditioning.**



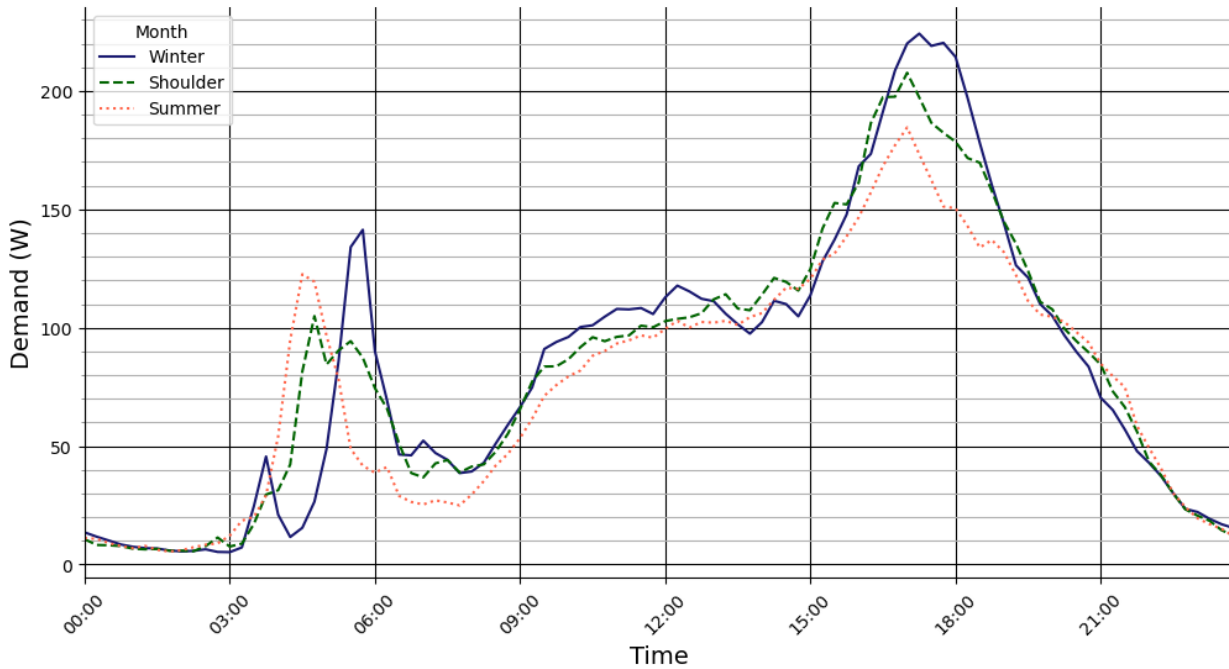
DHW, HVAC, and MELs by far made up the vast majority of total energy consumption, each accounting for between 3 to 6 kWh/day, depending on season and apartment size. On an individual apartment basis, DHW accounted for between 15 to 38 percent of annual consumption, and HVAC between 25 to 45 percent. On average, MELs (plugs, lighting, and bathroom and kitchen 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 in Appendix E).

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



The presence of HVAC and DHW results in highly variable demand shapes across months to seasonal impacts (see Figure 22 and Figures E-6, E-7, and E-8 in 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 pm in the summer and 9 pm in the winter.

**Figure 22: Space Conditioning and Water Heating Loads Drive the Seasonal Demand Profile.**



*Summer:* The variance was highest in about the late afternoon, largely a result of behaviorally driven cooling and cooking energy. Variance increased again during the second peak (roughly 9 pm) as many HPWHs recovered from hot water consumption earlier in the evening.

*Winter:* Winter demand was distinguished from other months by a relatively high daily variance. This largely was due to variability in the performance of HPWHs, as 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 on demand variance were significantly lessened. Higher spring DHW drove late peaks, and fall heat waves drove midday afternoon ramp-up.

*Annual:* During all seasons, the earliest contribution to morning peak was from cooking (5 to 6 am) and was followed by a similarly sized increase in demand resulting from HPWH operation (at roughly 7 am) as tanks recovered from early morning water use. Cooking diminished shortly after the morning peak but increased steadily until evening, where 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 pm. 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 baseload was constant. Small increases in refrigerator and kitchen GFCI energy also was present around peak times. Finally, a significant amount of baseload consumption resulting from heat pump crankcase heaters (see the Heating, Ventilation and Air Conditioning section and Figure 22 below) was present throughout the year.

## **Domestic Hot Water**

With optimization of domestic hot water being a key research focus, the research team delved into the individual HPWHs and also 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 analysis was restricted to November 2019 through July 2020, the time 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 in Appendix E). The HPWHs are located in unconditioned sheds on the roof that are affected by ambient air and incoming water temperature, and therefore affect HPWH performance.

Ambient air temperature, as well as the temperature within the HPWH shed, was monitored throughout the period of experimentation. 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 in Appendix E).

Temperatures *inside* the HPWH shed (where HPWH air is being sourced) was subject to significant solar gain and colder than ambient nighttime temperatures (0°F to 3°F 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 of 4°F–8°F greater than the outdoor air temperature (OAT) in the afternoon (Figure E-11 in Appendix E). During the middle of the day, especially in summer, solar gain warms the shed; in the absence of sun and exposure to ambient temperatures and cold air vented from HPWHs, the shed is a refrigerator.

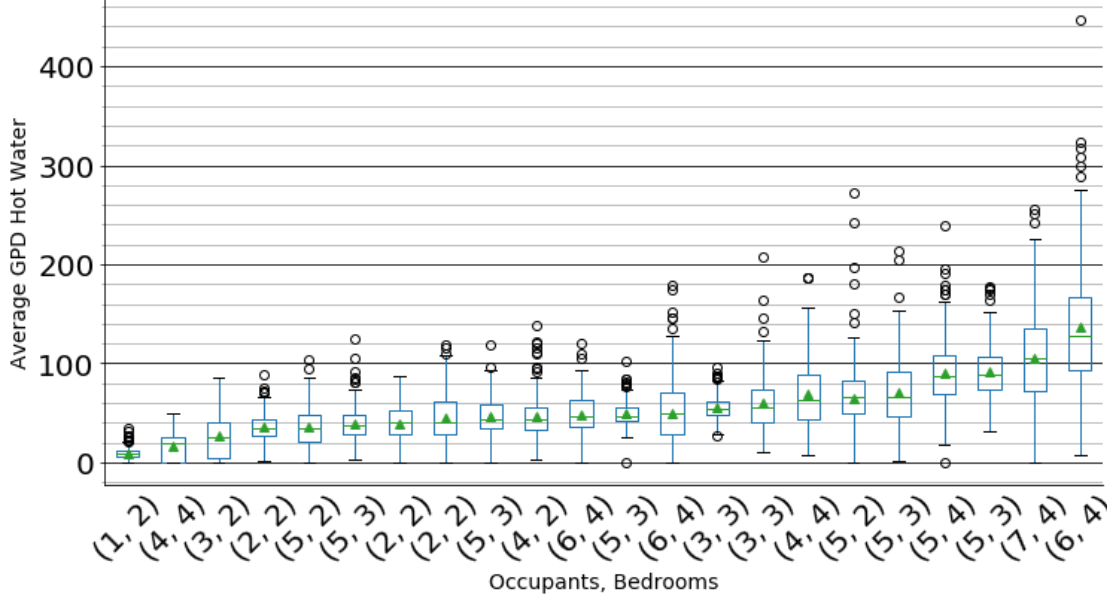
Colder incoming water temperatures fluctuated more seasonally due to location and were exacerbated in the winter; therefore they required a greater amount of heat to bring the water to temperature. Incoming water temperatures were affected due to the length of time the incoming water was exposed to the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

In addition to reduced efficiency from cold incoming water temperatures, these HPWHs have an operating range of 37°F–145°F, and during large flow events, lower tank temperatures could approach incoming water temperatures. This could lead to large spikes in resistance energy even when the tank is reasonably full, as the compressor does not operate below 40°F.

Due to colder temperatures, rates of heat loss in the tank were greater in the winter and lessened in the summer. This was initially noticed due to a few pieces of anecdotal evidence: (1) incoming water temperatures would get warmer during periods of no hot water demand due to conduction at the tank's cold-water inlet, and (2) 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 that of the ambient air. Calculated rates of heat loss for periods where there was no demand and average tank temperatures were 135°F showed higher rates of heat loss compared to modeled assumptions, especially at lower ambient temperature (Figures E-13 and E-14 in Appendix E).

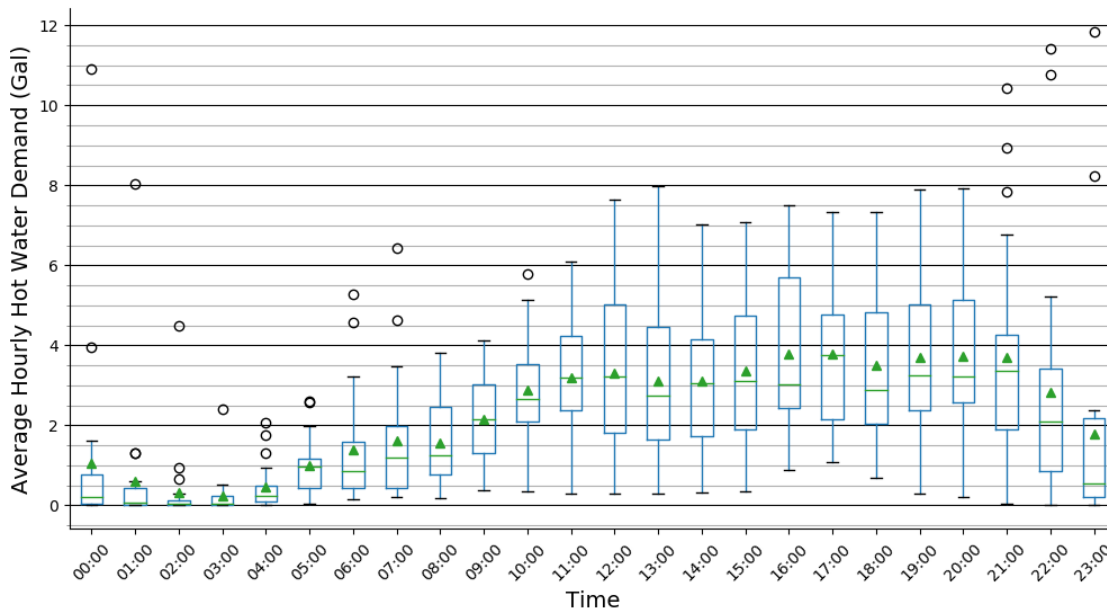
Water consumption on average was relatively constant across long time periods, but variance was high, primarily due to occupancy and secondarily to behavior. Generally, greater occupancy resulted in greater hot water demand and variance (Figure 23). Average daily hot water demand by apartment ranged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

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



Higher occupancy apartments generally have increased probability of coincident draws and consecutive draws. Coincident demand and drawdown of tank storage result in longer recovery time. Hours of subsequent demand compound 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 relatively constant from 12 pm to 9 pm.

**Figure 24: Average Gallons per Hour over a Nine-Month Period**



The most common hour at which hot water demand peaked, by apartment, ranged from 6 am to 12 am. Sixty percent of apartments most commonly peaked during the late afternoon or evening, 22 percent in the morning, and the remaining 18 percent during midday or after 10 pm. However, hourly peaks can be isolated (especially in the morning), 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 <25th percentile), highest-consuming (approximately 75th percentile), average-consuming, and median-consuming apartments, demonstrating a 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 Hot Water During Time Period**

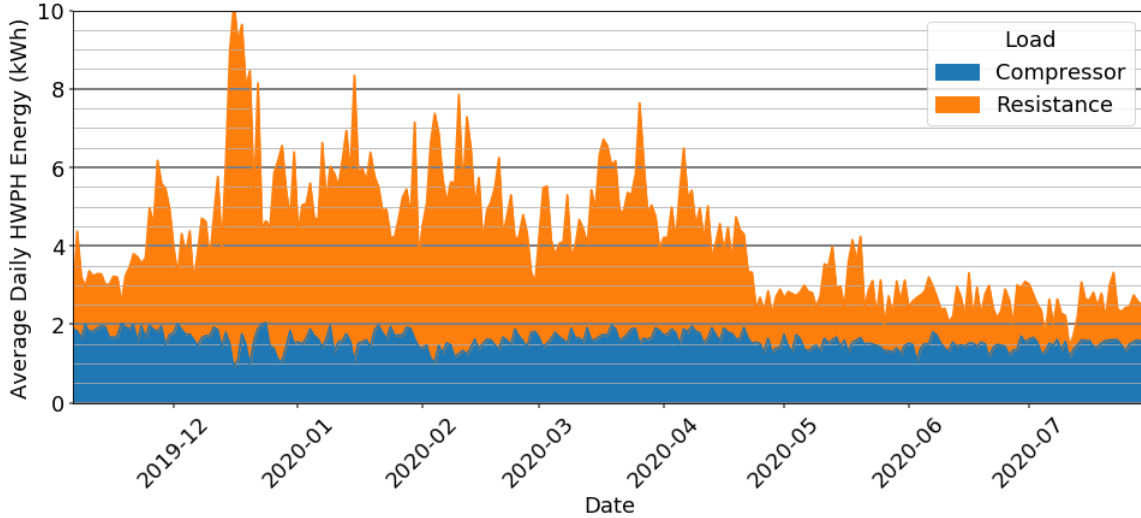
|                        | Lowest-Consuming | Highest-Consuming | Average-Consuming | Median-Consuming |
|------------------------|------------------|-------------------|-------------------|------------------|
| Night (12 am–5 am)     | 0.1              | 27.6              | 2.6               | 1.2              |
| 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 in Appendix E).

