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Energy Research and Development Division

FINAL PROJECT REPORT

Zero-Energy Residential Optimization Project

Community-Scale Research and Demonstration Site

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DISCLAIMER

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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 emissions 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.

Zero-Energy Residential Optimization Project Community Scale Research and Demonstration Site is the final report for the Zero-Energy Residential Optimization Project (Grant Number EPC-15-042) conducted by California Homebuilder Foundation (CHF). 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 website at www.energy.ca.gov/research/ or contact the CEC at 916-327-1551.

ABSTRACT

De Young Properties is building California's largest zero net energy residential community to date in Clovis, California. Unfamiliarity with zero net energy construction and features, high upfront costs for energy-efficient home design, all-electric appliances and rooftop solar systems, and unproven business models for financing energy-efficient home mortgages are significant barriers to advancing zero net energy home construction in California. This project addresses (1) how homebuyers in California perceive zero net energy and what their preferences and priorities are in buying zero net energy homes, (2) what are the most cost-effective energy efficiency measures that can be used when building new homes to achieve zero net energy, (3) what design considerations and advanced construction techniques can be utilized to achieve zero net energy homes, (4) how zero net energy homeowners interact with the advanced features of their homes, (5) how the ventilation systems used in the zero net energy homes affect indoor air quality, (6) how various moisture mitigation technologies perform in unvented attics, (7) how accurate the CBECC-res energy compliance software energy estimates are relative to actual circuit level data, (8) what the cost differences are between all-electric and mixed-fuel homes, and (9) what are the challenges related to implementing community solar and what are the funding mechanisms available to finance it.

Keywords: community solar, energy compliance software, zero net energy

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Introduction and Background

To address the State's pronounced and prolonged housing shortage, California builders will need to construct hundreds of thousands of new housing units in each of the next ten years. To ensure that this new supply of housing will also help combat California's rising housing costs, these new residences must be affordable to purchase, maintain, and operate.

Despite the potential downside that many Californians encountered during the great recession, purchasing a home is still one of the most effective means of building wealth and achieving financial stability for low-and-moderate-income California families. And despite statewide and regional regulations aimed at limiting sprawl and encouraging high-density infill development, single-family homes are still the predominant type of new, for-sale housing in the State. Homebuyers—particularly those in California's fast-growing inland regions—continue to demand single-family detached homes in traditional residential subdivisions.

At the same time, State policymakers have become increasingly aware that, when accounting for the CO_2 emissions associated with the electricity they use, buildings are responsible for a large percentage of the world's greenhouse gas (GHG) emissions. So, although the State needs to build more homes, those homes must be designed and constructed to reduce GHG emissions and help combat the climate crisis.

To achieve these GHG reductions, California must upgrade existing buildings (especially those built before the advent of California's Title 24 Standards) while aggressively pursuing technological and regulatory advancements in new construction. Zero Net Energy (ZNE) is one such advancement, which means designing a home to produce as much renewable energy as it consumes over a typical year. When smartly designed, well-constructed, and brought to scale, ZNE new homes can be a key contributor to the State's GHG reduction goals—while offering a suite of other benefits to homeowners and the electrical grid.

As such, in 2015 policymakers at the California Public Utilities Commission and California Energy Commission (CEC) agreed to a policy goal in the California Energy Efficiency Strategic Plan for all residential new construction to be ZNE by 2020—the year the project was slated to end.

However, over the ensuing years changes to utility rates—specifically the decline in value for excess rooftop solar electricity that goes back to the grid—reduced the cost-effectiveness of ZNE construction. As a result, when the Energy Commission finally adopted the 2019 Title 24 Standards (which took effect January 1, 2020), those new Standards required enough PV to offset electric uses in mixed-fuel homes but could not cost-effectively require all-electric homes to reach ZNE. In the case of an all-electric home the Standards require generation to offset the electricity consumption of an equivalent mixed-fuel home. This dual baseline was established in order to prevent an outcome that unfairly discouraged all-electric homes.

Although many other parts of the U.S. continue to pursue policies and incentives around ZNE, California's focus has recently shifted away from that specific ZNE goal and metric—at least as it pertains to Title 24 Standards.

However, the 2019 Standards do—for the first time—require builders to install solar panels on every new home. And, as part of its increased focus on building decarbonization, the State has begun encouraging builders to install electric equipment, (which can be powered by electricity from clean, renewable sources) instead of the GHG-emitting natural-gas appliances most builders install in new homes.

So, although this EPIC demonstration project did not dovetail with the 2019 Standards in the way that the project team originally thought it would, many of the construction techniques—including electric heat pump HVAC and water heaters—are now more relevant than ever. The anticipated focus on residential electrification in the 2022 Standards increases the relevance of data on heat pump HVAC and water heaters. And, since the project approached the diverse topic of ZNE construction from many different angles, most of the information is more broadly applicable.

Project Purpose

The primary purpose of this project is to help scale up single-family ZNE construction from individual pilot homes to community-scale, and by doing so develop tools and understanding to support ZNE construction at the statewide scale. Prior to this project, several California production builders, including project partner De Young, had constructed ZNE pilot homes. However, these were all one-offs; carefully designed and slowly constructed to accommodate new techniques and unexpected challenges resulting from changes in construction practice. Furthermore, it was hard to know whether typical homebuyers would be willing to spend extra money for ZNE, or what other barriers might prevent broader adoption of ZNE as a construction practice.

Since all prior experience with ZNE was limited to one or two homes, no California builder had shown that ZNE could be brought to scale successfully—that is, without unsustainable cost burdens or other issues for the builder or the buyer. To show that it is possible to build ZNE at "production-scale"—and to learn more about how it might be done—in 2016 the Energy Commission provided grant funding to the California Homebuilding Foundation team to construct and study "ZNE Communities."

Building ZNE homes at the community (or subdivision) scale requires the builder to integrate advanced construction techniques into regular practice. To remain profitable, production builders must construct homes quickly and efficiently—there is no time for each building trade to customize or adapt their technique for each new home they build, the way they do when building a single ZNE pilot home. The builder and their trades must identify and implement efficient and replicable techniques they can use for every ZNE home. Through the repetitive process of constructing a whole subdivision, they will refine those techniques until they become "standard practice."

This project supported that transition by offsetting some construction costs, providing a team of consultants for technical support, and conducting research and analysis needed to overcome various obstacles to the broader adoption of ZNE.

The project also served another very important purpose by observing, monitoring, and analyzing energy data and other information to better understand nearly every aspect of ZNE construction—from consumer preferences to building performance.

When the project began, the purpose of building these homes and conducting analysis was to support the transition to ZNE as standard construction practice—since at the time that was the State's policy goal for 2020. Although that goal did not become part of the Title 24 Standards as expected, the study of ZNE communities and the related research is still relevant and applicable to many of California's policy goals and objectives, including GHG reductions, increased grid reliability, and protecting public health.

Project Approach

The project approached the challenge of scaling-up ZNE from several different angles. Since achieving scale is a technical, practical, regulatory and economic/market challenge, the project scope included nine overall tasks, each designed to address different barriers or challenges related to ZNE construction.

The body of this report is organized around these nine tasks, so if the reader is interested in one or more specific topics, that content can easily be found. Likewise, the project approach, results, and conclusions are summarized within that same framework:

Market Assessment. The increased energy efficiency and rooftop PV of ZNE homes increases the selling price builders must charge, but the reduced homeowner utility bills can more than offset the increased cost over time. However, conventional mortgage lending criteria do not account for these substantial cost savings, and it is unclear what value buyers, lenders, and appraisers will assign to Zero Net Energy. To better understand how home shoppers view these features relative to other new-home attributes, and to determine what premium buyers might be willing to pay, the team performed a survey of potential and recent new homebuyers. To better understand how lending and valuation decisions account for energy savings and rooftop generation, the team interviewed various real estate market actors.

Cost-Optimized Strategies for ZNE. California's Title 24 Standards offer prescriptive and performance-based paths to compliance. Performance-based compliance relies on building energy simulation software to determine an energy budget for a home of any given size and location (climate). This software allows builders to trade off a variety of energy saving measures, so long as the design does not exceed that energy budget.

ZNE homes are designed to "reduce before produce", with modeled energy consumption typically 20-30 percent lower than the Title 24 energy budget. To determine what combination of energy saving features offered the lowest-cost pathway to achieve that reduction, the team collected extensive cost data and ran thousands of energy models. By ranking each combination of measures by "bang-for-the-buck" of energy savings, the team identified the most cost-effective options for different building types in climate zones with the most construction activity.

Design and Construction. The team supported the homebuilder through the process of marketing and constructing ZNE homes in two subdivisions, which included implementing a variety of advanced construction techniques and high-performance appliances. The team developed energy models and further refined estimates of annual energy consumption to advise the builder on PV sizing for ZNE. The team worked with a leading architect to develop two all-new floor plans that put energy savings at the forefront. By engaging with the designers from the outset, the team explored a variety of design-based approaches to energy savings and documented where those strategies were successful, and where they were at odds with the demands of production homebuilding.

Behavioral Evaluation. Occupant behavior is a significant factor in annual home energy consumption. The habits of different homeowners can determine whether a home achieves Zero Net Energy over a year—or not. Furthermore, providing real-time feedback to homeowners can influence behavior and may increase energy savings. The team conducted surveys and analyzed circuit-level consumption data to better understand the role of occupant behavior in the energy consumption of new homes.

Indoor Air Quality (IAQ) Assessment. Reducing uncontrolled outdoor air infiltration reduces the amount of energy needed for heating and cooling. However, lower infiltration also means less dilution and slower removal of indoor air contaminants. As such, Title 24 Standards include requirements for mechanical ventilation: fans that provide consistent outside air for occupant health but require additional energy to operate. The project team evaluated the ventilation system designs employed by the homebuilder, provided recommendations for more efficient ventilation strategies, and worked with building trades to determine how to implement these changes. The team also measured airflow rates and took air samples from unoccupied homes to evaluate the efficacy of various ventilation strategies.

Moisture in Sealed and Insulated Attic Assemblies. The ZNE homes utilize unvented attics, which relocate the insulation from the attic floor to the underside of the roof deck and eliminate traditional attic vents, which brings the attic inside of the building envelope. This results in more moderate attic temperatures and is, therefore, more energy-efficient; however, the elimination of the attic vents and sealing the attic creates the potential for unacceptably high moisture levels. The risk factors for moisture issues in these assemblies include North-facing roof slopes, cold climates, clear night sky conditions, elevated indoor humidity, and others. Over extended periods, moisture risks can develop in these assemblies. The research team installed monitoring equipment to observe the temperature, relative humidity, and wood moisture content of the attics. The research team analyzed the data to evaluate the risk of condensation on the monitored home roof decks.

Analysis of Energy Use and Comparison to Modeled Estimates. As discussed above, builders rely heavily on CBECC-res software to evaluate tradeoffs and select the most cost-effective efficiency measures for code compliance and above-code construction, including ZNE. Reaching ZNE also requires PV sized to offset all of a home's modeled energy use, while the 2019 Standards require PV to offset the electric *part of* that modeled energy use. In all cases, it is important to California builders and other stakeholders that the software provides accurate estimates of each energy end-use in a home, as well as total annual consumption. The team collected energy consumption data from every panel circuit in each ZNE demonstration home and compared the amount and timing of the modeled energy use to actual use to assess the accuracy of CBECC models and to suggest revisions as needed.

Cost Analysis of All-Electric and Mixed-Fuel ZNE. Conceptually, rooftop PV generation can offset both electricity and natural gas consumption to reach Zero Net Energy. However, since electricity cannot power gas appliances, mixed-fuel ZNE designs send a lot of excess generation back to the grid, and the utility credit for that excess generation has declined substantially. At the same time, the cost of electric appliances—particularly electric heat pumps—has fallen, making it more practical for builders to consider all-electric designs that can be powered by rooftop PV, or at least that result in a balanced annual true-up. Finally, if builders and buyers are comfortable with all-electric homes, there is no need to install natural gas infrastructure—which could be a big cost saving. The research team collected extensive data to evaluate all the above considerations and determine whether it is more cost-effective to buy and operate an all-electric or mixed-fuel ZNE home.

Financing Community Solar. The standard definition of ZNE assumes "on-site" renewable generation to match annual consumption. Likewise, the Title 24 2019 requirement by default requires rooftop PV. However, there are potentially major cost advantages to using larger, community-scale PV arrays to provide that power. Because of those potential advantages, the Energy Commission included a mechanism to allow for offsite solar in the 2019 Standards. Larger, more concentrated systems can benefit from reduced equipment and installation costs achieved through economies of scale; and larger systems can benefit from lower long-term maintenance costs through central facilities management, and parts and equipment uniformity. However, the association between that off-site generation and the individual homes has proved challenging. Furthermore, California law allows municipalities and utility districts to leverage unique financing mechanisms to fund the construction of various shared community resources, such as parks and sewage treatment facilities. Although those mechanisms have not previously been applied to community solar, that resource includes many common features with other shared community resources commonly funded using these mechanisms. The team analyzed the challenges related to community solar, as well as potential funding mechanisms that might be leveraged to achieve ZNE on a community basis.

Project Results

Market Assessment. The survey results revealed that homebuyer awareness of ZNE is low, with only 7 percent of respondents able to accurately define it. Despite not understanding what ZNE is, most homebuyers (72 percent) believe that energy efficiency is very important, identifying efficient appliances, solar panels, energy use monitoring, and batteries for energy storage as desirable or very desirable. Most homeowners and homebuyers are also willing to pay at least 2 percent more for a ZNE home, without consideration of utility bills. Homeowners and homebuyers expressed a willingness to pay 4 percent more for a ZNE home if they would see a $150 per month savings on their electricity bills. The study also found that market actors, including homebuilders, real estate agents, home appraisers and lenders all play an important role in influencing the ZNE home purchase process and each need to be equipped with tools to better influence homebuyers to purchase ZNE homes. Homebuilders need a skilled workforce to be able to build more efficient houses, realtors need resources and training to promote efficient home features, appraisers need training in how to accurately appraise ZNE home features, and mortgage lenders need training in the options available for energy-efficient mortgages and how they can approach homebuyers. The barriers identified to increase the market uptake of ZNE homes include most homebuyers not being aware of what ZNE homes are even though the vast majority identify energy efficiency as a top concern and most homebuyers not being aware of financing possibilities for ZNE homes through an energy-efficient mortgage, which can increase the amount of money that they can borrow.

Cost-Optimized Strategies for ZNE. The analysis revealed that the most cost-effective single energy efficiency measure varied by climate zone. The only measure that consistently performed as one of the top 10 most cost-effective across all climate zones and house types was the upgraded water heater. The parametric modeling of packages of measures revealed that no one package is universally the most cost-effective. Rather, there are multiple ways in which builders can meet code, which allows them to choose measures based on concerns other than pure cost efficiency. The most common measures in the top packages were upgraded water heaters, furnaces, and windows, all measures that require little or no additional labor. The analysis of renewable energy vs. efficiency measures revealed that it is most cost-effective to implement efficiency features until 2019 code is reached and then to utilize renewables to achieve ZNE from there. Implementing efficiency measures that exceed 2019 code can become less cost-effective due to diminishing energy savings. Modeling efficient refrigerators and laundry equipment revealed that installing these appliances is one of the most cost-effective ways to decrease building energy use. Builders would benefit from being able to claim credit for the appliances when calculating the building energy use; however, this is not currently possible in the CBECC-Res software.

Design and Construction. The results of the analysis revealed that the builder is implementing several energy-efficiency measures that result in buildings that exceed the energy code by upwards of 30 percent. The analysis also revealed that the actual estimated energy use of the buildings was less than what was estimated in CBECC-Res due to the software's inability to model efficient refrigerators and heat pump dryers. The BEopt PV generation estimate, which the builder has been using to determine necessary rooftop PV system size, was revealed to be recommending systems that are 14-23 percent oversized, depending on plan type, after efficient appliance energy savings are considered. Observation of data from two homes that the research team put on a thermal storage schedule revealed that the schedule was resulting in only a minimal amount of domestic hot water energy consumption (7-8 percent of total use) during the peak rate time of between 4:00 PM and 9:00 PM.

Behavioral Evaluation. The results of the analysis were limited to a sample size of four homeowners, which is not statistically significant; however, it does provide early insights into the experience of ZNE homeowners. The four homeowners surveyed had all graduated from college and had family incomes that exceeded the median for the area. All the surveyed homeowners have relatively small household sizes, despite having fairly large homes (2,000-2,5000 square feet). All four of the homeowners cited energy efficiency, solar panels, curb appeal and high-end finishes as "very important." Despite this, homeowner feedback showed a general lack of understanding about ZNE, with only one respondent providing a correct definition. Two of the homeowners surveyed said that they have tried to be more efficient since moving in, one said they have not changed how they use energy, and one said they now use energy more freely since their home is efficient. All homeowners reported limited interaction with the ZNE features of their homes but did indicate that they planned to track their annual energy use and solar panel production. Feedback from the homeowners about energy-using equipment and practices suggests a general trend towards energy-saving behaviors. The homeowners were however generally not aware of the thermostat features to control their high-efficiency heat pumps, with all stating that they manually adjust their thermostats. Alternatively, three homeowners were aware of and used at least one of the messaging channels of the CURB energy management system on a somewhat regular basis, but only one reported changing their behavior based on what they saw in the CURB interface. The survey results indicated to the researchers that more effort needs to be taken to familiarize the homeowners with the use of the ZNE features in their homes.

Indoor Air Quality (IAQ) Assessment. The research team concluded that upgrading the ventilation system to Enthalpy Recovery Ventilation (ERV) or Heat Recovery Ventilation (HRV) would add relatively little cost and save energy; however, the builder ultimately decided against it due to the recommendation coming too late in the design process.

The research team also recommended utilizing a Honeywell HVC001 switch rather than a standard on/off switch for the exhaust fan, which the builder did implement. Observation of the electrical circuit data indicated that the Honeywell switch is resulting in the exhaust fans running sufficiently, which is in sharp contrast to prior field studies that found that homeowners commonly turned the fans off when they were controlled by simple on/off switches. The research team also observed that the exhaust fans being installed in the homes tended to be left in the default settings rather than being customized for the given homes, based on the total area and number of bedrooms. The researchers discussed this with the builder and properly setting the fans was added to the preparation list of the customer experience team. The research team also suggested that relocating the intake air filter from the attic to the home would make it more likely that the homeowner would regularly change it; however, this design change could not be incorporated. Testing of the summer and winter air exchange rates for different ventilation conditions revealed that there is more total ventilation in the winter than there is in summer and that only running the exhaust fan met the required ventilation rate for Title 24 regulation, while running the central fan integrated ventilation system and exhaust fan together (balanced ventilation) resulted in little additional ventilation. Testing of indoor/outdoor $PM_{2.5}$ ratios for different ventilation conditions was inconclusive due to unusually high outdoor $PM_{2.5}$ levels in the summer (estimated to be due to ozone, terpenes from the fresh pine wood used in construction, and cleaning chemicals) and unusually low outdoor $PM_{2.5}$ in the winter (estimated to be due intermittent rain events that removed the particles from the air).

Moisture in Sealed and Insulated Attic Assemblies. The dataset used in the analysis was limited due to a small sample of monitored homes (10) and a limited amount of winter data that has thus far been collected and analyzed. From the data available, it is difficult to identify if the monitored attic moisture levels are safe or unsafe and if the roof deck condensation mitigation measures are working. Preliminary analysis however appears to indicate that some of the roof deck condensation mitigation measures are having dubious impacts. The two monitored homes that had no roof deck condensation mitigation measures showed little indication of moisture risk. Four of the five homes that utilized the vapor retardant boxed netting had the highest overall moisture levels. The one home that had a vapor diffusion vent appeared to have safe moisture levels. The one home that had the heat pump water heater ducted to the attic still showed moderately high roof deck wood moisture levels. The builder has implemented a design change where all new homes are being outfitted with vapor retardant boxed netting, vapor diffusion vents, and an always-on switch for the whole-house exhaust fan to address the moisture issues. All existing homes will also be retrofitted with vapor diffusion vents.

Analysis of Energy Use and Comparison to Modeled Estimates. The dataset used in the analysis was very limited due to slower-than-expected sales and construction of the ZNE homes. From the data available, using both average weather data (TMY) and actual weather data (AMY) resulted in the CBECC energy simulation models underestimating space heating and cooling, overestimating water heating use, and overestimating ventilation energy use. Overall, the modeling software overestimated regulated loads (space heating/cooling, ventilation, and water heating) by 9 percent using AMY data and by 25 percent using TMY data. The modeling software overestimated total home usage by 27 percent using AMY data and by 31 percent using TMY data. Analysis of weekday and weekend load profiles revealed that the modeling software tended to overestimate the number of occupants in a home and underestimate the amount of time that the occupants are home. The analysis also revealed that homeowners use certain unregulated loads, namely dishwashers, clothes washers, and clothes dryers later in the day than the modeling software assumes. The modeling software also significantly overestimated the energy use of efficient clothes dryers, clothes washers, dishwashers, and refrigerators. CBECC, however, does not currently allow for modeling high-efficiency appliances.

Cost Analysis of All-Electric and Mixed-Fuel ZNE. The study revealed that all-electric appliances for a home are $200-$500 less than natural gas appliances when home infrastructure savings are included, namely from avoided natural gas plumbing and flue vents. These findings, while consistent with other electrification analyses, are not consistent with feedback from builders who report all-electric appliances as being $2,2000 to $3,500 more expensive due to the oversizing of heat pumps for heating and additional electrical infrastructure. Further research and engagement with builders are necessary to improve the estimate. An average cost of $1,423 was determined from eight sets of homebuilder data, representing over 400 homes, for connecting a home to natural gas from the utility. This derived cost is significantly less than other parties have identified and represents the most robust estimate known on connecting a home to natural gas from the utility. The researchers found that the annual utility cost for a home, whether mixed-fuel or all-electric, is highly dependent on the rate structure selected, with all-electric homes being much more susceptible to this variation. When selecting the rate structure most favorable to each home, it was revealed that all-electric homes can have annual utility bills that are significantly less than mixed-fuel homes when those homes are enabled with battery storage. The lifetime electrification costs vary heavily depending on the assumed natural gas infrastructure costs and the electric appliance and construction costs. The only scenario in which electrification was found undesirable was when low natural gas infrastructure costs and high all-electric appliance and construction costs are assumed. Findings also concluded the all-electric home to have GHG emissions a full 75 percent lower than the mixed-fuel home using current utility emissions factors.

Financing Community Solar. Research into community solar systems revealed several benefits to implementing them, such as a less expensive per kilowatt cost due to the large size of the system and avoidance of the need to place individual solar systems on every roof. However, the financing of community solar systems can be difficult. Direct financing places the entire upfront burden of the cost of the system on the developer, forcing them to carry that burden until all homes have sold. Utility-financed off-site systems avoid the development risk to the builder but have been met with significant public and industry opposition, with concerns that they would discourage the development of rooftop solar and home energy storage and negatively impact the rooftop solar industry. SMUD has proposed a utility-financed system, known as "Solar Shares," but the CEC drove it. Another option is land-secured financing, or the Mello-Roos approach, where homeowners who benefit from the community solar agree to a lien on their property that is repaid through a special tax. Land-secured-financing however also has disadvantages, such as difficulty getting the off-site system approved by the CEC, risk of default, changes in interest rates making repayment difficult, prospective buyers being deterred by the special tax, and poor public opinion of Mello-Roos in general.

Technology/Knowledge Transfer/Market Adoption

As a demonstration project, one of the primary purposes was simply to *show* the public and other builders that ZNE can be achieved at scale. To spread awareness of effort and accomplishment—and to help ensure that buyers were aware of the benefits and opportunity to buy one of the homes—the team pursued and achieved extensive media coverage for the project. The team included a public relations firm that issued press releases, coordinated interviews, and organized events. The press releases were highly effective in drawing the attention of local, regional, and national publications.

However, due to the loss of the first two builder partners involved with the project, and the subsequent delays that the final builder encountered when selling and building the ZNE homes, there were limits on the amount of data and analysis that was available to share during the project term. In light of this, the project team made its best efforts to share available data and lessons learned in progress. The team worked closely with CBIA and local BIAs, as well as with energy and infrastructure consultants to discuss the incremental cost impacts of ZNE building design. Additionally, there are several topics surrounding ZNE that continue as matters in significant flux. In particular, the costs and performance regarding batteries for home energy storage remain largely speculative, with very little long-term data available. Likewise, heat-pump HVAC and water heater appliances are still relatively new to the California building environment, and both stand to see significant learning cost curves as relevant parties become more familiar with the underlying technology, and modern performance attributes.

Benefits to California

The advancement of Zero Net Energy homes offers the potential for numerous benefits. This project has delivered distinct benefits across numerous categories related to the development of ZNE homes. To best appreciate these benefits, it helps to first contextualize the purpose and promise of ZNE buildings generally. ZNE means that a building generates as much energy as it consumes over a year. Typically, this is achieved through high-performance construction standards, high-efficiency appliances, and onsite solar power generation. It takes the combination of these elements to achieve ZNE cost-effectively. ZNE was adopted as a policy goal by the State of California to achieve the combined goals of stabilizing the electric grid and reducing greenhouse gas emissions. When measuring building energy performance California uses a weighted metric that normalizes electricity and natural gas and incorporates the hourly "costs of energy to the consumer, the utility system, and to society." This metric uses localized weather data to more accurately reflect the energy use associated with a given building. California's use of TDV for measuring energy efficiency has been crucial in maximizing the effectiveness of the energy infrastructure in the state. TDV cost increases with demand on the utility system, reaching its highest values when demand on the electric grid is at its peak in summer evening hours.

ZNE offers benefits to the homeowner through reduced utility bills, and a higher efficiency, more comfortable home. ZNE offers benefits to the public at large by reducing the burden on the electric grid and reducing the emission of climate change-causing greenhouse gases. This project shows the benefits of ZNE through the construction of dozens of new ZNE homes, simplifying the process of producing ZNE homes, and significantly reducing the costs associated with building ZNE homes.

CHAPTER 1: Introduction

To address the State's pronounced and prolonged housing shortage, California builders will need to construct hundreds of thousands of new housing units in each of the next ten years.[1] To ensure that this new supply of housing will also help combat California's rising housing costs, these new residences must be affordable to purchase, maintain, and operate.

Despite the potential downside that many Californians encountered during the great recession, purchasing a home is still one of the most effective means of building wealth and achieving financial stability for low-and-moderate-income California families.[2] And despite statewide and regional regulations aimed at limiting sprawl and encouraging high-density infill development, single-family homes are still the predominant type of new, for-sale housing in the State.[3] Homebuyers—particularly those in California's fast-growing inland regions—continue to demand single-family detached homes in traditional residential subdivisions.

At the same time, State policymakers have become increasingly aware that, when accounting for the CO_2 emissions associated with the electricity they use, buildings are responsible for a large percentage of the world's greenhouse gas (GHG) emissions.[4] So, although the State needs to build more homes, those homes must be designed and constructed to reduce GHG emissions and help combat the climate crisis.

To achieve these GHG reductions, California must aggressively pursue technological and regulatory advancements in new construction. One such advancement is Zero Net Energy (ZNE), which means designing a home to produce as much renewable energy as it consumes, over a typical year. When smartly designed, well-constructed, and brought to scale, ZNE new homes can be a key contributor to the State's GHG reduction goals—while offering a suite of other benefits to homeowners and the electrical grid.

In 2015, the CEC issued a Grant Funding Opportunity (GFO) for the construction of one or more ZNE demonstration projects. In addition to constructing the demonstration project, the CEC sought proposals that would help ensure that the statewide transition to ZNE could be made without significant disruption to the housing market, burdens to California builders, or risks to California homebuyers.

In response, the California Homebuilding Foundation proposed to build and study a subdivision of 40-50 ZNE homes. Alongside construction, the project was designed to

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[1] The Sacramento Bee, July 23, 2019
[2] HSH, September 23, 2019
[3] First Tuesday Journal, December 18, 2019
[4] EPA Global Greenhouse Gas Emissions Data

evaluate ZNE from many different perspectives and answer many of the Energy Commission's key policy and technical questions:

- Can ZNE be built cost-effectively?
- If so, what combination of efficiency measures provides the lowest-cost path to ZNE?
- Are California consumers willing to pay for ZNE? How much? How do these consumers value energy features relative to other new home attributes?
- What issues might arise from changes to construction practices? How might these issues be resolved?
- How do occupant behaviors affect energy use and achieving ZNE?
- Can real-time information about energy use impact behaviors, and if so, how much energy could be saved?
- Do new construction practices (including tighter envelopes) put consumers at risk for poor indoor air quality (IAQ)?
- If so, what type of ventilation system should builders install to mitigate IAQ risks?
- How accurate are the CEC's models for the energy use in ZNE homes, and can researchers use circuit-level data from the demonstration homes to improve those models?
- How do mixed-fuel homes compare to all-electric homes in terms of horizontal (infrastructure), vertical (construction), and operational (utility) costs? Can all-electric ZNE homes pass cost-effectiveness tests given the latest information about appliance and infrastructure costs?
- Is community-scale solar a viable way to achieve ZNE on a community basis? Can financing tools enabled for shared community resources be applied to community solar, and if so, do those tools provide a substantial cost reduction vs. conventional financing mechanisms?
- Did the homes in the study achieve ZNE? Did the community as a whole?

To answer these questions and help the State move towards ZNE as a Statewide policy, the CEC funded this study. The chapters that follow describe in detail the approach, results, conclusions, and recommendations that the research team reached through the process of building and studying two communities of ZNE homes in Clovis, California. Along the way, the project encountered several challenges including the loss of the first two builder partners. However, the team formed a strong collaborative relationship with the third and final builder partner, De Young Properties, enabling the construction and research envisioned in the original grant.

CHAPTER 2: The Market for ZNE Homes

Introduction

Zero Net Energy (ZNE) buildings will play an important role in meeting future energy use and CO_2 emissions goals in the state of California. As such, stakeholders from across the residential real estate market, including builders, realtors, appraisers, and energy industry professionals must gain a better understanding of how homebuyers in California perceive ZNE, and what their preferences and priorities are in buying new ZNE homes. To support this effort, the California Energy Commission (CEC) funded a Market Assessment for ZNE Home Construction. The purpose of this phase of the study was to assess awareness and understanding of ZNE, the financial value placed on ZNE homes, and the importance of different non-price characteristics in the home purchase decision. This information can be used by California homebuilders to determine which ZNE home designs will be the most marketable, and what messaging around ZNE will be best received by consumers. This will help ensure that leading edge builders who are willing to take risks related to building ZNE ahead of code requirements be rewarded for those efforts through increased sales volume or selling price increases.

Project Approach

Surveys and Interviews

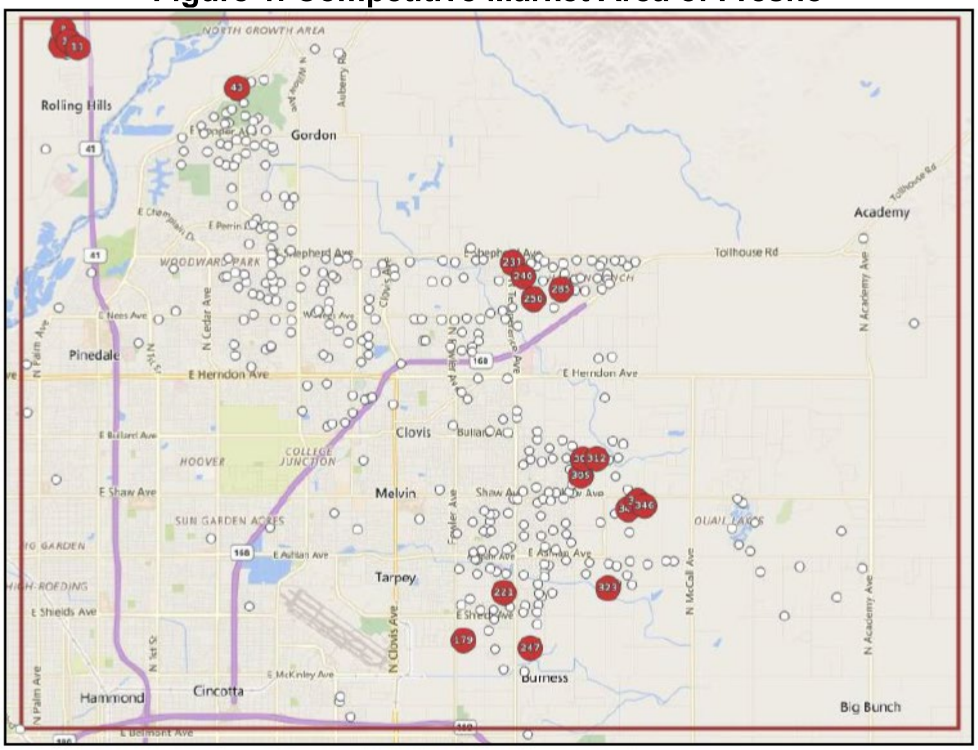
The research team surveyed 500 individuals in the California homebuyer market, including homeowners who purchased a home in California in the last year and homebuyers who are currently in the market for a new construction home.

The research team also conducted in-depth interviews, and secondary research on the California homebuying process, including market reports and conference proceedings. The study team conducted in-depth interviews with eleven real estate market actors, including builders, appraisers, lenders, and energy label certification experts. Since the general population of market actors may not have experience with ZNE homes, the team targeted market actors who had previous experience with ZNE and thus could offer informed perspectives on the California market. Each market actor segment addressed research questions tailored to their specific expertise (e.g., financing or appraising).

MetroStudy

To best support the development of a ZNE community a thorough report analyzing the regional economy and local market preferences was conducted. Prepared by MetroStudy, this analysis reviewed typical housing prices, consumer preferences, and consumer types, including various incomes, lifestyles, and family structures in the competitive market area (CMA), see Figure 1. Next, the study sought to determine the potential price premium for a ZNE home. Because there were no comparable ZNE developments in the CMA, the study analyzed the available data from similar ZNE developments across the country. Using these inputs, the study identified the types of buyers most likely to purchase a ZNE home, established a recommended price premium, and outlined how to define successful competition of a ZNE home in an otherwise highly competitive market.

Figure 1. Competitive Market Area of Fresno



Shows the Competitive Market Area (CMA) of Fresno, generally encompassing the City of Clovis, and stretching slightly into Madera.

Source: MetroStudy Report

Project Results

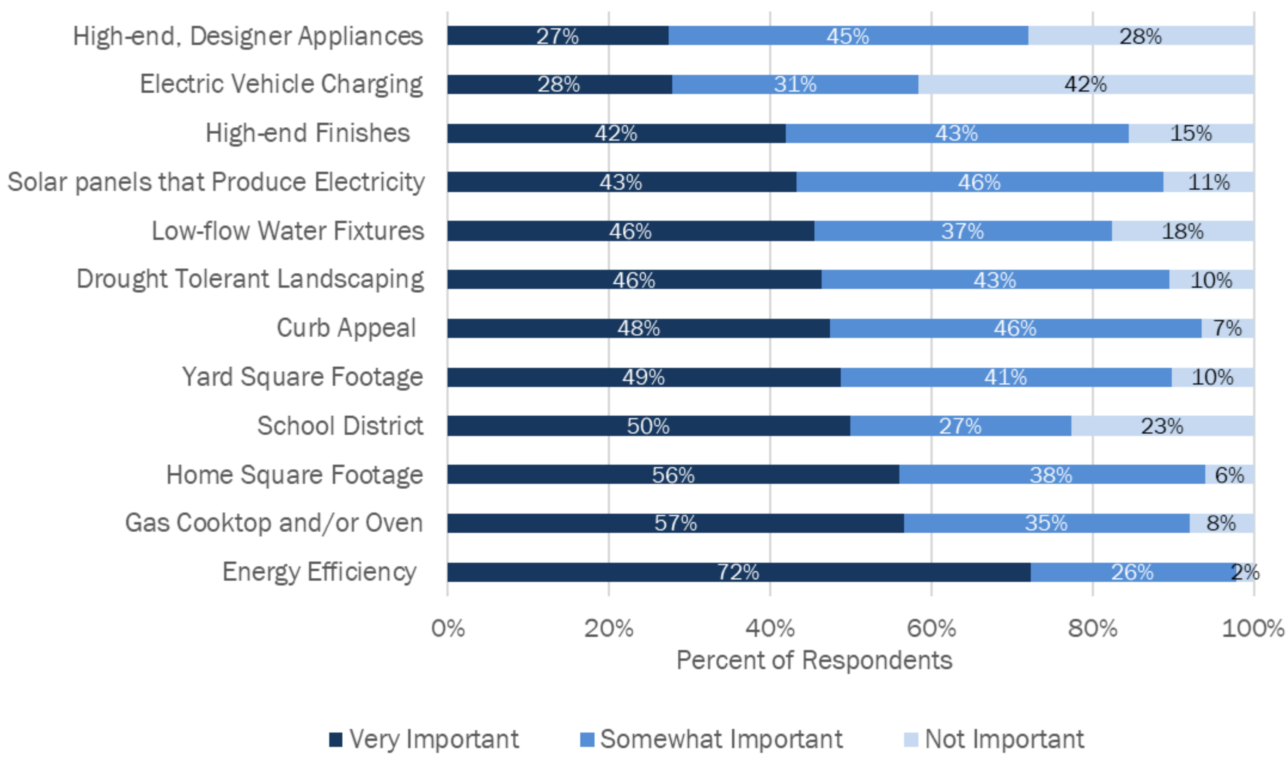
Key Results: ZNE in the California Homebuyer Market

California homebuyer market survey results revealed awareness of ZNE is low and most people do not have an accurate understanding of what ZNE is. While 32 percent of homeowners and homebuyers state they are aware of ZNE when asked what they think of when they see the term "Zero Net Energy," only 7 percent of all respondents responded consistent with the definition of ZNE. Further, 22 percent of respondents reported that they do not know what ZNE is or said they had never heard of it. The fact that nearly a quarter of respondents could not deduce the meaning of "Zero Net

Energy" when prompted suggests that the terminology is not intuitive and, therefore, not an effective cue for consumers.

All survey respondents were asked to rate non-cost home attributes as "very important," "important," or "not important." Overall, most attributes scored similarly, with between 40-50 percent of respondents reporting that they were very important when shopping for a new home (Figure 2) and the highest percentage of respondents reported that energy efficiency was a very important attribute (72 percent).

Figure 2. Importance Ratings of Non-Cost Home Attributes (n=500)

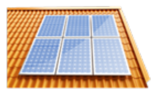


Displays the results of the survey question: Please tell us, in general, how important each of the following characteristics are to you when shopping for a new home?

Source: Opinion Dynamics

The majority of respondents identified individual home attributes that are characteristic of ENERGY STAR® and ZNE homes as being either desirable or highly desirable (Figure 3). In particular, solar panels, batteries for electricity storage, and high-efficiency appliances had the highest percentage of respondents reporting that they were desirable or very desirable home features. Notably, seventy percent of respondents also reported that anonymous energy use monitoring was desirable (39 percent) or very desirable (31 percent).

Figure 3. Desirability of Common Zero Net Energy Home Features (n=500)

	Very Desirable	Desirable	No Opinion	Undesirable	Very Undesirable
 Battery for electricity storage	41%	35%	18%	4%	2%
 Energy-use monitoring	31%	39%	22%	4%	3%
 Solar panels	48%	34%	12%	4%	2%
 High-efficiency appliances	52%	31%	13%	3%	1%

Displays results of survey question: The following list provides features that are often part of ZNE homes. Please indicate the level of desirability of the following features.

Source: Opinion Dynamics

To determine whether homeowners and homebuyers would be willing to pay for the attributes explored above, researchers assessed willingness to pay for a ZNE home in relation to the price that homeowners had either already paid for their home or the budget of homebuyers' future home purchases. As such, the team measured respondents' willingness to pay as a percentage of their budget or purchase price and created three levels by which to evaluate cost: low purchase price/budget ($100,000-$350,000), mid purchase price/budget ($351,000-$800,000), and high purchase price/budget ($800,000 to over $1,000,000).

Overall, willingness to pay more for a ZNE home declined as the price of the home (and therefore ZNE as a percentage of the selling price) increased. In the low budget range, presenting information on energy savings may positively influence decisions to purchase ZNE, as a willingness to pay for ZNE increased in the scenario with electricity bill savings considered. In the highest price/budget ranges, greater percentages of respondents reported willingness to pay for ZNE, likely due to their ability to afford a more expensive home.

Without consideration of utility bill savings, most homeowners and homebuyers were willing to pay at least 2 percent more for a ZNE home than their original purchase price or budget, with a cumulative 73 percent of recent homeowners and a cumulative 88 percent of homebuyers in the low price/budget range reporting that they would pay a price increase 2 percent or more for a ZNE home. Twenty-seven percent of recent homebuyers in the lowest purchase price range were unwilling to pay more for the same home with ZNE features. Twenty-four percent of those still on the market in the lowest budget range were unwilling to pay more for a ZNE home.

When researchers asked homeowners and homebuyers about their willingness to pay more for a ZNE home if they saw $150 in savings on their electricity bill per month, willingness to pay increased and the fraction of those that would not pay anything more for a ZNE home decreased. Overall, the majority of respondents were willing to pay at least 2 percent more for a ZNE home under this scenario.

Key Results: ZNE and the California Home Market

Achieving ZNE in the residential real estate sector is complex, given the number of integral parties involved in building and selling new homes to consumers. This goal requires not only building to code, but for all actors in the real estate market to have viable tools that promote, valuate, and finance ZNE construction. In-depth interviews with builders, appraisers, and lenders, revealed these market actors' unique insights into the conditions of their respective roles in the home purchase process and how these circumstances affect the proliferation of ZNE construction and new home sales.

The study found that market actors in new home construction, new home sales, new home appraisals, and mortgage lending all play a role in the ZNE homebuilding and purchase process and these market actors face barriers at each step in the ZNE home construction and purchase process (Figure 4).

Figure 4. How Market Actors Influence Each Step of the ZNE Home Purchase Process

Displays the role of homebuilders, real estate agents, home appraisers, and lenders in influencing the ZNE home purchase process.

Source: Opinion Dynamics

The barriers to increasing the market uptake of ZNE homes can broadly be divided into two categories, education, and financing:

Education

As shown by the survey results presented in the previous section, prospective homebuyers are interested in the benefits of an efficient home, with energy efficiency being among the most highly rated features of a new home. However, most homebuyers are not looking for ZNE homes due to unfamiliarity with the definitions of ZNE and the arithmetic of costs and savings. Education of the homebuying public should be a focus of any efforts to promote ZNE homes—with fewer than 1 in 10 prospective buyers able to correctly define ZNE, selling the homes will remain an uphill struggle.

Financing

In addition to a lack of awareness of the definition and benefits of ZNE, most buyers are unaware of the financing possibilities for ZNE (or other highly efficient) homes. Many prospective buyers start the process by determining how much they can borrow and use that figure to guide their home search. The figure they are given is usually based on a standard ratio where their mortgage payment (principal, interest, taxes, and insurance) is set at 28 percent or less of their income. Roughly half of them will, when completing the purchase, borrow the maximum amount. At no point in the process does a typical buyer become aware that the ratio of payment to income could be increased via an Energy-efficient Mortgage (EEM) and that the amount they can borrow could be higher if they buy a more efficient house. Educating the home buying population about EEMs will be vital in increasing the demand for ZNE homes.

Even if the buyer is familiar with EEMs, market actors at each step of the home purchase process must be trained and willing to facilitate the sale of a ZNE home. For example, realtors should be aware of the latest ZNE features so that they can communicate those selling points to their customers when touring homes. Then, the appraiser must include the monetary value of the ZNE features in their appraisal so that buyers can get a higher mortgage, which covers the cost of those upgrades. If an appraiser fails to take the ZNE features into account, a lender, by law, will have to offer a smaller loan.

MetroStudy

MetroStudy's analysis established several significant findings. The study found that ZNE homes could demand a price premium of 3-15 percent in the given market area.[5] MetroStudy identified the prices between $300,000 and $374,999 as the most efficient in the market area. The study made a significant effort to highlight the competitive and tight nature of the local housing market. Unlike many localities in California, the Fresno market is lower income, and faster growing, which leaves far less room for margin than

[5] See MetroStudy Zero Net Subdivision, Fresno, California, October 2018, pg. 26

other markets in the state. However, even given the constrained nature of this market, MetroStudy was able to identify an opportunity and potential premium for ZNE homes.

The premium for ZNE homes was supported by particular purchasing groups, and by identifying those groups that have more nuanced interests in their purchasing patterns, a seller can maximize the opportunity to sell advanced quality homes without compromising profits or competitiveness. The analysis cautions that the market in the area is extremely price sensitive and competitive. The market is one of the more affordable in California and conditions such as school and neighborhood quality are of primary concern.

Conclusions and Recommendations

Surveys and Interviews

Overall, the findings from this study indicate that marketing homes to homebuyers simply as "Zero Net Energy" is not likely to be effective. Not only do the majority of homeowners and homebuyers not know what ZNE is, but the term "Zero Net Energy" does not effectively convey the concept to someone unfamiliar with it. However, homeowners and homebuyers value the attributes of ZNE homes and when educated about it, there is evidence to suggest they are willing to pay more. The research team presents the key findings, as well as associated recommendations below:

- Key Conclusion: Awareness of ZNE is low and most people do not have an accurate understanding of what it is.
    - Recommendation: Do not emphasize ZNE terminology in messaging designed to sell new ZNE homes in the short term. While explaining ZNE and its benefits to homebuyers in-person or in one-on-one settings may motivate them to purchase this type of home, the terminology is not appropriate for use in broader marketing campaigns at this time. It is also important for builders and other stakeholders to consider whether the ZNE label is important from a customer facing perspective because until homebuyers understand ZNE, labeling is unlikely to increase sales.
    - Recommendation: Determine the best way to explain and capture the concept in outreach to consumers. Conduct qualitative research with homebuyers to test messaging related to ZNE homes. This will help ensure the messaging can be understood, resonates, and motivates buyers.
- Key Conclusion: Energy efficiency is the highest rated non-price home attribute and ZNE home attributes are desirable to a majority of homeowners and homebuyers.
    - Recommendation: Promote new ZNE homes by focusing on their features. Homebuilders and others promoting new ZNE homes should emphasize

    those characteristics that are understood by and appeal to homebuyers such as energy efficiency, solar, and energy storage. Marketing that focuses on these features rather than the ZNE concept may be more effective in reaching homebuyers.

- Key Conclusion: The majority of homeowners and homebuyers were willing to pay more for a ZNE home.
    - Recommendation: Because most respondents were willing to pay either 2 percent or 4 percent more for a ZNE home, builders should aim to keep ZNE prices within this range, if possible. Prices that are 8-10 percent above a non-ZNE home will have fewer interested buyers, though some individuals are willing to pay up to 10 percent.
- Key Conclusion: The study found that each step of the home building and purchase process plays a unique and critical role in advancing the transition to ZNE homes (Figure 3). However, at each step in the process, market actors face considerable barriers.
    - Recommendation: Though education of buyers is a critical aspect to promoting ZNE construction across the state, every other actor in the real estate market must receive education and training respective to their trade:
        - Homebuilders need a skilled workforce, not only to meet the demand for standard houses in California, but to execute the increasingly complex and refined building requirements set forth by the state.
        - Realtors and other sales agents need options for promoting energy-efficient home features on websites such as the multiple listing service (MLS), and they need training on how to most effectively promote ZNE and EEMs.
        - Appraisers need training in how to use the Green Addendum, or other similar methods, so that the features of ZNE homes can be accurately valued in the appraisal of the home[6].
        - Mortgage lenders need training in the mechanics and options for EEMs and how they can approach buyers.
- Key Conclusion: Because each step in the home buying process is dependent on the step before it, failure to support ZNE at any stage results in homebuyers either being unaware of ZNE, or not getting financing for it.

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[6] The Green Energy-efficient Appraisal Addendum allows builders and realtors to more effectively communicate to appraisers and lenders all the information needed for an equitable appraisal of ZNE homes. The appraisal form addendum ensures that the added values of a ZNE home is properly valued by the appraisers.

- Recommendation: The solution to this will necessarily require all players in the real estate market to place a higher value on energy efficiency, so that it is sought after by buyers, marketed by realtors, valued by appraisers, and covered by lenders. A critical step in achieving this paradigm is quantifying the long-term financial benefits of energy efficiency, which can offset higher initial home prices. Additionally, more widespread adoption of the Green Addendum, or a similar method, would bolster the ZNE market by providing prospective buyers with standardized information about energy efficiency and solar generation features. Lastly, education and training programs for builders and realtors may drive down the costs of ZNE and assure that it is adequately marketed, respectively. Taken together, these steps should result in a residential market that begins to fully value energy efficiency.

MetroStudy

The detailed analysis by MetroStudy shows a clear potential premium value for ZNE homes. The report points out the clearly distinguishable value of homes that reduce annual energy costs. The study also makes clear how price sensitive the market is, and given the housing crisis otherwise, price premiums come with a clear risk in especially competitive markets. Given these findings, it is clear that ZNE homes can include a price premium over non-ZNE homes, but any premium comes at the risk of reducing the pool of potential buyers. Further study should be conducted to understand the market performance difference between ZNE and non-ZNE homes, especially in the resale market. This further analysis should be able to compare the development and construction cost difference against the price premium to determine whether ZNE homes are or can be neutrally competitive against non-ZNE homes.

CHAPTER 3: Measure Costs and Tradeoffs

Introduction

The purpose of this section is to investigate the most cost-effective energy efficiency measures that can be used when building new homes to achieve the State's goal of Zero Net Energy (ZNE) for new residential buildings.[7]

Part 6 of Title 24 of the California Code of Regulations (Title 24) uses a Time Dependent Valuation (TDV) of energy to reflect the higher cost of energy at peak hours compared to off peak.[8] ZNE is defined not as net zero energy consumption (kWh or kBTU) over the course of a year, but as net zero TDV, which represents both time dependent gas and electricity consumption.[9] TDV and thus Title 24 rewards energy efficiency measures that save or generate energy at peak times more than those that save or generate at off-peak times. The increasing use of residential solar photovoltaic systems (PV) to generate energy on-site has intensified the difference in demand between peak and off-peak, which has led the CEC to increase the TDV multipliers at peak hours and shift demand peaks to later in the day, when PV generation begins to decline. The energy performance of a new building is measured by its Energy Demand Rating (EDR), a rating based on the relative performance of buildings.[10] An EDR of 100 is equivalent to the efficiency of a building that would meet the prescriptive requirements of the 2006 International Energy Conservation Code, and a score of 0 represent a building that uses no net TDV energy.

Title 24, Part 6 prescribes efficiency levels for each energy element of a building (water heater efficiency, wall insulation, etc.). A building designed using all prescribed methods will meet the required standard and receive a permit, although this type of "prescriptive" compliance is exceedingly rare. A permit will also be issued for a building that does not follow the prescribed standards but achieves the same overall efficiency, provided it first meets mandatory minimum code requirements. This method, also known as the "performance path", allows trades-offs in efficiency between different elements of the building—for example using lower insulation level but a more efficient HVAC system.[11] These tradeoffs will result in different building costs, as not all efficiency measures are equally cost-effective. Additionally, the impact of an energy-efficiency measure will typically differ between climate zones–upgrading the efficiency

[7] For a detailed explanation of the State's goals of ZNE, see Appendix 3A
[8] For a detailed explanation of Title 24, Part 6, see Appendix 3B
[9] For a detailed explanation of ZNE, see Appendix 3C
[10] For a detailed explanation of EDR, see Appendix 3D
[11] For a detailed explanation of prescriptive vs. performance pathways for compliance, see Appendix 3E

of the HVAC system will cost the same in all climate zones but will provide the most benefit in the zones with the highest cooling and heating needs.[12]

Title 24 stipulates that all newly required energy-efficiency measures be cost-effective when measured over the 30-year lifetime of the residential building by providing energy bill savings that outweigh the initial extra cost. As such, the prescriptive package of measures adopted in each code cycle is intended to represent the most cost-effective design available at the time. Title 24 does not require that builders use the most cost-effective measures to achieve compliance, nor does it require that any measures used to improve the efficiency of a house above the level *required* by the code be cost-effective. However, for obvious reasons builders are very interested in finding the lowest-cost approach to meeting and/or exceeding code, including reaching ZNE.

Project Approach

This study modeled several building types in multiple California climate zones to determine the cost-effectiveness of various measures to improve energy efficiency. The measures included both building envelope improvements and equipment upgrades and were modeled both as standalone measures and as part of packages of improvements.

Construction Industry Research Board

The research team used data from the Construction Industry Research Board (CIRB) to determine which of the 16 Energy Commission California Climate Zones presently have the most residential construction activity. This ensures that the information would be applicable to the greatest number of builders and/or homes constructed. CIRB, part of the California Homebuilding Foundation, surveys over 95 percent of California's building departments monthly to acquire data on the numbers of permits issued by authority and building type.[13]

Description of Models

The focus of this study is for-sale single-family housing, so the buildings modeled were all single-family homes, ranging from a single-story detached building to a 7-plex of 3-story row houses, the latter of which are considered multifamily in CIRB's reporting. The type of building in the CIRB data—multifamily vs. single-family—was used as proxy for detached vs. attached. That data was then mapped to climate zones with significant construction volume for that building type to determine which models to run in which climate zones. The base models were designs provided by California production builders

[12] For a detailed explanation of climate zones, see Appendix 3F

[13] For quantities of construction permits issued for single-family and multi-family units per climate zone, see Appendix 3G

and were selected as representative of typical high-volume building designs currently being constructed in the state.[14]

ConSol Database

To determine the cost of each measure a database was created containing both material costs and labor costs for every relevant aspect of the building. The values in the database were obtained from a variety of sources (e.g., manufacturers, distributors, builders, contractors, online sources) to ensure they accurately reflect actual builder costs. The cost of each measure for each building was calculated by combining details from the model (e.g., square footage) with numbers from the cost database (e.g., $/sqft.).[15]

California Building Energy Compliance Calculation Software

Modeling was performed using the CEC-approved CBECC-Res compliance software. The effectiveness of individual measures was determined by comparing the EDR of the base model with the EDR of a model differing only by the inclusion of the measure being considered.[16]

Cost-effectiveness

The difference in EDR determined from CBECC is divided by the cost of the measure to calculate relative cost-effectiveness. For the purposes of this study, cost-effectiveness is measured using the ratio of reduction in EDR to measure cost, which allows direct comparison between different measures. A measure costing $100 and giving an EDR reduction of 1 point would have the same cost-effectiveness ratio as a $200 measure with an EDR reduction of 2 points but would be half as cost-effective as a $100 measure giving an EDR reduction of 2 points.

This research is intended to provide guidance to builders and their energy consultants to identify the lowest cost approaches to building ZNE homes. The process of finding these lowest-cost performance paths is best referred to as "cost optimization." For the purposes of this report the terms "cost-effective" and "cost-effectiveness" are used to describe the *relative* performance of measures with respect to one another, as a function of first costs to TDV savings. Designation or description of a measure or technology as "cost-effective" in this report does not necessarily mean it will meet other definitions of that term, such as having a short payback period.

In addition to being climate dependent, the effectiveness of an energy efficiency measure depends on the features of the house in which it is being used, including which other energy efficiency measures are being installed. For example, upgrading the windows will have a greater impact in a home with more total glazing. Likewise, those

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[14] For a detailed description of the models used in the analysis, see Appendix 3H
[15] For a detailed description of the ConSol cost database, see Appendix 3I
[16] For a detailed explanation of the CBECC modeling software, see Appendix 3J

upgraded windows will reduce the heat load on the building during the cooling season, which will in turn reduce the savings achievable by upgrading the HVAC system. To determine the combined effectiveness of multiple measures it is necessary to model them as a package and find the total EDR reduction and the total cost.

Single Energy Efficiency Measures

For each building and climate zone, various single energy efficiency measures were modeled, and the cost-effectiveness of the various measures was determined. The measures were then ranked in terms of cost-effectiveness, allowing for direct apples-to-apples comparison between measures.[17]

Packages of Measures

For each building and climate zone approximately 10 measures were selected, based on their individual cost-effectiveness, and the building was modeled with every possible combination of the selected measures. This approach necessitated many modeling runs which would have been prohibitively time consuming to run individually but was made possible by the use of a parametric software tool to allow the models to be run in batches.[18] Packages of measures that brought the building to at least the minimum level needed to meet code were ranked in order of cost-effectiveness.

The measures studied here to bring the buildings up to code inevitably suffer from the law of diminishing returns. As buildings are made more efficient the cost of incremental efficiency increases and becomes prohibitively expensive. To reach ZNE, all buildings will require some form of renewable generation, which will typically be solar PV. Once the building has met the envelope efficiency required by code, the cost of further reducing energy use through efficiency improvements must be compared to the cost of generating energy using PV.

Renewable Energy

The cost-effectiveness of PV was modeled for three different scenarios. First, buildings are modeled with the largest PV system allowed by the compliance software, which corresponds to the size for which utility companies will typically allow interconnection. Secondly, buildings are modeled with the same PV system and battery (one battery per unit in the multifamily buildings). Finally, the PV size is increased as needed to bring the building to ZNE, using the CEC's TDV-based definition.

Efficient Appliances

Modeling was also carried out to find the $/EDR savings that would be achieved using more energy-efficient refrigerators and laundry equipment. Since CBECC does not allow for modeling of more efficient appliances, an engineering analysis had to be done to estimate the annual energy use of more efficient equipment for each building prototype

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[17] For a detailed explanation of the single energy efficiency measures modeled, see Appendix 3K

[18] For a detailed explanation of the parametric modeling tool, see Appendix 3L

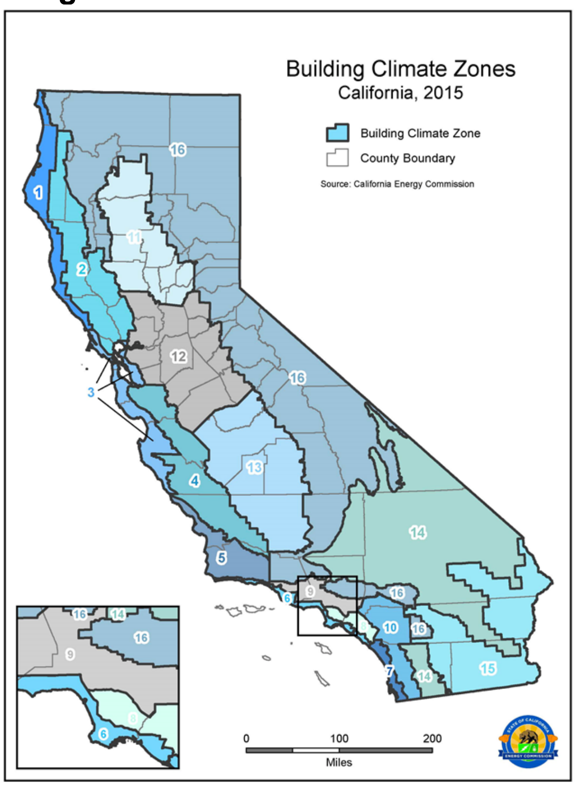
and climate zone in the parametric analysis. The estimated distribution of the energy savings was then applied to each of the 8,760 hour profiles based on "load profile" data derived from residential submetering microdata from Northwest Energy Efficiency Alliance's (NEEA) 2014 Residential Building Stock Assessment.[19] The energy savings were then converted into TDV savings based on the 2016 Title 24 TDV multipliers and then into EDR savings.

Project Results

Construction Industry Research Board Results

For single-family buildings in Q3/Q4 2016, the most active residential building climate zones were 10,12, and 13, which accounted for 48.1 percent of all single-family permits. For multifamily permits, Climate Zones 3, 7, 8, and 9 accounted for 67.7 percent of all permits. No other climate zone accounted for more than 10 percent of permits issued for either single-family or multifamily construction, which was used as a threshold for determining which climate zones to use for energy modeling.[20]

Figure 5: California Climate Zones



Shows a map of the 16 different CEC defined California Climate Zones.

Source: California Building Climate Zone Areas

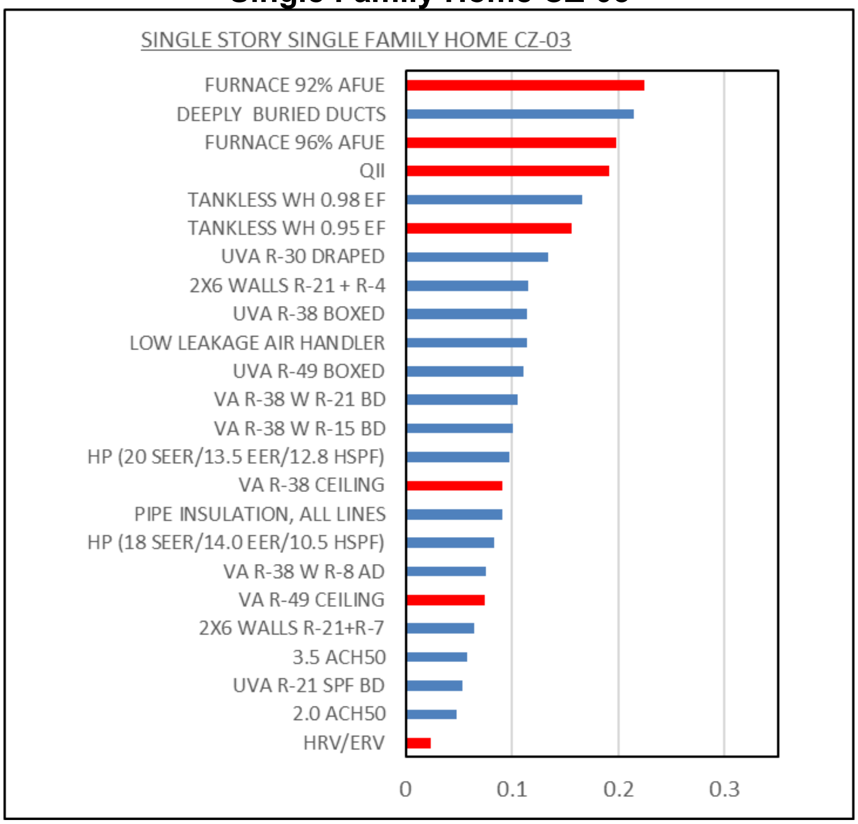
[19] NEEA 2014 Residential Building Stock Assessment
[20] For the full CIRB results, see Appendix 3M

Cost-effectiveness Results

Single Energy Efficiency Measures

The most cost-effective measures vary between climate zones and building types. Most of the measures modeled are climate dependent, with HVAC and envelope measures providing the greatest energy savings in climates with significant heating and cooling loads. Because the climate does not affect all measures equally, the relative cost-effectiveness changes between climate zones. The only measure that consistently appears in the top 10 most cost-effective across all climate zones and house types is the upgraded water heater, which is relatively unaffected by climate conditions. Figure 6 shows a ranking of the cost-effectiveness of energy efficiency measures for a 1-story home in Climate Zone 3. See Appendix 3N for the measure rankings of all other building types and climate zones.

Figure 6: Cost-Effectiveness of Energy Efficiency Measures for Single Story Single Family Home CZ-03



Shows a ranking of single energy efficiency measures by reduction in EDR points per $100 spent for the 1-story single-family home in Climate Zone 3. AFUE stands for Annual Fuel Utilization Efficiency, QII stands for Quality Insulation Installation, UVA stands for Unvented Attic, VA stands for Vented Attic, BD stands for Below Deck Insulation, AD stands for Above Deck Insulation, HP stands for Heat Pump, ACH50 stands for Air Changes per Hour with a 50 Pascal pressure difference, HRV stands for Heat Recovery Ventilation, and ERV stands for Energy Recovery Ventilation. The red cost-effectiveness bars represent measures that are relatively common.