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

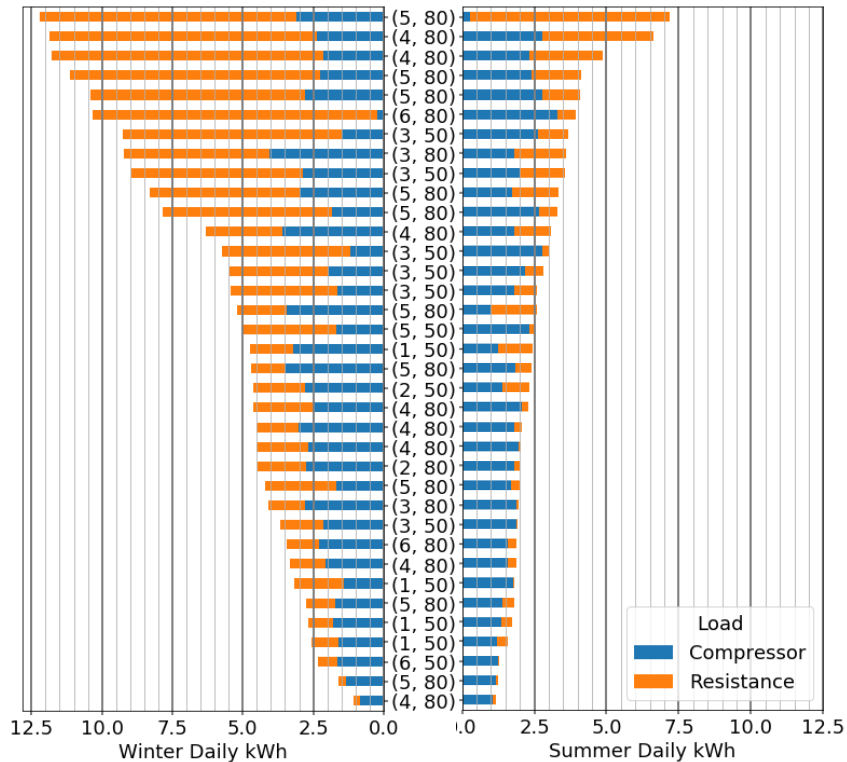
Figure 25 shows average energy for a nine-month period for all apartments in the control group. These units were set to 125°F, Energy Saver mode, which represents a typical configuration. Compressor usage was reasonably constant, and with a few exceptions, both compressor and resistance energy was greater in the winter (Figure 26). Resistance backup was more prevalent during periods of time with greater hot water demand, especially 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) average daily energy consumption was 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, yet it was negligible in summer. Yet, even in the summer there was significant resistance usage (Figures E-16 and 17 in 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 window of time (i.e., larger draws) and that the factory settings (125°F, Energy Saver mode) are inadequate to meet demand regularly without significant use of electric resistance element(s).

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



June 2018 marked the beginning of monitoring the HPWHs, which had been installed with a set point of 140°F in High Demand mode, the most aggressive configuration and most reliant on electric resistance elements to ensure customer satisfaction. The design specified 140°F, Energy Saver. After this was identified, all HPWHs were switched to 125°F, Energy Saver. This was intended to improve performance with less resistance.

Overall, this change did reduce energy. Average daily energy usage was reduced 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) to summer 2019 (Energy Saver, 125°F) (Figure 27). However, the fraction of resistance energy actually increased from 2018 to 2019, despite a less aggressive mode. A lower set point temperature increased the chance that the tank would be depleted of hot water. When resistance is called for, it charges the tank to its set point before it will switch 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 size.

**Figure 27: The Difference in the Resistance Usage from 2018 with High Demand at 140°F (top graph) to Energy Saver at 125°F (bottom graphic)**

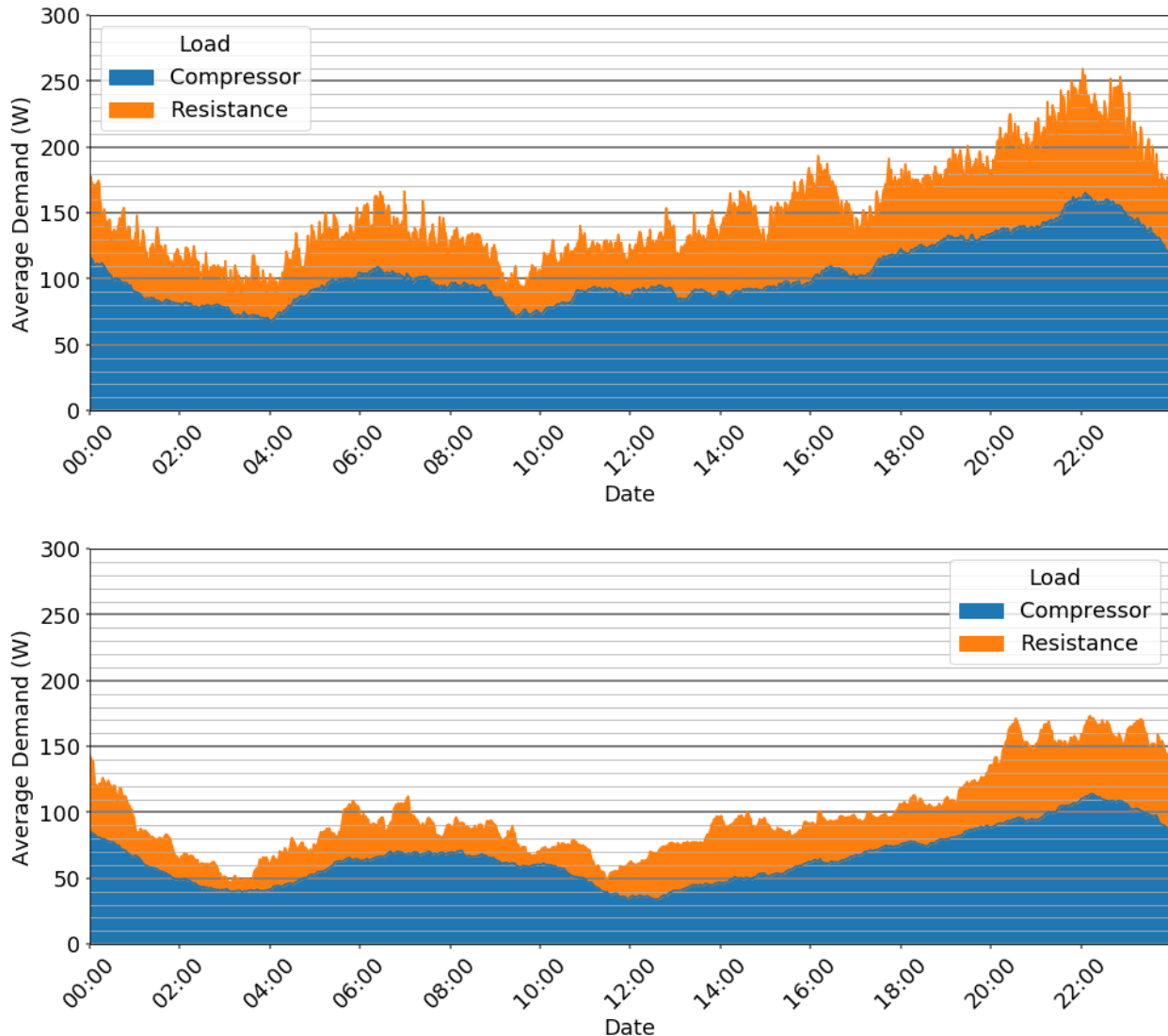




Table 13 compares compressor and resistance use as a function of occupancy. Higher-occupancy units actually showed a decrease in compressor energy from 2018 to 2019 as a result of decreased thermal storage, reinforcing that 125°F was not enough storage for many units to prevent use of electric resistance.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

**Table 13: Average Daily kWh**

| Occupants | Summer 2018, 140°F High Demand |            |            | Summer 2019, 120°F Energy Saver |            |            |
|-----------|--------------------------------|------------|------------|---------------------------------|------------|------------|
|           | 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 ASHRAE and the plumbing code to field data from Atascadero. Compared to assumptions for ASHRAE sizing which are more favorable for three-hour peaks and incoming water temperatures than those found in the field (Table E-3 in Appendix E). While average demand was lower than the 31 gallons in the ASHRAE calculations, sustained draws across all hours affected hot water availability. Assessing 3-hour demands in Atascadero draw data, in 30 percent of the days, the water heater did not meet demand when three-hour demands exceeded 31 gallons for 2 bedroom units.

Secondly, the research team utilized the actual draws from Atascadero in a model to determine the frequency that the HPWH would not be able to deliver hot water. Each of the 22 dwelling unit's hot water draw profiles were evaluated in the model based on the HPWH that was installed for the study (50 Gal RHEEM ProTerra 2 and 3 bedrooms, 80 Gal RHEEM ProTerra 4 bedrooms) and evaluated using "code-sized" HPWHs based on Table 501.1 (2) in the 2019 California Plumbing Code<sup>11</sup>, for sizing residential hot water heaters according to number of bedrooms and bathrooms served. Both HPWH sizes were evaluated in hybrid (compressor and resistance heating available) and heat pump only (compressor heating available) modes. As the number of bedrooms increase, the occurrence that the HPWH cannot provide hot water also increases (Table E-3 in Appendix E). 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 occurrence that the

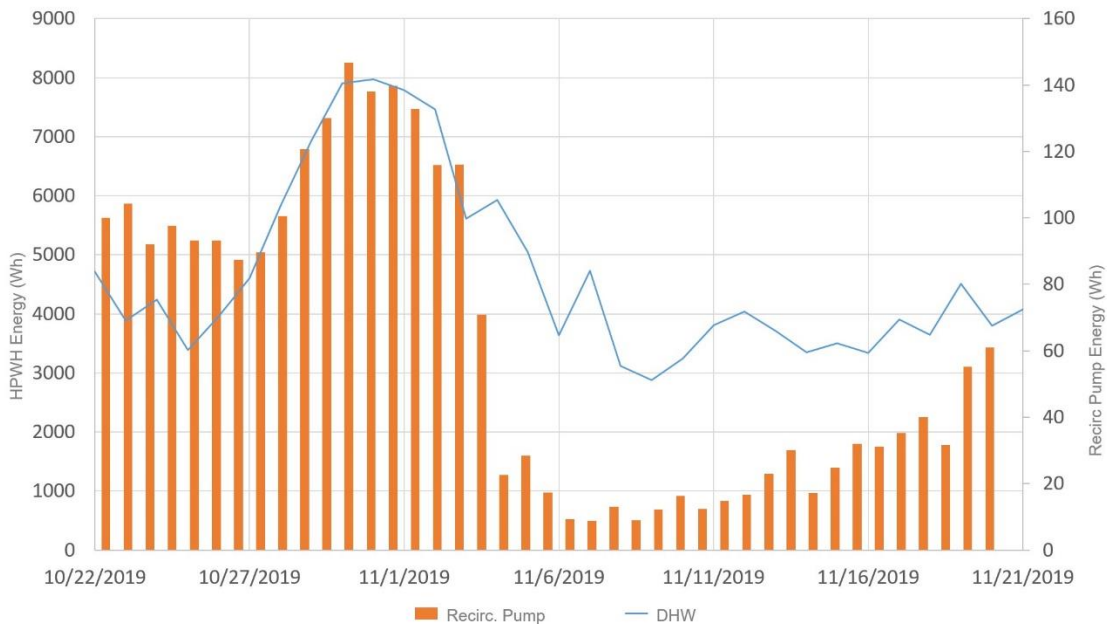
<sup>11</sup> Plumbing Code: <https://up.codes/viewer/california/ca-plumbing-code-2019/chapter/5/water-heaters#5>

HPWH cannot provide sufficient hot water is 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 includes the HPWH usage and recirculation system. Each apartment’s recirculation pump was controlled by two to three infrared occupancy sensors installed at the kitchen sink and in each bathroom across from the mirror. Monitoring data showed the sensitivity of the infrared occupancy controls, which would frequently trigger unnecessary operation, as evidenced by the lack of hot water demand after activation and activation in unoccupied apartments. The recirculation pumps operated more than 100 times a day in three-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 the winter, due to lower ambient temperatures and greater pipe losses. The frequent runtimes circulated warm water into the tanks throughout the day, decreasing stratification of the stored water and wasting energy through heat loss during unnecessary recirculation. The occupancy sensors were replaced with push-button demand controls in early November 2019, which reduced both the pumping and water heating energy use (Figure 28). After control replacement, 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 the 22 HPWHs (Table 14) binned into three groups with staggered scheduling<sup>12</sup> changes for the HPWHs by 15 minutes across the groups.

The initial load shifting strategies were informed by draw patterns seen during the load up (charge) period (1 to 4 pm) as well as the peak (shed) period (4 to 9 pm) to reduce the risk of negatively affecting the tenants' hot water delivery temperatures. The results discussed are from November 2019 through June 2020, representing 8 of the 19 experiments. The others were omitted due to misoperation of the recirculation pump controls, bad data, or incorrectly programmed schedules.

---

<sup>12</sup> 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.

Table 15 shows a summary of these eight selected experiments. The team iterated on the individual experiments to better understand opportunity for thermal storage for this property using the 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 the scheduling, temperature set point, and mode parameters, as well as the experiment's intent and results. The results also graphically show the average demand plot of electric resistance and compressor energy with an accompanying box plot of average daily draws to show outliers.

A single metric cannot represent the thermal storage capacity for any experiment. The set of metrics below were selected to demonstrate the complexity of the experiments and the need to understand the trade-offs associated with 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.<sup>13</sup> Overall, the results of the experiments can be categorized under seasonal performance, storage capacity, and monitoring.

---

<sup>13</sup> 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.

**Table 15: Summary of Thermal Storage Experiments**

|   | Experiment          |                 |                |                   |                 |                  |                  |                  |
|---|---------------------|-----------------|----------------|-------------------|-----------------|------------------|------------------|------------------|
| Metric  | 1e                  | 1h              | 1i             | 1j                | 1k              | 1o               | 1p               | 1q               |
| Time Frame  | 12/2/19-<br>1/10/20 | 2/7-<br>2/14/20 | 2/14-<br>21/20 | 2/21 -<br>2/28/20 | 2/28-<br>3/9/20 | 5/22-<br>6/12/20 | 6/12-<br>6/22/20 | 6/22-<br>7/10/20 |
| Average Ambient Temperature (°F) (inside water heater enclosure)                  | 46.78               | 48.49           | 52.22          | 56.06             | 53.02           | 71.00            | 69.65            | 72.48            |
| Average Incoming Water Temperature (°F)   | 52.81               | 52.56           | 55.34          | 58.34             | 56.66           | 57.37            | 69.04            | 70.83            |
| Average Tank Delivery Temperature (°F) (at top of tank when there is demand)      | 131.1               | 132.9           | 119.3          | 133.9             | 133.9           | 135.1            | 134.2            | 136.5            |
| Percentage of Time Delivery Temperatures <105°F                                   | 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<br>(13%)       | 1.32<br>(18%)   | 0.82<br>(14%)  | 0.79<br>(18%)     | 0.73<br>(14%)   | 0.10<br>(4%)     | 0.11<br>(4%)     | 0.48<br>(21%)    |
| Daily Resistance  | 59                  | 60              | 52             | 15                | 42              | 5                | 12               | 1                |

|                                      |      |      |      |      |      |      |      |      |
|--------------------------------------|------|------|------|------|------|------|------|------|
| Energy Fraction (%)                  |      |      |      |      |      |      |      |      |
| 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 <sub>2</sub> e)    | 2.67 | 2.9  | 2.23 | 1.77 | 2.00 | 0.52 | 0.52 | 0.53 |

*Mode Configuration.* Experiments were conducted to understand performance under Heat Pump Only and Energy Saver mode to meet load shifting goals and hot water delivery demand.