Source: Zero Net Energy Analysis and Prioritization Report

Packages of Measures

The results of the ranking of the packages of measures that were modeled with the parametric modeling tool showed that there is no one package that is universally most cost-effective. Rather, there are multiple ways in which builders can meet code, which will allow them to choose measures based on concerns other than pure cost efficiency. The measures that featured most commonly in the top packages were upgraded water heaters, furnaces, and windows. The common feature of these is that they require little or no additional labor when compared to the base case. Table 1 shows a ranking of the most cost-effective packages of measures for a 1-story home in Climate Zone 10. See Appendix 3O for the package rankings for all other building types and climate zones.

Table 1: Most Cost-Effective Compliance Packages for Single Story Single Family Home CZ-10

DHW Eff. (EF)	FURNACE Eff. (AFUE)	DUCTS OPTION[a]	QII	WINDOWS (U/SHGC)[b]	ATTIC OPTION[c]	HVAC (SEER)	WALLS[d]	WHF	TOTAL COST	$/EDR REDUCTION	EDR MARGIN	EDR REDUCTION
0.95	80%	DCS	✓	0.31/0.22	1	18	2x4	X	$4,115	$354	0.11	11.6
0.95	92%	DB	✓	0.31/0.22	1	18	2x4	X	$4,117	$355	0.11	11.6
0.95	92%	DCS	✓	0.31/0.22	1	18	2x4	X	$4,310	$357	0.59	12.1
0.80	92%	DCS	✓	0.31/0.22	3	18	2x4	X	$4,155	$357	0.13	11.6
0.95	92%	DB	✓	0.31/0.22	3	18	2x4	X	$4,332	$363	0.44	11.9
0.95	80%	DCS	✓	0.31/0.22	3	18	2x4	X	$4,330	$364	0.39	11.9
0.95	92%	DB w/ LLAH	✓	0.31/0.22	1	18	2x4	X	$4,341	$365	0.41	11.9
0.95	92%	DCS	✓	0.31/0.22	3	18	2x4	X	$4,525	$366	0.86	12.4
0.95	92%	DCS	✓	0.32/0.25	1	18	2x4	X	$4,263	$369	0.06	11.6
0.80	92%	DCS	✓	0.31/0.22	4	14	2x4	✓	$4,296	$371	0.08	11.6

[a] DCS = ducts located entirely in conditioned space, DB = deeply buried ducts, DB w/ LLAH = deeply buried ducts with low leakage air handler

[b] First number refers to u-factor and second number refers to solar heat gain coefficient

[c] 1 = vented attic w/ R-38 ceiling, and R-13 below deck, 3 = vented attic w/ R-38 ceiling and R-19 below deck, 4 = vented attic w/ R-49 ceiling and R-19 below deck.

[d] 2x4 = R-15 cavity insulation and R-4 sheathing.

Source: Zero Net Energy Analysis and Prioritization Report

Renewable Energy

The costs of building efficiency and renewable generation range between $154/EDR and $618/EDR, without any clear pattern emerging. The diminishing returns from building efficiency measures, with each successive reduction in EDR costing more than the previous one, contrasts with the scalability of renewables, where the unit-cost is unchanged as the system size is increased—and, in fact, it usually goes down as size increases. This difference suggests that ZNE can be reached more cost-effectively by increasing the use of PV and storage than by further increasing building energy efficiency beyond 2019 code requirements. Table 2 shows the cost per reduction in EDR point for the optimal energy efficiency package, PV, PV+battery, and for reaching ZNE.[21]

Table 2: Comparison Between Cost of Building Efficiency Measures and Renewables

House	CZ	$/EDR best EE package/unit	$/EDR PV/unit	$/EDR PV+Battery/unit	$/EDR ZNE/unit
1 story single-family	9	$ 348	$ 289	$ 272	$ 274
1 story single-family	10	$ 354	$ 306	$ 276	$ 276
1 story single-family	12	$ 323	$ 339	$ 313	$ 310
1 story single-family	13	$ 274	$ 403	$ 351	$ 353
2 story single-family	3	$ 340	$ 388	$ 367	$ 368
2 story single-family	10	$ 335	$ 470	$ 415	$ 411
2 story single-family	12	$ 356	$ 530	$ 468	$ 478
2 story single-family	13	$ 276	$ 618	$ 543	$ 563
4-plex	3	$ 333	$ 248	$ 358	$ 329
4-plex	7	$ 354	$ 190	$ 277	$ 261
4-plex	9	$ 272	$ 270	$ 364	$ 338
7-plex	3	$ 154	$ 238	$ 381	$ 337
7-plex	7	$ 560	$ 188	$ 301	$ 274
7-plex	9	$ 285	$ 260	$ 396	$ 350
7-plex	10	$ 272	$ 286	$ 425	$ 377

Source: Zero Net Energy Analysis and Prioritization Report

Efficient Appliances

The results of modeling the energy-efficient refrigerators and laundry equipment showed that upgrading the efficiency of these appliances is one of the most cost-effective ways to reduce building energy use. Costs of appliance efficiency range from $135/EDR to $908/EDR for primary refrigerators and $148/EDR to $1,031/EDR for laundry equipment. The incremental costs for the more efficient primary refrigerator and washer-dryer pair were $88 and $646, respectively. The efficient appliances were more cost-effective to implement in multifamily buildings than they were to implement in single family homes. This is due to the appliances making up a larger overall share of the total consumption for multifamily units over single family homes. Figure 7 shows the cost-effectiveness of energy-efficient appliances (white goods) versus building efficiency measures and PV/storage.[22]

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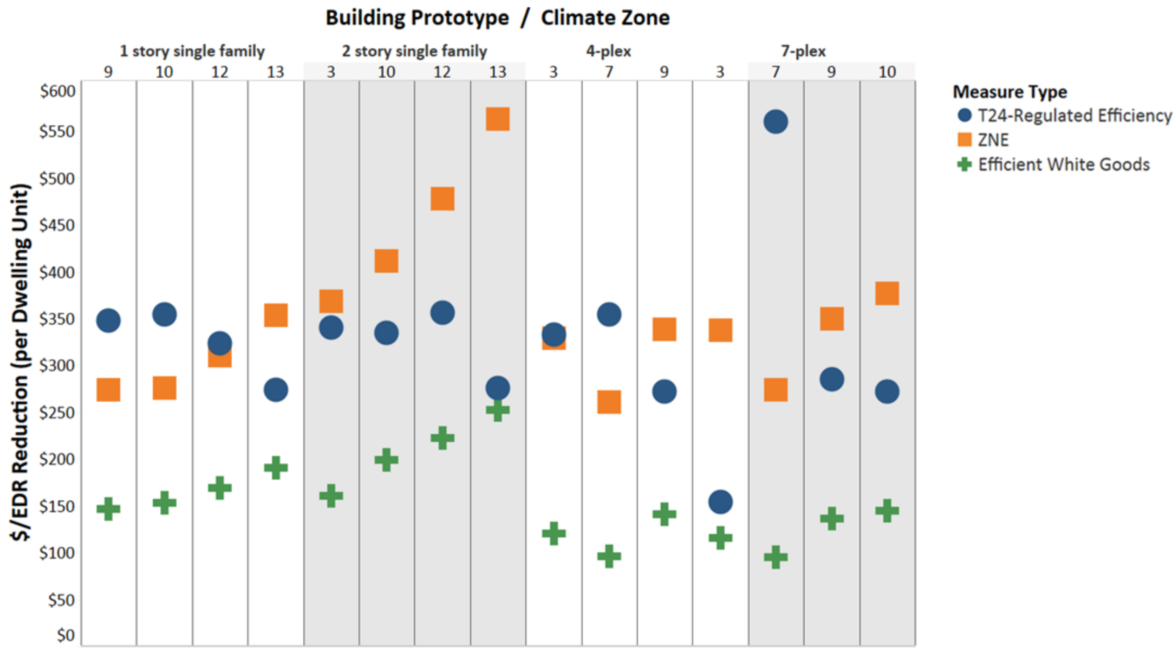
[21] For the full results of the renewable energy analysis, see Appendix 3P

[22] For the full results of the efficient appliances analysis, see Appendix 3Q

Figure 7: Comparison of Costs Effectiveness for Building Efficiency Measures, Renewable Energy Reaching ZNE, and Efficient Appliances (White Goods)



Shows a comparison of the cost-effectiveness of building efficiency measures to reach 2019 code (blue dots), renewable energy (PV+Battery) to reach ZNE (orange squares), and energy-efficient appliances, or white goods (green crosses), across all building types and climate zones. The appliances consisted of energy-efficient refrigerators and laundry equipment. A lower $/EDR value represents a more cost-effective measure. The efficient appliances were more cost-effective than either building efficiency measures or renewable energy across all building types and climate zones.

Source: Zero Net Energy Analysis and Prioritization Report

Conclusions/Recommendations

Climate Zone Prioritization

Most of the new residential construction activity occurs in 7 of the 16 total California Climate Zones. For that reason, efforts should be prioritized into producing literature that informs builders in these areas of the most cost-effective ways to reach ZNE. It is important to remember that the benefit/cost ratio for each energy efficiency measure depends on the specific house design, in addition to the climate zone. Each specific design for a home or multifamily building has a unique energy use profile and must be modeled to determine whether it will comply with code and/or achieve ZNE, so this analysis cannot substitute for project-specific calculations. However, it is useful to look at a variety of designs in different climate zones in order to help builders prioritize measures with the highest benefit/cost ratio, which can then be incorporated into project-specific models. Likewise, it is important that the designs for each modeled home or building be sourced from actual floor plans constructed by today's production homebuilders, rather than a “prototype” building that is not representative of a building that will be constructed.

Cost-effectiveness Perspectives

Title 24 requires all newly required energy efficiency measures to be cost-effective. This cost-effectiveness test, established by the Warren Alquist Act, requires that any new energy savings measure or increase in code stringency not result in a net cost increase over the lifetime of the measure. This requirement does not, however, address the relative effectiveness of different measures, nor does it address any above-code measures; making this determination can be considered “cost optimization,” and is critical for homebuilders to understand.

A measure whose construction cost increase is more than offset by energy bill savings over the effective useful life of the measure (typically 30 years) will pass the cost-effectiveness test from the perspective of the CEC, but it will not necessarily be a measure a builder will want to include in an efficiency package to reduce loads and reach ZNE. For builders, the most important factor will be how much reduction in EDR a measure delivers—and more importantly, what is benefit/cost ratio in terms of EDR point per dollar spent. Providing a ranking of code-compliant and above-code measures in terms of the benefit/cost ratio for each measure can help builders identify the lowest-cost path to ZNE, given the fixed attributes of the house, such as climate zone, size, amount of glazing, number of stories, and the presence or absence of shared walls.

Cost-effectiveness will not be the only consideration when deciding whether to include a measure in a building. Familiarity with construction techniques will continue to make 2x4 framing an attractive option despite the better performance of 2x6 framed walls. The impact on interior dimensions and lot line clearances will also affect builders’ choices. For other measures, the possible adverse impact on purchasers will influence choices: bringing ducts into conditioned space by lowering ceilings in corridors will improve efficiency but at an aesthetic cost which may deter buyers.

Single Energy Efficiency Measures

The results of the single measure analysis clearly underscore the purpose and validity of California’s performance-based energy code—energy efficiency is not a “one size fits all” strategy. Builders need to be able to select measures that offer the best savings given their other design constraints, including location (climate zone), square footage, number of stories, ratio of and orientation of glazing, consumer preferences—as well as cost. This study focuses on that final (and often most important) constraint to help builders narrow down their focus and find “low hanging fruit” that they can reliably implement to achieve cost-effective EDR reduction.

Packages of Measures

The results of the parametric analysis show that despite considerable variation among climate zones and building types, nearly every measure in the analysis appears as part of a highly cost-effective package in one or more situations. This proves that there are many ways in which to build cost-effective energy-efficient homes and reinforces the position that there are good alternatives for builders who include considerations other than pure efficiency (e.g., lowering hallway ceilings to bring ducts into conditioned space may be an effective measure energetically but comes at an aesthetic cost).

While the measures used in the most cost-effective packages vary considerably between different building types and across different climate zones, there are some measures that are almost always cost-effective: upgraded water heaters, furnaces, and windows. These measures share the fact that they can be implemented with little or no additional labor costs when compared to the base case. This is also true of air-conditioners, which do not make the cost-effectiveness measure list. This is most likely because air-conditioners have been developed to a point where the basic unit is sufficiently efficient as to render the incremental benefits of a more efficient unit prohibitively expensive, whereas water heaters and furnaces still have room for relatively inexpensive increases in efficiency.

Renewable Energy

The cost-effectiveness of building efficiency upgrades decreases as homes exceed 2019 code, as opposed to just reaching 2019 code. This is reflective of the diminishing returns in efficiency upgrades as homes become increasingly efficient. It can be concluded from this that the balance between building efficiency and renewable generation required by the 2019 building code is appropriate from a cost-effectiveness perspective. Lower building efficiency requirements would reduce the cost of the efficiency packages and require larger more expensive renewable generation systems. Higher building efficiency requirements would allow smaller renewable systems at the expense of more expensive efficiency packages.

Efficient Appliances

The cost-effectiveness of upgrading refrigerators and laundry equipment is such that builders would benefit from being able to claim credit for the appliances when calculating the building energy use. This is not currently possible with the CBECC-Res software. For further information on this topic readers are referred to the CASE Initiative report "Plug Loads and Lighting Modeling," which includes proposed algorithms to credit more efficient appliances.[23]

A concern that the energy commission has with allowing credit for efficient appliances however is that builders would be trading off long-lasting measures, like high-performance walls and attics, for appliances that are potentially short-term measures.

[23] Codes and Standards Enhancement Initiative – Plug Loads and Lighting

Additionally, the high-efficiency measures may not be installed at the time of inspection, making verification impossible. For builders to claim credit for efficient appliances, it would need to be determined how to ensure that the homeowner never swaps out the efficient appliances for less efficient appliances and how to guarantee that the high-efficiency appliances are going to be installed, as it may not be present at the time of inspection. The difficulty in verifying energy-efficient appliances are installed and remain in place may make allowing a credit to be claimed for them impractical.

CHAPTER 4: Construction

Introduction

To receive a building permit, the "proposed design" for a house following the performance path must use no more energy than a "standard design" house—one using all prescriptive features listed in the Title 24 Standards.[24] Energy consultants use an CEC-approved software package, such as CBECC-Res, to perform the calculations needed to compare the two designs—proposed vs. standard. Utility incentive program managers also use the software to determine incentive amounts for builders participating in the California Advanced Homes Program (CAHP). Similarly, some jurisdictions adopt local Reach Codes, which require a home to exceed Title 24 by 15-30 percent, as calculated by the software.

In the case of this project, the builder used compliance software to show that the floor plans for the demonstration homes were all designed to Zero Net Energy, which includes exceeding the efficiency requirements of Title 24 by 20-30 percent and sizing PV to match annual energy consumption and achieve zero EDR.[25] This report describes the advanced construction techniques incorporated by the builder to achieve that 20-30 percent reduction.[26]

The only end-uses regulated by Title 24 are space heating and cooling, water heating, and ventilation, so those are the only compliance variables subject to user inputs into the software and the only energy-using features most builders are concerned with.[27] Although the user cannot alter specifications for lighting, appliances, or plug loads, the software still performs those calculations to arrive at annual whole-home consumption. So, if the builder has installed highly efficient equipment (as is the case in the ZNE demonstration homes), the software may overestimate annual energy consumption for one or more of those appliances. Since these estimates are used to size PV for Zero Net Energy, the team felt that it was appropriate to provide the builder with refined estimates using additional, external data. This chapter presents the modeled energy use predicted by the CBECC-Res software (version 2016.3.1 (1019)) alongside the team's refined estimates of the energy use to reflect specific equipment choices.

[24] See Appendix 3E for a description of performance compliance.
[25] See Appendix 3D for a description EDR.
[26] Although the same techniques were deployed in all floor plans, the resulting savings vs. Title 24 varied from 20-30 percent.
[27] For more discussion about Regulated and Unregulated loads, see Chapter 8 Introduction

Additionally, this chapter details challenges related to integrating advanced energy features into construction and the data collection process, and how the technical support the team provided to help overcome those challenges.

Finally, this chapter describes the process of developing two all-new floor plans with a focus on design-based strategies for energy efficiency. Since one of the main opportunities for this type of early-stage design engagement is the ability to influence the location of mechanical equipment and distribution systems, the report also discusses the tools and metrics the team used to assist architects in space planning for compact distribution systems. This chapter documents that process, details the lessons learned, and highlights trade-offs other builders may face when striving for efficiency while still working within the design constraints and buyer demands for production homes.

Project Approach

Above Code Design and PV Sizing

The builder-partner in the ZNE demonstration project has been a leader in energy-efficient and ZNE construction for over a decade, so some of the energy-efficient practices they used in the ZNE homes have become "standard practice" for all homes they build. As Title 24 Standards have gotten increasingly stringent, some of those practices are no longer "above-code" such as the 2x6 High-performance Walls the builder includes in all of their homes, which became a prescriptive code requirement for Climate Zone 13 in the 2016 Standards. However, even after implementation of 2016 code, most California builders retained traditional 2x4 walls.[28]

The builder combined a mix of practices they use on standard, minimally compliant homes, with advanced features aimed at reducing regulated loads by 20-30% below Title 24 2016 Standards for the ZNE demonstration project. Perhaps more importantly, the builder replaced the two major natural gas appliances in the home (water heater and furnace) with electric heat pumps and offered buyers the option to go all-electric by selecting an induction cooktop. This is important for three reasons:

1. Electric appliances can be directly powered by rooftop PV at times of the day and year when the system is generating sufficient power.
2. The electric utility conducts an annual true-up of total PV production against total electricity consumption, so even though the electric appliances must draw power from the grid when the sun is not out, the homeowner's electricity bill can be close to zero or even result in a credit.
3. Unlike natural gas appliances, electric appliances do not directly emit GHGs. So, even over the hours of the day and year when they are not powered by 100

[28] 71% of homes built under the 2016 code utilized 2x4 walls per CHEERS data, see Appendix 4A

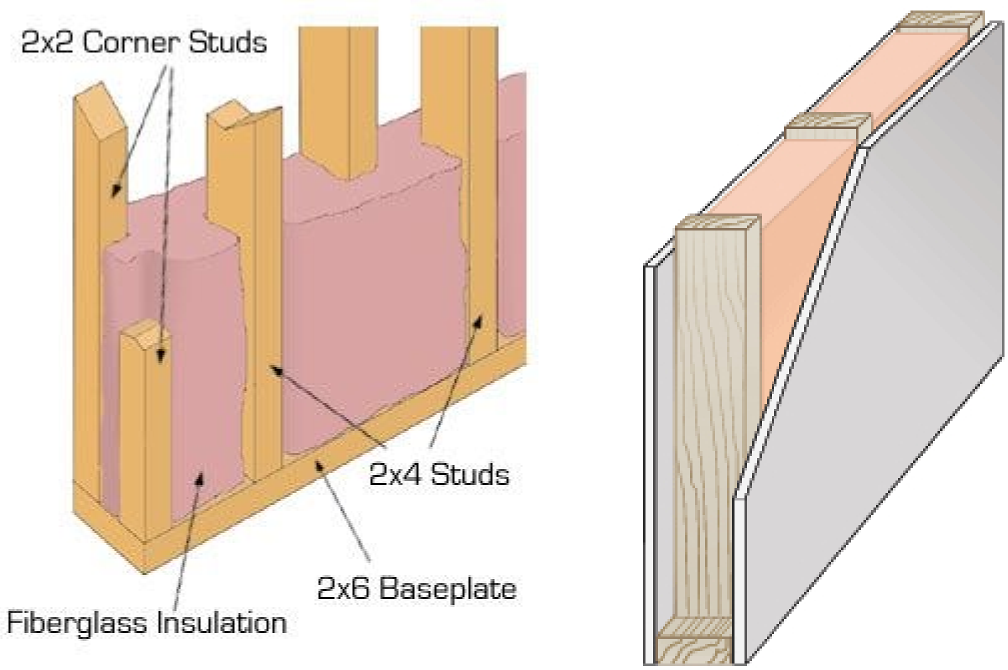
percent clean energy from the rooftop PV, their emissions are simply a factor of the fuels used to provide electricity on the grid. As the grid becomes cleaner, so do those end-uses.

Efficiency Measures

The envelope measures the builder used to meet and exceed Title 24 code include:

- **2x6 24 inch on center (IOC) High-performance Walls with R-21 Cavity Insulation and R-4 Sheathing; Advanced Framing and Staggered Studs.** Standard practice for most California builders is to use traditionally framed 2x4 16 IOC walls with cavity insulation ranging from R-13 to R-15 and R-4 or R-5 sheathing. With traditionally studded walls, the framing acts as a thermal bridge that allows heat to flow more easily between interior and exterior. Staggered-stud framing utilizes a 2x6 baseplate and 2x4 studs, alternating between contact with the exterior side of the wall and the interior side of the wall. This eliminates the thermal bridge between the two sides of the wall, making the wall much more resistant to heat transfer.

Figure 8: Staggered Stud vs. Traditional Stud Framing

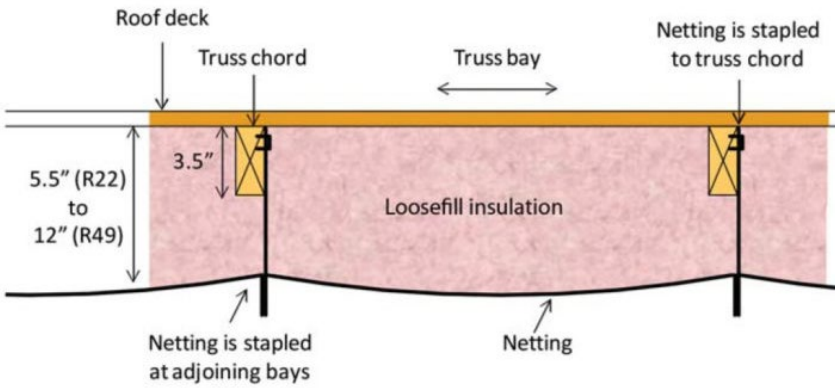


Shows staggered stud framing, which utilizes a 2x6 baseplate ad 2x4 studs, alternating between contact with the exterior side of the wall and the interior side of the wall (left) and traditional stud framing (right).

Source: Staggered Stud Wall Detail

- **High-performance (Unvented) Attics with R-38 Boxed-Netting Below Deck Insulation.** Standard practice for most California builders is to use a vented attic with R-38 ceiling insulation and a radiant barrier on the underside of the roof deck. Unvented attics are superior from an energy standpoint because they bring the attic within the building envelope, which moderates attic temperatures. This is particularly important because new homes have ductwork in the attic. The unvented attic also reduces heat transfer between the attic and living space, which reduces heating and cooling loads. Since unvented attics cannot rely on the vents traditionally used to control humidity and avoid roof deck condensation, the builder used vapor retardant boxed netting and vapor diffusion vents in the attics. To aid humidity control while also offering improved air quality, the builder combined always-on whole-house exhaust fan with damper-controlled fresh air supply ducts that are integrated within the central heating and air distribution system. See Chapter 7 for more discussion on the moisture mitigation measures.

Figure 9: Boxed-Netting Insulation



Shows boxed-netting insulation assembly.

Source: Owens Corning Boxed-Netting Insulation Assembly

- **4.4 ACH50 Sealed and Tested Envelope Leakage.**[29] Standard practice for most California builders is to default to 5 ACH50. 4.4 ACH50 represents less air that needs to be conditioned and is therefore tighter and more efficient. Air sealing is typically done by using a large canister filled with polyurethane, which expands when it comes into contact with the air. It is sprayed from the canister through a long metal hose to get into hard to reach areas in the attic and seal the attic off to the outside. Another option is to pressurize the home and release a vapor sealant that plugs any leaks to the outside.
- **0.26 U/0.20 SHGC Argon Insulated Double Pane Vinyl Windows.**[30, 31] Standard practice for most California builders is to use 0.32 U/0.25 SHGC vinyl windows. A smaller U-factor equates to less heat transfer through the windows

[29] ACH50 refers to the amount of air changes in an hour.
[30] U refers to U-factor (Btu/hr-ft^2-°F).
[31] SHGC refers to Solar Heat Gain Coefficient, the fraction of solar radiation admitted through a window, door, or skylight.

and a smaller SHGC equates to a smaller amount of radiation gain through a window.

Efficiency/Electrification Measures

The measures that the builder converted to electric, while also exceeding code are:

- Lennox 20 SEER/13.5 EER/10 HSPF Split System Heat Pumps.
- Rheem 3.55 UEF 50 Gallon or 3.70 UEF 65 Gallon Hybrid Heat Pump Water Heaters.
- Heat Pump Clothes Dryers.
- Electric Ovens.
- Electric Induction Cooktop (Option)..
- Upsized 225A main and 125A subpanel, also equipped for EV and battery with that capacity. Prewired for EV.
- CURB Energy Monitoring System.
    - Provides real-time data on energy consumption and production.
    - Allows for smarter decisions about energy use.
    - Recognition of abnormal usage patterns indicating potential problems.
    - Utility bill estimation.
- 100 Percent LED lighting.
    - Most energy-efficient lighting technology available.
- WiFi Lighting Controls, Dimmers, and Switches.
    - Allows users to control lighting through their mobile devices.
- Samsung SmartThings hub (can be integrated with CURB).
    - Connects to a variety of smart devices.
    - Allows the user to monitor and control the connected devices and receive alerts from connected activities when there's unexpected activity.
    - Automates connected devices in your home and sets them to turn on/off when doors are opened, as people come and go, etc.
- Smart USB Outlets.
    - Allows the device being charged to specify exactly how much current it requires, up to the limit of the charger, and disconnect the current once it is fully charged.
- Lennox iComfort S30 Advanced Smart Thermostat.
    - Actively monitors system operations and sends alerts to homeowner and dealer should problems arise.
    - Detects when occupant is leaving and automatically increases system efficiency; resumes normal schedule when occupant returns.
    - Balances temperature with humidity to achieve "Feels Like" temperature.[32]
    - Generates performance reports to help homeowner fine-tune settings.

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[32] "Feels Like" refers to the perceived temperature when humidity is considered. For example, 70 °F at 100% relative humidity will feel hotter than 70 °F at 10% humidity.

HVAC Equipment

As the largest use of energy in most homes, investing in highly efficient heating and cooling equipment is one of the most effective ways to reduce loads. The builder installed Lennox XP-20 ducted heat pump heating and cooling. The system is 20 SEER/13.5 EER/10 HSPF, which far exceeds the 2016 standards of 14 SEER/8.2 HSPF.[33] The system consists of an outdoor condensing unit and an air handler located in the attic. The air handler includes a variable speed fan that was also be used for supply ventilation via a dedicated 12 inch fresh air duct equipped with a MERV 8 filter. This supply duct included a mechanical damper designed to open each time the fan runs, whether the system is heating, cooling or just recirculating and pulling in supply air.[34]

The air handler also included resistance heating elements designed to supplement the heat pump during periods of extreme cold or when additional heating capacity was called for over a short duration, such as a homeowner returning from vacation or substantially increasing the thermostat set point. Since the resistance heating element draws far more power than the heat pump, its use could create notable spikes on the grid if many homes ran simultaneously. Is therefore important to consider whether the resistance heating element is an important part of heat pump heating systems in California, or simply a convention that homeowners are used to due to the prevalence of gas furnaces and the ability of those systems to provide rapid increases in indoor temperature.

Furthermore, heat pump heating and air equipment in much of the world is ductless, instead using refrigerant lines to distribute heating and cooling throughout homes and apartment buildings. However, ductless systems require separate fan units in each room and the unconventional appearance tends to be unacceptable to homebuyers and homebuilders, who are more accustomed to conventional ducted systems and supply registers. For that reason, the builder selected a ducted heat pump rather than the lower cost ductless version.

Since air-source heat pumps like the ones used in the demonstration homes extract heat energy from the air, their heating performance declines as outdoor temperatures decline. However, other than taking longer than a gas furnace to reach setpoint, switching to electric heat pump heating is generally not a problem in California's relatively mild winter climates.

The HVAC technician for the demonstration homes reported slightly higher than usual homeowner complaints in callbacks, mostly pertaining to this aspect of heat pump performance. However, after explaining the difference in operation the technician reported that customers were generally accepting of the technology and were able to maintain comfort with minor changes to behavior, expectations, and system settings.

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[33] There is no mandated minimum EER for central air source heat pumps <65,000 Btuh.

[34] See Chapter 6: Indoor Air Quality for more information about the supply and exhaust ventilation.

Lennox iComfort advanced smart thermostats were also installed which include several advanced features. See Table 9 in Chapter 5 for descriptions of the advanced features.

Water Heating

Following space heating and cooling, water heating is typically the largest single energy end-use for homes in California's interior and can be the largest use for homes in mild coastal climates. Each of the demonstration homes included a RUUD/Rheem hybrid heat pump water heater located in the garage. The performance of these units ranged from 3.55 to 3.7 UEF depending on size. The water heaters include both electric heat pump technology and conventional resistance elements, which improve recovery times in periods of high demand for hot water. The water heaters were each equipped with a Wi-Fi radio, and a technician connected several of the water heaters to the Wi-Fi router, so that the user could control the water heater settings remotely.

The domestic hot water distribution system includes a recirculation loop with a push-button recirculation pump. Recirculation loops are a consumer preference for large houses to avoid long wait times for hot water fixtures that are located far away from the water heater. Push-button recirculation systems save energy compared to standard always-on recirculation pumps or recirculation pumps on timers because the pump only runs when the homeowner wants it to run, eliminating excess runtime and energy use. This also helps to prolong the life of the pump.

Strategies for Heat Pump Water Heaters

The default PG&E utility rate for new homes with PV systems includes peak pricing between 4:00 PM and 9:00 PM (TOU-B). This rate structure is reflective of the fact that the abundant solar electricity on California's grid tapers off in the late afternoon/ evening-just when residential demand is ramping up. Due to these high rates, any decrease in energy consumption during this time can yield significant cost savings for the customer and help reduce strain on the grid. A strategy to reduce energy consumption during this time is to "load shift," which essentially means to use electricity during one time period to avoid using it during another. Water heating loads can be shifted by heating water to exceed the default setpoint (120 °F) during less expensive off-peak hours and using that stored thermal energy during expensive peak hours. This minimizes the risk of the electric resistance elements coming on during the peak times. The electric resistance elements are much more energy intensive than the heat pump, so avoidance of their use is critical during peak times.

While in heat pump mode, the water heater operates as an air source heat pump, where heat is transferred from the surrounding air into the domestic hot water in the tank.[35] After the heat has been extracted from the intake air, the air is exhausted and is both cold and dry, since cold air holds less moisture than warm air. Typically, this cold air would be discharged directly into the garage, where it would serve little purpose

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[35] See Appendix 4B for a more thorough description of how the heat pump water heater operates.

since the garage is not part of the conditioned space. If the cold air is instead ducted and discharged into the unvented attic, the attic air temperature can be reduced, which decreases the heat transfer from the attic down into the house, requiring less space cooling during the cooling season. The cool air being discharged into the attic will necessitate some additional space heating in the home during the heating season; however, it will amount to significantly less energy than that of the savings from the reduced cooling, given the characteristics of this climate zone. Additionally, the intake air for the heat pump water heater can be ducted from the attic to balance out the intake air, with the added benefits of additional heat energy being extracted from the attic and attic dehumidification.

The heat pump water heater for one home in the ZNE community did elect to have its intake and outlet air ducted into the attic. OmniSense sensors were placed at the ends of ducts to monitor intake and outlet air conditions. See Appendix 4C for a detailed description of how the heat pump water heaters are ducted to and from the attic.

In order to use the water heaters for thermal storage/demand response, the team developed a schedule that heated the water to 140 °F during off-peak times and reduced the temperature to 120 °F during peak times. The team hypothesized that the extra 20 °F of thermal energy within the tank would still meet hot water demand between 4:00 PM and 9:00 PM while minimizing or altogether avoiding electricity use during that peak pricing period. Additionally, a modest amount of thermal energy (extra 10 °F) was stored during the nighttime to meet the domestic hot water needs of the morning and avoid use of the electric resistance elements as much as possible. Table 3 shows the daily schedule.

Table 3: Weekday Heat Pump Water Heater Schedule

Hour	Set Point	Mode
1:00	130	Heat Pump
2:00	130	Heat Pump
3:00	130	Heat Pump
4:00	130	Heat Pump
5:00	130	Heat Pump
6:00	130	Heat Pump
7:00	120	Energy Saver
8:00	120	Energy Saver
9:00	120	Energy Saver
10:00	120	Energy Saver
11:00	140	Heat Pump
12:00	140	Heat Pump
13:00	140	Heat Pump
14:00	140	Heat Pump
15:00	140	Heat Pump
16:00	140	Heat Pump
17:00	120	Energy Saver
18:00	120	Energy Saver
19:00	120	Energy Saver
20:00	120	Energy Saver
21:00	120	Energy Saver
22:00	130	Heat Pump
23:00	130	Heat Pump
24:00	130	Heat Pump

Source: Thermal Storage Schedule

The researchers have implemented the above schedule on three (3) homes thus far, with the consent of the homeowners. One of the homes, however, had internet connectivity issues and was ultimately not analyzed.

Setting domestic hot water temperatures above 120°F carries significant risk of scalding. In order to prevent injury, the team worked with the builder’s plumber to install a tempering valve in ten homes. The tempering valve mixes cold intake water with the hot outlet water from the water heater, which prevents the water leaving the tempering valve (tempered water) from exceeding unsafe temperatures at the tap.

Appliances

To further reduce whole-home energy consumption to minimize PV needed for ZNE, the builder installed the following high-efficiency ENERGY STAR® rated appliances:

- High-efficiency GE® Standalone Refrigerator (Model No. GYE22HSKKSS).
- High-efficiency Whirlpool Clothes Washer (Model No. WFW5620HW0).
- Heat Pump Whirlpool Clothes Dryer (Model No. WHD560CHW0).

Heat pump clothes dryers get their heat from the condenser coil of a heat pump, which is much more efficient than standard electric resistance heating elements. The moisture from the damp clothes condenses on the evaporator coil, and the condensed water is discharged into the same drainpipe used by the clothes washer.

Heat pump clothes dryers do not require ducting of exhaust air, but the builder elected to put a damper to the outside anyways for future use by homeowners that may want a natural gas or conventional electric dryer.

The researchers found annual energy consumption for specific appliances on the ENERGYSTAR® website, which they used to refine the modeled consumption estimates from CBECC.[36] The team presented these revised estimates and PV sizing options to the builder.

PV Sizing

Prior to the start of the project, an external energy consultant used the "BEopt" software program to estimate annual kWh and Therm consumption for each of the builder's ZNE floor plans, in all four cardinal orientations. The builder provided these estimates to the PV provider who used this information to size rooftop solar systems to offset each home's energy annual energy use. Since the homes use some gas, the PV systems were sized to offset both the electrical consumption and the equivalent gas consumption on a "source" basis. The builder used the following equation to determine necessary PV generation:

$$kWh_{Generation} = kWh_{Site\ Consumption} + Therms_{Site\ Consumption} * \left(29.31\frac{kWh}{therm}\right) * \left(\frac{1.09}{2.4}\right)$$

The 1.09 conversion factor is the ratio of source natural gas to site natural gas. The 2.4 conversion factor is the ratio of source electricity to site electricity.

Ground-up Design for ZNE

The floor plans offered to buyers at the two ZNE demonstration subdivisions are the same floor plans the builder offers at their conventional (non-ZNE) subdivisions. As described above, the builder upgraded materials and equipment to reduce loads and electrify end-uses prior to sizing solar PV. Although they would not be complete in time to be offered for sale at the demonstration site, the team of efficiency experts worked

[36] ENERGY STAR® estimated appliance usage

with the builder, a leading production-home architect, and the technical advisory group to create two all-new floor plans, which will serve as the builder's "next generation" ZNE designs. The purpose of generating these plans was twofold: first, the process would yield two new floor plans for the builder, which offered them an added incentive to participate in the project. Second, the process allowed the team to explore and document the idea that early-stage intervention in the design process could help identify low-cost and no-cost design-based strategies that are rarely, if ever, included in production home designs.[37]

Project Results

The "results" presented below are one of many ways in which the outcome of designing and building these homes can be understood and measured. Chapters 5, 8, and 11 include analysis of behavior, system-level, and whole-home performance, respectively. The results presented in this chapter relate primarily to design-based metrics for efficiency and PV sizing to reach ZNE. As such, quantitative results are focused on modeling and other sources of "typical" energy use for homes and appliances, whereas qualitative results describe the lessons learned through the ground-up architectural design process.

Above Code Design

Regulated Loads

Table 4 shows the compliance margins of the regulated loads for the various plans utilizing more efficient envelope, HVAC, and water heating features.

Table 4: Regulated Loads Compliance Margins

Plan	Proposed kTDV/ft^2-yr	Standard kTDV/ft^2-yr	Compliance Margin[a] (%)
190	59.66	77.9	23%
210	62.67	83.94	25%
210 Flex A	59.8	79.68	25%
240	49.6	70.17	29%
260	51.46	71.59	28%
320 Flex A	43.81	60.07	27%
320 Flex B	44.22	60.56	27%

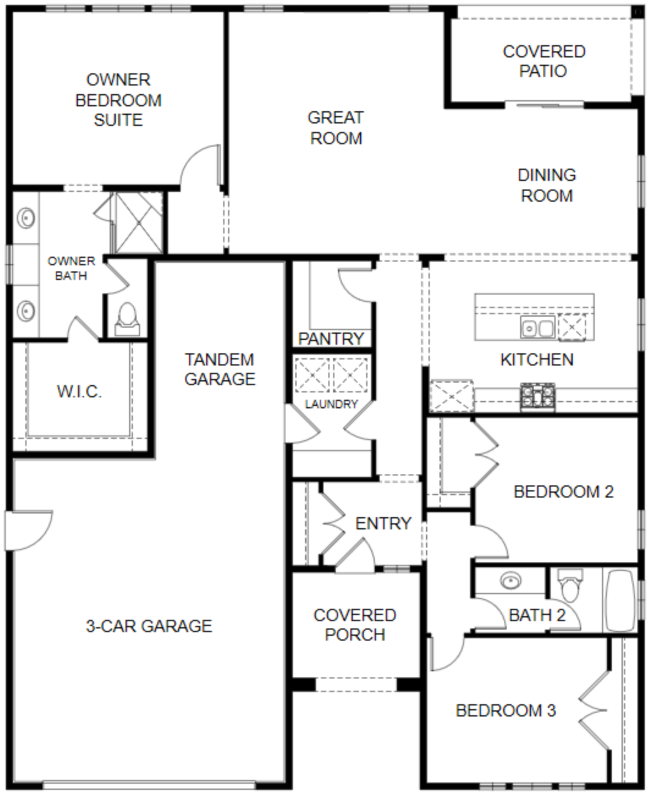
[a] The compliance margin is the amount that the proposed design is above or below the standard (minimally code compliant) design.

Source: ConSol Modeling Results

[37] Production-home architectural designs do not usually include any consideration of energy efficiency until after the layout and structural plans are complete. The Title 24 consultant is usually one of the last professionals in the process to provide input, at which point all of the key decisions have already been made. Efficiency upgrades at this stage are limited to higher-performance equipment and materials, or minor changes to design such as removing vents and relocating insulation to create an unvented attic.

Shows the floor plan for Plan 190, a 1,904 square foot single family home. See Appendix 4H for all the floor plans in the analysis.

Figure 10: Plan 190



Shows the floorplan for Plan 190.

Source: De Young Architectural Plans

Appliances

The high-efficiency appliances result in refrigerator appliance savings of 7-26 percent, and clothes dryer appliance savings of 46-54 percent over CBECC default (standard) appliance energy use assumptions, depending on plan type. Table 5 shows the refrigerator and clothes dryer savings for Plan 190. See Appendix 4D for the appliance savings for the other plan types.

Table 5: Appliance Savings - Plan 190

Appliance	Model Number	CBECC Modeled Energy Use (kWh)	ENERGY STAR® Modeled Energy Use (kWh)	Savings (kWh)	Savings (%)
Refrigerator	GYE22HSKKSS	712	665	47	7%
Clothes Dryer	WHD560CHW0	845	460	385	46%
Total		**1,557**	**1,125**	**432**	**28%**

Source: CBECC and ENERGY STAR® appliance modeled energy use

When the savings from the high-efficiency appliances are factored into the estimated CBECC energy use, the following refined estimates of energy use are determined:

Table 6: Refined Estimated Energy Use per Plan

Plan	CBECC Estimated Energy Use (kWh)	CBECC Estimated Energy Use (Therms)	Appliance Savings (kWh)	Estimated Energy Use with Efficient Appliances (kWh)	Estimated Energy Use with Efficient Appliances (Therms)
190	8,018	13.9	432	7,586	13.9
210	9,074	15.2	527	8,547	15.2
210 Flex A	9,166	15.2	526	8,640	15.2
240	8,989	15.2	524	8,465	15.2
260	9,995	16.5	722	9,273	16.5
320 Flex A	10,490	15.2	523	9,967	15.2
320 Flex B	11,361	16.5	768	10,593	16.5

Source: CBECC and ENERGY STAR® appliance modeled energy use

PV Sizing

Sizing PV by the equation the builder is currently using results in PV systems that are oversized. Table 7 shows how oversized the current PV systems are relative to what is necessary, when the savings from the upgrades are included.

Table 7: Over-Generation of Current PV Systems

Plan	Estimated Energy Use (kWh)	Estimated Energy Use (Therms)	Necessary Generation (kWh)	BEopt Estimated Necessary Generation (kWh)	Over-Generation (kWh)	Over-Generation (%)
190	7,586	13.9	7,771	9,272	1,501	19%
210	8,547	15.2	8,749	10,096	1,347	15%
210 Flex A	8,640	15.2	8,842	10,076	1,234	14%
240	8,465	15.2	8,667	10,225	1,558	18%
260	9,273	16.5	9,493	11,002	1,509	16%
320 Flex A	9,967	15.2	10,169	12,549	2,380	23%
320 Flex B	10,593	16.5	10,813	12,577	1,764	16%

Source: ConSol modeling results

Water Heater Load Shifting

Observation of the water heating energy consumption for the lots participating in the thermal storage water heating schedule indicates that only 8 percent d 7 percent of the total water heater energy consumption of lots L and M, respectively, is occurring during the peak time of between 4:00 PM and 9:00 PM.[38] Another way of looking at this

[38] See Appendix 4E for the full results of the load shifting analysis

would be that only 8 percent or 7 percent of total water heater consumption occurred during 21 percent of the day, and at a time when water heater consumption would otherwise be assumed to be high.

Architectural Design Process

The process of designing two all-new floor plans for ZNE included the following steps:

1. Establish builder requirements. This is typically the first step in developing new plans. It allows the design firm to elicit feedback the builder's sales team has received regarding their targeted homebuyer and existing floor plans. It establishes key design criteria including number of stories, square footage, number of bedrooms and number of bathrooms. The architect, principal investigator, and builder held a phone conference to outline the builder requirements prior to involving the rest of the team.
2. Exploratory discussion. This two-hour conference call included TAC members, team members, the architect, and the builder. This was a wide-ranging pre-design meeting to orient the architect about design for energy efficiency without ruling anything in or out, just discussing ideas.
3. Design charette. This in-person meeting at the builder's offices included several key project team members, the builder, the architect, and the builder's HVAC subcontractor. This meeting stretched over two days, which allowed the architect to begin developing floor plans during the first day and presenting those to the team on the second day.
4. Revisions to preliminary designs. This process occurred on phone calls, over email, and through web meetings over the course of several months. It involved just the architect and project team, with only minimal input from the builder during the process. Once complete, the team presented near-final design options to the builder to choose from.

Design Requirements/Trade-offs with Efficiency

The builder requested two all-new one-story floor plans:

1. An entry-level starter home that could serve as the price-leader, bringing buyers in the door to their model homes. This plan would target younger families, who typically prefer to have the children's bedroom close to the master bed. This home would be between 1,750 and 1,800 square feet.
2. A slightly larger home that includes an additional bedroom, powder room, and one car garage. The is home would be between 2,025 and 2,100 square feet.

The first call and part of the charette included relatively free-form exploration of design concepts. The team established this free-form approach to reduce the risk that preconceived ideas about single-family design would derail new ideas without adequate consideration.

Passive Solar

The group explored the concept of passive solar design for the two production floor plans. Although not widely available in central and southern California, several manufactures sell high-SHGC windows in the Pacific Northwest and the products can be imported as-needed to meet design specifications. The project team discussed using high-SHGC windows in combination with overhangs on south-facing windows to allow for passive heating in the winter when the sun is lower in the sky and block solar gains in the summer when the sun is overhead. The architect reported that they could create attractive overhangs for most architectural styles, but that it would be difficult to integrate overhangs with certain elevations. Team members submitted that side-yard clearance requirements may prevent the installation of overhangs on any side other than the front and back of the home. Furthermore, practicing "tuning" to place the high-SHGC product only on the south-facing side would be challenging to implement correctly in the field, and sourcing materials for just one side of the home could cause excess delays. The alternative—to install high-SHGC glazing with overhangs on all sides of the home—could add substantial cost.

Alternate Locations for Ductwork

The builder currently uses unvented attics to moderate the temperature environment for ductwork. However, low-cost, design-based strategies can negate the need for unvented attics. The team explored other options for ductwork, including beneath the home in a crawlspace or small basement that could also house mechanical equipment. Due to geothermal mass and shading/tempering by the home above, underground spaces are cool year-round, which addresses the primary issue of cooling loads on ductwork in conventional attics. However, the builder typically builds on slab rather than raised-subfloor foundations, so creating either a crawlspace or small basement would require significant retraining of subcontractors and cost. Some team members speculated that west-coast concrete contractors simply did not know how to build basements due to the lack of market demand. The team, therefore, ruled-out changes to the foundation needed to house ductwork. However, a group member observed that builders working in hilly areas of California typically prefer raised-subfloors and that may provide a good opportunity to integrate that design-based strategy for efficiency.

Next, the group explored locating ducts in conditioned space, either by eliminating the attic to create cathedral ceilings, or by creating dropped soffit. The builder expressed concerns about the practicality and cost of cathedral ceilings, and the architect said that the style was not presently popular with buyers. The group then focused on dropped soffits or plenums to house ductwork. To control costs for the smaller, entry-level floorplan, the builder said they would prefer 9-foot plates (ceiling heights), which would make it difficult to drop soffits by 12 to 18 inches, as needed to house ductwork. The architect suggested that the smaller floor plan could include 10-foot plates at very little additional cost, so the team agreed to move forward with drop-soffit designs for both floor plans.

Dropped soffits would allow the builder to locate the ducts entirely "in conditioned space," which would in turn cause them to return the attic to a conventional vented design with radiant barrier under the roof deck and R-38 at the ceiling. The builder expressed concern that the framing and drywall work to create the soffits would create additional expense but acknowledged that some or all the expense could be offset by eliminating the unvented attic. The HVAC contractor expressed concerns about increased labor costs to install ductwork in the soffits instead of the open attic area. The principal investigator pointed out that, if designed correctly, locating the ductwork in soffits could also greatly reduce the length of the ducts and material costs.

Compact Design for HVAC

The builder and architect expressed concerns about the visual impact of dropping ceilings on house ductwork because 10′ plates are a key selling feature. The principal investigator suggested that the ducts could follow a compact layout, which could avoid the need to lower ceilings in the large living spaces within the homes (kitchen, living room, family rooms, and bedrooms). The architect agreed with this strategy and pointed out that lowering ceilings in smaller spaces (laundry room, bathrooms, hallways, pantries, and closets) would result in a better appearance due to improved scale—the ratio of floor area to wall height.

The team agreed to pursue compact duct layouts and to limit dropped soffits to smaller rooms. To provide conditioned air to the living spaces, the team identified the area above the kitchen cabinets for dropped soffits, which could be crafted in a visually appealing manner to abut the top of the cabinets. In the instance where ductwork would need to cross the entryway, the architect suggested that they would incorporate the dropped ceiling as an archway. Each successive iteration of floor plans and the dropped soffit layout can be seen in Appendix 4F.

Compact Design for Plumbing

The technical team also worked with the architect to create floor plans where the water heater, hot water using appliances (dishwasher, clothes washer) and plumbing fixtures were located as close to each other as possible. The objectives included gaining credit for compact design in Title 24 compliance software and eliminating the need for a recirculation loop and pump while still providing reasonable time-to-tap for hot water.

The team explored various layouts including those with indoor mechanical rooms. In some draft floor plans the plumbing layout achieved one or more of the above objectives. However, unlike the HVAC layout, achieving compact plumbing had significant impact on the location of fixtures and therefore the location of the kitchen. The team had agreed to use central entryways for both floor plans, and the compact design strategy required that the kitchen be located in the center of the home. This combination would result in the homeowner entering the kitchen, which the builder felt was unappealing to buyers. Alternately the entryway could be located on the far side of the home so that the homeowner entered the living area. However, other design constraints eliminated this option. As a result, the team was unable to accomplish the desired degree of compactness for plumbing. The design process for compact plumbing is shown in Appendix 4G.

Indoor Mechanical Room

Locating the water heater and air handler in a mechanical room would allow for more compact HVAC and plumbing design. The architect, however, described a mechanical room in the center of the home as undesirable because it impacts the indoor/outdoor feel of the home. There are also concerns about leaks from the water heater. The team agreed that a floor drain should be implemented and that the mechanical room should be located next to the laundry room so any leaks from the clothes washer would also drain. The same drain would be used for both HVAC condensation and water heater condensation. The final plans include mechanical rooms so that all HVAC equipment is in conditioned space.

Conclusions/Recommendations

A number of conclusions and recommendations can be drawn from the analysis:

- The CBECC modeling results revealed that the houses, as currently designed, far exceed the 2016 Building Energy Efficiency Standards.
- CBECC cannot model energy-efficient appliances, which is resulting in overestimation of their energy use and subsequent overestimation of necessary PV size to achieve ZNE.
    - Recommendation: Allow CBECC to consider energy-efficient appliances.
- The BEopt estimation of necessary generation is too high and resulting the PV systems being oversized.
- The thermal storage schedule appears to be working for the homes participating, where the water heaters are only consuming a low amount of energy during peak rate times (4:00 PM-9:00 PM).
- An architectural design process, as outlined previously, should be included early on in all ZNE home projects to achieve more energy-efficient floor plans.

CHAPTER 5: Homeowner Behavioral Evaluation

Introduction

While some residential ZNE new construction currently occurs in California, there is a paucity of information regarding how ZNE homeowners interact with and utilize ZNE home features. To address this need, the CEC has ordered a study of homeowners' engagement with ZNE home features. The goals of this behavioral evaluation are as follows:

- Solicit and record feedback from homeowners related to their interactions with the products and systems in ZNE homes.
- Observe homeowner interactions with energy using systems within the home.
- Evaluate the effect of information and messaging provided in real-time through the smart thermostat and home energy management systems.
- Assess the relative importance of behavior as it relates to total home energy consumption.

The following chapter summarizes the behavioral evaluation approach, results, conclusions, and recommendations.

Project Approach

To achieve the objectives outlined above, the research team conducted a web survey with homeowners in the ZNE demonstration community during the fall of 2019. Homeowners were sent survey invitations approximately six weeks after move-in and set up of the ZNE systems within their homes, along with up to three reminder emails. A $40 incentive was offered to those homeowners who completed the survey.

Outreach

The research team worked with the builder (De Young) and the energy use management system vendor (CURB) to conduct outreach to the homeowners prior to fielding the survey. Homeowners were given account access to CURB after the research team had verified that the CURB energy management system was set up in such a way as to be easily understood by homeowners (e.g., all circuits were appropriately labeled and mostly disaggregate by end use).[39] Next, the research team sent an introductory letter to homeowners, which included instructions for accessing their CURB account, as well as an overview of the upcoming survey they would be invited to participate in.

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[39] For a more detailed description of the CURB energy management system, see Circuit Level Monitoring in Chapter 8

Homeowners received the initial survey invitations approximately six weeks after the introduction letter, thereby ensuring adequate time for engagement and interaction with the CURB system, among other ZNE features. However, delays associated with internet connectivity and set-up of the energy monitoring system meant that homeowners were often living in their homes for extended periods of time before they were formally introduced to and invited to access the various energy management systems (particularly CURB). The research team anticipated between 20 and 50 homes with at least eight weeks of occupancy to field the survey to, but because of the delays in CURB set-up and slower than expected sales and construction of the ZNE homes, the available sample of homeowners was reduced significantly.[40,41] Ultimately, the research team invited eleven homeowners to participate in the survey, four of which responded.

Survey Instrument Design

The research team translated the goals of the homeowner behavioral evaluation task into the web-based survey. Where applicable, survey questions were identical to or were modeled after the structure of questions in the 2009 Residential Appliance Saturation Survey (RASS), which was a major data source used to develop the current estimates of unregulated load energy use in the Title 24 compliance software.[42] In addition to the Task 5 behavioral evaluation, the responses to these survey questions were used in the interpretation of the circuit-level monitoring data in Chapter 8 for three surveyed homeowners. Feedback from one homeowner, Home C, was not included in the Chapter 8 analysis as that homeowner was not invited to access CURB until the end of October and therefore had insufficient monitoring data for the analysis.

Project Results

It is important to note that the results presented below are qualitative findings based on the opinions and feedback of four homeowners in the ZNE demonstration community. These findings are neither statistically significant nor representative of the full demonstration community homeowner population. However, they provide early insights into the experience of ZNE homeowners.

Homeowner Characteristics

The four surveyed homeowners are well-educated and have annual household incomes that exceed that of the area median income of $71,943.[43] All homeowners completed higher education, half receiving bachelor's degrees and the other half receiving graduate degrees (e.g., J.D., MBA, MD, Ph.D.). Two of the reported annual household

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[40] Sales were affected by regional economic trends as well as lower-cost options for conventional (non-ZNE) homes in the surrounding areas.
[41] Construction was delayed by ongoing skilled labor shortages and delayed ground-breaking due to the extremely wet winter of 2018-2019.
[42] KEMA, Inc. 2010. 2009 California Residential Appliance Saturation Study. California Energy Commission. Publication number: CEC- 200-2010-004-ES. Available here
[43] City of Clovis census data

incomes were between $75,000 and $100,000, one between $100,000 and $150,000, and one between $150,000 and $200,000. Despite the size of the homes (between four and five bedrooms with 2,000 - 2,500 sq. ft.), all surveyed homeowners had relatively small household sizes. Three households had two occupants and one household was a family of four. Two homeowners also tend to be home during the weekday more often than the typical household, with one answering frequently (3 to 5 weekdays per week) and another answering occasionally (1 to 2 weekdays per week). The other two homeowners are rarely or never home (less than 1 weekday per week).

Homeowner Perceptions and Decision-Making Surrounding ZNE

Feedback from the four ZNE homeowners suggests that homeowners find ZNE attributes desirable. In particular, when asked to rate the importance of several factors they considered when shopping for a new home, all four cited energy efficiency, solar panels, curb appeal and high-end finishes as "very important" to their decision. This supports the findings from California homebuyer survey conducted as part of the market assessment: homeowners find ZNE attributes (e.g., solar panels, EE appliances etc.) highly desirable.[44] In contrast to the market assessment, home price was cited as "very important" for three of the four homeowners and "somewhat important" for one of the homeowners. This suggests that for some segment of ZNE homebuyers, home price may not be as important a factor.

Homeowner feedback also suggests a lack of understanding about ZNE. For example, homeowners were asked to rate their level of familiarity with the term "Zero Energy" on a scale of one to seven, where one is “I have only heard the phrase” and seven is “I know a lot about it.” Similar to the California homebuyer survey, homeowners who rated their familiarity at a five or higher were asked to provide a definition of the term in their own words. Of the three homeowners who indicated familiarity, only one provided a correct definition and the other two had answers speaking to energy savings and reducing carbon footprint.[45]

The four surveyed homeowners had distinct reasons for why they decided to purchase a "Zero Energy" home instead of a traditional home.[46] Their verbatim responses to this question is included in Table 8 alongside feedback homeowners provided at the end of the survey when asked to comment on how they use energy since moving into their new home. A side-by-side comparison of these two questions suggest that pre-purchase attitudes and understanding of ZNE tend to determine the level of engagement a homeowner has with the energy-saving features of the home and the steps they take to reduce their energy use (and not the other way around). This observation is based on a

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[44] For further details surrounding the results of the market assessment, see Chapter 2

[45] As a point of comparison, 8% of valid responses from the market assessment provided a correct definition of the term, meaning their response included a balance between energy production and consumption.

[46] The term "Zero Energy" is used here for consistency with how the question was asked in the homebuyer survey shown in Chapter 2

short time period since move-in, however, and should not be assumed to remain static over time. In fact, it is possible that prolonged exposure to the ZNE features and homeowners increased interaction with them will eventually impact perceptions and behavior surrounding energy usage.

While more time and a greater number of respondents is needed to draw definitive conclusions, data from one homeowner suggests there is some possibility that homeowners will use more energy once they have ZNE features. For this particular homeowner (C), the ZNE features of the home caused the homeowner to use more energy, as they believed their onsite generation would offset the energy costs of a pool.

Table 8: Role of ZNE in Homeowner Decision-Making (Before and After Purchase)

Home	P3. Why did you decide to purchase a Zero Energy home instead of a traditional home?	B4. Which of the following best describes how you and/or your household use energy since moving into this home?
L	Energy Efficiency and ZE home features such as solar: *"Zero energy home not only uses renewable energy but also is designed to conserve energy."*	I/We have tried to be more efficient since moving into this home.
C	ZNE expectations lead to consumption, not conservation: *"We were attempting to build a pool and have our full house with zero extra PG&E besides our gas bill"*	Since this house has efficient features, we can use energy more freely than we did before.
O	An added bonus feature, but not the driving force behind a decision to purchase a home: "*When we looked for models we liked and found the zero energy was available.*	I/We have not changed how we use energy since we moved in.
B	Mainly cost: "*Save money and do my part to protect the environment."*	I/We have tried to be more efficient since moving into this home.

Note: Question P3 was open-ended. Verbatim responses are italicized. Homeowners selected from a series of options for Question B4.

Source: ZNE Behavioral Evaluation Survey Data

Additionally, although surveyed homeowners report limited interaction with the ZNE features of their new homes to date (as subsequently discussed), all homeowners indicate that they plan to track their annual energy use and solar panel production to see if their household is achieving Zero Energy.

Household Consumption and Energy-Saving Behavior

After the initial questions surrounding purchasing decisions, the survey gathered data about energy-using equipment and practices unique to each home which allowed the research team to assess the relative importance of behavior as it relates to total home energy consumption. As previously mentioned, this data was collected to inform the analysis in Chapter 8. See Appendix 5A for a summary of appliance usage and consumer electronics penetration and saturation by surveyed homeowner.

Feedback from the four ZNE homeowners suggests a general trend towards energy-saving behaviors, although there are some consumption trends related to household electronics and lighting that increase energy use. For example, homeowners were asked questions designed to explore energy-saving behaviors, or lack thereof, that a given homeowner took on a routine basis. Homeowners were asked if they always wait until their dishwasher is full before they run a load (all four answered "yes"), how often they turn off /unplug appliances while not in use (two answered "most of the time" and two said "all of the time"), and how often they turn off lights while not in use (three said "all of the time" and one said "some of time"). While these responses suggest a general trend towards energy-saving behaviors, there is also opportunities for improvement. For example, the survey found limited quantities of LEDs, zero smart plugs, and a high frequency of devices left plugged in and running for most of the day.[47]

Feedback on the complementary heat pump clothes dryer was overall mixed from the three homeowners who elected to receive it.[48] One homeowner was "not at all satisfied," one was "very satisfied" and one "slightly satisfied." Negative feedback centered on the extended drying time, with one homeowner saying *"It takes 3x longer to dry clothes than a gas dryer. Does not seem efficient."*

All customers expressed satisfaction with the heat pump water heater, with two "very satisfied" and two "moderately satisfied." Only one homeowner reported adjusting the water heating settings, saying that he has increased the temperature on one occasion. Despite the high-efficiency air source heat pump installed in their home, and the advanced smart thermostat to run it, homeowners were generally not aware of the features to control their high-efficiency systems.[49] Additionally, two of the four homeowners reported connecting their smart thermostat to the Wi-Fi.

Engagement with ZNE Features in the Home

Table 9 provides a summary of homeowner awareness of the smart thermostat features and illustrates that most homeowners are not aware of the features. One of four homeowners was aware of most of the features (specifically the iHarmony Zoning System, voice control and Smart Away™ Mode) and reported connecting the thermostat to Wi-Fi. However, while this homeowner reported using the iHarmony Zoning System, he never used the voice control capability and rarely used the Smart Away™ Mode. When asked why, the homeowner wrote *"Haven't had time to really learn the system. plus, when we moved in the heating system was giving us ongoing issues and needed constant repairs."* This echoes feedback provided by all four homeowners throughout the survey; all four respondents reported at one point or another that they have not

[47] LEDs made up 50%, 10%, 30% and 0% of portable lighting bulbs for each of the four homeowners, respectively.
[48] One homeowner was unsure if they had received it.
[49] Homes in the demonstration community were equipped with a Lennox XP-20 ducted heat pump HVAC and a Lennox iComfort® S30 Ultra Smart Thermostat. For more details on the systems and features of the demonstration community homes, see Chapter 4 and Chapter 6.

lived in their home long enough to try the different features, although, as mentioned above, all four homeowners intend to track their ZNE status throughout the year.

Table 9: Summary of Homeowner Awareness of Thermostat Features

Are you aware of the following features of the thermostat? (Yes/No)	Home L	Home C	Home O	Home B
iHarmony Zoning System (directs heating or cooling to areas most used while reducing it in rarely used rooms)	Yes [a]	No	No	Yes
Alexa/Apple home kit iComfort® (voice control for HVAC system)	No	No	No	Yes
Smart Away™ Mode (Uses smartphone's GPS to detect occupants leaving and adjusts the temperature to a more energy-efficient setting and then resumes normal schedule and comfortable temperature when customer gets closer to home)	No	No	No	Yes
iComfort Monitoring (actively monitors system operations and sends reminders and service alerts, such as when it is time to change filters)	No	No	No	No
Performance Reports (Includes historical data on system's operation and performance (e.g., temperature ranges, runtime etc.). Daily and hourly reports are available via the website and monthly reports are emailed directly)	No	No	No	No

[a] If a homeowner said they have not connected their thermostat to the Wi-Fi, then they were not asked about frequency of use.

Source: ZNE Behavioral Evaluation Survey Data

Additionally, the four homeowners do not appear to be taking advantage of the energy-saving features of the smart thermostat. All four homeowners said they control their new homes' temperature by manually adjusting the thermostat based on their comfort level, preferences and the weather. Three homeowners reported manually adjusting their thermostat a few times a week and one homeowner said a few times over the course of the summer. Notably, all homeowners said they did not receive any training or materials on how to use their thermostat, or the various features offered by it, upon move-in. When asked how they heard about the tech features in their home all answered, "Seeing the device in my home." None of the four selected the other multiple response options (i.e., "an email from De Young," "informational packet at the time of closing," and "electrician or other contractor working on the home").

In contrast to the utilization of the smart thermostat features, three homeowners indicated awareness and usage of at least one of the messaging channels of CURB system (i.e., via email, the app or the desktop website). This increased awareness could be due to the introductory letter sent by the research team prior to survey deployment, or it could be due to the fact that simply viewing one's energy usage is easier to do than setting up any of the features of the smart thermostat. Table 10 summarizes the awareness and frequency of use of the various CURB messaging channels for the four homeowners and demonstrates that overall, more homeowners accessed CURB on a more frequent basis (compared to the smart thermostat). Despite the increased usage, only one homeowner (B) answered "yes" when asked if they or another member of their household had ever taken an action to reduce their energy use as a result of what they saw in CURB. In this case, the homeowner reported adjusting the heating system as a result of seeing the CURB report.