Several experiments used Energy Saver mode to avoid unsatisfactory low temperature hot water delivery for occupants. Yet, in general, Energy Saver mode appeared to trigger unrequired electric resistance, making strategies ineffective due to operation of the resistance element, the operation of which hinges on differentials between upper and lower tank temperatures and/or incoming water temperature. This was most evident in the winter, when colder incoming water temperatures (40°F–60°F) would trigger resistance operation even when the upper tank temperatures were much higher. In addition, because electric resistance is 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 prescribe an optimized schedule.

In regards to the Heat Pump Only approach, the main concern was 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 at 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) during winter Heat Pump Only operation, they were concentrated among one or two apartments with very unusual and high demand patterns (>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. Except for a few extremely high-water-usage outliers, experiment 1j

delivery temperatures were favorable, with peak demand (including during peak hours), costs, GHG emissions, and overall energy usage the lowest of any experiment, as shown in Table 15.

*Set Point Temperature.* To support load shifting and shedding, set point temperature was increased in charge periods and decreased in shed periods for 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 demands 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 should be made prior to temperature changes, to again avoid unintended electric resistance use to meet the set point temperature.

Maintaining a set point of 140°F for all hours, either in Energy Saver or Heat Pump Only mode results in: (1) minimized thermal storage depletion due to large coincident demands; (2) smoothed out variable demand, especially in apartments with outlying usage patterns (i.e., very late peaks or unusually high peaks); (3) mitigated very low delivery temperatures; and (4) lowered COPs (elevated tank temperatures reduced heat pump efficiency), but not significantly enough to offset the gains from reducing the frequency of resistance energy. To summarize: when ambient conditions are unfavorable for keeping up with demand, it was better to take a conservative approach and keep the temperature as warm as possible with the heat pump, rather than risking resistance-driven recovery by attempting to eliminate energy consumption entirely during peak hours. This point is particularly salient when considering populations of unpredictable and highly variable hot water users.

*Seasonal Performance:* The initial winter experiments attempting to load shift using load up and shed approaches were less successful than hypothesized. Conditions during the winter made operation difficult for the reasons previously discussed. For these experiments, the most successful winter schedule involved less load shifting and more 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 set point at all times. This approach also had the lowest overall daily energy consumption and lowest overall costs, compared to other winter experiments. This setting resulted in greater average peak demand than some of the other winter experiments, but without high demand post-peak. As mentioned, increased storage at 140°F more than offsets thermal losses and the probability of incurring resistance heating. This is especially true when compared to 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 for the reasons described at the beginning of this section. Experiments undertaken during the summer that were nearly identical to winter schemes proved to be highly effective. Charging tanks to 140°F enabled us to eliminate peak load almost entirely from 4 to 9 pm. A second experiment to extend the shift to 10 pm was slightly less effective on average, but still widely

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 to increase the quality of delivery.

Given the significant influence of proprietary mode logic, the research team utilized similar methodology for code compliance sizing to evaluate thermal storage potential and HPWH sizing. The model was then used to evaluate the effect of load shifting between the hours of 5 pm and 9 pm for each bedroom type and each HPWH heating modes (hybrid and heat pump only). The analysis was completed for a 50-gallon, 65-gallon, and 80-gallon RHEEM ProTerra. 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 pm–9 pm peak period with insignificant hot water interruptions. For the select two- and three-bedroom units with larger draw profiles, the HPWH can successfully load shift when set to hybrid mode. For the four-bedroom units, an 80-gallon HPWH does not provide enough storage to sufficiently provide hot water when load shifting based on the draw profiles of this specific site (Table E-13 in Appendix E). 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 time and baseload energy.

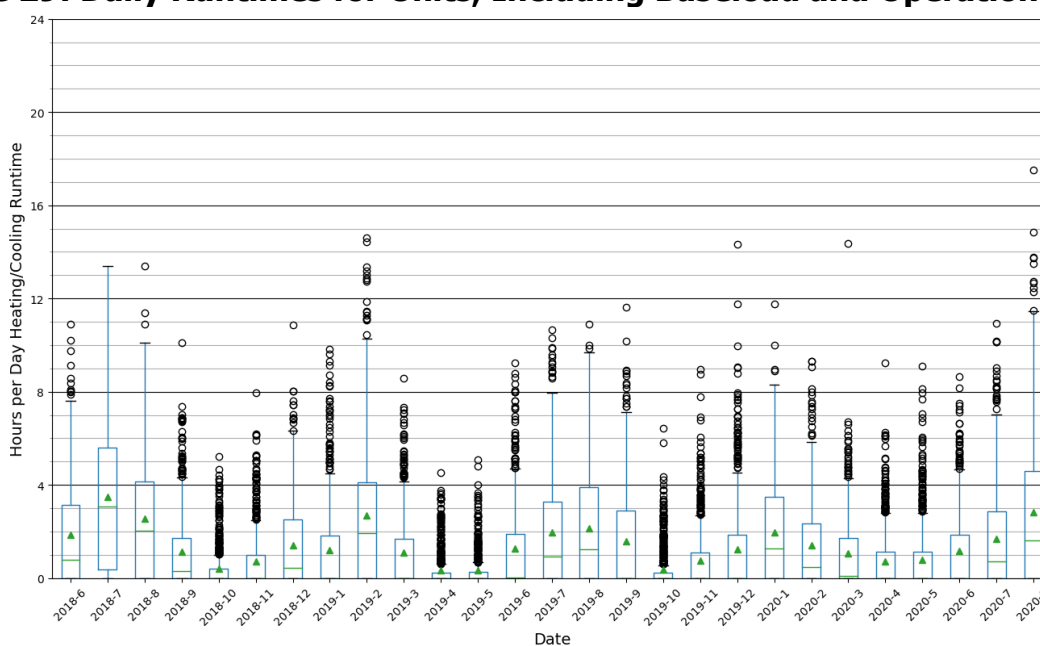
In general, runtimes were somewhat lower than expected for heating and cooling energy. The heat pumps operated, on average, 33 percent of all days (121 days per year). This varied by apartment (6 to 43 percent of total days) and seems to be largely behaviorally driven (rather than driven by orientation, building floor, or conditioned floor area). With the exception of a few outliers, cooling was the predominant load, being utilized 7 to 50 percent of days (a mean of 37 percent). Winter usage was similar (8 to 50 percent of all days; a mean of 33 percent) and shoulder season significantly less (2 to 40 percent of days; a mean of 23 percent). Generally, there was a strong correlation between consumption throughout seasons by apartment, where 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 in Appendix E). There is little demand for heating or cooling below an average daily temperature of 60°F, 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–83°F, and



heating balance points ranged from 44°F–68°F. In three apartments, there was no apparent significant heating load at all.

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



Total annual energy (heating/cooling as well as parasitic loads) averaged from 2.5 to 6.4 kWh/day by apartment (Figures E-27 and E-28 in Appendix E). Cooling and heating energy made up 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).<sup>14</sup> Due to proprietary engineering calculations, it is not possible to identify the actual distribution of baseload consumption between the crankcase, inverter controls, and the reversing valve.

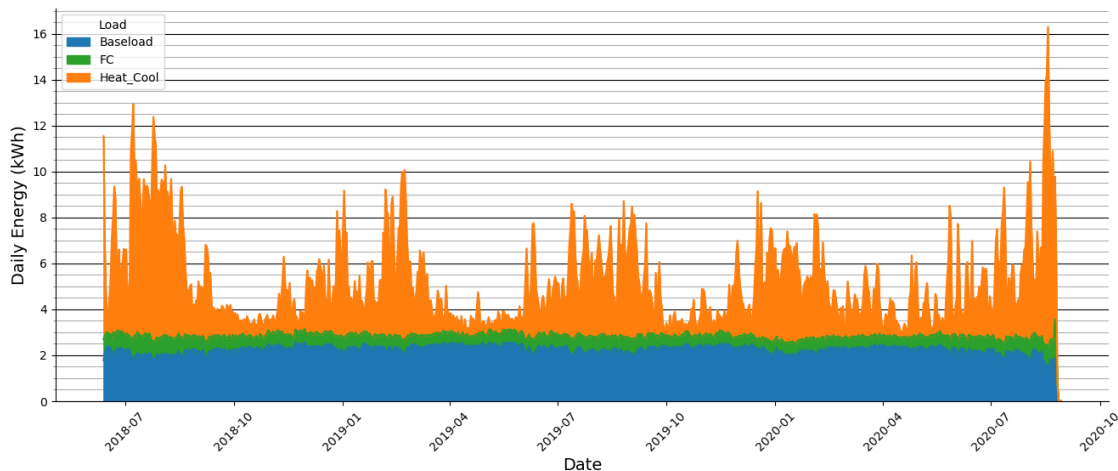
Seasonal demand patterns were as expected (Figures E-29 and E-30 in Appendix E). Shoulder months (October, April, and even November and March) were, on average, flat due to weather pattern changes on shorter time frames resulting in a mix of heating and cooling. Summer months peaked in mid-afternoon. Winter heating was much more persistent but did not experience a real peak with a decreased demand between 10 am and 4 pm. Both anecdotal and survey data suggest that tenants used their thermostats manually rather than taking a “set it and forget it” approach, which accounts 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/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 also was 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

<sup>14</sup> 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 to additional verification. The evaluation of baseload consumption and crankcase heater loads is ongoing.

conditioning. The total baseload uses approximately 2.5 kWh a day, even though the primary need for a crankcase heater in these units is when air temperatures drop below 40°F, less than 10 percent of annual operating hours (Figure E-31 in 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 annually. Figure 30 shows their contribution to total load (on average) throughout the period of monitoring, along with the fan coil unit and actual heating and cooling energy. Baseload energy per apartment varied based on space conditioning operation time.

**Figure 30: Contribution to Total Load (on Average) throughout the Monitoring Period**



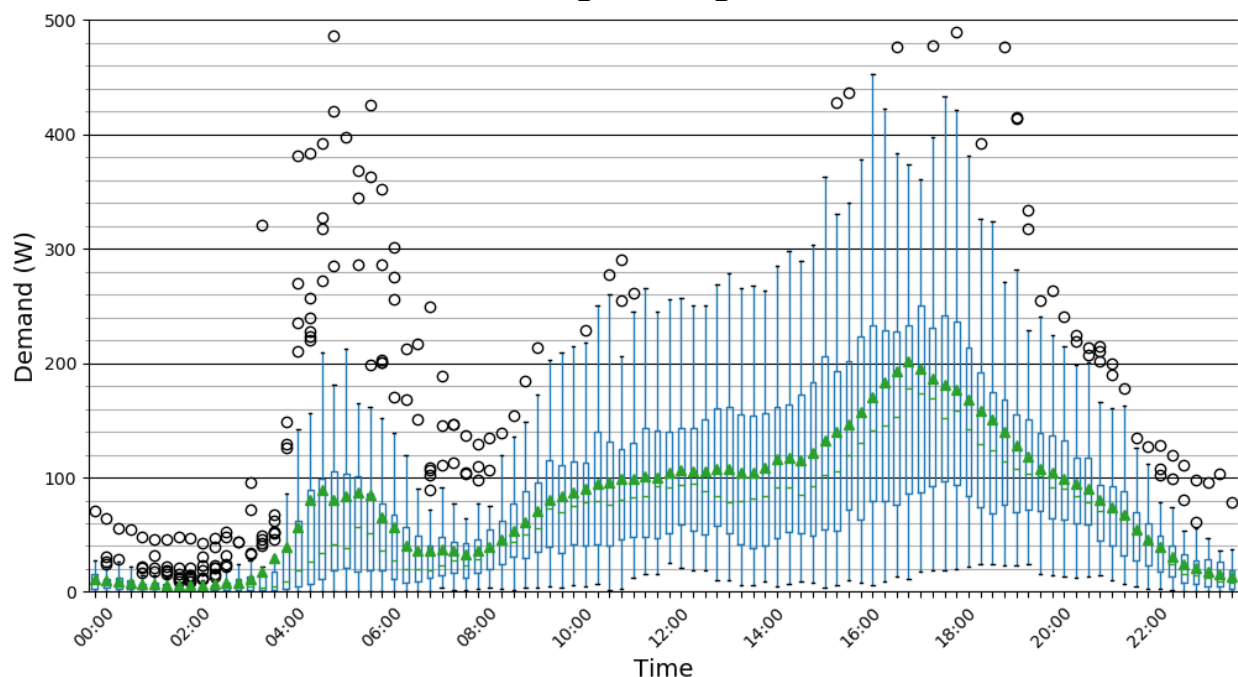
## Cooking

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

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

Yet, daily cooking demand was highly variable across apartments, except between 12 to 4 am, where it was virtually nonexistent. Most apartments followed a similar pattern that is present in Figure 31, involving a late evening peak (5 pm) and often an early morning peak (5 am).

**Figure 31: Cooking Demand by Hour Showed a General Morning Peak and Strong Evening Peak.**



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 number of bedrooms or occupancy. General receptacles and lighting comprised on average over 90 percent of the load. These loads included observed appliances such as cold/hot 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 in 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 in Appendix E).

## **Nexi Evaluation**

A primary goal of our end use monitoring was to study the behavioral change possible with energy feedback displays, but as mentioned this was not possible at Atascadero. That said, 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, whereas 54 percent were aware after the installation, with 46 percent of respondents noticing 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 consistent with the other projects, but also completed an analysis of code compliance modeling for the hot water draws and consumption.