Table 10: Summary of Homeowner Awareness of CURB Features

C2. Prior to today, which of the following CURB features were you aware of? If yes, how often do you use the feature? [a]	Home L	Home C	Home O	Home B
The weekly CURB energy reports emailed to me or a member of my household	No	No	Yes (Almost every week)	Yes (Almost every week)
The desktop website that I can log into from any web browser	No	No	No	No
The mobile CURB application for my smart phone	Yes (A few times a month)	No	No	Yes (A few times a week)

[a] If a homeowner indicated awareness of a CURB feature, they were asked about how often they used each feature.

Source: ZNE Behavioral Evaluation Survey Data

Conclusions and Recommendations

Given the limited sample size and the amount of time since move-in, the perceptions, behaviors, and data collected from the four homeowners surveyed are not generalizable to the rest of the demonstration community. Further research is necessary, ideally with more homeowners who have had at least three months to interact with the features of the home prior to providing feedback. It is with these caveats in mind that the research team presents the following conclusions and recommendations:

- **Increase access to and awareness of the ZNE tech features**. Homeowners have to be aware that the ZNE features exist, and they have to be invited to access them. One of the challenges in this demonstration community was ensuring timely set-up and access to the CURB energy management system. Moving forward, builders should develop processes and assign responsibilities that ensure homeowners have access to the energy use monitoring systems in their homes and that these systems accurately present the circuit-level energy usage to the homeowner.
- **Provide education and training on energy monitoring systems and smart thermostat technology.** None of the four homeowners reported receiving training on how to use their thermostat, and only one homeowner reported receiving training on the CURB system. While feedback from the four homeowners suggests that they will eventually explore these features because they see them in their home every day, education and training can accelerate engagement and effective use of ZNE features. Since ZNE performance is determined on an annual basis, education and training could be the difference between ZNE-verified and ZNE as designed.

- **Improve homeowner engagement at the time of move-in:** Given that ZNE performance requires post-occupancy commissioning and calibration, the new construction builder-homebuyer relationship must evolve beyond a transaction that ends when the keys are handed over. The research team recommends that where possible, the builder conduct a ZNE focused walk-through with homeowners to introduce homeowners to the various ZNE tech features of their home, help them to set up access to such features, and instruct them how to use such features correctly so that they can achieve optimal efficiency and performance from their systems.[50]

[50] For example, the research team suspects that homeowner dissatisfaction with the high-efficiency heat pump clothes dryer is due to a lack of understanding around how to effectively use the appliance

CHAPTER 6: Indoor Air Quality

Introduction

The indoor air quality (IAQ) in homes is important because people breathe more and take in more air pollutants at home than at any other location. On average Americans spend roughly two-thirds of our lives inside our homes. The air pollutants in our homes come from various sources including but not limited to outdoor air; the materials used to construct, finish, and furnish our homes; our pets; activities such as cooking; and products that people use for cleaning, personal care, and hobbies.[51]

Venting range hoods and appliances mounted over the cooktop that combine a microwave oven and an exhaust fan (often called "over the range" microwaves or OTRs) can enable efficient removal of odors, moisture, and pollutants emitted during cooking activities. The term "venting" means that the hoods are connected by ductwork to the outdoors; they are designed to extract air from the kitchen, above the range, and expel or exhaust it outdoors. Several studies including both modeling and experimental tests have shown reductions in cooking related indoor air pollutants due to range hood use (Logue et al. 2014; Singer et al. 2012; Rim et al. 2012; Delp and Singer 2012; Lunden, Delp, and Singer 2015; Singer et al. 2017; Revzan 1986).

The air pollutant that is estimated to cause the most health impacts in US homes is fine particulate matter, or "$PM_{2.5}$" (Logue 2012). $PM_{2.5}$ enters homes with outdoor air and is emitted indoors from cooking, candles, and people moving around, among other sources. $PM_{2.5}$ can also form in the air from chemical reactions involving ozone–which comes from outdoors–and a subgroup of volatile organic compounds that includes alpha pinene, which is emitted from natural wood and wood products, and limonene, which is the main constituent of orange oil and an ingredient in many "green" cleaning products (Weschler 2011). Concentrations of outdoor particles are reduced as outdoor air infiltrates through the building shell or is pushed through filters on supply ventilation systems. And particles in indoor air (including those originally coming from outdoors) are removed through ventilation, filtration, and deposition (sticking to materials). More information is included in Appendix 6B. Formaldehyde is a VOC and is another compound of concern that mostly comes from indoor sources, such as composite wood products used in cabinetry, furniture, interior doors and trim (Salthammer et al. 2010).[52]

[51] For more information on air pollutants, see Appendix 6A

[52] The 2010 California Green Building Code banned the use of formaldehydes in resin and set limits for formaldehyde emissions.

Since the mechanical systems that create comfort conditions typically use a substantial portion of the total energy used in a home, designs for efficient low-energy homes must include efficient heating and cooling systems, good insulation, and airtight shells to reduce uncontrolled outdoor air infiltration. However, lower infiltration also means less dilution and slower removal of indoor contaminants; it thus becomes necessary to bring in outdoor air through mechanical means. Mechanical ventilation systems require additional energy to operate and must be carefully designed and sized to avoid unnecessary increases in overall energy consumption.

In recognition of this, the Energy Commission has developed code requirements for ventilation to maintain IAQ in new California homes.[53] The current code requires that each home have mechanical ventilation to force a minimum amount of air exchange with the outdoors on an ongoing basis. The requirement can be satisfied with a supply fan that pushes air into the home, an exhaust fan that pushes air out of the house, or a balanced system such as a heat recovery ventilator that has both supply and exhaust fans. The goals of this task were to evaluate and make suggestions on home design elements that impact ventilation and IAQ, and to collect data to evaluate the performance of different ventilation approaches for outdoor air pollution protection.

Project Approach

Consultation on Design for IAQ

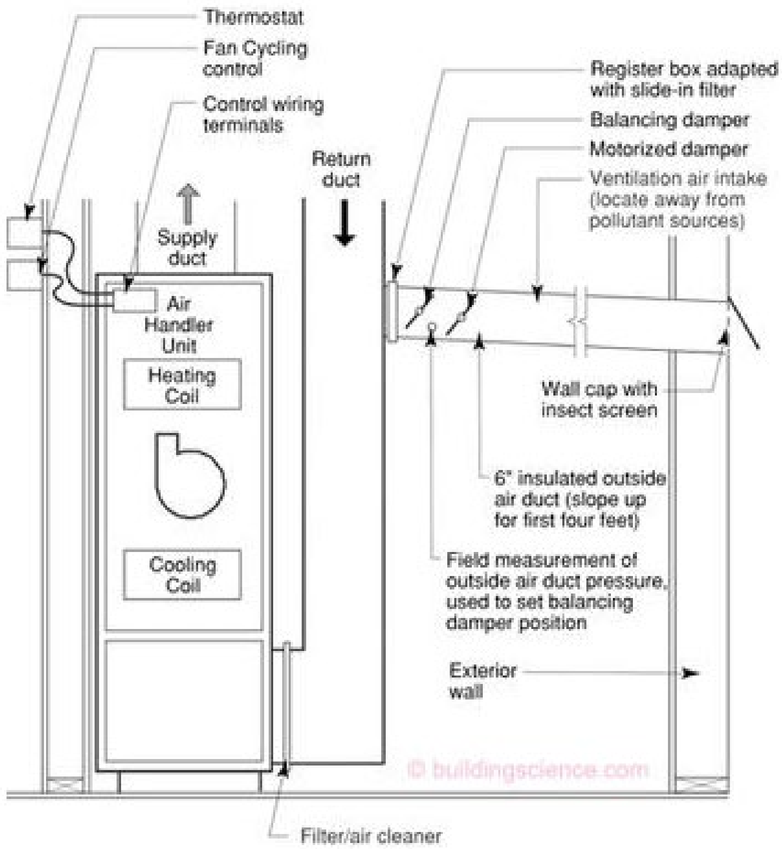
Due to the timing of the project, the research team was not able to comment on the ventilation system design for one of the builder communities; it will be consistent with the builder's standard practice for ZNE and conventional construction.[54] However, the team convened a working group that reviewed the designs for another development and made recommendations for potential improvements and enhancements of the system to be implemented.

The ZNE Homes were designed to follow the builder's recent practice of using whole-home exhaust ventilation to meet the code requirements for ventilation combined with supplemental central-fan-integrated-supply (CFIS) ventilation provided with the intent to achieve better IAQ. The CFIS approach connects the return side of the central forced air heating and cooling system (HAC) to the outdoors with a section of ductwork and a powered damper, as shown in Figure 11. When the HAC fan operates the damper is opened and outdoor air is pulled in through negative pressure in the system. The HAC fan can be operated intermittently to provide ongoing supply air; however, this set-up typically provides only a small fraction of the code-required ventilation airflow for the home. The research team considered other options as compared to this planned scenario.

[53] For more information on California codes and regulations that impact IAQ in New homes, see Appendix 6C

[54] For more information on the current builder approach to ventilation, see Appendix 6D

Figure 11: CFIS Ventilation System Diagram



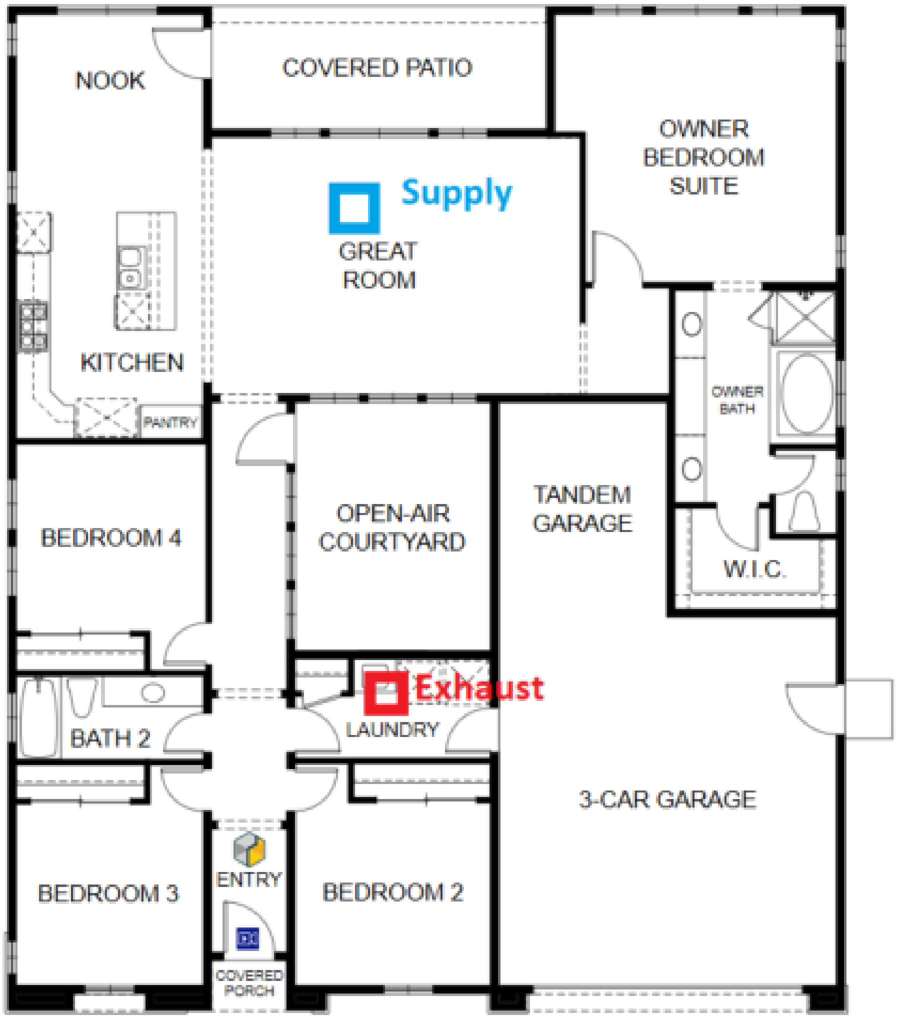
Shows a diagram of how a CFIS ventilation system works. Fresh air is pulled in from the outdoors through a section of ductwork to the return air duct. A powered damper is also present to modulate the amount of fresh air coming in.

Source: Central Fan Integrated Ventilation Systems

When using an exhaust fan to meet the ventilation rates required by the code, the fan can be set to run continuously or intermittently to provide the required airflow on an hourly basis. Limited data indicate that the most common approach statewide is to use a laundry or bath exhaust fan to meet the requirement. The data also indicate that the ventilation fan is commonly turned off, particularly when it is controlled by a wall switch with unclear or no label indicating its purpose (Chan et al. 2019). Discussions included alternatives to improve the probability of fan use.

Figure 12 shows the locations of the supply air intake and exhaust fan for Plan 210, the current bestselling floor plan.

Figure 12: Plan 210 Supply and Exhaust Fan Locations



Shows the approximate locations of the supply air intake (blue square) and exhaust fan (red square) in Plan 210. The supply air is pulled through a duct into the return air duct leading to the air handler in the attic, as part of CFIS ventilation system. The exhaust fan is located in the laundry room. There are also smaller exhaust fans in the kitchen hood and bathrooms; however, they do not run continuously.

Source: De Young Architectural Plans

Measurement Methods to Evaluate Ventilation and IAQ

In the absence of indoor emissions or formation, the concentration of $PM_{2.5}$ indoors will be lower than outdoors because particles are removed during air entry and also by deposition to indoor surfaces. The ratio of indoor to outdoor particle levels (I/O $PM_{2.5}$ ratios) when there are no indoor sources is a measure of the degree to which the ventilation system protects building occupants from outdoor particles. One focus of the IAQ research plan was to measure $PM_{2.5}$ concentrations simultaneously indoors and outdoors to calculate I/O $PM_{2.5}$ ratios when ventilation is provided for different ventilation approaches. Outdoor air exchange rates were measured simultaneously. Measurements were made for at least four scenarios:

1. All mechanical ventilation systems off.
2. Exhaust only (CFIS off).
3. Balanced (CFIS circulate, exhaust on).
4. CFIS only (exhaust off).

The air exchange rate was measured for each of the ventilation settings. A harmless, inert gas which is used in the air conditioning system in automobiles was released into the home. A fan was used to mix the air in the home. The concentration of the gas was recorded for 4 hours. The concentration steadily declined, and from the slope of the decline, the air exchange rate was determined. Flow rates through the exhaust and supply fans were also measured. A particle monitor (DustTrak-II 8530, TSI incorporated) was placed in the backyard of one of the homes being tested (selecting the one that was most centrally located). A particle monitor (DustTrak-II 8530 or DRX-8533) was placed on the kitchen counter inside each home being tested. Additional details about these measurements are provided in the Appendix 6F. Measurements were made in model homes and/or recently completed homes before they were occupied. For efficiency, the team planned to make measurements when multiple homes were available for testing over the course of multiple sampling trips.

Project Results

Consultation on Design for IAQ

The team concluded that the ventilation system could be upgraded to Enthalpy Recovery Ventilation (ERV) or Heat Recovery Ventilation (HRV) for relatively little added cost after factoring in utility incentive programs. The team believes that this change would save both fan energy—by using a smaller fan to deliver the supply air—and space conditioning energy. However, the builder ultimately decided against using an HRV.

The minimum Title 24 requirement for ventilation is met by the exhaust fan. To address concern that the fans may be turned off, the builder identified the Honeywell HVC0001 switch as a possible solution. The switch is set to run the laundry exhaust fan a fraction of each hour based on the square footage (A_{floor}) of the house and the number of bedrooms (N_{br}), which are programmed into the switch. The fan then operated to have a total hourly flow (Q_{fan}) to meet the ASHRAE 62.2 and Title 24 requirements, assuming an air infiltration rate of 0.02 cfm per square footage of floor area, calculated as:

$$\boldsymbol{Q_{fan}} = \mathbf{0.01\ A_{floor} + 7.5 \times (N_{br} + 1)}$$

There is also a button that can cease operation for 24 hours in the case of high outdoor air pollution levels, such as during a wildfire. The switch is difficult to turn off altogether. One important lesson was learned during a visit to conduct IAQ sampling in

August 2019. The settings on the exhaust fans were set at the default levels provided by the manufacturer, and not customized for the given homes. The researchers discussed this with the builder staff and setting the exhaust fans prior to occupancy was added to the preparation list of the customer experience team, ensuring that they were consistently set prior to owner occupancy.

While there is not yet much data for the electrical circuits, what the research team does have indicates that these fans are operating, and therefore the desired ventilation is being supplied. This is in sharp contrast to prior field studies that found the exhaust fan often switched to the off-setting. As more data from the electrical circuits becomes available, additional analysis will be done to determine what fraction of the homes are running the exhaust fan.

Another design improvement that could not be incorporated was the relocation of the filter for bringing outdoor air into the home. In the builder's properties, the intake is in the attic. The team had a concern that the homeowner would not change the filter unless they had a contract with an HAC maintenance contractor. For more information on evaluation and recommended ventilation changes, see Appendix 6E.

Measurement Methods to Evaluate Ventilation and IAQ

The team conducted several rounds of field sampling in an effort to determine the I/O ratios. Unfortunately, uncontrollable environmental variables impacted the measurements each time. The first set of data were collected in August and included 3 newly constructed homes and the model home. In an unusual finding for an unoccupied home, the indoor $PM_{2.5}$ was higher than outdoors. Though not definitively confirmed, our hypothesis is that formation of particles from ozone (from outdoor air) and terpenes from the fresh pine wood used to build the homes along with products used by cleaning crews that worked in the house in the days prior to our measurements (our team did not have visibility into the cleaning schedule). Therefore, the plan to use the $PM_{2.5}$ I/O ratios as a measure of the efficiency of the home and ventilation settings to remove PM would not be effective, and thus the research team did not schedule any subsequent summer sampling. The winter sampling was also less effective than planned due to intermittent rain events which act to remove particles from the outdoor air, making evaluation of $PM_{2.5}$ I/O ratios ineffective as outdoor concentrations were too low. The final visit had satisfactory results for one home, while the other home was cleaned twice during the visit, elevating indoor concentrations. Details on the difficulties sampling homes are in Appendix 6F.

There were also scheduling issues associated with the delayed build schedule that occurred. To conduct measurements efficiently, the team needed access to multiple fully completed homes (e.g., building shell complete, electric power supplied, HAC fully operational) at the same time, and the homes were often not available at the same time. Also, the team planned to use the model homes to supplement the available homes for sampling, but the ventilation controls differed enough that this was not feasible.

Air exchange rates were successfully measured for 7 different homes, with a total of 34 air exchange measurements, with various ventilation settings, conducted. Measurements were of total ventilation, which is the combination of infiltration and mechanical ventilation. Infiltration is driven by factors such as wind and temperature differences. Measurements occurred during the summer and the winter. Results differed between seasons and are therefore listed by season in Table 11 below. (All individual measurements in the Appendix 6F). Infiltration rates, measured while all mechanical systems were turned off, were much lower in summer than in winter. The ventilation rates provided by the mechanical system can be estimated by subtracting the value measured with ventilation off from the values measured with mechanical ventilation operating. The "Exhaust only" setting typically supplies additional ventilation to the home as compared to all ventilation systems off (details in the Appendix 6F). Little additional ventilation is provided when both the CFIS system and exhaust fan are operated. In single-story homes, the CFIS system operating without the exhaust fan provided considerably less ventilation than the exhaust fan. In the two-story homes, the ventilation rate was higher, but still less than with the exhaust fan.

Table 11: Air Exchange Rates (AER) Measured with Various Ventilation Settings

Ventilation Condition	***Mean Summer AER (1/h)***	***Mean Winter AER (1/h)***
All mechanical ventilation systems off	0.07 (n=2)	0.20 (n=5)
Exhaust only (CFIS off)	0.22 (n=4)	0.39 (n=6)
Balanced (CFIS circulate, exhaust on)	0.27 (n=4)[a]	0.34 (n=7)
CFIS only (exhaust off)	0.18 (n=4)[b]	0.16 (n=4)[c] 0.43 (n=2)[c]

Shows the mean AER measured for various ventilation settings. "n" refers to the number of measurements.

[a] These measurements were made with exhaust fans having default settings for timing of intermittent operation, not the run-time that is required for specific homes in which they were installed.

[b] Only one home was sampled with the exhaust off in summer because the team was not informed until midway through the visit how to disable the exhaust.

[c] Two one-story homes were measured in this condition in winter and had relatively low AERs, 0.17 and 0.15 1/h. A two-story home was measured two times, and had higher values, 0.38 and 0.49 1/h.

Source: IAQ Team Field Results

The air flow rate was measured for exhaust fans in the laundry room and bathrooms in 5 homes, and for the outdoor air inlet of the CFIS system in two of those homes. The flow rate through the laundry fans averaged 105 cfm, exceeding the required ventilation of 60-80 cfm for most homes in the tract, thus the fan runs only a portion of the time by the Honeywell switch. The flow through the bathroom fan averaged 107 cfm, meeting the requirement of at least 50 cfm. The average flow rate through the CFIS intake was 46 cfm. It is important to note that for all of these fans, the effective hourly ventilation rate, i.e., accounting for intermittent operation, is much lower than the flow rate when the fan is operating.

The indoor and outdoor $PM_{2.5}$ concentrations, I/O ratios, and ventilation condition are reported by house and sampling event in Appendix 6F, and the I/O ratios are summarized in Table 12 below. The limited results that our team was able to obtain during this project are insufficient to resolve the question about relative performance of the ventilation systems for outdoor $PM_{2.5}$ protection. The results from Lot F indicate substantially lower I/O ratio when supply system was operating, with or without the exhaust fan operating. And Lot H had lower I/O when the exhaust fan was off and the supply with recirculate was operating. These are consistent with a benefit of filtration occurring in the forced air system. Note that the balanced system had higher I/O ratio compared to exhaust only for Lot D.

Table 12: Measured $PM_{2.5}$ Indoor/Outdoor Ratios

Ventilation Condition	Lot D	Lot F	Lot H	Lot A
All mechanical ventilation systems off	-	*/0.57	0.85	
Exhaust only (CFIS off)	0.70	0.81/ 0.38	*	0.62
Balanced (CFIS circulate, exhaust on)	0.91	0.38/ 0.58	0.67	0.85
CFIS only (exhaust off)	*	0.35/ 0.49	0.42	0.66

Shows the measured $PM_{2.5}$ indoor/outdoor ratios for various ventilation conditions at different lots.
*** O.utdoor levels were too low to calculate I/O ratio for Lot D with CFIS only (exhaust off), Lot F with all mechanical ventilation systems off, and Lot H with exhaust only (CFIS off).**
- No measurements were taken for Lot D with all mechanical ventilation systems off.

Source: IAQ Team Field Results

Conclusions/Recommendations

The research team recommended two equipment changes to improve IAQ and related energy use in the second phase of the ZNE project. The first is to utilize an HRV for balanced ventilation and heat recovery in place of exhaust ventilation to satisfy the code and additional central fan integrated supply ventilation with the intent of improving IAQ. The second is relevant only if the homes continue to use exhaust ventilation; it is to incorporate a labeled switch that is not easily turned to the off position. The research team also participated in a design meeting for a future project.

The builder decided against using an HRV, in part because of the difficulty of making changes so late in the design process.

The builder and HVAC contractor did, however, change the exhaust ventilation control switch, selecting a switch that can be set to temporarily discontinue ventilation airflow –

e.g., during a severe outdoor air quality event--then automatically restart it after 24 hours.

If the builder uses this switch, there is a dedicated person or process to ensure that the switch settings are customized to the floor area and number of bedrooms in the home. The team recommends this type of switch be used more widely in new home construction in California.

The homes are designed to have a balanced ventilation system, with both supply air being brought in through the HAC system and an exhaust fan. The air exchange measurements indicate that the supply fan on its own generally provides enough ventilation. From a ventilation standpoint, running the supply system is not a very efficient way to supply additional ventilation. However, based on our limited PM measurements, running the HAV system does seem to lower $PM_{2.5}$ concentrations. This is the expected result as the indoor air runs through the MERV8 intake filter.

CHAPTER 7: Moisture in Sealed and Insulated Attic Assemblies

Introduction

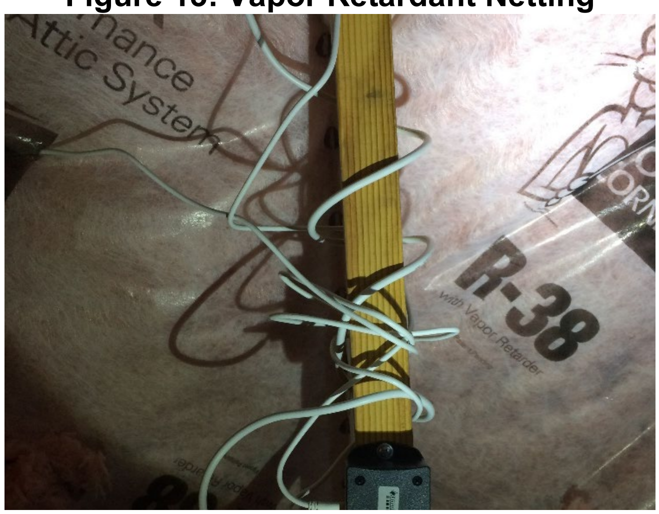
By moving the insulation to below the roof deck and eliminating traditional attic vents, sealed and insulated roof assemblies bring the attic into the indirectly conditioned space of the dwelling. When HVAC equipment is located in the attic, the thermal losses from the duct system can be drastically reduced, leading to whole dwelling HVAC savings in the range of 10-20 percent (B. Less et al., 2016).

Yet, unacceptable moisture levels in sealed and insulated attics have been documented in past research. The risk factors for moisture issues in these assemblies include North-facing roof slopes, near the roof ridge, cold climates, clear night sky conditions, elevated indoor humidity, and others. Aside from cases with actual topside roof leaks, the source of moisture in these assemblies is the air in the home's living space. If the relatively humid house air reaches the wood roof deck surface, and that surface is very cold (as it often is in winter or at nighttime with clear skies), then elevated surface humidity occurs locally, and wood moisture content will rise. In some conditions, condensation of liquid water can occur. Over extended periods of time, moisture risks can develop in these assemblies.

Two primary moisture risks can occur in sealed and insulated attics: mold growth on the underside of the roof sheathing material and wood rot organisms degrading structural integrity of wood components of the roof. Mold growth typically occurs with surface humidity in excess of 80 percent, and this condition must be relatively long-lasting for surface growth to be visible. Accordingly, ASHRAE Standard 160 used to specify that the 30-day running average surface RH in building assemblies must never exceed 80% while the 30-day running average surface temperature is between 5 and 40°C. This corresponds with equilibrium wood moisture content of approximately 16 percent. This approach was criticized as being too conservative as it failed in building assemblies with demonstrated, long-term adequate field performance (Glass et al., 2015, 2017). The current version of Standard 160 uses a different approach, based on the VTT mold index model (ASHRAE, 2016, p.160; Ojanen et al., 2010; Viitanen & Ojanen, 2007). This model predicts the likelihood of surface mold growth based on material risk classes, combined with time-varying surface moisture and temperature conditions. It has been validated in laboratory and limited field experiments. A value that exceeds 3 indicates a high likelihood that surface mold will be visible and 3 is the maximum value allowed. Wood rot organisms take hold only in wood with higher moisture content than is required for mold growth. For example, wood rot organisms will typically only develop in wood with moisture content >30% for extended periods of time (Richard et al., 2010). Wood rot is a safety issue as it can greatly increase the risk of structural damage to a dwelling. This moisture issue is less common in sealed and insulated attics and is typically only found in very cold climate regions. Since mold risk is the more conservative metric, it sets the bar for acceptable moisture performance of building assemblies.

The typical response to managing roof deck moisture in sealed and insulated attics has been through the use of air and/or vapor impermeable insulation materials (e.g., spray polyurethane foam insulation, SPF) The foam can be installed either above or below the roof deck surface and it works by controlling the surface temperature, relative humidity, or access of moist indoor air to the underside of the roof sheathing. The model building codes (Section R806.5) require air impermeable insulation in milder climate regions, and they require use of vapor retarding materials (e.g., closed cell SPF) in colder climate regions (ICC, 2012). Cost, health, and carbon emission considerations have driven interest in sealed attic assemblies that do not use foam insulation materials. Recently, the model codes were changed in some conditions to allow sealed and insulated attic assemblies in mild climates using air and vapor permeable insulation materials (e.g., fiberglass and cellulose). Homes must be located in mild climate regions, and they are required to provide vapor diffusion vents near the roof ridge. Vapor diffusion vents allow vapor to diffuse through the membrane but prevent the escape of air. Research has assessed the efficacy of these vapor diffusion vents, as well as the potential risks and benefits of providing a vapor control layer on the underside of the permeable insulation (e.g., by applying a vapor retarder between the insulation surface and the attic air, shown in Figure 13).[55]

Figure 13: Vapor Retardant Netting



Shows vapor retardant netting in one of the homes. An S-2-2 monitoring sensor is also shown in the picture.

Source: LinkUs site visit photos

[55] Uneo & Lstiburek, (2015, 2016, and 2018)

Past research in two new California homes in the Fresno region assessed if adequate moisture performance might be possible in California's mild and dry Central Valley using permeable insulation with no other moisture mitigations.[56] These homes utilized high-performance attics with Johns Manville wired-batt insulation on the roof deck. Year-long roof deck moisture monitoring revealed elevated surface RH and moisture content in one attic; but an inspection revealed that attic to be free of mold growth. The second home had lower measured wood moisture at the north-facing roof deck; but an inspection after the year of monitoring indicated light mold growth across the north roof deck surface. The authors concluded that moisture mitigations were required for these permeable insulation assemblies in California's Central Valley.

Project Approach

Mitigation of Sealed Attic Moisture Risk

The builder used several approaches to mitigate potential moisture issues in sealed attics:

- Utilized a vapor retarder on all but the first three homes.
- Installed a vapor diffusion vent on the north-facing attic slope on all but the first ten (10) homes.
- Utilized a whole-house ventilation exhaust switch on all but the first three (3) homes. Continuous whole-house ventilation is expected to lower interior humidity conditions in winter.
- Installed wood moisture probes on the underside of the roof deck (north facing slope and east facing slope) to monitor wood moisture levels in 10 homes including various combinations of controls; unfortunately, the monitored attics included only one with a vapor diffusion port.

[56] B.D. Less et al. (2018)

The following table lists the measures included in each home that was monitored.

Table 13: Roof Deck Condensation Mitigation Measures

Lot	VR Attic Netting?	Vapor Diffusion Roof Vent?	Vent. Exhaust Switch?
L	NO	NO	NO
M	NO	NO	NO
N	YES	NO	YES
O	YES	NO	YES
P	YES	YES	YES
B	YES	NO	YES
C	YES	NO	YES
J	YES	NO	YES
K	YES	NO	YES
G	YES	NO	YES

Source: OmniSense Sensor Locations

The list below details the approximate costs for the various roof deck condensation mitigation measures (per the builder):

- Vapor Retardant Netting: $400 (incremental cost, varies by roof size)
- Vapor Diffusion Roof Vent: $400
- Vent Exhaust Switch: $50

Monitoring of Attic Moisture and Humidity

The researchers installed monitoring equipment in ten homes to evaluate surface relative humidity (RH) and wood moisture content (WMC) for the assessment of moisture risk. Table 14 provides a summary of the areas of the ten (10) monitored homes outfitted with sensors. Since the most challenging location is thought to be a north-facing roof slope with a clear view of the night sky during winter, this location was monitored in all homes. Monitoring inside the vapor retarder netting was based on conversations with Joe Lstiburek and Kohta Ueno of Building Science Corporation and Iain Walker and Brennan Less of LBNL, who noted the potential for condensation at this location. During daytime periods, the solar heat gains on the roof surface can drive moisture from the roof deck material into the attic. The placement of the vapor retarder material might lead to elevated moisture conditions in the insulation assembly; sensors were thus placed in this location to assess this potential risk. The locations where sensors were placed were not perfectly uniform due to limitations in sensor connectivity and attic space. Details and photos of sensor installations are provided in Appendix 7A.

Table 14: Areas Monitored in Homes

Lot	North Roof Slope	East Roof Slope	Lower Attic Area	East Facing Mini Attic	Return Air Duct	Top of Kitchen Cabinets
L	Monitored	Monitored				Monitored
M	Monitored	Monitored			Monitored	
N	Monitored			Monitored	Monitored	
O	Monitored		Monitored		Monitored	
P	Monitored	Monitored	Monitored		Monitored	
B	Monitored	Monitored	Monitored		Monitored	
C	Monitored	Monitored	Monitored		Monitored	
J	Monitored	Monitored	Monitored		Monitored	
K	Monitored	Monitored	Monitored		Monitored	
G	Monitored	Monitored			Monitored	

Source: OmniSense Sensor Locations

Roof Deck Moisture Analysis

The preliminary attic moisture analysis presented here focuses on identifying periods of surface RH that are in the range potentially supportive of mold growth. The research team used a threshold of 80 percent while noting that 75 percent could be sufficient for some mold species and consider extended periods of time at elevated RH to increase the risk of mold growth. Cold winter periods drive increased moisture levels at sealed and insulated roof decks. When roof and attic materials warm during spring, the moisture is re-emitted and absolute humidity levels in attic air increases. Due to the limited monitoring period from late Summer 2019 to early January of 2020, the research team cannot offer a full assessment of these effects; nor can they use the mold index metric currently embedded in ASHRAE 160. This preliminary analysis focuses on identifying conditions that indicate potential risk, and on assessing whether the employed moisture mitigation measures appear to be effective. A preliminary analysis with incomplete data cannot by its nature reach a conclusion that there is no future risk; but it can identify conditions that indicate risk. The analysis will be repeated with complete winter data and the intent is to analyze a full year of data to support mold index calculations. The final evaluation may also include visual inspections of the monitored roof locations.

Project Results

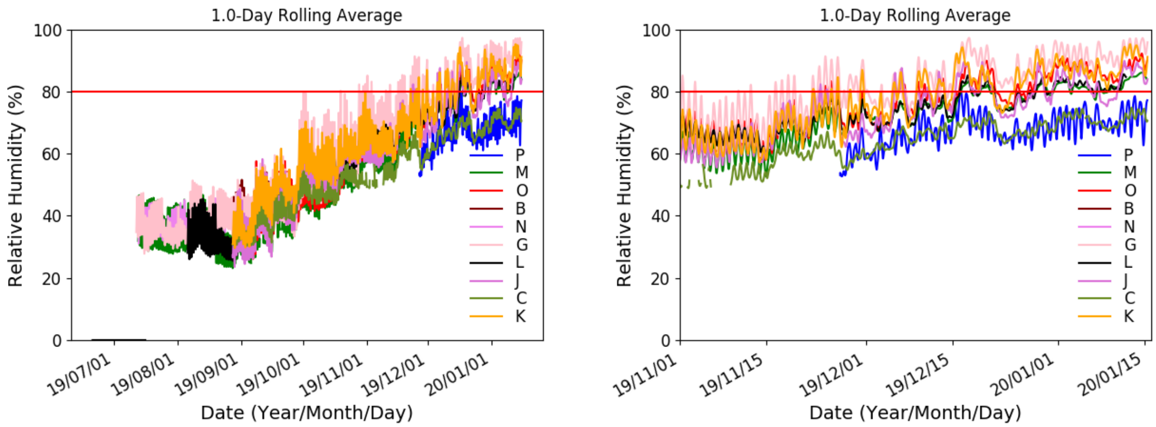
The research team processed, reviewed, and cleaned the data from the OmniSense data acquisition system as needed. An exploratory data analysis was done of the relative humidity and wood moisture content from all sensors, with the focus on identifying conditions conducive to mold growth. Correlations were used to explore potential linkages between surface RH at the insulated roof deck and other conditions in the dwelling (e.g., the general attic air RH). The results presented below focus on the North roof deck locations near the ridge, as they were consistently the worst locations in each dwelling.

Figure 14 shows the North roof deck surface RH and Figure 15 shows the WMC data. Left panels show all available data and right panels show only winter data (November 1, 2019 through January 15, 2020). The data, presented as daily means, clearly show that many, though not all, of the homes had surface RH values above mold growth thresholds for extended periods during the winter. The RH and WMC data are fairly correlated, which is expected, but one home—Lot K—has by far the most elevated WMC at the North sheathing, peaking in the low-to-mid 20 percent range. It is not clear why the WMC is so elevated in this location, while the surface RH is in-line with other dwellings.

The fraction of winter hours spent above RH thresholds from 75 percent to 95 percent, in 5 percent increments, are tabulated in Table 15 along with indicators of which moisture mitigation measures were implemented in each house. All but two of the monitored homes with winter data had North roof decks above minimum mold growth limits for substantial periods of time, with the time above 80 perce t surface RH varying from 12 to 60 percent of winter hours. The 30-day running average threshold of 80 perent constituted a building assembly failure according to the former ASHRAE 160 Standard. While no longer used in the Standard, this metric is useful in assessing the short-term performance of these assemblies; homes that failed this criterion are marked with "*" in Table 15. Five of the eight homes with winter data failed this criterion.

The roof deck data were also assessed for any correlations with sensor data from other locations in the dwelling. Using winter data only, Figure 16 shows comparisons between the mean roof deck RH (or vapor pressure) and compares that against corresponding values in the attic air volume or in the living space of the home. The correlations are weak, with the exception of the relation between the vapor pressure at the North roof deck and in the attic air volume (bottom left in Figure 16). No clear pattern is observable in the data when analyzed by winter mean values.

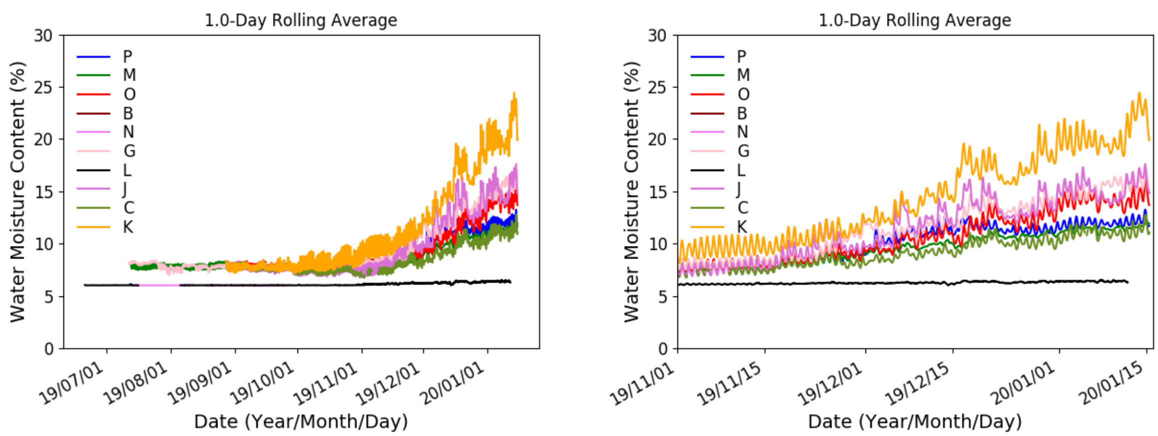
Figure 14: Relative Humidity on North-Facing Roof Slopes (Unvented Attics)



Shows the time-series plots of the relative humidity for sensors on north facing roof decks. The left graph shows all measurements, and the right graph shows measurements from November 1, 2019 – January 15, 2020.

Source: OmniSense Monitoring Data

Figure 15: Moisture Content on North-Facing Roof Slopes (Unvented Attics)



Shows the time-series plots of the moisture content for sensors on north facing roof decks. The left graph shows all measurements, and the right graph shows measurements from November 1, 2019 – January 15, 2020.

Source: OmniSense Monitoring Data

Table 15: Percent of Time During the Winter that the North-facing Roof Deck Exceeded RH Threshold Values (Unvented Attics)

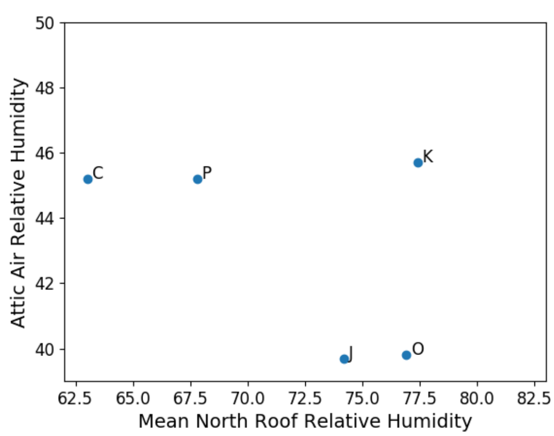
House	RH>75% (%)	RH>80% (%)	RH>85% (%)	RH>90% (%)	RH>95% (%)	Vapor Retarder Netting	Diffusion Venting	Ventilation Exhaust Switch	Heat Pump Water Heater
G*	75	60.2	43.4	25.4	7.8	yes	no	yes	no
K*	67.6	54	34.2	11.8	0.6	yes	no	yes	no
O*	56	38.8	21.6	3.7	0	yes	no	yes	no
J*	69.3	41.3	18.5	1.6	0	yes	no	yes	yes
L*	30.2	16.9	1.3	0	0	no	no	no	no
M	22.9	11.6	1.1	0	0	no	no	no	no
P	14.9	0.5	0	0	0	yes	yes	yes	no
C	0.3	0	0	0	0	yes	no	yes	no

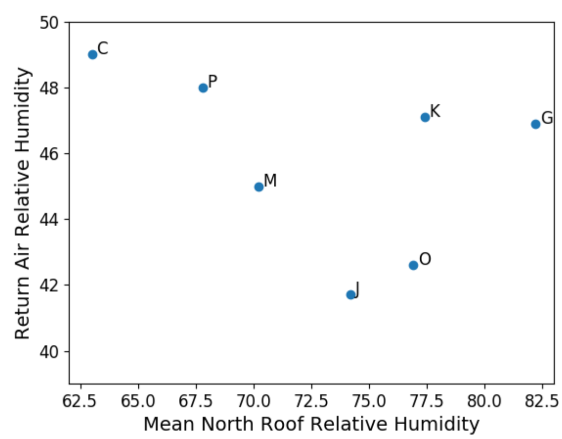
*** The 30-day running average relative humidity exceeded 80 percent.**

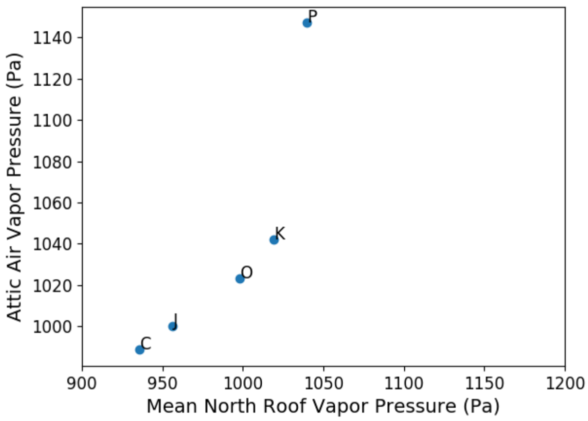
Note: winter data were not available for Lots B and N, so these are not included in the tabular summary.

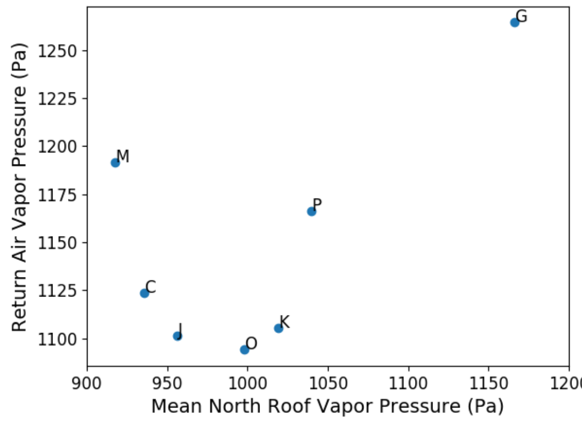
Source: OmniSense Monitoring Data

Figure 16: Comparisons Between Home Sensors During Winter









The top left graph plots mean attic air relative humidity vs. mean north-facing roof deck relative humidity. The top right graph plots mean return air relative humidity vs. mean north-facing roof deck relative humidity. The bottom left graph plots mean attic air vapor pressure vs. mean north-facing roof deck vapor pressure. The bottom right graph plots mean attic return air vapor pressure vs. mean north-facing roof deck vapor pressure. All measurements shown are from November 1, 2019 – January 15, 2020.

Source: OmniSense Monitoring Data

Conclusions/Recommendations

Based on this limited data and analysis, the research team cannot conclude that any of the assemblies are necessarily safe or necessarily at high risk of mold growth. What is clear is that most assemblies are not obviously, or unambiguously, dry and low risk. Longer measurements paired with mold index modeling and possibly visual inspection of the roof surfaces will provide a better assessment of moisture performance. It is critically important to recognize that these roofs have, at this time, not failed any currently accepted risk assessment standards. The research team used very conservative indicators to identify potential moisture issues. While the drivers of elevated moisture at sealed and insulated roof decks remain unclear, the analysis to date suggests that some of the mitigation measures and combinations used in the study homes (e.g., vapor retarder netting and heat pump water heater) are not adequately effective as deployed. The available data are not adequate to evaluate all of the deployed combinations of measures.

While no final conclusions can be drawn from this analysis, there are some notable trends related to the moisture mitigation measures

- Two homes with **no moisture mitigation measures** (L and M) showed little indication of moisture risk during the first part of the winter. Of the six homes with more than 1 percent of winter hours above 80 percent RH, these two homes had the lowest overall roof deck RH and the shortest time periods in risky moisture conditions. Lot L was the driest of the five homes that failed the former

ASHRAE 160 criteria, and M passed that criteria. Without a vapor retarder in place, these roofs surely had the most drying potential during daytime hours.

- Use of the **vapor retarder boxed netting** provided by Owens Corning does not, on its own, control roof deck RH to below levels at risk of mold growth. Of the five homes using the VR netting and no diffusion vents, one dwelling was the lowest risk of all homes (C), while the remaining four homes had the highest moisture levels and risk. Future assessments will attempt to identify why C is lower risk compared with its VR netting peers. VR netting may be effective in reducing RH; however, it is just not effective enough to reduce RH levels below mold growth risk levels.
- The combination of **VR netting and vapor diffusion vents** appears to be performing in safe moisture conditions (P); but this finding has limited certainty since only one home with the combination was evaluated. For example, one dwelling with VR netting and no diffusion vents was even drier and lower risk (C). With further research, this combination of measures could prove to be a robust solution for sealed and insulated attics using permeable insulation.
- A **heat pump water heater** was ducted into and out of the attic in home J, which was hypothesized to potentially reduce the attic air moisture content. Indeed, the attic and living space air in this dwelling had the lowest winter mean RH and second lowest vapor pressure. Yet, this home's roof deck was in moderately risky territory, with over 40 percent of winter hours exceeding 80% RH. While the HPWH appears to be helpful, it did not eliminate moisture risk in this assembly. Future analyses will assess the attic air moisture in this home and associated HPWH effects.

CHAPTER 8: Energy Use Analysis and Comparison to Modeled Energy Use

Introduction

Title 24, Part 6 uses compliance software to determine whether a particular building design meets the energy code requirements. While not currently a code requirement, builders pursuing ZNE in California can leverage the same software to demonstrate that a home's design meets that objective.

The software uses various algorithms and assumptions to estimate how much energy each end use (e.g., space heating, ventilation, lighting) will consume over the course of the year, as well as when in the year, season, and day that consumption will occur. That time factor, which is a key compliance variable in the software, is increasingly important as California moves towards reliance on intermittent renewable energy sources.

Since builders can trade-off different efficiency measures to achieve compliance or above-code targets like ZNE, it is important that the software assumptions represent actual use patterns and performance, as this will allow builders and designers to prioritize the correct strategies for meeting energy code requirements. Since the building code now requires new homes to include rooftop PV, the size of which is determined by these consumption estimates, additional accuracy in the software will ensure those systems are right-sized.

This project compares the modeled energy usage from the California Building Energy Code Compliance Residential (CBECC-Res) software with monitored energy usage from individual circuit level data to evaluate the accuracy of CBECC-Res software algorithms and assumptions, and to identify possible areas of improvement. Additionally, the research team assessed the impact of several high-performance appliances implemented in this project such as electric heat pump water heaters and heat pump clothes dryers. This effort could help determine if a future "compliance credit" for high-efficiency appliances would be viable and could potentially reduce over-sizing of PV systems.

Although these overarching project goals apply to all residential end uses, this report often distinguishes between "regulated" and "unregulated" end uses (also called "loads"). "Regulated loads" refers to the user-controlled variables of space heating, space cooling, water heating, and ventilation, which are the only energy uses regulated by Title 24. The builder can specify (and trade-off) the performance of various building elements (insulation levels, HVAC efficiency, etc.) in the software to demonstrate compliance. "Unregulated loads" are lighting and "plug loads," which include kitchen and laundry equipment, consumer electrics, small appliances, and other miscellaneous electric loads (MELs). A diagram clarifying this terminology and the hierarchical relationship between these categories can be found in Appendix 8A. In the context of this report, the most relevant difference between regulated and unregulated loads is that CBECC's estimates for regulated loads are far more dependent on weather and building characteristics, while unregulated load estimates are based on equations that simply consider the number of bedrooms or total conditioned floor area in the building.

Project Approach

The research team collected circuit-level data in newly constructed demonstration homes in Clovis, California that were designed to be ZNE, and compared the data to predicted loads as modeled by CBECC-Res compliance software. Then the research team used the data to create hourly load curves for each energy end use in the home, as well as overall (i.e., across all homes). The research team then compared the monitored energy consumption and modeled site-specific energy from the CBECC-Res software using two software models: one using the Typical Meteorological Year (TMY) for California Climate Zone 13 (the location of the ZNE demonstration community) and the other using the Actual Meteorological Year (AMY) weather data for the monitoring period using the nearest weather station in Fresno, California.[57]

In addition to any discrepancies that might be identified through this comparative analysis, the research team was previously aware of several existing inconsistencies between the published algorithms for unregulated end uses and the actual outputted energy uses and highlighted these differences as part of the analysis.

The research team also implemented a strategy with the home builder to supply each home with a selection of high-efficiency large appliances: an ENERGY STAR® Most Efficient (ESME) refrigerator, clothes washer, and heat pump clothes dryer (see Chapter 4). The research team also used online survey responses from the behavioral evaluation (see Chapter 5) to identify the occupancy characteristics and use patterns that were potential large-impact drivers of energy consumption in the homes.[58]

Data Collection

The research team collected data on regulated and unregulated loads from each home in the ZNE demonstration community. As part of the sales agreement, the homebuyer agreed to provide this data to the research team and was made aware of the research study. The research team installed circuit-level monitoring devices, which the builder marketed as a feature of the homes. The homebuyer then received the online survey on a predetermined date after moving in.

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[57] For a detailed explanation of the actual weather data used in the AMY model see Appendix 8B

[58] The online survey received responses from four homeowners in the demonstration community, three of which are also included in this analysis. The survey data is used to interpret the energy usage patterns for these three homes only.

Ultimately, the research team assessed a total of six homes in Clovis, California, with homeowners moving in between July 2019 and November 2019. Further discussion of the sample and associated limitations of this project are reported in the Project Results section.

Circuit-Level Monitoring

The research team worked with the builder's electrician to install circuit-level electricity monitoring devices in each of the demonstration homes after all of the homes' wiring and electrical panels had been installed. The research team worked with the builder and the electrician to separate and label distinct loads to the extent practicable, taking care not to mix primary end uses.[59] The electrician installed two CURB Energy monitoring devices in each home, one in the main panel and one in the subpanel. The two CURB units used current transformers to record current data from up to 32 circuits in each home. It was occasionally necessary to run more than one circuit through a CT, but circuits in shared CTs were grouped by common end use. All major appliances, including the water heater, heat pump heating and cooling, washer, dryer, dishwasher, and refrigerator occupied distinct circuits and CTs. Other, smaller loads were on shared circuits, but grouped with like uses (e.g., lighting with lighting, outlets with outlets). The data monitored by these devices was uploaded to a CURB cloud server that could be accessed by the homeowner and research team in real-time.[60]

The data in the CURB cloud server provides average watts for a given time period, circuit, and location (home address). The research team performed analyses on a time-series interval of five minutes with a more granular dataset used only for quality assurance purposes.

Compliance Software Models

ZNE home energy use was modeled using the CBECC-Res software and then modified in the California Simulation Engine (CSE). The research team coordinated with the home builder and the builder's Title 24 consultant to acquire and update CBECC-Res energy models that were used to generate compliance documentation. The team then worked in the CSE to replace the TMY stock weather data with actual weather data and other minor modifications noted below to create AMY models. The research team used both output sets for the comparison of monitored energy to modeled energy for regulated loads. For unregulated loads, the researchers only used AMY-modeled energy usage because there were negligible differences in the end use outputs.

Monitoring Hot Water Use

With storage water heaters, the use of hot water often occurs at a different time than the energy used to heat it. As a result, one of the improvement strategies investigated

[59] Aside from exhaust ventilation fans and water heater recirculation pumps, circuits were successfully separated by end-use category.
[60] CURB provides an application programming interface (API) for downloading the meter data. The research team established an automated download protocol to store the meter data in a separate server.

in this project was to use the water heater as a thermal battery. The concept was to let the water heater use electricity during periods of excess renewable energy availability and store that energy as hot water so that the heater would not need to come on during peak electrical periods. This thermal energy storage approach was offered to two of the ZNE homeowners in this analysis along with a gift card as incentive. Both of these homeowners opted-in to the study and allowed the research team to modify the schedule and setpoint for their heat pump water heater via over-the-air updates from the manufacturer. As such, water heating energy use for these two homes was not compared to the default assumptions in CBECC-Res. Instead, the water heating setpoint schedule for these two homes was modified in CSE to reflect the schedule used in the thermal energy storage pilot.[61]

Analytical Approach

Comparison of Monitored Versus Modeled Energy Consumption for Regulated Loads

The research team compared both the monitored site-specific and overall (i.e., across all homes) energy consumption to TMY- and AMY-modeled site energy consumption for the demonstration homes. The comparison was conducted at an hourly level (e.g., load profile) and total level (e.g., aggregated energy consumption) for regulated loads.

Daily Load Profiles

Daily load profiles are the average energy use (kWh) consumed during each hour of the day, analyzing weekdays and weekends separately. The research team used circuit-level monitoring data to characterize how energy use was distributed over time. Accurately predicting the timing of energy use will become increasingly relevant as the California grid increases its reliance on intermittent, renewable energy sources.

Due to the design of the homes' electrical wiring, exhaust ventilation fans and plumbing recirculation pumps were typically on circuits that included either lighting or plug loads, and the researchers could not successfully or consistently isolate those end-uses. As such, those two regulated loads may have been incorrectly categorized as unregulated loads in the aggregate analysis. However, since both are highly subject to occupant behavior (i.e., turning off ventilation fan) the impact aggregate analysis, if any, is likely negligible. Likewise, since in most cases those two uses could not be isolated, they were not part of the regulated loads analysis for most homes.

The research team aggregated the observed energy use of unregulated loads that were not on dedicated circuits, and compared the total to the aggregate modeled energy use

[61] In Chapter 4, this data was analyzed to determine whether the modified schedule and set point accomplished the desired effect of reducing or completely avoiding energy consumption during periods of peak electrical demand.

for the same unregulated loads in CBECC-Res.[62] For each separately analyzed load and the whole-home total, the research team created daily load profile charts that superimpose monitored data from each home, the average of all homes, and the modeled output (for both the TMY and AMY models).

Total Energy Use

In addition to analyzing the timing of energy use, the research team compared total monitored energy use for the observation period to the modeled outputs for the corresponding time periods for each demonstration home. For each home, the team compared the energy consumed in that period to what the model would predict based on each home's design, using both TMY- and AMY weather files. From this comparison, the researchers derived the percent difference between actual consumption, TMY-modeled consumption, and AMY-modeled consumption for each observed end use and for the whole-home.[63]

Comparison of Monitored Versus Modeled Energy Consumption for Unregulated Loads

For unregulated loads, the research team compared the observed energy consumption to the modeled energy consumption by creating average daily load profiles for weekends and weekdays and by comparing total energy usage. The research team used only the AMY models because the end use outputs from the two models had a negligible difference.

In addition, the research team analyzed differences between the compliance software estimates (which barely meet the federally-rated energy usage) and the actual rated energy usage of the products from as reported in the U.S. Department of Energy (U.S. DOE) Compliance Certification Management System.[64] The analysis looked specifically at clothes washers, clothes dryers, and dishwashers to develop a utilization analysis based on number of cycles as well as an average cycle energy usage. A summary can be found in the Project Results section of this chapter.

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[62] For more detail on how the research team mapped circuits to loads modeled in CBECC-Res, see Appendix 8C

[63] The underlying assumption in the compliance software is that the products are minimally compliant with the federal standards when they were purchased. This is necessary because of federal regulations that prevent California from setting state efficiency standards that exceed federal efficiency standards for appliances covered by U.S. DOE.

[64] The Compliance Certification Management System is the online interface through which manufacturers of covered products and commercial equipment must electronically submit compliance and certification information to DOE.

Analysis of Behavioral Factors

Using the comparisons from the observed versus modeled analysis described previously, the research team analyzed the extent to which modeled energy use varies from monitored energy use as a result of actual weather patterns, space/water heating and cooling schedules, and laundry/dishwasher usage.

Assessment of Strategies to Address Unregulated Load Energy Use

The research team analyzed monitored energy use and consumer acceptance of heat pump clothes dryers and other high performing appliances, to assess the following factors:

- **Monitored energy consumption:** The research team compared observed energy use for the high-efficiency appliances to both the rated energy consumption (described above) and the modeled energy consumption in the compliance software based on number of bedrooms in the home.
- **Acceptability of heat pump clothes dryers**: The research team analyzed the observed drying times of heat pump clothes dryers in regular mode and eco mode, based on analysis of the submetering data.

By analyzing these factors, the research team aimed to not only comment on the strategy of installing high-efficiency appliances, but also to support the potential development of compliance credits in CBECC-Res for these builder-supplied, high-efficiency large appliances.

For additional information on the products selected for this strategy, including their rated energy savings, incremental cost, and their effectiveness in achieving a ZNE design per dollar spent compared to other strategies for achieving ZNE, see Chapters 3 and 4.

Project Results

Overall Findings and Key Results

The research team anticipated more than a year of data from over 10 homes. However, the deployment of homes was delayed due to slower than expected sales and construction of the ZNE homes, which in turn resulted in significantly less data than expected. [65,66] The research team found it necessary to further limit the dataset to include homes with five weeks of continuous occupancy prior to November 2019, so as to ensure more accurate and representative occupant behavior and energy usage. Table 16 summarizes the six selected homes that fit the data completeness criteria

[65] Sales were affected by regional economic trends as well as lower-cost options for conventional (non-ZNE) homes in the surrounding areas.
[66] Construction was delayed by ongoing skilled labor shortages and delayed ground-breaking due to the extremely wet winter of 2018-2019.

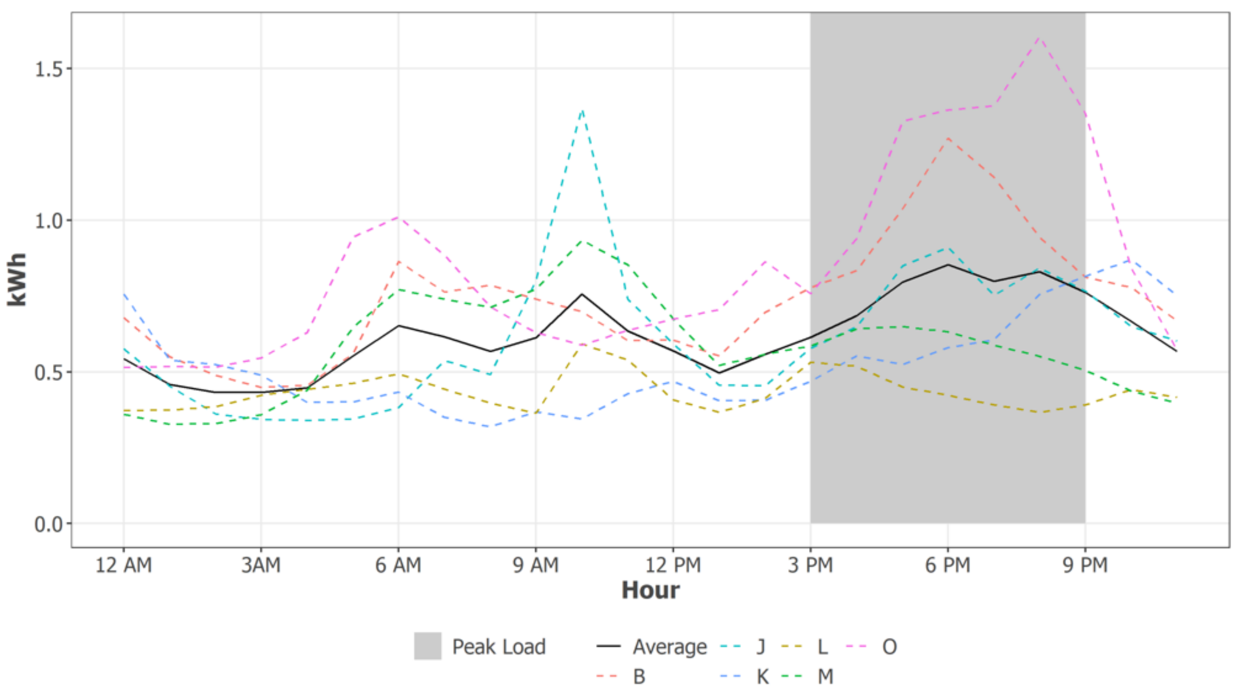
along with some basic attributes of the properties. Figure 17 displays the hourly average usage of the six homes included in the analysis.

Table 16 Summary of Homes Used in Study

Home ID	Model (Floor Plan) Identifier	Square Feet	Bedroom Count	PV Size [kW]	Monitoring Period
B	Residence 240	2,361	4	6.615	Sept. 25 - Nov. 18, 2019
L	Residence 210	2,019	4	6.615	Sept. 25 - Nov. 18, 2019
M	Residence 210	2,019	4	6.615	Sept. 25 - Nov. 18, 2019
J	Residence 210	2,019	4	6.615	Sept. 25 - Nov. 18, 2019
K	Residence 210	2,146	4	5.985	Sept. 25 - Nov. 18, 2019
O	Residence 260	2,544	5	6.615	Oct. 1 - Nov. 18, 2019

Source: CURB Monitoring Data and TMY and AMY Models

Figure 17: Monitored Load Profiles and Average Profile of All Homes (n=6)



Displays the hourly average usage of the six homes included in the analysis, as well as the average usage (indicated by the black line).

Source: CURB Monitoring Data

Regulated Loads Energy Use Comparison Results

The research team compared monitored home energy use of regulated loads with the TMY- and AMY-modeled projections for the monitoring period (September to November 2019 for six homes).

Table 17 summarizes the results of this analysis. For space heating and cooling, the AMY and TMY model underestimated energy use by 53 percent and 26 percent, respectively. Both the AMY and TMY model overestimated water heating energy use by 83 percent and 94 percent, respectively. For ventilation, both the TMY and AMY models overestimated energy use by 29 percent. Despite the substantial differences between modeled and monitored energy use, regulated loads account for less than one-third of the total monitored energy consumed by these homes during the analysis period (or 30 percent of 4.7 MWh).[67] Both models were used because predicted consumption for regulated end uses is impacted by weather, unlike unregulated loads which are driven by occupancy and showed negligible differences between TMY and AMY. The following sections present the detailed results of this comparison by regulated end use.