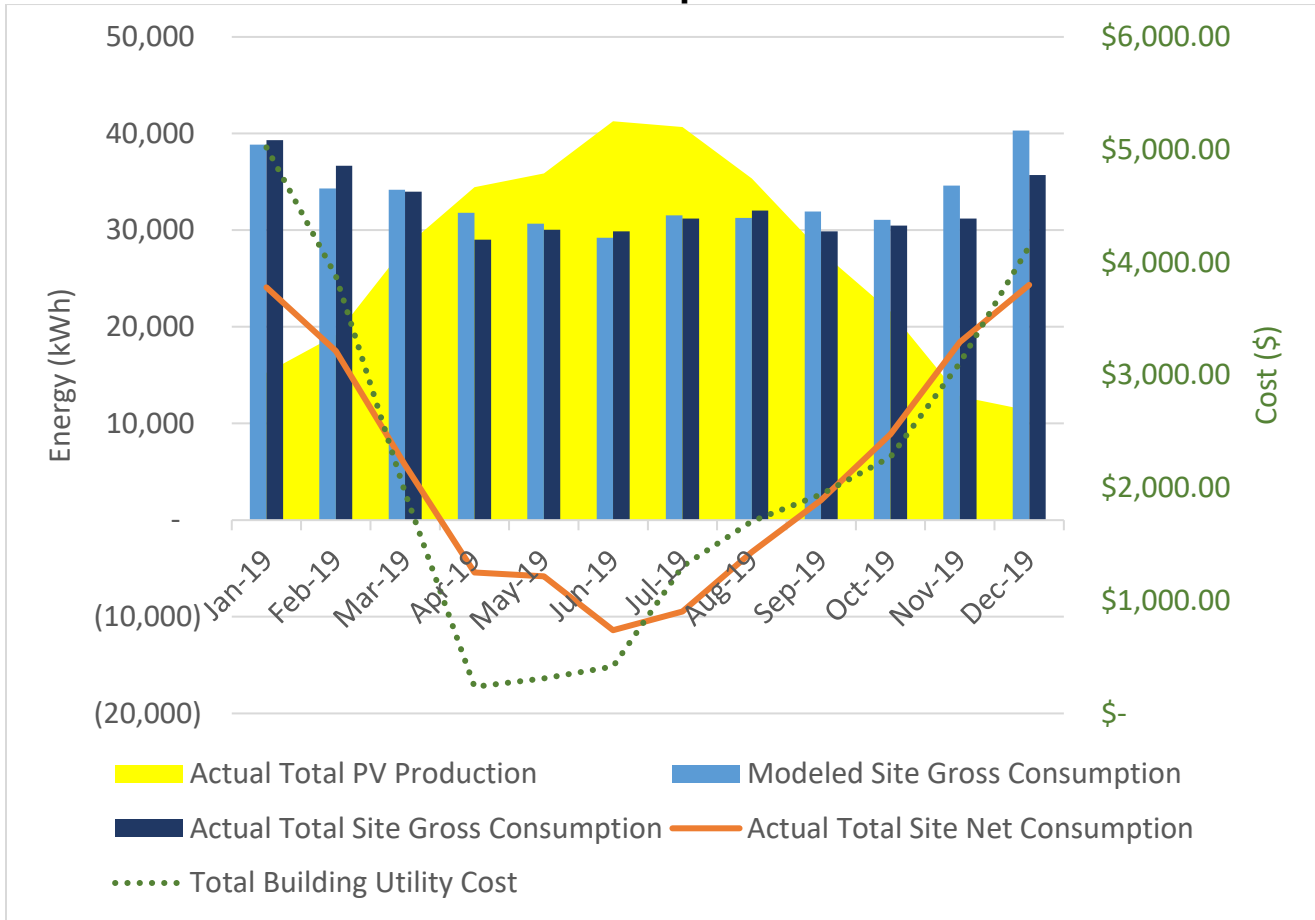
To properly size a zero net energy solar system, the property's energy usage was calculated by combining energy estimates from EnergyPro for a building's heating, cooling, and fan loads and the CUAC to estimate the building's lighting, plug loads, and appliance loads.

As others, Atascadero was originally modeled in EnergyPro 5.1 for code compliance, which showed 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 below 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 load. 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 around DHW, HVAC, and MELs and lighting. The source of the discrepancy of the PV model's output to its actual output is 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, therefore the discrepancy may be attributed to shading, equipment performance, panel

maintenance needs, system configuration, and/or yearly weather variance. It is likely the impact is a result of a combination of these factors.

**Figure 32: Atascadero Modeled Versus 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 reference an average over multiple years, and may not reflect actual weather patterns of specific years.

**Hot Water Use: Planned vs. Actual**

Given the ability to model individual heat pump water heater 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, predicts water use versus the actual water use of this project.

This evaluation compared daily water use on an apartment basis by number of bedrooms. On average the field water use was higher per unit and was closer to the modeled assumptions on

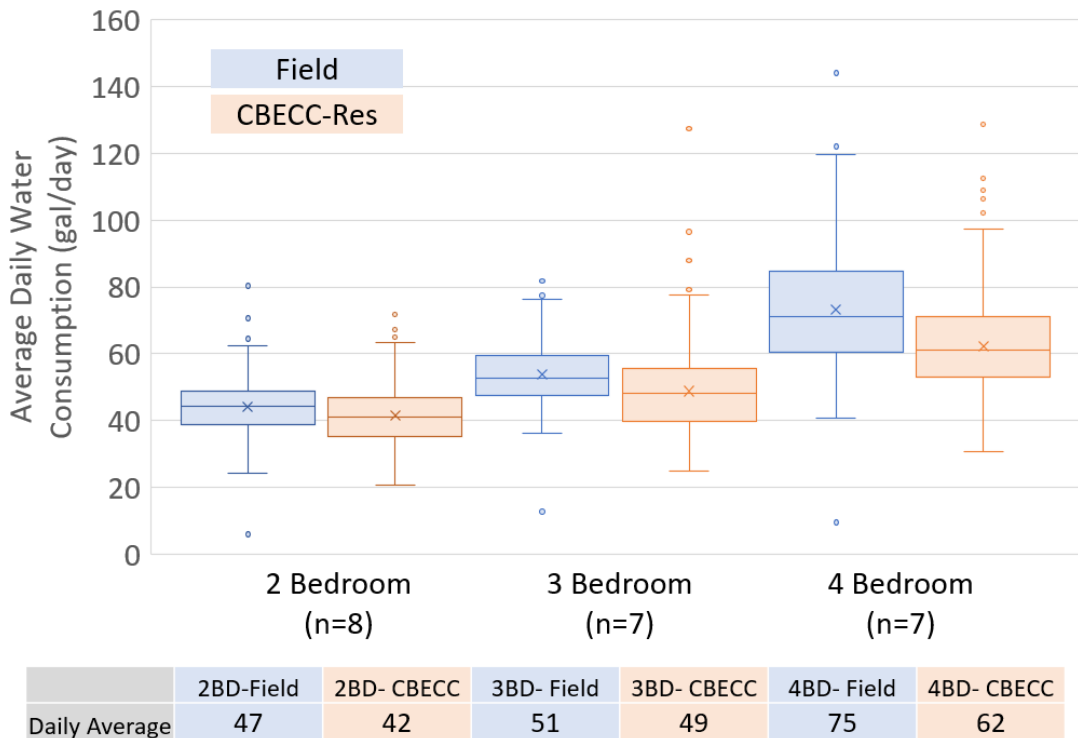
average for the smaller units and higher by 13 GPD for the four-bedroom units. This can be attributed to Atascadero having higher occupancies than what CBECC-Res predicts (see Table 16). The average occupancy in CBECC-Res is based on market rate apartments that have a lower occupancy than observed in these demonstration sites. At Atascadero the three- and four-bedroom units mostly had five occupants, whereas CBECC-Res predicts that the three-bedroom units mostly have three occupants, and the four-bedroom units mostly have four occupants.

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

| Occupancy | Atascadero Occupancy |                  |                  | CBECC-Res Occupancy for Multi Family Homes |           |           |           |           |       |
|-----------|----------------------|------------------|------------------|--|-----------|-----------|-----------|-----------|-------|
|           | 2 Bedroom (n=21)     | 3 Bedroom (n=23) | 4 Bedroom (n=14) | Studio                                     | 1 Bedroom | 2 Bedroom | 3 Bedroom | 4 Bedroom | 5+    |
| 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%               | -  | -         | -         | -         | -         | -     |

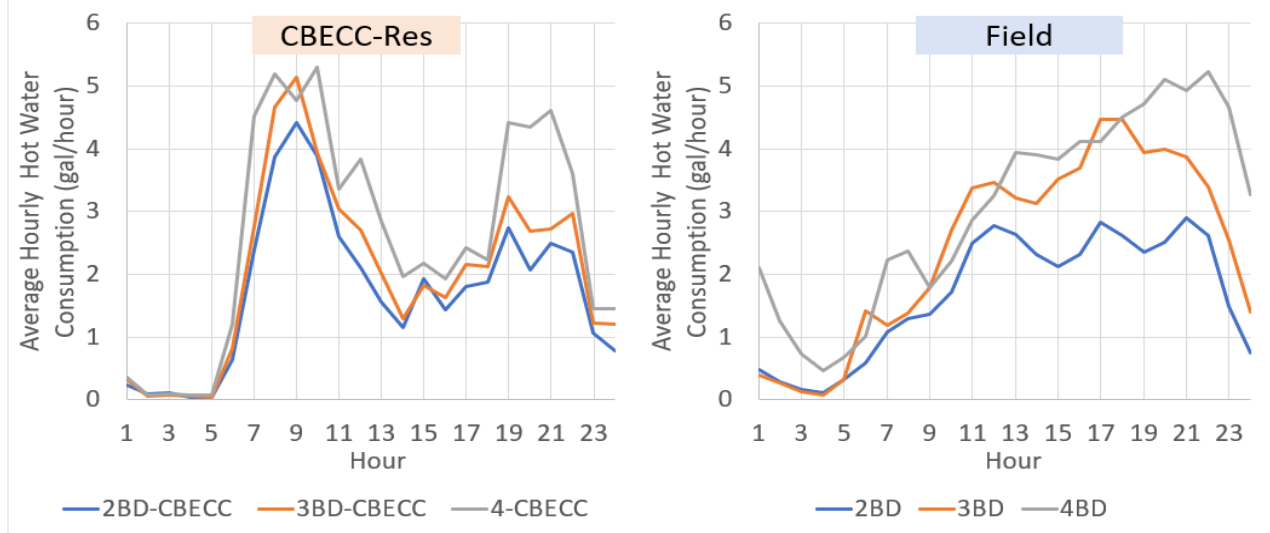
The spread of daily draws was similar between the field and CBECC-Res for the two- and three-bedroom units, but for the four-bedroom units there was more variation of daily draws in the field data. Generally, the average daily water usage was higher than the model assumptions, as summarized in Figure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

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



The average hourly use also varied from the field versus CBECC-Res data. There was a much stronger evening peak at Atascadero, and CBECC-Res has a larger and later morning peak and a later and smaller evening peak (Figure 34). Time of use has implications for TDV energy use and grid impacts. Because Atascadero has greater evening peaks, it may 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 the actual end uses, as discussed in the performance of HVAC and HPWHs. The evaluation of hot water draws and modeling have informed findings.

## Sunnyvale

The Sunnyvale project was monitored from February 2019 to July 2020. While the whole building central heat pump system performs well, this is 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

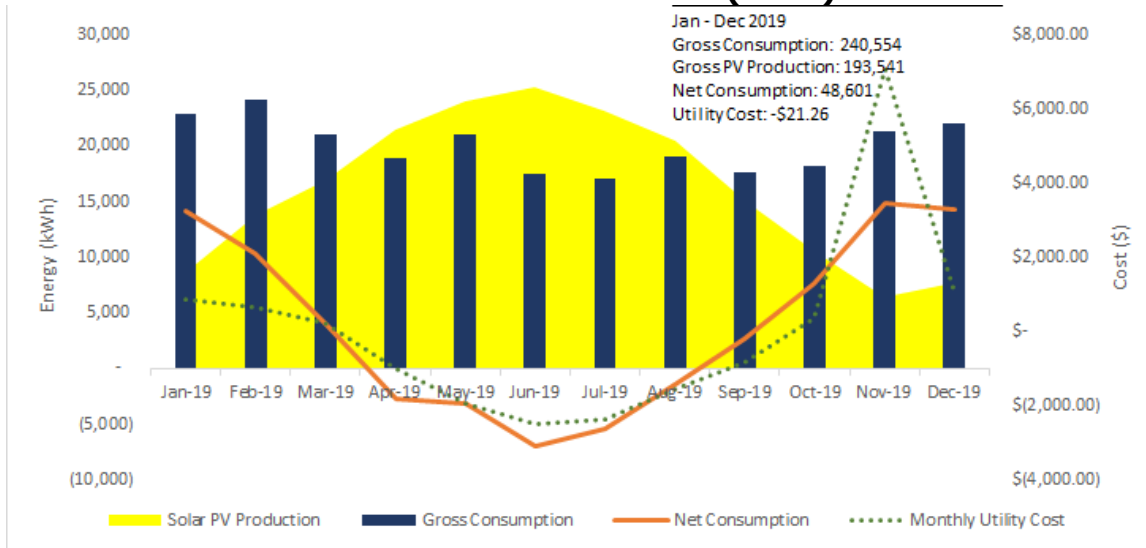
Overall, the Sunnyvale project did not meet the goal of common area ZNE goals defined in the design stages.

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, 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 the performance improved from the beginning of 2019 compared to the end of the year. Also, the building was not fully occupied until January 30, 2019. The resulting downward trend in energy consumption coinciding with more favorable spring conditions is evident 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 is inclusive of the annual true up. This was possible because the common area meter is 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 the price for electricity, and therefore solar credit value, is higher during the afternoon and evening when peak consumption occurs, as well as higher in the summer. This aligns with solar production. This creates a greater cost offset than a production offset.

In terms of missing the ZNE mark, the discrepancy came from the energy consumption, rather than from the energy production (see the Planned Actual and Modeling section below). 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, the argument to invest in a larger or more production PV solar system is challenging.

**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 hood—but not the range. 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 an SD card with the stored data.

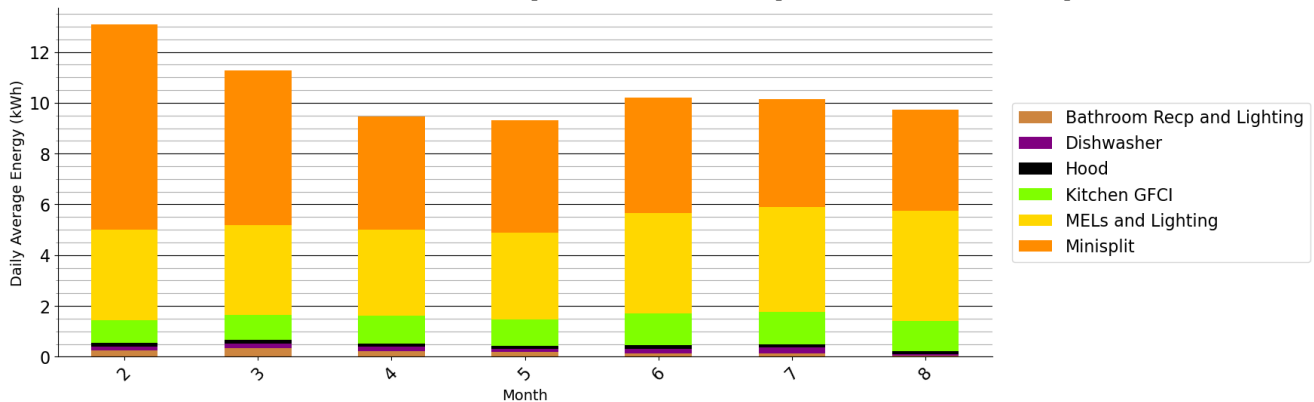
Whole apartment consumption is largely sensitive to occupancy, individual behavior, and seasonality (Figures F-1 in Appendix F). That said, since the tenant loads do not include DHW, there is less representation of seasonality and occupancy impacts than those seen at Atascadero. Figure 36 shows total 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 is normally distributed across apartments (Figure F-3 in Appendix F). Overall, averages aligned with the other projects, assuming exclusion of DHW.

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

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

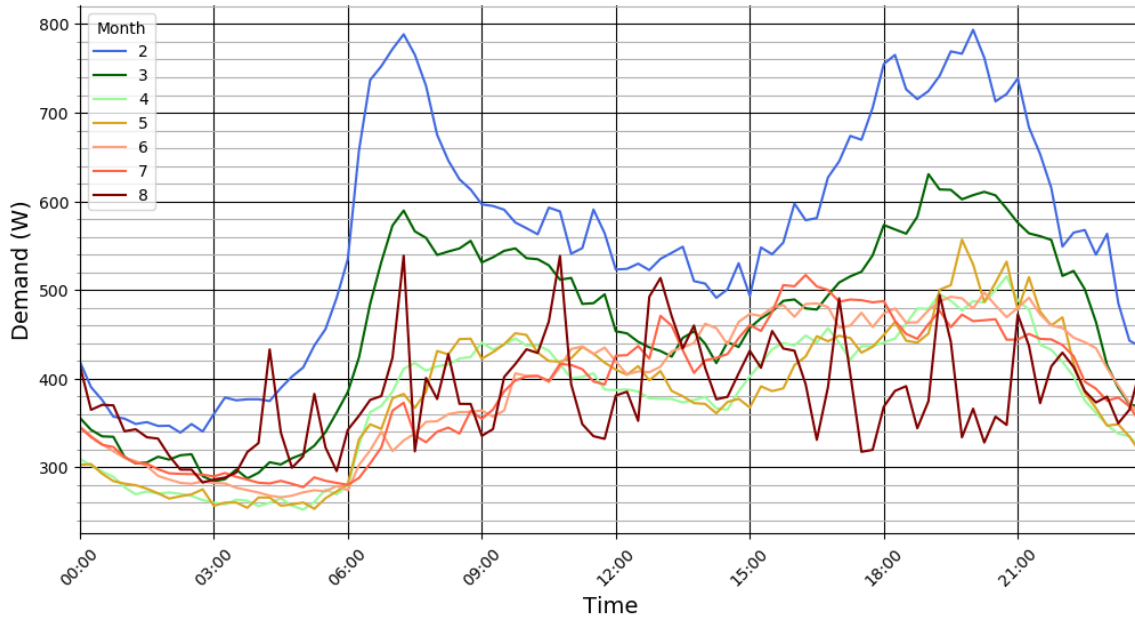
HVAC, MELs, and lighting made up the vast majority of consumption, as shown in Figure 36. On an individual apartment basis, HVAC accounted for between 29 to 76 percent of annual consumption, and on average, MELs (plugs, including kitchen and bathroom) and lighting accounted for approximately 15 to 70 percent of the total annual load. At its seasonal peaks, HVAC made up on average 44 to 80 percent of total consumption in July and 27 to 82 percent in February. In shoulder season, 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 quite 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 to <500 W in the evening in summer. Morning peaks in the summer were almost nonexistent. The peaks shown seem driven largely by HVAC.

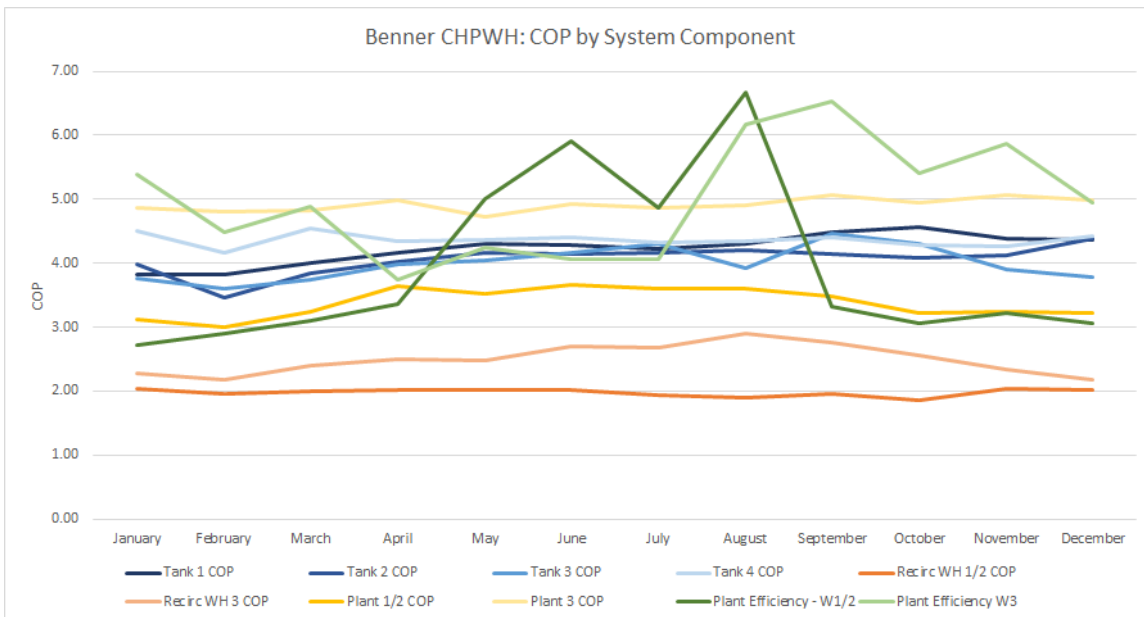
**Figure 37: Demand Is Driven by HVAC Loads and Can Clearly Be Seen in Greater Demand in February.**



**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 in Appendix F) shows the calculated COP of the plants and plant components, as well as the efficiency of the plants.

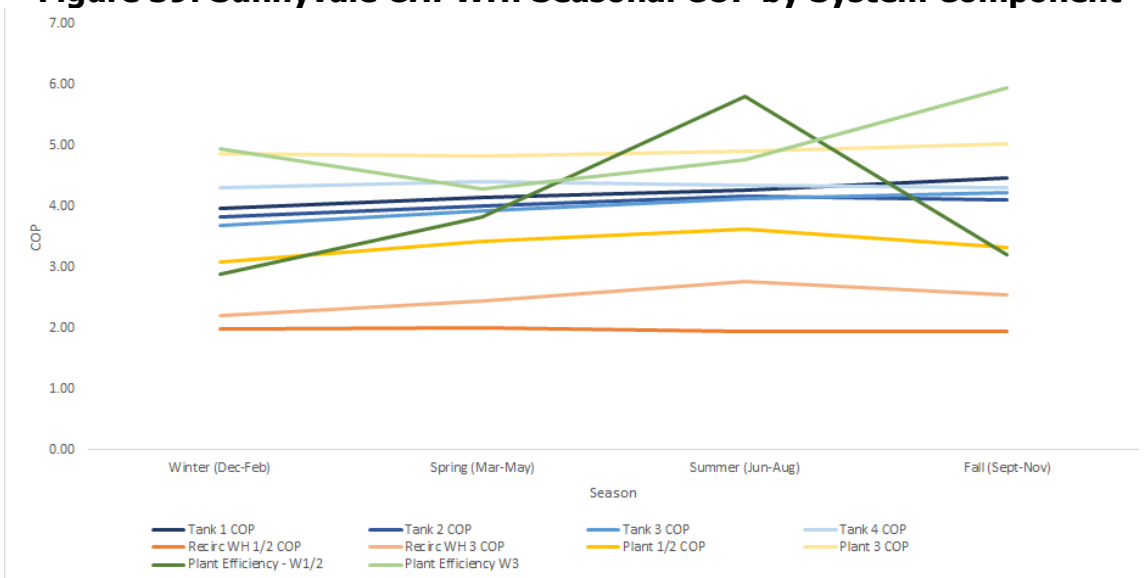
**Figure 38: Sunnyvale Monthly COP by System Component**



The Sanden heat pumps generally performed around or slightly below the specified COP of 4.5,<sup>15</sup> 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 annually and for most months of the year. Bank 2 performed second best, and bank 1 performed the best, in terms of average monthly and annual COPs. It is important to note along with these findings that bank 3 and tank 3 carry the largest portion of the DHW production load for the plant for wings 1 and 2, bank 2 carries the second most, and Bank 1 the least, as a result 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, rather than reverse return, tank 1 sees the least amount of flow and thus contributes 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 distributed, 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 performance during the summer and fall. On average, the air temperatures in the summer and fall were warmer than those in the winter and spring; fall was typically warmer than spring in comparing shoulder seasons (Figure 39). This was generally reflected in the average COP data and in that the COP followed air temperature. The variations from this trend were limited and marginal.

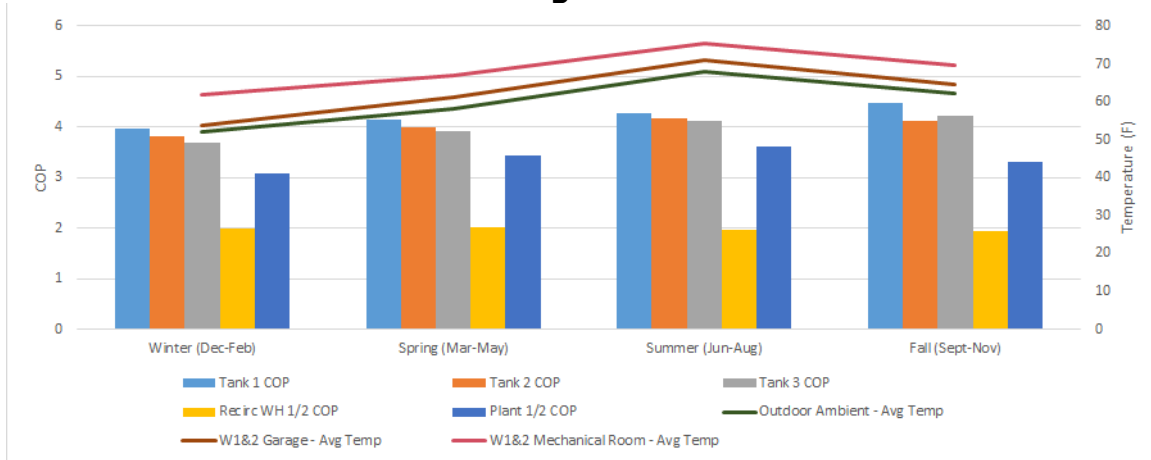
**Figure 39: Sunnyvale CHPWH: Seasonal COP by System Component**



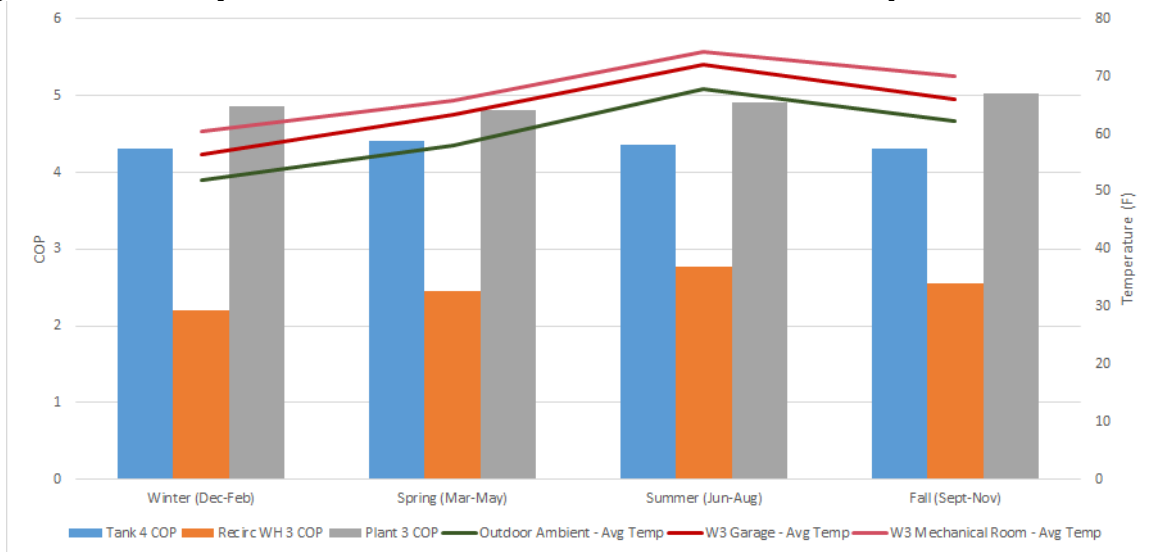
<sup>15</sup> Referencing COP @60°F, as shown in the Sanden technical manual.

One of the driving factors of the heat pumps' performance is 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, as well as improved COPs for each bank with 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 data collection was used to evaluate and inform heat pump water heater sizing best practices. DHW demand by way of 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 one-hour, two-hour, and three-hour intervals were used to inform continued demand events versus short, large events, which would affect the recovery capacity needed. Twenty-four hour demand was included for comparison, to understand if the demand event was a one-time event occurring during an otherwise low or

normal usage or sustained usage throughout the days. Table 17 includes three-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 inform the output and storage capacity of the DHW system. These values were then compared to two hypothetical systems of DHW plants sized using the Ecotope Ecosizer.<sup>16</sup> 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 (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, the actual and Low and Low-Medium design estimates indicated the original design of 400-gallon storage tanks for an effective storage of 960 gallons met the actual three-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 demand, based on 25 gallons per person per day, appears to be the most reasonable basis for sizing future domestic hot water systems.

**Table 17: 99th Percentile 3-Hour, and Daily Peak Demand 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

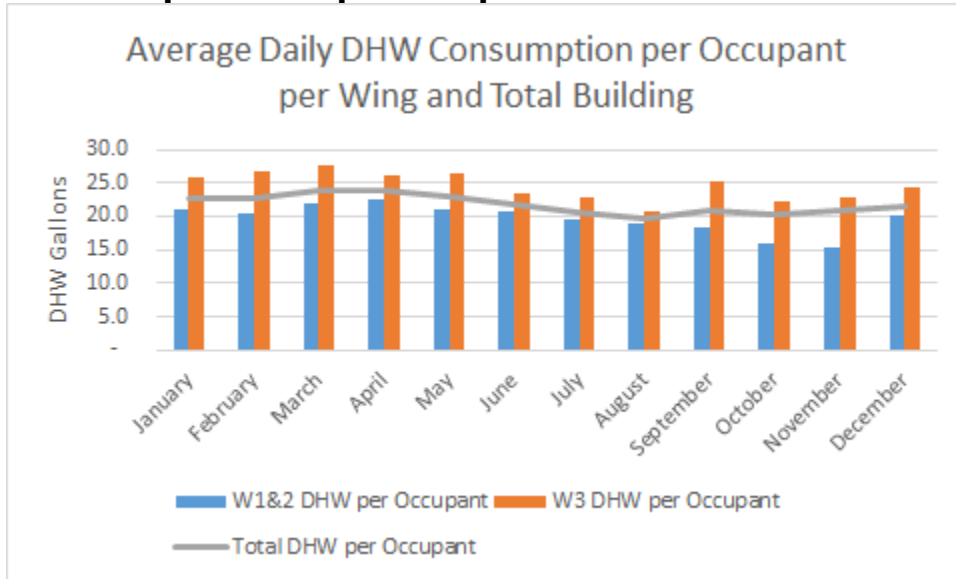
Because occupancy, rather than unit count, is the main driver of domestic hot water consumption, it was the most fitting normalizer to quantify both domestic hot water and energy consumption.