Table 17: Summary of Monitored vs. Modeled Results for Regulated Loads

Regulated Loads	Monitored (kWh)	AMY (kWh)	TMY (kWh)	Delta Monitored - AMY	Delta Monitored - TMY	% Difference (AMY)	% Difference (TMY)
Space Heat/Cool	640	301	471	339	169	53%	26%
Water Heater	461	845	894	-384	-433	-83%	-94%
Ventilation	287	370	370	-83	-83	-29%	-29%
Total Regulated Circuit Usage	**1,388**	**1,516**	**1,735**	**-128**	**-347**	**-9%**	**-25%**
Total Home Usage	**4,698**	**5,943**	**6,152**	**-1,245**	**-1,454**	**-27%**	**-31%**

Source: CURB Monitoring Data and TMY and AMY Models

Space Heating and Cooling

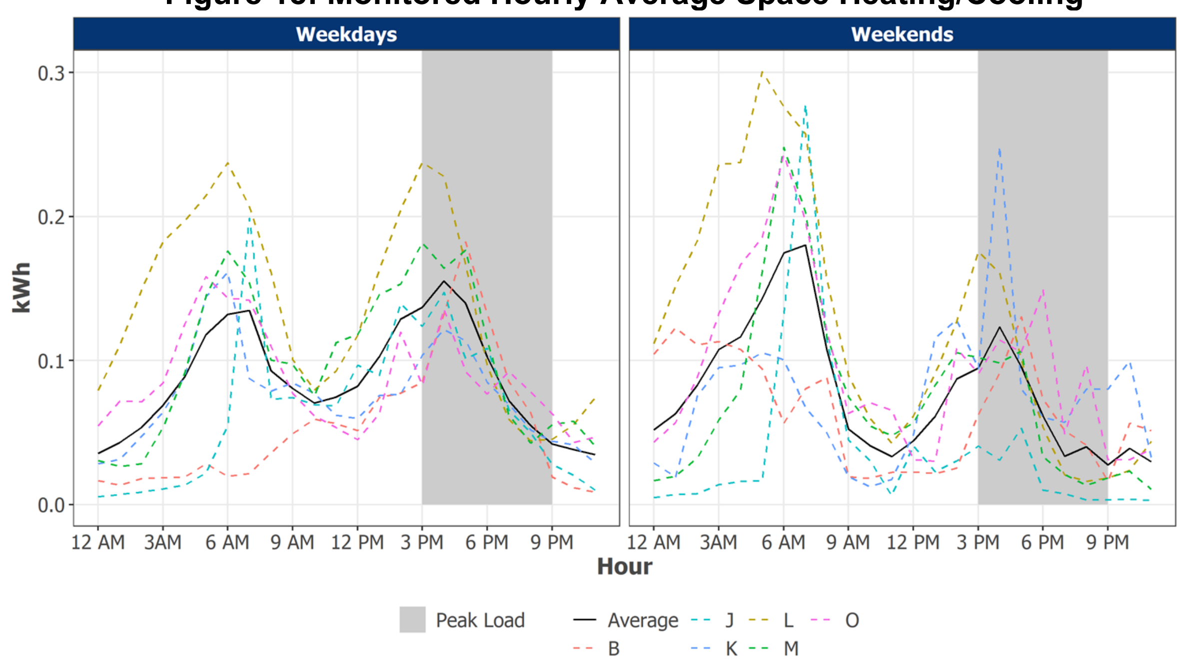
Figure 18 shows weekday and weekend load profiles for space heating and cooling for each of the six homes in the analysis. Figure 19 compares monitored space heating and cooling to both models (TMY and AMY) in terms of average hourly energy use. Despite the larger variability of observed energy use (most likely due to the small sample size), monitored space heating and cooling is consistently larger than modeled, particularly during the daytime on weekdays as well as the late afternoon and early evening on weekends. Since the research team did not review indoor air temperature for the homes included in this analysis, it is uncertain whether the discrepancy primarily derives from differences between actual heating and cooling thermostat setpoints and schedules, other characteristics impacting heating and cooling such as air infiltration or distribution duct leakage rates, or the modeling algorithms used by CBECC-Res to

[67] The time period covered by this analysis coincides with the fall shoulder season (i.e., the months between summer cooling and winter heating). As such, regulated energy usage for space heating and cooling is substantially less compared to other times of year.

simulate heat pump space cooling and space heating. Despite the limitations, the substantial differences are likely due in part to the following:

1. **Hourly thermostat setpoints**. CBECC-Res's default assumptions for the thermostat's hourly setpoints are fairly conservative with a constant 68°F heating setpoint and cooling setpoints at 83°F from 8:00 AM until 2:00 PM and dropping by one degree thereafter until 6:00 PM at which point it stays at 78°F for the remainder of the evening/night.[68] The research team was unable to receive thermostat data for the monitored homes, and therefore could not update the models to reflect actual thermostat set-point schedules.
2. **Occupant behavior:** The individual load profiles for each home's space heating and cooling suggests that occupants were often home during the weekdays and were therefore more likely to manually adjust their thermostat to suit their comfort level and preferences. Feedback from the three homeowners surveyed supports the occupancy patterns and the manual adjustments of the thermostat that deviate from the default assumptions of the setpoint schedule. Of the three homeowners who responded to the survey and are included in this analysis, two are home frequently or occasionally during the weekdays. Additionally, all three homeowners said they manually adjusted temperature settings depending on their schedule, comfort level, or the weather. As detailed in Chapter 5, survey data suggests that homeowners did not take advantage of the energy saving features offered by their smart thermostats due to a lack of awareness.

Figure 18: Monitored Hourly Average Space Heating/Cooling

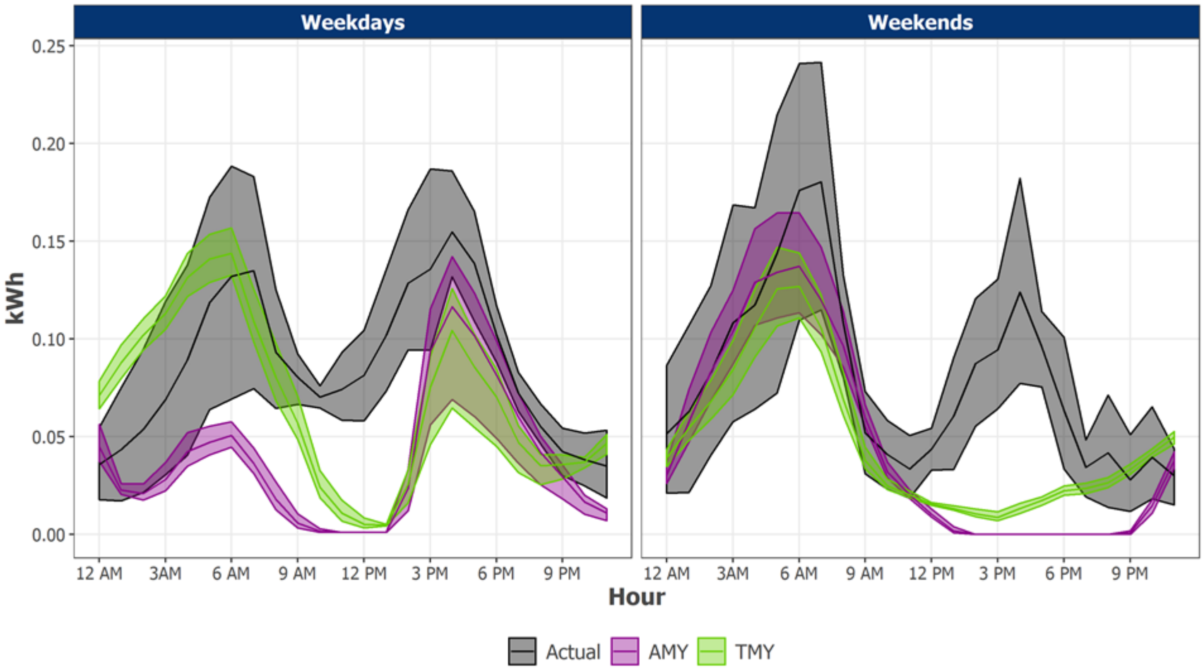


[68] See Table 22, Hourly Thermostat Setpoints in the 2019 ACM Reference Manual, available here

Load profiles showing weekday and weekend average hourly observed usage of space heating and cooling in the six monitored homes.

Source: CURB Monitoring Data

Figure 19: Space Heating/Cooling Variability Monitored vs. Modeled



Average load profiles for observed space heating and cooling usage on weekday and weekends compared to both the TMY and AMY models' load profiles shows underestimation of energy use by the model.

Source: CURB Monitoring Data and TMY & AMY Models

Water Heating

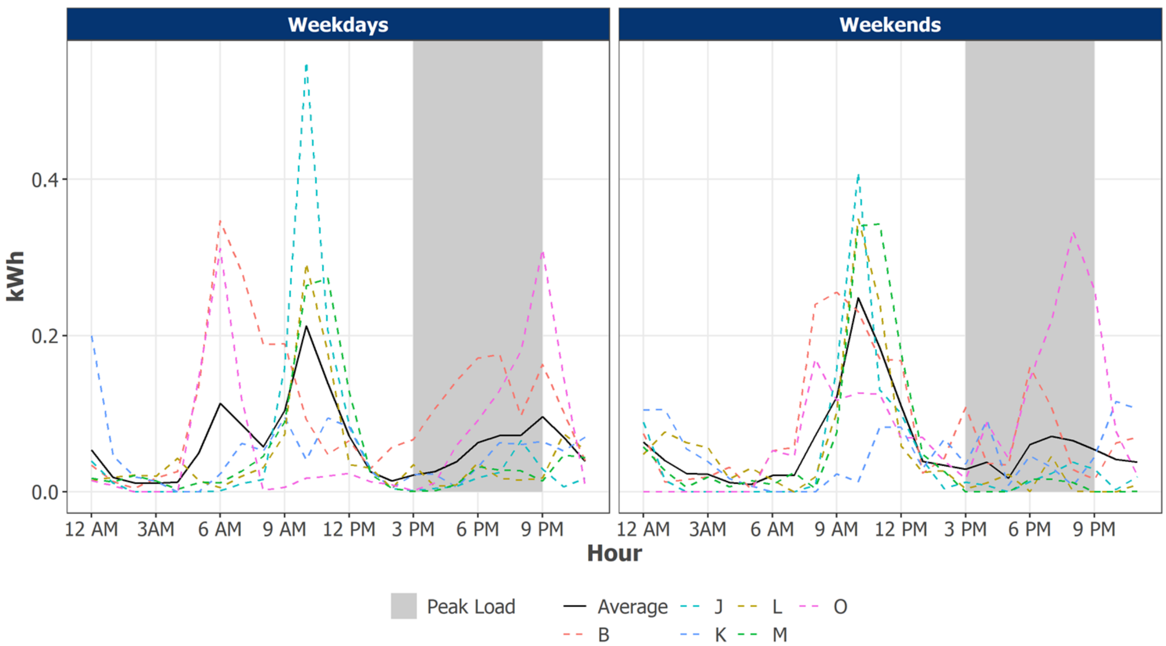
Figure 20 shows weekday and weekend load profiles for water heating for each of the six homes in the analysis. Figure 21 compares monitored water heating energy to both models in terms of average hourly energy use. Despite the larger variability of observed energy use (most likely due to the small sample size), monitored water heating energy use is consistently smaller than modeled. While the research team was unable to isolate the monitored energy use of the recirculation pump from the garage circuit that they suspect it was connected to, the pump is included in the modeled assumptions. However, the CBECC-modeled marginal daily usage of the pump is nominal (approximately 0.063 kwh),[69] so it is not likely the main reason for the discrepancy. The overestimation of water heating usage by the model is possibly due to the following:

1. **Overestimation of hot water consumption in CBECC-Res due to occupancy assumptions**. CBECC-Res's algorithm for estimating hot water

[69] See Table B-6, SF Recirculation Energy Use by Hour of Day in the 2019 Alternative Calculation Methods Reference Manual, available here

consumption (in terms of gallons per day) includes assumptions around the number of home occupants, which is in part based on the number of bedrooms. Given the bedroom count of the homes, hot water consumption is estimated for five occupants in five of the homes, and six occupants in one home, with slight daily variations as required by the ACM Reference Manual.[70] However, survey data and discussions with the builder revealed that there is one occupant in two homes (M and K), two occupants in three homes (L, J, and O), and four occupants in one home (B).

Figure 20: Average Hourly Monitored Usage of Water Heating



Load profiles showing weekday and weekend average hourly usage of water heating in the six monitored homes.

Source: CURB Monitoring Data

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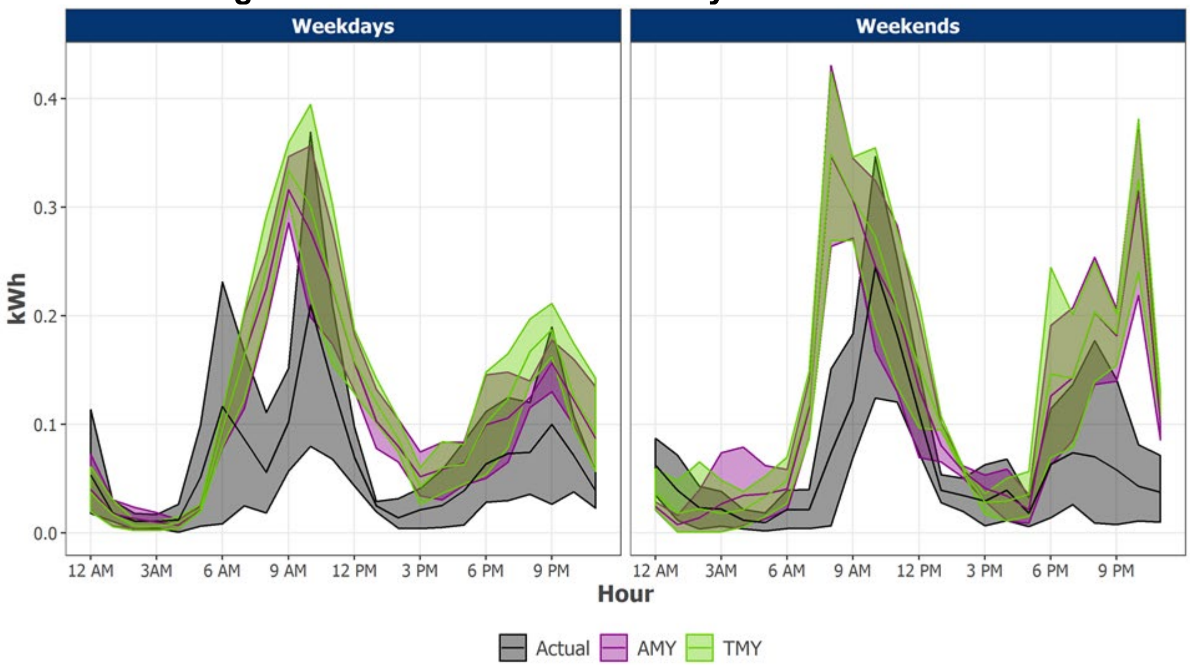
[70] CEBECC-Res models hot water consumption through a method that varies the number of occupants each day based on the number of bedrooms. For example, a 3-bedroom home varies the number of occupants from 1-6. It repeats this daily variation 4 times per year and has additional variations for weekends and holidays. For each day, there are specific hot water events ranging from very low water use and few events to very high water use and many events. See Appendix B, Water Heating Calculation Method of 2019 Residential ACM Reference Manual for more information. Available here.

Figure 21: Water Heater Variability Monitored vs Modeled



Average load profile for observed water heating energy use on weekday and weekends compared to both the TMY and AMY models' load profiles shows consistent underestimation of energy use by the model.

Source: CURB Monitoring Data and TMY & AMY Models

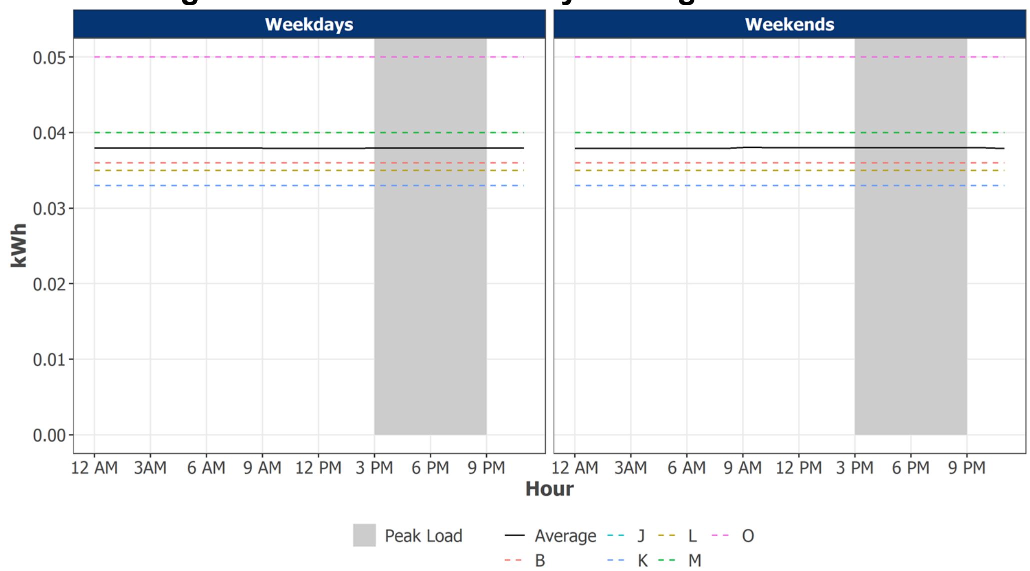
Ventilation

Figure 22 shows weekday and weekend load profiles for ventilation for each of the six homes in the analysis. Figure 23 compares monitored ventilation energy to both models in terms of average hourly energy use. Despite the larger variability of observed energy use (most likely due to the small sample size), monitored ventilation energy use is consistently less than TMY- and AMY-modeled usage. Ventilation energy use comes from the heating and cooling supply fan and the exhaust fan, both of which are on separate circuits in each of the homes. The research team therefore had to disaggregate and combine both ventilation sources in order to compare monitored energy use to modeled ventilation. The supply fan in each home is characterized by an 'always-on' load on the circuit labeled "Central Fan and Supplemental Heat" and is therefore easily disaggregated from the supplemental heating load on the same circuit. The research team disaggregated energy use for the exhaust fan for the only home in which it was running continuously.[71] As illustrated in Figure 22, the ventilation load profile for the one home where the research team was able to isolate both supply and exhaust fan energy (light pink dotted line) is the only home that matches the modeled

[71] The exhaust fan in Home 43-02 had a 25W "always-on" load running on a circuit labeled "Exhaust, Bedroom 2,3 Lights." The other five homes' exhaust fans could be turned on and off by the homeowner, and since they shared a circuit with unregulated loads (typically bed and bath MEL outlets and lighting), it was impossible to isolate the energy use from the exhaust fans for those circuits.

energy use shown in Figure 23. The inability to disaggregate exhaust fan energy is therefore likely the primary driver of the discrepancy between modeled and monitored energy use.

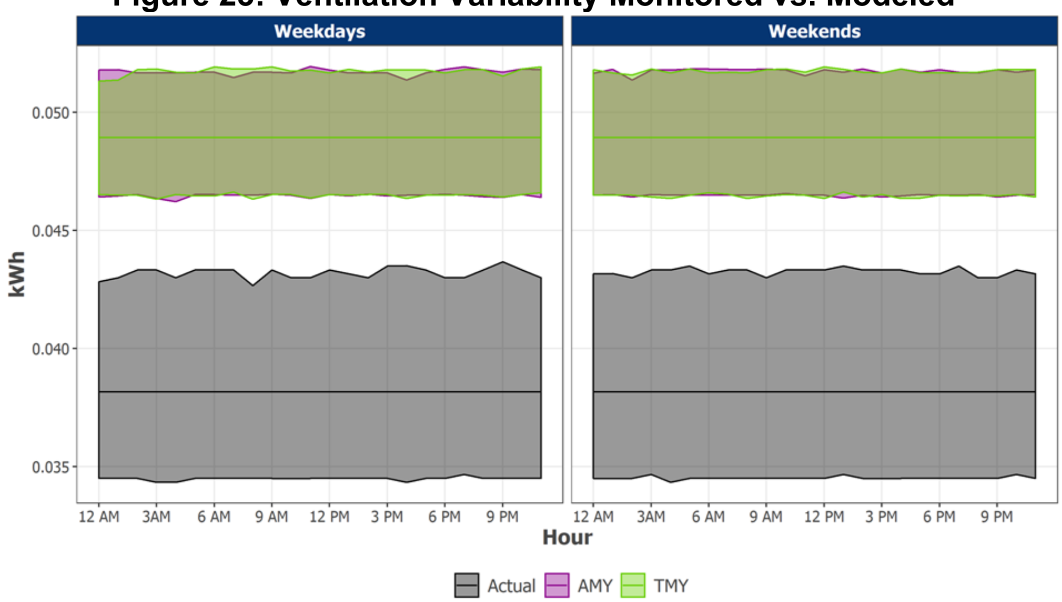
Figure 22: Monitored Hourly Average Ventilation



Load profiles showing weekday and weekend average hourly usage of ventilation in the six monitored homes.

Source: CURB Monitoring Data

Figure 23: Ventilation Variability Monitored vs. Modeled



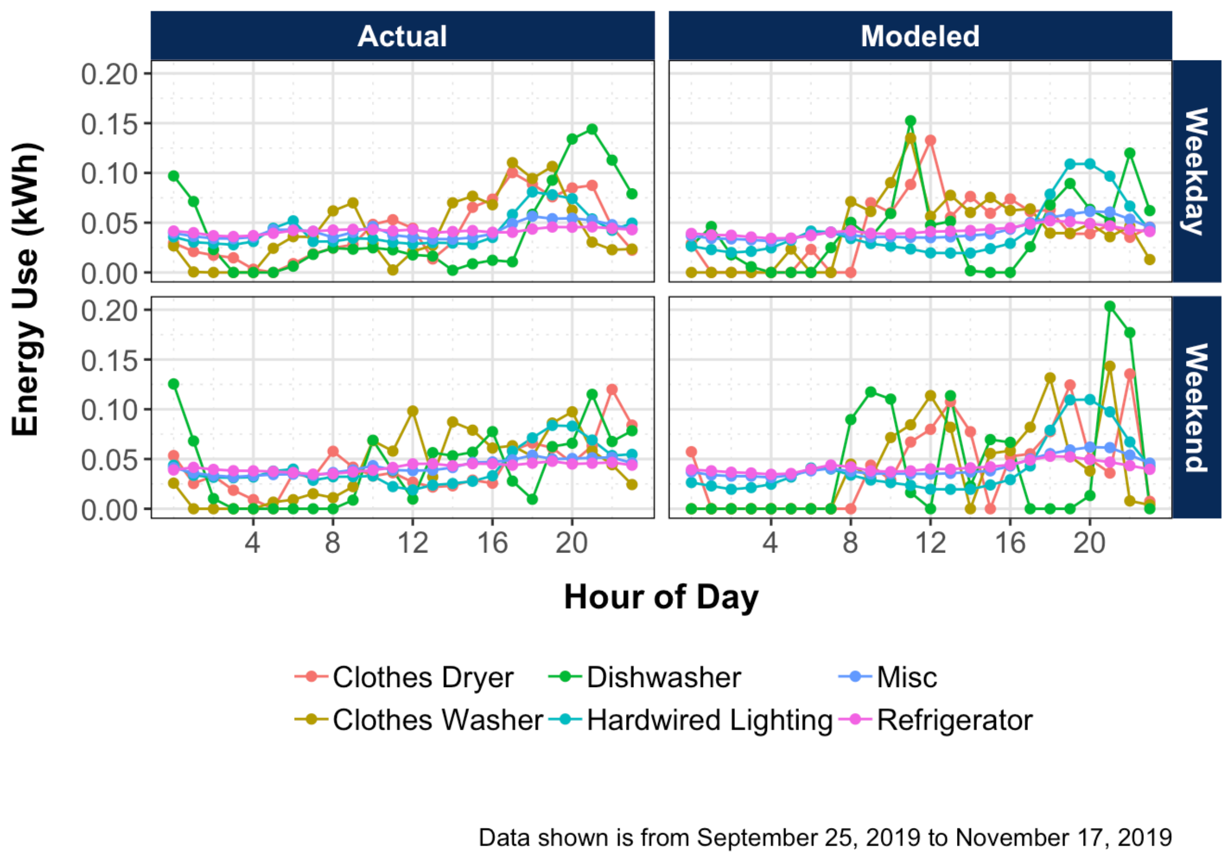
Average load profile for observed ventilation energy use on weekday and weekends compared to both the TMY and AMY models' load profiles shows consistent overestimation of energy use by the model.

Source: CURB Monitoring Data and TMY & AMY Models

Unregulated Loads Energy Use Comparison Results

The research team conducted a rigorous analysis of unregulated loads, comparing the modeled energy outputs in CBECC-Res with the circuit-level monitoring (actual) data of energy usage across different end use types (dishwasher, refrigerator, etc.) for each of the six houses. For the hourly load profiles, the research team filtered the data by end use and then aggregated it into weekends and weekdays to control the behavioral differences between weekend occupancy and weekday occupancy. Individual plots for each unregulated end use can be found in Appendix 8C. Figure 24 summarizes the results showing load profiles for weekday and weekend and modeled vs. monitored.

Figure 24: Load Profiles for Unregulated Loads

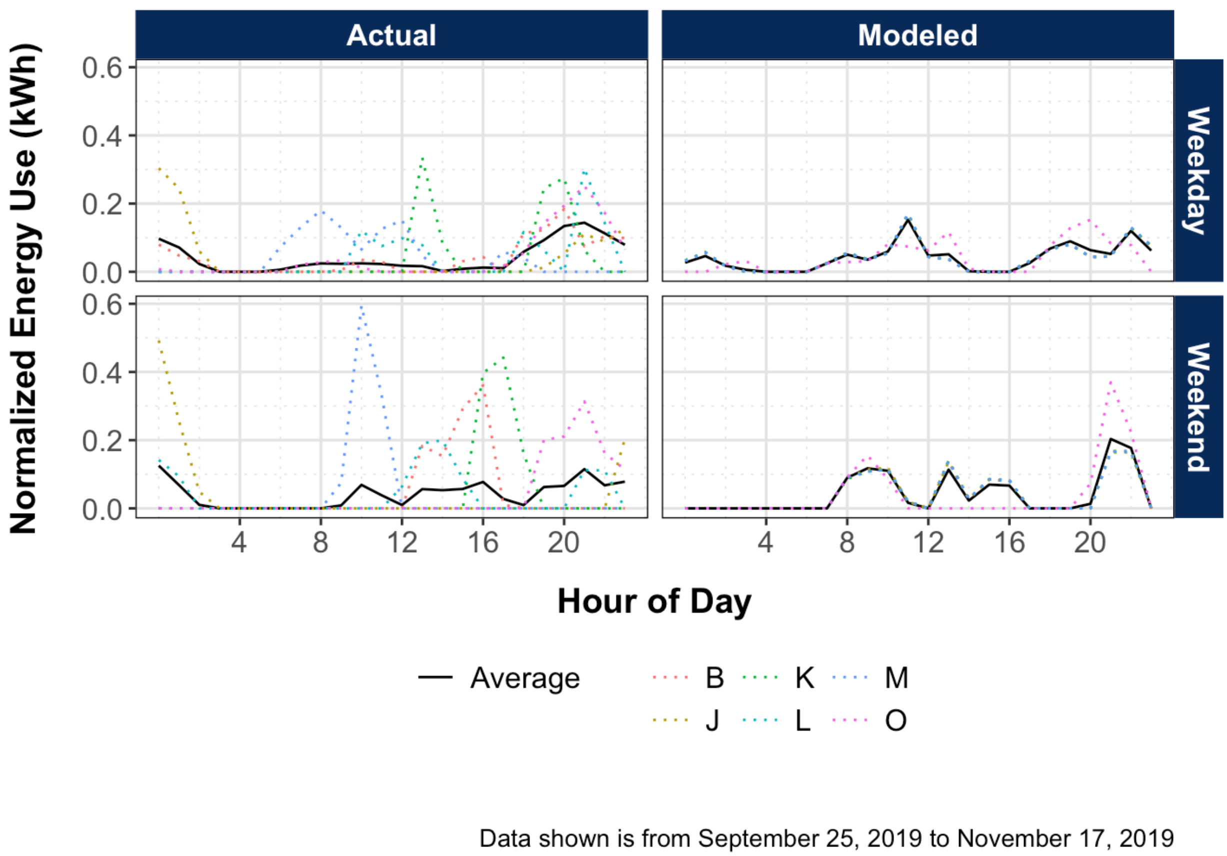


Load profiles showing average hourly usage for all unregulated end uses.

Source: CURB Monitoring Data and AMY Models

In comparing modeled energy use to monitored energy use, Figure 24 shows that some end uses had significant deviation from the modeled energy usage with all homes averaged together while others showed little change. For example, the weekday (top) and weekend (bottom) usage of dishwashers (green line) showed much higher energy usage in the late night/early morning in monitored energy usage (left side) than the modeled energy usage (right side) while other end uses such as the refrigerator usage (pink line) showed little change. In addition to this aggregated view of all homes, the research team also developed individual load profiles for each end use and each house. For example, the dishwasher and clothes dryer end use graphs can be found in Figure 25 and Figure 26.[72] The research team would like to express caution as the data availability was limited to just six homes and just five weeks and while occupants have moved in, regular habits/behaviors may not have settled. Therefore, data from appliances that have a high behavioral component such as dishwashers and clothes washers should be viewed with less confidence than those that run continuously such as a refrigerator. However, the data illustrates more volatile usage patterns than suggested in the software model.

Figure 25: Dishwasher Variability Monitored vs. Modeled

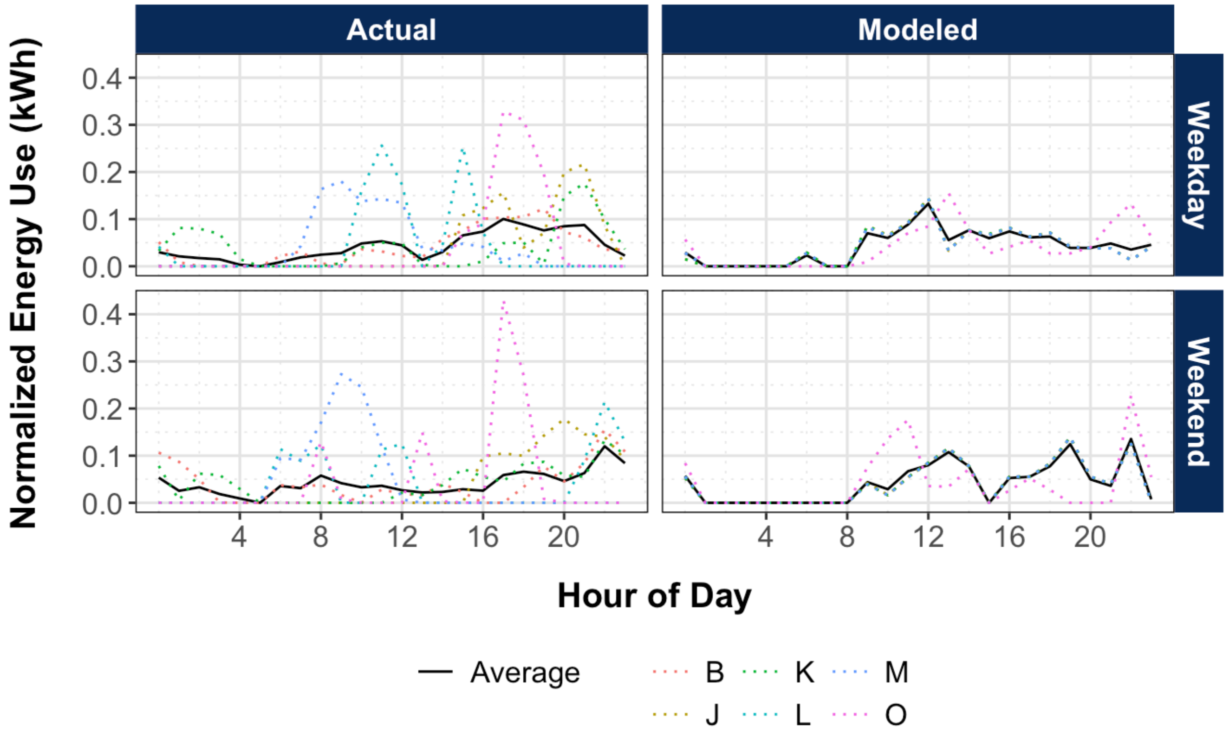


Load profiles for dishwashers showing weekday and weekend use of each of the six monitored homes and weekend/weekday averages.