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 in Appendix F).

---

<sup>16</sup> Ecotope’s Ecosizer sizing is based on the number of units and unit layouts (1 bed/1 bath, 2 bed/1 bath, etc.), using ASHRAE Low- and Medium-demand profiles, as well as a Low-Medium demand that is in between the two (e.g., peak gallons/day/person: Low = 20, Low-Medium = 25, and Medium = 49).

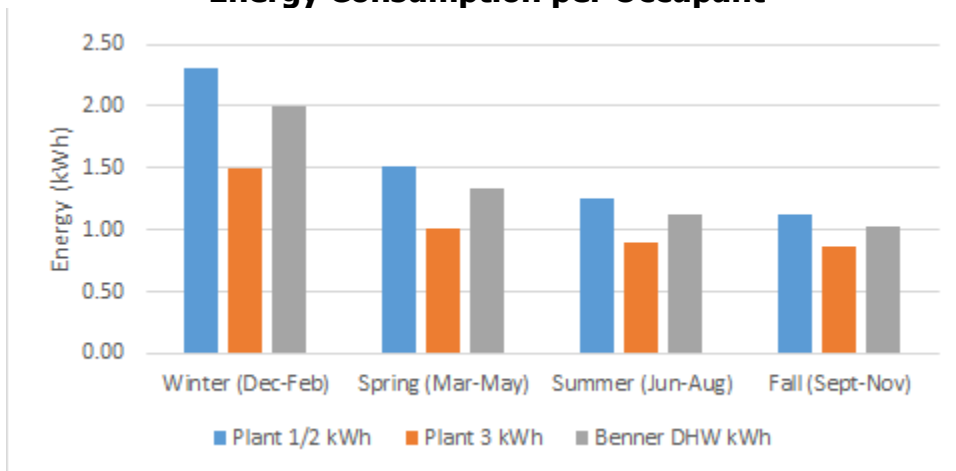
**Figure 42: Average Daily Plant and Total DHW Consumption per Month per Occupant over 14 Months**



The mid-morning peak tapers a bit, but continues throughout the day and leads to an even larger evening peak. The evening DHW peak climaxes during the 8 pm hour and then starts 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 is somewhat unique due to the continuous nature of consumption as compared to other properties and is likely indicative of the demographics. Generally, based on survey data, apartments are 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 in 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**



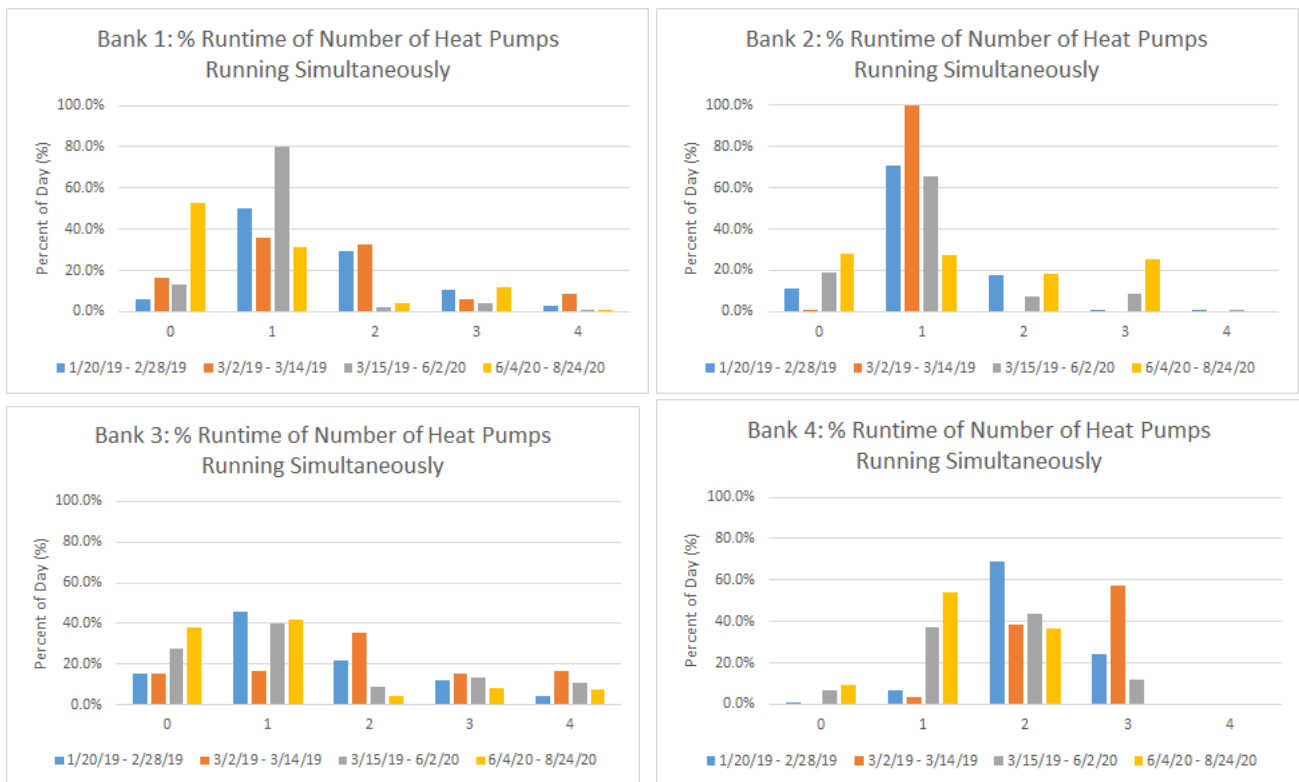
Consistent with system performance and efficiency, both DHW plants consumed less energy during the summer and fall months, with the highest average daily consumption in the winter months. The Sanden heat pumps do not operate as efficiently in colder ambient air temperatures as they do at warmer temperatures, so they must 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 an intent 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 is challenging to isolate that impact. See Table F-4 in Appendix F that includes detailed runtimes for specific time periods.

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

**Figure 44: Simultaneous Heat Pump Operation:  
Percent Runtime within Each Bank**



The bucketed date ranges within the graphs represent time periods of differing control; 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 to 9 pm 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 below).

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 changed (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 is not necessarily problematic from an energy or performance perspective. It is 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 has a recirculation system served by a dedicated HPWH 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 of 100 W per apartment (Table F-5 in 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). The wing 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 Performance**

|                 | Single Speed                         | Variable Speed                     |
|-----------------|--------------------------------------|------------------------------------|
| Average gpm     | 30.2 gpm (W1 and 2)<br>2.2 gpm (W3)  | 3.5 gpm (W1 and 2)<br>1.5 gpm (W3) |
| Average kWh/Day | 28.0 kWh (W1 and 2)<br>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 was 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 mode and set point for the recirculation water heater. Starting in High Demand mode at 140°F, mode and set point adjustments were made to reduce energy consumption. When switched to Energy Saver mode, the unit could not keep up with the recirculation load and hot water supply temperature fell. The set point was incrementally adjusted downward to 125°F, at which temperature the units maintained recirculation load.

Though it could not be determined definitively why the Rheem HPWH unit could not maintain recirculation loop temperature in any mode other than High Demand, it is hypothesized that it is largely attributable to the operating algorithms for the Energy Saver mode. As seen at Atascadero, there was more electric resistance use to achieve set point in addition to intermittent periods of the unit being totally off, as the tank temperature continued to drop 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.

A heat pump water heater was used as the recirculation loop heater for 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 of an electric resistance heater. The seasonal differences in COPs were negligible and fairly stable throughout the year, with little impact on efficiency, due to consistent water temperature as compared to the Sanden heat pumps, which received variable incoming water temperature.

The HPWH in wings 1 and 2 had a significantly larger operating time and electric resistance usage, as shown in Table 19. The lower flow rate (1.5 gpm in wing 3) and lower load resulted in more efficient operation compared to wings 1 and 2. The higher DHW load and the reduced

stratification caused by the higher recirculation flow rate increased energy consumption in the HPWH serving 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 of the aspects that was not evaluated in this research project was the distribution system, as thermistors were not installed on each riser to capture this data. A limited sample of tenant satisfaction surveys indicated range of satisfaction with domestic hot water that do not readily correspond to floor or plant. While understanding plant and recirculation system performance is 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 wing 1 and 2 plant by cutting power to one bank during the peak demand period defined by the utility rate. Based on the measured average and peak loads on the specific bank of heat pumps, Bank 1 heat pumps, which had 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. Instead 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 pm each day and then restore power at 9 pm. With this methodology, the load that would have been accrued during this five-hour peak time period was shifted to 9 pm 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 is 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 discernable 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.

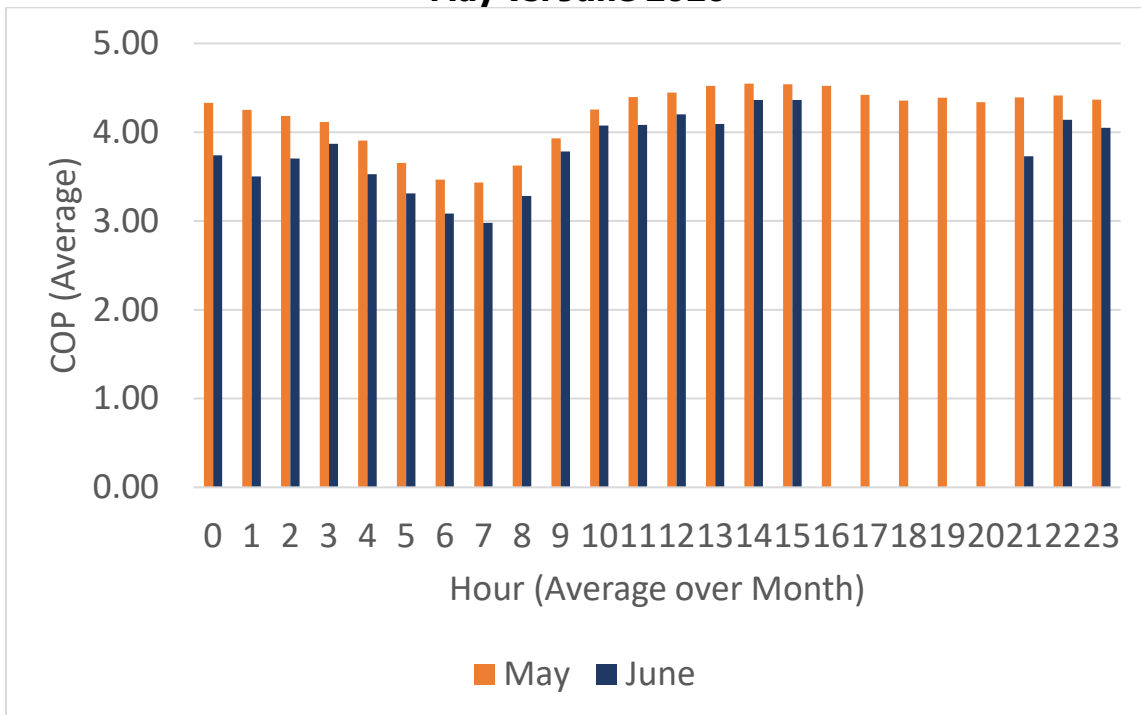
**Table 20: Total kWh for Two-Week Pre- and Post-Load Shifting**

| 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      | <b>412.20</b>           | 2,462                   |
| 6/4–6/20 (load shifting)     | 68.10       | 73.27       | 0.02        | 201.18      | <b>342.56</b>           | 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 to 10 pm hour after conclusion of the load shift period. Because of this, it is 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, which was 6.3°F 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/cooling energy (represented mostly by compressor and fan energy) and baseloads.

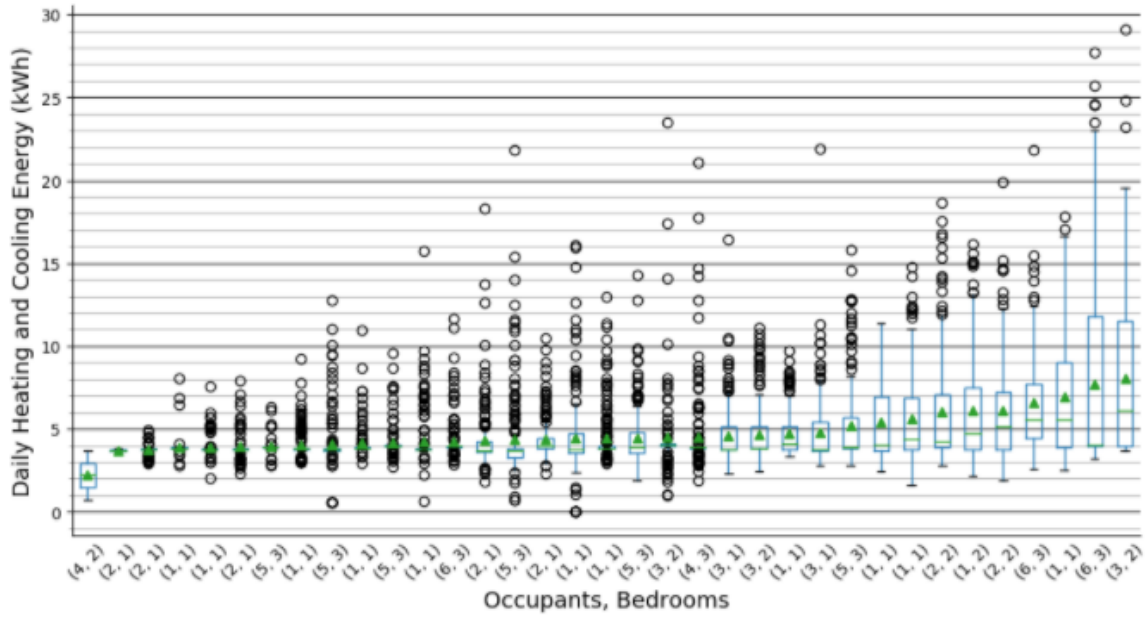
The space conditioning is provided by Mitsubishi ductless mini-splits with two to four heads in each unit, depending on the number of bedrooms per apartment, as shown in Table 21.

**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                              |

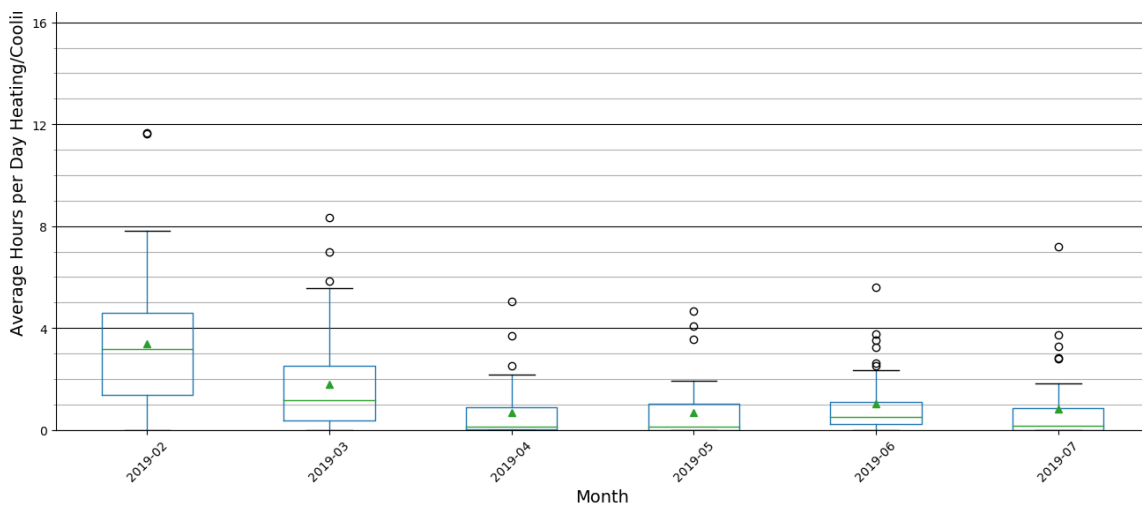
Overall heating and cooling loads were low, with heating being the dominant load. Summer loads were mainly driven by non-compressor loads (or baseloads) defined as 250 W or less, identified through monitoring (Figure 46) (Figure F-7 in Appendix F).

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



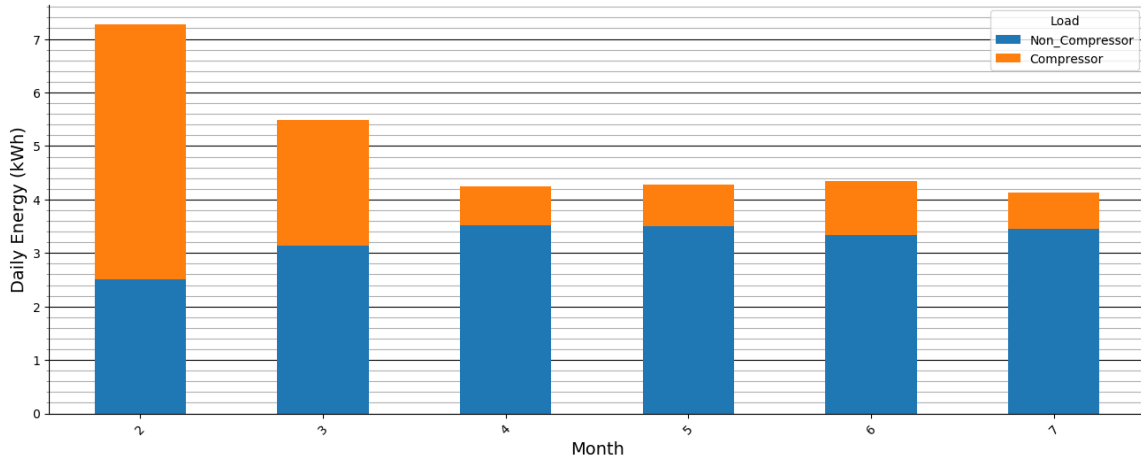
In general, runtimes are somewhat lower than expected for heating and cooling energy. Even for apartments that consistently heat or cool daily, daily runtimes are low, although generally longer in the winter (Figure 47). Runtimes on average for the whole six month period range from 0 to 274 minutes per 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. Small sample of tenants (16 percent response rate) responded to maintain lower set point temperatures than data showed. Averages and variance in runtimes across apartments was greater in the winter, but varied greatly in response to short-term weather patterns (Figure F-8 in 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 Clearly Higher Consumption in Winter.**



The research team identified the high baseload 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 the heating or cooling load itself did, as shown in Figure 48. The load was relatively evenly distributed across apartments (Figure F-9 in Appendix F).

**Figure 48: The HVAC Load Was Disaggregated by Compressor and Non-compressor (<250W) Runtime to Understand the 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 at 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 is a baseload present at all times when the unit is 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, and the manufacturer has been 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 to 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 to 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 is 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

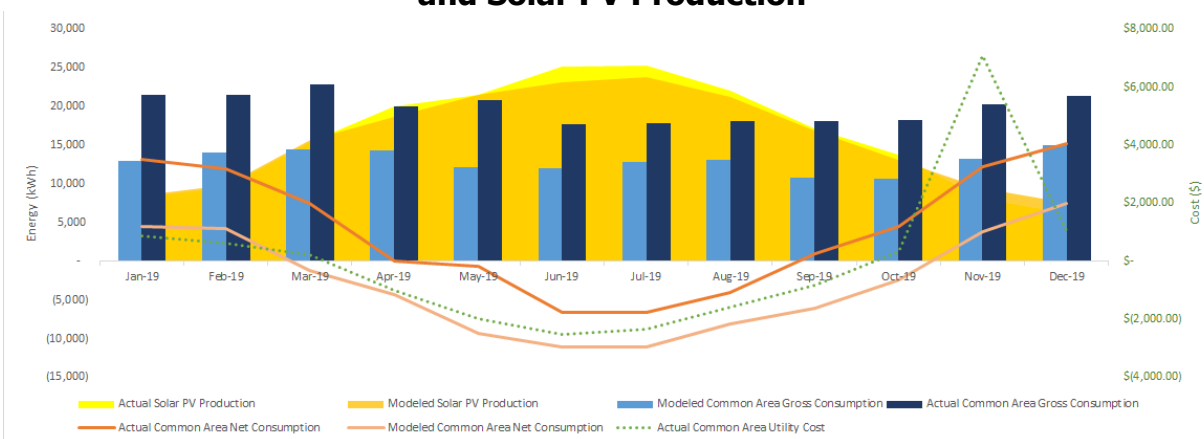
Similar to Atascadero, Nexi evaluation at Sunnyvale is limited to surveys with 33 percent response rate. That said, 54 percent of survey residents noticed the Nexi display at least three times a day. The lighting displays were installed at move-in so at this development, there was not a period without the lighting displays installed. Therefore, it is hard to evaluate energy awareness pre and post installation of the lighting display. Yet, 45 percent indicated the Nexi

influenced their behavior (rating of 6 or greater on scale of 1–9) and 80 percent if 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 (i.e., 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<sup>17</sup> 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 to the average. The building model underestimated energy consumption of both the total building and common area loads. The modeled energy consumption of the common area loads, including that of the DHW system, was much lower than the actual measured consumption; missing the ZNE target therefore does not necessarily indicate poor performance, but highlights the discrepancy of the modeling tools. The actual total gross building consumption was 20 percent higher than was modeled, and the actual total gross common area consumption was 53 percent higher than was modeled. The central heat pump water heater 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 is attributed to other modeled loads, but our monitoring did not support evaluation of all common end uses disaggregated.

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.

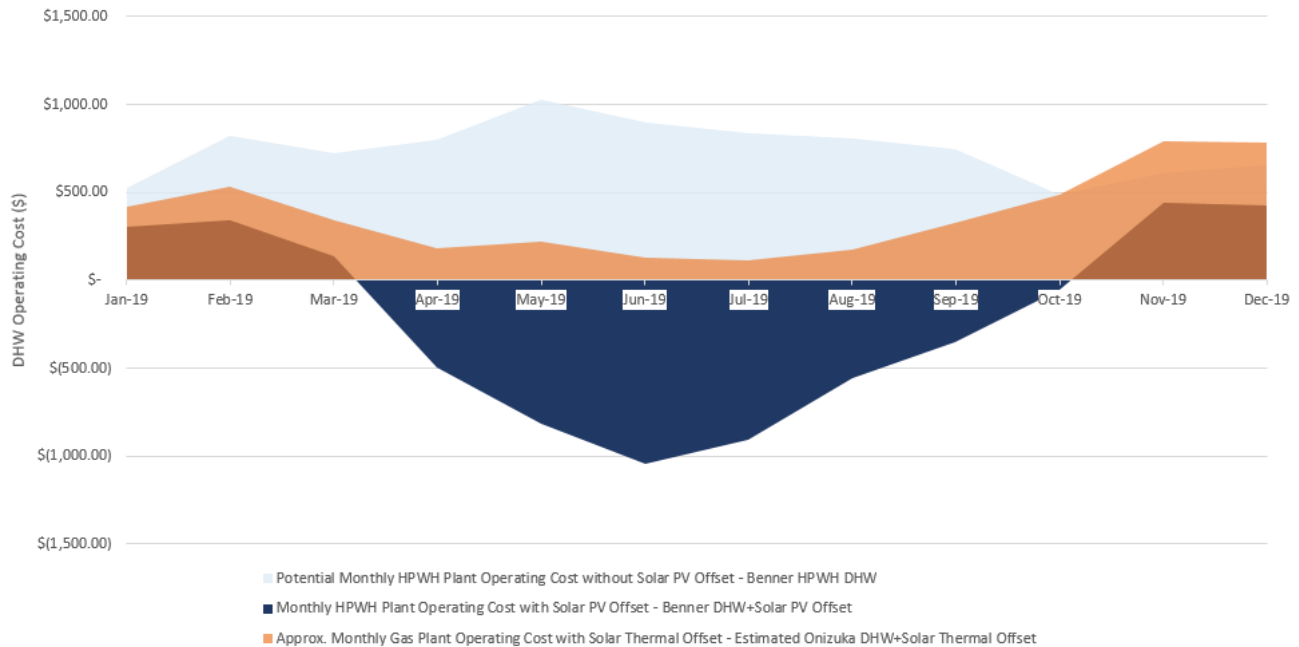
17 The PV Watts tool has a far smaller chance of a shading calculation error for a system installed on a high rise building in a dense urban environment without neighboring tall buildings.

## Operations and Maintenance

Understanding operations and maintenance of an all-electric system is critical to decision making.

CHPWH plant operational costs were estimated for this 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 baked into 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 contribution compared to a gas boiler central system where the costs are never offset by renewables, though load is reduced by the solar thermal. The findings demonstrate the cost-effectiveness of all-electric central heat pump systems when paired with PV and that zero net energy 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 the significant performance and energy consulting during design and installation, this study enabled support and training provisions to the maintenance and property staff. An operations and maintenance manual was prepared, along with a 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 also identifies with what frequency the recommended actions should be taken.

Finally, support was provided to the building owner staff to effectively utilize utility data and solar PV monitoring data to track operations and operational cost of the new building once fully occupied, which provided useful insights into the project's design success. The utility data



can also indicate specific system performance, depending on the operational condition; if there is an egregious issue with a large end use like the CHPWH system on the owner-paid house electric meter, it will 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 into a 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 the projects and individual systems, as well as the impacts of the electrical loads, and to understand opportunities and challenges to achieving zero net energy on each of these projects. The data analysis has informed findings and recommendations to advance all-electric zero net energy multifamily buildings, and these will be discussed in Chapter 5.

## CHAPTER 5:

# Findings and Recommendations

---

This research demonstrated that all-electric zero net energy 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 aspect and ZNE aspect 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 affordability of utility costs. Each of the projects were within 17 to 20 percent of achieving ZNE in 2019. Yet, with adjustments, 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 systems 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 material costs of central gas boilers and chillers is 18 percent greater than 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 system for each apartment. However, lacking Labor costs, we cannot conclude that individual systems are actually less expensive than central systems, only that gas 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 to support the 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 (HVAC)
- 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 has 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 pm. 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 use 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 is 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 to Energy Saver 125°F (both scenarios have mixing valves installed and set to 120°F), there was an overall decrease in energy consumption while in Energy Saver mode at 125°F, but an increase in the fraction of electric resistance usage. This is in part due to the fact that the smaller volume of available hot water that exists when storing at lower temperatures (125°F in this case and mixing down to 120°F) compared to storing water at 140°F mixed down to 120°F. This lower volume of available hot water resulted in the water heater having to spend more time trying 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 set point to a 125°F 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 the California Plumbing Code sizing guidance, as the number of bedrooms increase, the occurrence that the HPWH cannot provide hot water also increases. 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 occurrence that the HPWH cannot provide sufficient hot water is increased when running in heat pump only mode for all bedroom types and both HPWH sizes. If the intention is to avoid running the HPWH with

the electric resistance element to maximize 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 is 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 5pm -9pm 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 from 9 pm to 4 pm and then switch to Energy Saver Mode with a set point of 115° from 4 pm to 9 pm. The manual would describe how it worked, when it made the switch, and what the trade-offs/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 (i.e., 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) flexibility to expand available hot water for any given tank size, (2) flexibility for load shifting, (3) the ability to ensure safe hot water delivery temperatures, and (4) 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 which would increase energy consumption. This could be addressed in the energy code, building code or appliance standards. The energy savings aspect for HPWH with auxiliary heat would support energy efficiency goal of the energy code. It could be installed externally to the HPWH, or manufacturers could include a mixing valve that is integral to the HPWH. To allow for compliance with the plumbing code and accommodate various sizes of HPWHs, especially in multifamily residences, it would be helpful to consider an amendment to California Plumbing Code to clearly allow for first hour delivery based on a higher set point with the 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 140F.

**Monitoring.** These findings apply to operations and maintenance.

Systems may be monitored for research or for 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 to enable 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 nascent. Additional research on sizing HPWHs for load shifting would be beneficial as well as how load shifting should be addressed in models is needed.

## **Central Modular DHW**

Sanden currently makes the only commercially available low-global warming potential (GWP) heat pump water heating product that uses CO<sub>2</sub> as a refrigerant, which can be effectively employed in central water heating applications. Mitsubishi will be introducing its larger capacity QAHV CO<sub>2</sub>-based central HPWH to the U.S. market later in 2021, but for the time being Sanden remains the only commercially available low-GWP option for these applications. Even when other systems that are purpose built for central system applications become more widely available there will still be a market and a need for these types of modular systems due to 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. Therefore it is critical that best practices be developed for the effective design and installation of these modular Sanden systems and that some degree of standardization be developed. While this project has demonstrated that these systems can be deployed very effectively and achieve very high efficiencies, it also has revealed that it can be quite difficult to do and requires very careful planning and commissioning. Developing standardized approaches to design and installation will mitigate issues associated with system complexity and will be critical to achieving market adoption. The recommendations and findings below are based on the 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/or testing of each system is necessary. Development of system verification protocols should align with system complexity. The eventual goal should be simple post-installation HERS verification once design and installation of HPWH products become ubiquitous 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 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 undergoes 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 the specification (heat pump, recirculation heaters, pumps and balancing valves, pipe and storage tank insulation)
- Desired delivery temperature from the heat pumps to the tanks is achieved
- Supply temperature to the building after the mixing valve is meeting the mixing valve set point
- 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 is occurring
- 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: (1) when tanks and/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 for optimized efficiency, (2) use of an electronic mixing valve for finer tempering and control, and (3) 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 heat pump water heater to optimize performance.

When utilizing a heat pump water heater 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 evaluating 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. That said, 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 system installation and maintenance cost, 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 properties and owner entities are not purchasing and maintaining hot water systems that are larger than necessary.

**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 into/out of each storage tank temperature, supply post-mixing valve to building temperature, recirculation return temperature, supply from recirculation heater temperature (if applicable), supply and return temperature to/from each group of heat pumps, HP electrical, and CWMU flow. This monitoring can supplement routine maintenance and evaluation 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 O&M manual in tandem with the system's installation.

### **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 the intended operation. As more modular systems are put into 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 having multiple units run simultaneously for shorter durations, versus fewer units running for longer durations to minimize short cycling, will be beneficial to inform control strategies.
- **Load Shifting.** The load shifting results presented in this report demonstrate feasibility of 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 try and manage set points and heat pump operation using a more sophisticated control?
- **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 evaluation would be valuable.
- **Recirculation Heater versus 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 the installation requirements.

## **Combined Space Conditioning and DHW**

The high level of complexity of the combined systems monitored under this project proved to serve as a barrier to realizing the manufacturers stated potential energy performance. These systems are generally better suited for commercial projects that typically have more highly trained maintenance staff and typically involve commercial mechanical contractors during installation. These types of systems are also better suited for projects with a 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 in engineering and/or 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 complexity of combined space conditioning and water heating systems, there is 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/or design community to 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 having a far more complicated system; therefore, each project should be thoroughly assessed prior to system design to determine whether the climatic conditions and use cases for that property are well suited for heat recovery. High cooling loads that are coincident with DHW demand is the primary indicator 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 who have some experience with larger more complicated mechanical systems would be a better fit 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 systems and ductless mini-split systems that were not anticipated nor accounted for in the design or energy usage calculations for ZNE. Baseloads can be addressed through codes and standards and manufacturing, but they must be recognized in design and installation as well. Baseloads of interest may include those for crankcase heaters or preheaters, reversing valves, and inverter controls. At least one manufacturer indicated information on these baseloads were proprietary.

For split systems, specify equipment that either has (1) a crankcase heater with controls to limit operation to temperature bands when needed or (2) does not include a crankcase heater. This requires the design team to look very closely at the technical specifications and/or engage with the manufacturer, as they are not consistent across product types and are not apparent in energy data. For an existing condensing unit, a temperature relay may be an option to control crankcase operation. For ductless mini-splits, provide installation specifications to ensure preheater, fan operation, and air temperature sampling to optimize the system and minimize baseload operation. The research team is currently in the process of understanding this operation in order to make a clearer recommendation and determine if 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 of a heat pump, and are not consistently documented as an additional energy load within the technical documents. This can be addressed in several different ways: (1) through revision of national testing protocols to include these operational loads; (2) through disclosure requirements for crankcase, preheater loads and/or other baseloads associated with outdoor units; and/or (3) modifications to codes and standards to account for the 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 impact of these baseloads on projected building energy consumption and PV sizing.

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

As with heat pump water heater 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 the conditions for optimal performance, so they can apply those to their own circumstances. Providing additional information on the optimized schedules is necessary as these systems do not respond to short ramp up periods like gas furnaces. One tenant indicated he thought operating the equipment would be expensive, as it provided a lot more air than the system in his previous residence did.

### **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 important. Through this study, we understand tenants are more aware of energy use with an in-unit device such as the Nexi, but due to limited tenant loads, it was not possible to tie 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 their significant contribution towards peak (and off-peak) total demand is something that 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 the pie, there needs to be further research on the extent of plug loads and how to 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 display installed. Therefore, there is an opportunity to build off this awareness and understand opportunities to engage occupants in demand response and peak usage periods rather than 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 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, either for compliance and/or for overall building performance. Modeling is a critical component in determining performance, to meet design and goals of ZNE and funding. Knowing models are imperfect, it is imperative to continue to improve these tools to better serve these goals. The discussion below includes findings and recommendations, including cross-cutting findings and end-use specific applications.

All these findings apply to conditions in Codes and Standards.

**Nonresidential Baseline.** It is paramount that the nonresidential baseline for domestic hot water includes an electric baseline. Higher performing buildings, as those presented in this study, needed workarounds to comply with code because the systems were compared to gas domestic hot water 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 is using number of bedrooms as a proxy to inform occupancy using the algorithm: number of bedrooms plus 1.<sup>18</sup> This algorithm may underestimate occupancy and therefore the loads for higher occupancy homes and/or apartments. Consider revising the algorithms to include both number of bedrooms and square

---

<sup>18</sup> 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-BQ<sub>tot</sub> = 0.03A<sub>floor</sub> + 7.5(Nbr + 1) (Equation 150.0-B).

footage. Another approach could be to consider an option to indicate higher occupancy with guidance on eligibility or ability to select this criterion, through some other proxy.

For hot water draws, occupancy is based on a randomized changing occupancy to simulate the lifetime occupancy of a home or apartment. Table 22 summarizes the multifamily distribution of occupancies over time. For low-income multifamily or potentially low-income residences generally, these percentages may need to be adjusted to have less time with lower occupancy and more time at higher occupancy based on the 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 results in lower occupancy rates than what was observed at the project sites. This method underestimates DHW load in most cases; development of higher occupancy households will improve DHW load estimates. This issue is exacerbated in apartments with more bedrooms (i.e., 4+ 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 above, and this will affect draw schedules as well as the potential for consecutive draws. The 100th percentile draws of 80 to 135 gallons/day are not predicted by CBECC-Res, nor is their impact on electric resistance usage during high draw periods. High draw periods may lead to unsatisfactory delivery temperatures, thus triggering the need to switch the controls to High Demand mode with increased resistance. One-hundredth percentile use can affect tank sizing, GHGs, spikes of electric resistance, solar system sizing, and utility bill predictions.

**Set point.** Consider a methodology to support operational scheduling and/or set point in compliance software. Because the mode is specific to each manufacturer, it is difficult to

include this in modeling and standards with clarity. The set point temperature could be an input in CBECC-Res for individual tank HPWHs only if a mixing valve is installed. Consider how to do this, particularly as there can be changes to set points and schedules.

**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 model their determinants correctly. Currently, most software, including California's CBECC-Res, bases MELs on the 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, as better distribution would help inform distribution 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) which cannot currently be modeled in the software. This strategy should be added as an option. Currently, the software is limited to four recirculation configurations: (1) recirculation with temperature modulation, (2) recirculation with no control (continuous pumps), (3) recirculation demand control, and (4) recirculation with temperature modulation and monitoring.

**Accounting for Unconditioned Spaces.** The model needs to be able to accommodate more than one unconditioned space. With this limitation, building characteristics are 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 (e.g., 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 the hot water draw pattern for multifamily and higher occupancy households to inform peak periods and the 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 time and colder than expected temperatures in the winter. If HPWHs are 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 determined to be significant during colder periods of time, and calculated losses were greater, especially in low ambient temperature, when compared to 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 stronger benefit in performance or devalue a system not meeting compact hot water distribution requirements. Understanding 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 that are 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 be comprehensive to support zero net energy goals. Each project utilized multiple tools to attempt to estimate whole building loads to inform PV sizing. However, cooking and plug loads were underestimated in the modeling, resulting in a gap between predicted energy usage and actual usage. When the model will not allow an accurate estimate of loads or systems to be properly modeled, it is impossible to accurately specify the necessary amount of PV. Many end uses did not seem to be well accounted for in system design. For example, gym or exercise rooms, elevators, EV chargers, and others were not included in side calculations and therefore not accounted for in ZNE estimates.

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

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

**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/or commissioning. Currently, PV installations require minimal verification. Within multifamily projects that have larger systems, consider the requirements for verification in the field of installation other than installer-confirmation of operations/commissioning, including elements such as inverter settings. In one of this study's projects, the inverter settings were not configured properly, resulting in reduced production on a system for a least a six-month period. Convolved billing may suppress 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 to streamline the process of getting solar PV, and to make it more accessible for implementing systems. This would primarily benefit solar contractors, but would have a trickle-down effect to building owners. Streamlining the post-interconnection process on the utility end could also alleviate many of the issues, particularly billing-related issues that arise after system

permission to operate (PTO). Particularly for billing for VNEM systems, which relies solely on the utility to receive solar PV credits, the post-PTO billing process needs to be more streamlined, standardized, and rapid; automation is beneficial and potentially critical here. The utility has an incentive to manage each individual system and ensure it knows how much energy is flowing onto the grid from each project. Increased utility surveillance of VNEM systems would help alleviate billing issues, or missed billing setup, and would allow for electric grid management to benefit all.

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

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



## **CHAPTER 6:**

# **Knowledge Transfer Activities**

---

To provide the maximum benefit from the research, the team developed a strategy to share learnings through several different channels. The goal is to reach the largest possible audience through diverse media, to advance 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.<sup>19</sup> To broadly influence other researchers and those heavily involved in energy efficiency efforts, the team is writing peer-reviewed papers and creating conference presentations. The team's plan is to make all of the 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 will create 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 domestic hot water systems, and (6) modeling to achieve ZNE and (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 will 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 have been shown to provide demonstrated proof and get potentially interested parties to trust that an option is feasible for them. The team 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

---

<sup>19</sup> All knowledge transfer documents, including the technical briefs and case studies, will be available at [www.aea.us.org/research](http://www.aea.us.org/research).

performance. They also will cover energy using-, energy managing-, and energy producing-equipment used in the projects.

To ensure readability and appeal, the text will be interspersed with pictures, graphs, or tables. Contact information for the principle contributors will accompany short descriptions of their roles. 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, one of the most effective ways of knowledge sharing is through conferences and workshops. The team will present highlights of the research approach and findings at appropriate venues, potentially 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, Housing California, the California Association of Building Energy Consultants' semi-annual Conference, the Forum on Dry Climate Home Performance, and the Affordable Comfort's Home Performance Conference.

The papers that were 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. (Both papers and the three presentations are available through Franklin Energy.) 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 time frame to achieve California’s ZNE and carbon-neutral goals approaches, there is a critical need for more research and evaluation 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 remain 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 the California 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 offered timely opportunities to investigate ZNE issues in depth. These projects share a goal of all-electric ZNE construction with 100 percent renewable offset, and utilized breakthrough heat pump technologies to serve the buildings’ HVAC and/or water heating needs. These projects have provided an insight to optimizing technology, but this is only the start of ongoing research to evaluate how energy is used in a multifamily building, and how the complex, interdependent systems (e.g., envelope, mechanical systems) can work together to achieve ZNE cost-effectively.

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

- **Lower costs:** Better understanding of the economic and performance trade-offs for various technologies will lower costs for building multifamily ZNE developments. The research project has helped developers understand ZNE design decisions and how to reduce the risk of unanticipated costs for future developments. It ensured most optimal conditions were realized. This project will improve the 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 will lead to lower costs and more reliable utility costs for tenants.
- **Environmental benefits:** Optimizing strategies for achieving ZNE standards via 100 percent electric solutions will result in lower greenhouse gas emissions.
- **Greater reliability:** Electricity reliability will be improved by quantifying the load shifting benefits of thermal storage systems and increasing the energy self-sufficiency of 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 both reduce planning uncertainty.

- Public health: Optimizing systems for ZNE will improve indoor air quality in buildings.

The savings in the table below represent savings over baseline 2019 code building, to demonstrate the benefits if these projects were built today.<sup>20</sup> The savings for each project over the permitted code baseline would be greater than below because (1) natural gas usage was included in baseline for low rise and (2) 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 to 2019 modeled standard design from the model for each of the projects. Calistoga, Cloverdale, and Atascadero as low rise buildings include the minimum required PV in the standard design used for the savings baseline. Sunnyvale as a mid-rise building has the mixed-fuel standard design as the baseline for savings. GHG savings are based on a flat rate of 0.131 metric tons of CO<sub>2</sub>e per megawatt-hour. The consumption used in the calculation are based on the 2019 calendar year. In addition, the consumption for each project does not include the potential benefits of load shifting, as the research evaluated the potential rather than capturing a year's worth of performance with load shifting. Therefore, if load shifting was undertaken, savings for the project inclusive of 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 of future projects should be based on the Atascadero and Sunnyvale scenarios, as these two projects are most representative of typical multifamily developments. Therefore, these developments will reap greater savings.

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

|  | Calistoga | Cloverdale | Atascadero | Sunnyvale | <b>Total</b>   |
|--|-----------|------------|------------|-----------|----------------|
| Reduced kWh                                    | 74,320    | 105,086    | 150,759    | 511,130   | <b>841,295</b> |
| Equivalent GHG emissions (MTCO <sub>2</sub> e) | 9.73      | 13.7       | 19.74      | 66.9      | <b>110.2</b>   |

MTCO<sub>2</sub>e = million tons of carbon dioxide equivalent

<sup>20</sup> 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   |
| Btu                     | British thermal unit  |
| Btuh                    | British thermal unit per hour   |
| 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   |
| CO <sub>2</sub>         | 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. |
| °F                      | Fahrenheit  |
| FCU                     | fan coil unit   |

| Term                             | Definition  |
|----------------------------------|---|
| FHR                              | first hour rating   |
| FTP                              | file transfer protocol  |
| GFCI                             | ground-fault circuit interrupter  |
| 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   |
| 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   |

| <b>Term</b> | <b>Definition</b>                |
|-------------|----------------------------------|
| NSHP        | New Solar Homes Partnership      |
| OAT         | outdoor air temperature          |
| PG&E        | Pacific Gas and Electric         |
| PV          | Photovoltaic                     |
| rH          | relative humidity                |
| RTD         | resistor temperature detector    |
| SEER        | seasonal energy efficiency ratio |
| 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**