Source: CURB Monitoring Data and AMY Models

[72] Additional load profiles can be found in Appendix 8C

Figure 26: Clothes Dryer Variability Monitored vs. Modeled



Data shown is from September 25, 2019 to November 17, 2019

Load profiles for clothes dryers showing weekday vs. weekend and actual vs. modeled for each of the six monitored homes with weekend/weekday averages shown.

Source: CURB Monitoring Data and AMY Models

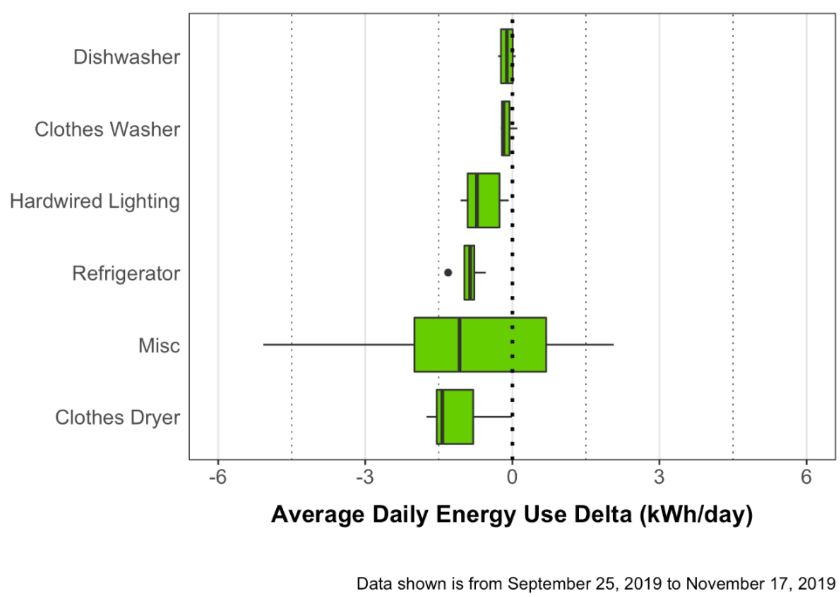
Additionally, the research team investigated total energy usage from this same time period and compared the monitored energy usage with the modeled energy usage. Table 18 shows the total difference and percent difference in energy usage between monitored and modeled. The research team also created box plots to illustrate the differences between homes once aggregated in Figure 27 below.

Table 18: Summary of Monitored vs. Modeled Results for Unregulated Loads

Unregulated End Use Category	Monitored Usage (kWh)	AMY Modeled Usage (kWh)	Average Delta (kWh)	% Difference from AMY Model
Clothes Dryer	326	687	-361	-111%
Clothes Washer	39	79	-40	-102%
Dishwasher	72	109	-37	-51%
Hardwired Lighting	309	501	-192	-62%
Miscellaneous	2,022	2,368	-347	-17%
Refrigerator	277	470	-193	-70%
Total	3,045	4,214	-1170	-38%

Source: CURB Monitoring Data and TMY and AMY Models

Figure 27: Difference of Average Daily Energy Usage: Monitored vs. Modeled



Boxplots showing the range of daily usage for all unregulated end uses.

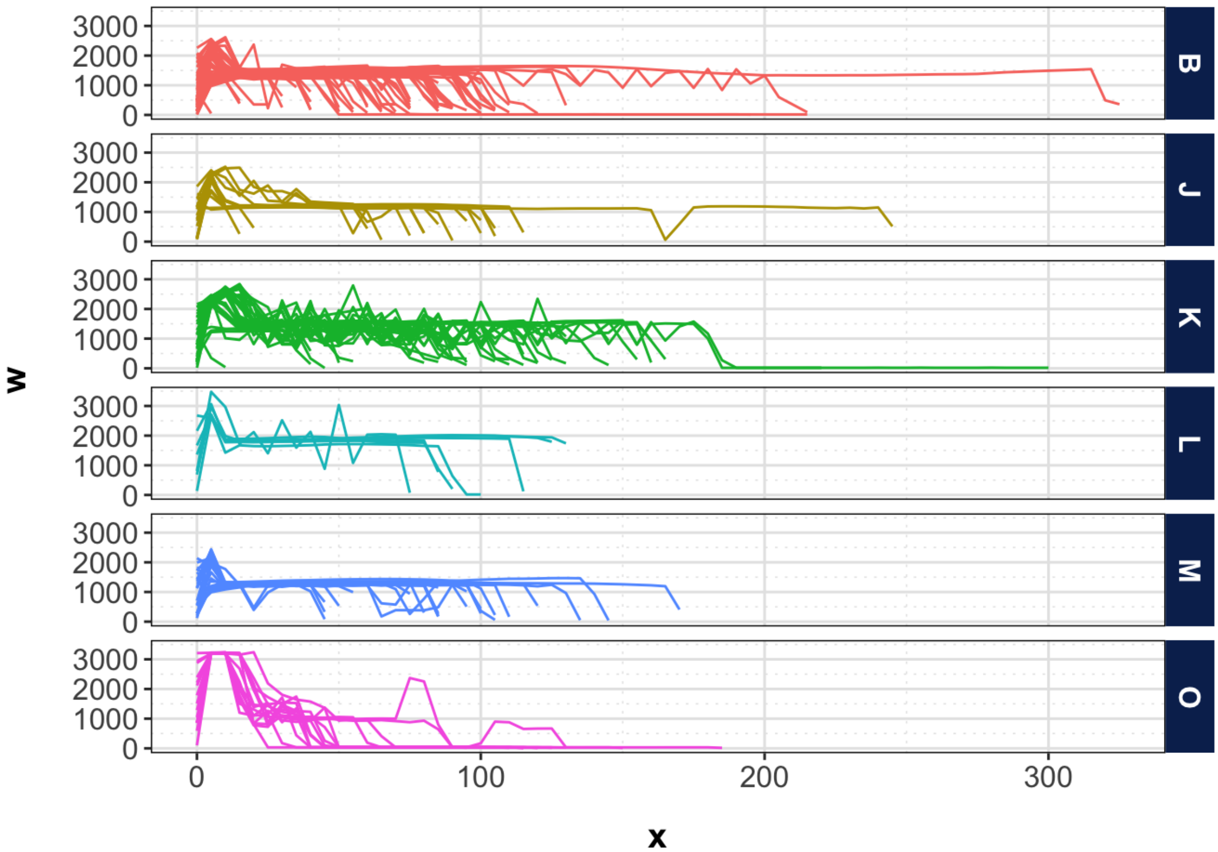
Source: CURB Monitoring Data and AMY Models

The results above indicate that for the population of this study, the aggregated average of the six homes showed that modeled end uses are over-estimated. The load profiles also indicate individual end uses for appliances show more variability than the team had previously expected. Additional information on individual end uses can be found in Appendix 8C.

Heat Pump Clothes Dryers and Eco Mode

The research team was interested in heat-pump dryers and the potential prevalence of "eco" mode operation. Circuit-level data from the six houses was analyzed to identify discrete uses of heat pump clothes dryers and the energy usage during this mode. Figure 28 summarizes the results below.

Figure 28: Analysis of all Heat Pump Clothes Dryers: Watts vs. time

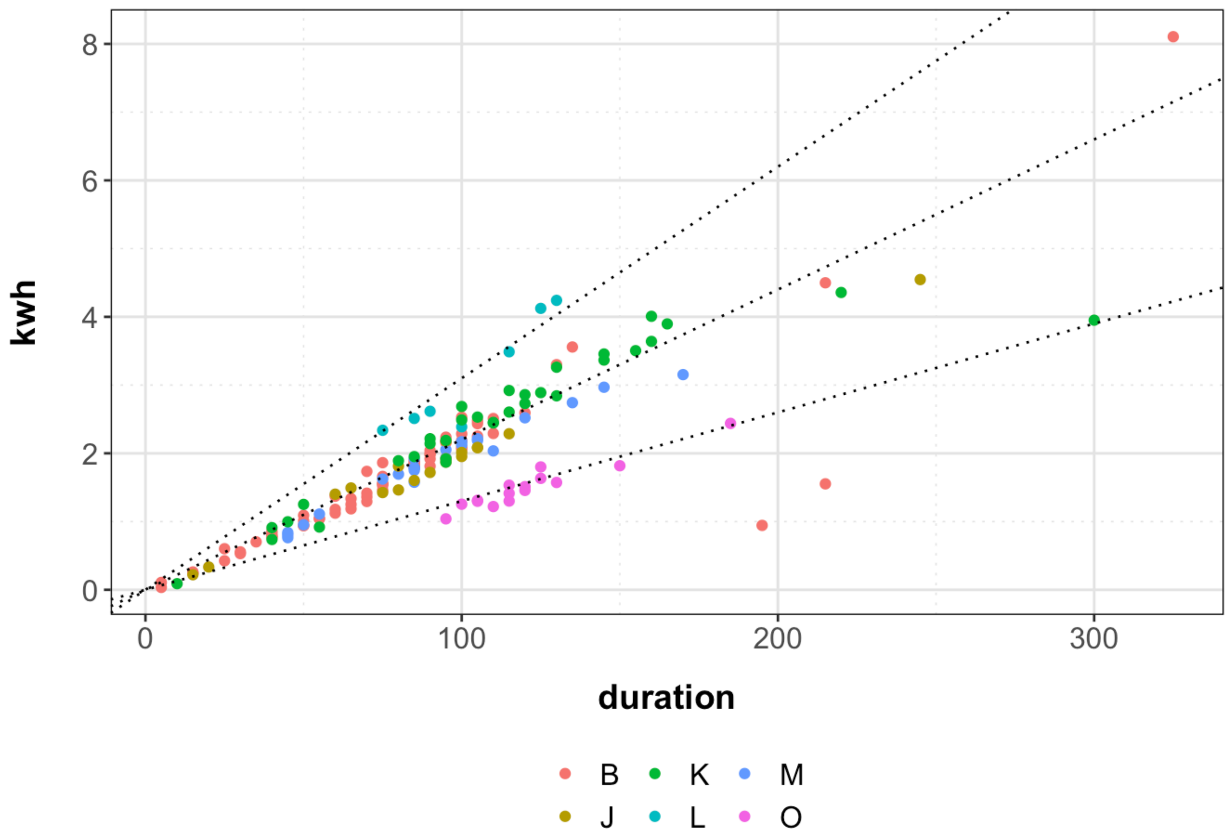


Line plots showing all heat pump dryer cycles recorded in the monitoring period.

Source: CURB Monitoring Data

The research team also integrated the total energy usage of individual cycles into a scatterplot of energy use per cycle metric (kWh/cycle) and plotted against time in order to identify potential eco-mode operation.

Figure 29: Scatter plot all Heat Pump Clothes Dryers cycles: kWh vs. time



Scatter plot of all heat pump dryer cycles recorded (kWh vs. time).

Source: CURB Monitoring Data

Because all the houses contain identical heat pump clothes dryers, Figure 29 shows a scatter of behavioral preferences. House O (pink) shows consistently low energy use per cycle, indicating likely use of eco mode. Meanwhile, house L is consistently on the high-end cycle energy (dark yellow).

Analysis of Rated Energy Use

The research team conducted a detailed investigation of the appliances by first comparing the annualized energy consumption of individually monitored appliances (Table 19). However, to adjust for the utilization rate of appliances from different houses, the research team factored in the utilization rate differences across all three annualized numbers (Table 20) to finally arrive at a cycle efficiency factor to compare the efficiency of the products used in the monitoring period vs. the modeled and rated appliance efficiency factors (Table 21).

Table 19: Comparison of Annual Energy: Monitored vs. Modeled vs. ENERGY STAR® Rated

Annual Energy Consumption (kWh/year)	Monitored*	Modeled*	ENERGY STAR® Rated
Clothes Dryer	371	789	460
Clothes Washer	45	90	139
Dishwasher	84	125	270
Refrigerator	468	794	665

Monitored* vs. Modeled* vs. Rated Energy Usage (*Extrapolated).

Source: CURB Monitoring Data, CBECC-Res 2019 Models, and EnergyStar.gov

Table 20: Comparison of Utilization Rates: Monitored vs. Modeled vs. ENERGY STAR® Rated

Utilization Rate	Monitored (cycle/day)	Monitored* (cycles/year)	Modeled (cycles/year)	ENERGY STAR® Rated (cycles/year)
Clothes Dryer	0.503	183.7	355.2	283
Clothes Washer	0.657	239.8	399.3	295
Dishwasher	0.217	79.1	141.5	215

Monitored* vs. Modeled* vs. Rated Energy Usage (*Extrapolated).

Source: CURB Monitoring Data, AMY Models, C.F.R. §430.23

Table 21: Comparison of Cycle Efficiency: Monitored vs. Modeled vs. ENERGY STAR® Rated

Appliance Cycle Efficiency (kWh/cycle)	Monitored*	Modeled*	ENERGY STAR® Rated
Clothes Dryer	2.019	2.22	1.625
Clothes Washer	0.188	0.23	0.471
Dishwasher	1.062	0.88	1.256

Monitored* vs. Modeled* vs. Rated Cycle Efficiency (*Extrapolated).

Source: CURB Monitoring Data, AMY Models, and EnergyStar.gov

Note that the rated efficiencies are not necessarily directly comparative to modeled or monitored for technical reasons related to their specific test procedures. For example, clothes dryers are tested and rated with test cloth at 50 percent remaining moisture content (RMC) which may not match the actual RMC of the monitored clothes dryers. For an in-depth review of each of the individual end uses, a detailed analysis can be found in Appendix 8C.

Conclusions/Recommendations

Overall, given the limited sample size and the duration of the monitoring period, the comparisons of modeled to monitored energy usage are unable to provide statistical depth and lack the external validity required for specific numerical changes to the CBECC-Res (2019) software and the Residential Alternative Calculation Method (ACM) Reference Manual. Bearing this limitation in mind, the following section details potential improvements and identifies areas for further research.

Suggested Improvements to Software Assumptions for Regulated Loads

Given the limitations described above, the research team recommends revisiting these findings with more data to ensure generalizability of the results. If, however, the research team can assume that the findings of this analysis remain consistent with more homes and a full year of monitoring data, the following list summarizes high-level opportunities for improvement and recommendations for further research:

- Additional research into observed household occupancy patterns and how this can be incorporated into CBECC-Res software assumptions, as the load profiles for the homes included in this analysis suggests that less total people are at home, but they are at home more often.
- Additional research on how to leverage smart thermostat data, specifically their learning strategies to potentially feed into updates to the CBECC software assumptions for compliance credits. Smart thermostat telemetry data can be a potential input for updated assumptions.
- Updates to thermostat hourly set point schedules based on smart thermostat customer preferences.
- DR-ready compliance credits for heat pump water heaters. See Strategies for Heat Pump Water Heaters in Chapter 4 for more detail.
- Conduct more research on residential heat pump HVAC systems operation in California climates. This research will improve understanding of heating and cooling energy use and help determine when—and whether—the auxiliary resistance heating is required to meet thermostat setpoints.
- Conduct more research into heat pump water heater operating conditions to understand when the auxiliary electric resistance heating is required to meet hot water demand, and compare findings to the relatively new heat pump water heating algorithms implemented by CBECC-Res. This additional research can help understand if CBECC accurately models the auxiliary resistance strip component of heat pump water technology.

Suggested Improvements to Software Assumptions for Unregulated Loads

Given the limited size of the sample and the duration of the monitoring period, the comparisons of modeled to actual energy usage are unable to provide statistical depth for specific numerical changes to the software. However, in addition to the modeled vs. monitored comparisons conducted, the research team also conducted two other analyses, (1) a comparison of published algorithms in the software system with the current outputs from CBECC-Res (2019)–a comparison between what the modeled usage is supposed to be and what it actually is and (2) a separate comparison looking at the rated energy usage.[73] The list below summarizes the high-level opportunities for future research and recommendations:

- Load Profiles: Additional research into observed household behavioral patterns and how this can be incorporated into CBECC-Res software assumptions would be beneficial, as the load profiles for the homes included in this analysis were significantly more variable than the software would suggest, even when aggregated from six homes into an average. This was much more pronounced for appliances which have discrete usage.
- Utilization Rates: The cycles analysis showed that appliances were not utilized at nearly the same rate as expected in the model. In this case, it appears that houses from this study were not equivalent to aggregate behaviors expected from the 2009 RASS study which was the basis for the end use algorithms. The CBECC-Res software would benefit from further analysis in the occupancy density of houses to validate or change the existing algorithms that make up the usage factors in the energy models.
- Appliance Efficiency: The CEC should continue investigating compliance credit for high-efficiency appliances for the CBECC-Res software. Current sample data is insufficient to make strong conclusions on the energy performance, however, in most cases the high-efficiency appliances utilizes less energy. Comparisons for each end use can be found in Appendix 8C.
- Heat Pump Clothes Dryers: Additional research into heat pump clothes dryers should be conducted particularly around typical usage factors ('eco' mode vs. other modes) as behaviors have not yet stabilized from this study. Ultimately, this data could be utilized to develop different usage assumptions for heat pump dryers that could be incorporated into CBECC-Res.
- Cooking Appliances: CBECC-Res should allow different configurations for cooktops and ovens as the homes in this study utilized an unprogrammable combination of electric ovens and gas stoves. As a result, the monitored electrical usage of this circuit was omitted from the study.

Ultimately, these recommendations will increase the accuracy of the model and limit over-sizing of PV systems and battery systems, leading to a better allocation of resources for builders, the housing market, and the State of California.

[73] CBECCC Version 2019.1.1

CHAPTER 9: Cost Analysis of All-Electric vs. Mixed-Fuel ZNE Homes

Project Approach

This section provides a detailed cost comparison between newly constructed dual-fuel and all-electric ZNE single-family homes. For the purposes of this report, a ZNE home is defined as a home with an Energy Design Rating (EDR) of zero.[74] The research team's analysis investigated three primary questions. First, how are construction costs different when building an all-electric home compared to a baseline mixed-fuel home? Second, what are the impacts on infrastructure costs in the development of an all-electric home? And third, what are the on-bill effects of an all-electric home as compared against a mixed-fuel home? Finally, these results were synthesized and extended over a 30-year cycle period, analyzed with a discount rate of 2 percent.[75,76]

In order to address the first question, the research team conducted a detailed cost analysis of several major electric and natural gas-powered home appliances. This comparison included split HVAC equipment, domestic hot water heaters, clothes dryers, ovens and cooktops. The research team's analysis was based on data drawn from our internal cost database, a tool created over a series of years to aid manufacturers and homebuilders in understanding the relative cost impacts of energy code compliance measures. This tool includes costs provided by manufacturers, builders, online retailers, and cost reference databases. The research team sourced installation costs from active industry building trades and builders. The database includes detailed parts and labor costs associated with installation and allows for calculation on a per-unit or a per-foot basis. ConSol maintains the database on an ongoing basis and cross-references sources to ensure accuracy.

In order to address the second question, the research team conducted a thorough analysis of the available literature addressing questions of all-electric construction and building decarbonization. Concurrent with that research, the research team has engaged developers, infrastructure planners and engineers, and utility companies directly. The research team's analysis, addressed in detail below, began with the understanding that there is a limited amount of data available to address this question of infrastructure costs. Builders and utility companies alike assert that the cost of

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[74] As demonstrated through a properly approved home energy modeling program. See: EIA report, at pg. 37, available here

[75] A 30 year period was chosen as reflective of the lifecycle standard used in California's TDV standards. See: Time Dependent Valuation of Energy for Developing Building Efficiency Standards Report, at pg. 13, available here

[76] The 2 percent discount rate is based on the Federal standing target interest rate of 2 percent.

natural gas infrastructure is extremely difficult to estimate beyond a case-by-case basis. This analysis is further complicated by the fact that the utilities often offer natural gas service through a rebate program. The utilities scale the rebates based on the number of natural gas appliances installed in individual homes. These allowances can be substantial enough to entirely offset the direct costs related to installing the natural gas infrastructure. The research team's analysis addresses this paradigm and compares available natural gas infrastructure cost estimates to derive a best-fit value.

In order to address the third question, the research team used the physical characteristics of demonstration homes constructed by De Young Properties in Clovis, CA as the basis for computer energy models. The research team modelled two homes: a 2,100 ft^2 single-story home and a 3,200 ft^2 2-story home, and then averaged the results from these two homes in the analysis.

The research team ran both models in the 2019 CBECC-Res software for the analysis.[77] CBECC-Res is the home energy modeling software provided by the CEC for analyzing home energy performance. CBECC-Res is not the only software approved for modeling home energy performance and compliance in California, however it is the only program directly funded by the CEC. Modeled outputs include an evaluation of the homes as built, the homes as all-electric with battery storage, and the homes with natural gas appliances and battery storage.[78] The research team's analysis uses the CBECC program to model hourly energy use over a one-year period. The models used consider the performance of these homes if located in Climate Zones 3, 7, 10, 12, and 13.[79] These locations were chosen because they represent areas where the majority of current new residential construction is taking place. These locations include both mild and cooling dominated climate zones. The research team then applied local utility rates to derive annual on-bill cost estimates. Although not available at the time of this reporting, the homes in the subdivision each have circuit-level energy monitoring which will allow researchers to later update this assessment using actual consumption and generation data instead of modeled energy use.

Avoidance of natural gas infrastructure is a substantial component of the potential savings associated with all-electric building construction. Without the inclusion of savings from the elimination of natural gas infrastructure, the all-electric home has a higher lifecycle cost than the mixed-fuel home. In order to highlight the potential range of outcomes the research team included high, middle and low values for natural gas infrastructure. The high value that was included is $5,750 from the *2019 Cost-Effectiveness Study* for the Statewide Utility Codes and Standards Program (referred

[77] Battery storage systems are available as options to homebuyers in the development. None of the existing homes presently have battery storage installed.
[78] The homes were designed as all-electric ready, and as built use natural gas only for cooking.
[79] The physical ZNE community is in Climate Zone 13.

hereafter as CASE).[80] This value is the net cost after discounts and allowances. The infrastructure cost without subsidy is $11,836.

The low value used is based on direct contract prices from builders that were able to provide actual contracts for infrastructure installation, and service from the utility. The research team received seven sets of contracts, representing over 400 houses in seven developments, which averaged a net cost of gas infrastructure of $1,423 per lot.

In order to determine total utility costs, the research team exported hourly and total annual solar generation from the CBECC-Res models and applied applicable utility rates, and annual net metering credits as necessary. The amount of solar power generated was based both on local climate, size of the home, and fuel type. In all cases all-electric homes required larger solar PV systems to reach ZNE. The incremental costs of the larger solar systems are included in the totals.[81]

Project Results

Appliances

Appliance costs are the least certain of the costs tested. A thorough literature review, in addition to an internal cost analysis found that all-electric homes have an appliance cost savings in the range of $200-$500.[82] These savings are primarily derived from the avoidance of natural gas plumbing and flue vents in the home. Heat pump water heaters tend to be more expensive than tankless natural gas water heaters, and electric and natural gas cooking appliances tend to be close in cost.

These appliance cost findings, while consistent among reports considering the issue of building electrification, are not consistent with cost estimates given by homebuilders. While these secondhand estimates find all-electric appliance cost savings, builders report a starkly different result. The builders interviewed for this report identify appliance cost increases for all-electric homes in the range of $2,200 to $3,500. In comparing the third party estimate to the feedback provided by builders, the research team found that two items tend to make the most significant impact. First, builders report that heat pump HVAC systems are significantly more expensive than traditional natural gas-fired furnace and AC systems. Purchasing agents and energy consultants interviewed suggest that this may be because all-electric systems tend to be of increased capacity in order to ensure adequate winter performance, where systems are as much as 25 percent larger for an all-electric house. Secondly, respondents suggested that the costs for increasing internal energy infrastructure (electric panels and wiring) are much higher than others have estimated.

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[80] California Energy Codes and Standards, *2019 Residential New Construction Cost-Effectiveness Study*, (August, 2019), available here, accessed February 7, 2020.
[81] Installed solar system costs were estimated on a scale of $4,500 (2kW) to $3,614 (10kW) per kW, holding equipment costs even with declining installation costs with size.
[82] See Appendix 9A – Market Sample Appliance Costs

The consequence of this wide-ranging combination of estimates and responses is the conclusion that the appliance cost impact of electrification is as of yet unclear. Further research and engagement with builders will be necessary to improve this data point.

Infrastructure

The costs associated with natural gas infrastructure have proven to be exceedingly difficult to identify with consistent and reliable results. While many parties have identified cost savings typically in the range of $5,000 to $12,000, others have offered estimates over $20,000. These estimates however are significantly higher than the costs reported by builders. In order to avoid a further trend of unverifiable estimates, the research team sought a collection of actual contract samples from builders. The research team gathered seven such sets from three homebuilders, and these samples delivered strikingly consistent results. All the results gathered fell into a range of $1,170 to $2,205, with a per home average of $1,423 over more than 400 homes.

In comparing the costs seen by builders to those estimated in other reports, the issue of subsidy was mentioned in numerous places. California gas utilities generally offer rebates to builders for natural gas appliance connections, some $1,500 to $2,000 per home. While it is true that these subsidies exist, further research indicated that they had little to no effect on the development of single-family homes. For single family home development, the allowances can cut against the cost of natural gas connections, however through interviews with builders and infrastructure consultants this report found the allowances to be rarely, if ever used. The reason for this is explained through how the utilities charge for gas connections. For single family homes the amount of the rebates is low compared to the value of the home, and it can take up to ten years to get them. The caveat to this is that in high-density multifamily developments these subsidies can often exceed the cost of connecting the natural gas, providing a net revenue to the developer.

It is important to distinguish that these figures are not estimates. After careful review, it was determined that builders incur natural gas infrastructure costs in two parts. First, there is the cost of the service provision. This is the amount charged by the utility company to activate, service, and maintain the newly installed gas lines.[83] Second, there is the cost to physically install the gas lines, a task which is generally contracted to a third-party infrastructure installation contractor. This contractor typically installs all "dry" utilities together in one single trench.[84] This combined approach appears to be one of the driving causes for the divergence between the estimates for natural gas infrastructure others have made, and those determined through sample contracts. Specifically, it appears as though others have made a common erroneous assumption where they have assumed that the costs for digging a utility trench are exclusive to

[83] All homes samples receive natural gas service from PG&E.
[84] Dry utilities are considered to be electricity, natural gas, and telecom service.

natural gas service. Whereas the experience of builders indicates that there is no marginal cost for natural gas trenching at all.

The all-electric home does carry one significant disadvantage in meeting ZNE. Because California uses TDV as the baseline for building energy performance, all-electric buildings require a greater amount of onsite solar generation in order to meet ZNE than mixed-fuel homes do.

Annual Performance

The annual utility cost for a home, whether mixed-fuel or all-electric, is highly dependent on the rate structure selected. All-electric homes are much more susceptible to this variation, and the difference can be so significant that it can dictate whether the cost benefit ratio of the all-electric versus the mixed-fuel home is greater than 1.[85] Using the rate structure most favorable to each home type reveals that the all-electric home can cost significantly less than a mixed-fuel one. Table 22 below shows an overview of these results. Each home is modeled with a 14 kWh battery and advanced demand response controls.

Table 22: Annual Combined Utility Costs for Mixed-Fuel and All-Electric Homes by Utility Company, Rate Type, and Climate Zone

Utility	Electric Rate	Climate Zone 3		Climate Zone 12		Climate Zone 13	
		All-Electric	Mixed-Fuel	All-Electric	Mixed-Fuel	All-Electric	Mixed-Fuel
PG&E	E-1 (Tiered)	$861.21	$811.82	$810.71	$740.61	$789.06	$727.58
PG&E	E-6 (TOU)	$857.63	$871.42	$815.97	$816.41	$791.17	$796.93
PG&E	E-TOU Option A	$778.30	$793.29	$735.43	$733.77	$739.51	$739.47
PG&E	E-TOU Option B	$905.14	$837.67	$831.58	$765.00	$862.66	$788.29
PG&E	E-TOU-C3	$784.70	$793.61	$746.53	$735.67	$746.69	$738.25
	EV2-A/G1	$481.18	$706.65	$496.93	$698.52	$512.33	$693.02
SMUD	R-TOD			$546.71	$799.41		
Utility	**Electric Rate**	**Climate Zone 7**		**Climate Zone 9**		**Climate Zone 10**	
		All-Electric	**Mixed-Fuel**	**All-Electric**	**Mixed-Fuel**	**All-Electric**	**Mixed-Fuel**
	Schedule D (Tiered)			$263.06	$409.94	$272.07	$421.47

85 A simple cost benefit ratio above 1 would suggest a given measure has benefits that outweigh the cost. Below 1, the costs outweigh the benefits, and at 1 the costs and benefit are equal.

SCE & SoCal Gas	TOU Opt. 4-9 PM			$261.22	$410.49	$267.17	$421.30
	TOU Opt. 5-8 PM			$264.94	$410.17	$271.81	$421.19
	TOU Opt. A			$190.77	$401.10	$190.04	$413.69
	TOU Opt. B			$351.84	$506.16	$365.35	$518.28
SDG&E	Schedule DR-SES/GR	$760.38	$641.53				

Shows the annual combined utility costs for miffed-fuel and all electric homes by utility company, rate type, and climate zone.

Source: ZNE CBA Report

In PG&E territory, Climate Zones 3, 12, and 13, the lowest cost rate is a special rate available only to customers with registered electric vehicles, or with residential battery storage systems installed. PG&E presently lists this rate plan as a pilot program, and it is not clear what its longevity or future structure may be.[86] However, because of the significant peak-load shifting ability of battery storage, and the attendant value to the electric grid, it is reasonable to expect such a plan to remain available. Apart from the EV rate plan, all other PG&E rate structures show mixed results, with results shifting based on climate zone and rate structure, showing mixed-fuel and all-electric homes as roughly equivalent in annual cost. For all other utility companies and rate plans, the all-electric home has lower annual costs.

In analyzing annual utility costs, this report also tracked annual GHG emissions based on fuel type and climate zone Table 23 below shows these results. The results show that the all-electric home consistently outperforms the mixed-fuel regarding emissions, by an average of 75 percent.

Table 23: Annual CO_2 Emissions (kg)

Climate Zone	All-Electric	Mixed-Fuel
CZ 3	525	2,156
CZ 7	421	2,018
CZ 9	320	1,782
CZ 10	373	1,356
CZ 12	426	1,445
CZ 13	447	1,264
Average	**419**	**1,670**

Source: ZNE CBA Report

Table 24 expresses the potential impacts on lifetime costs of various estimates of infrastructure and construction/appliance.

86 PG&E Schedule EV2-A

- Scenario One assumes a high estimate for natural gas infrastructure costs, and a low estimate for all-electric appliance/construction costs, yielding the best possible outcome for the all-electric building.
- Scenario Two assumes high natural gas infrastructure costs and high costs for all-electric appliances/construction.
- Scenario Three assumes low natural gas infrastructure costs, and low all-electric appliance/construction costs.
- Scenario Four assumes low natural gas infrastructure costs, and high appliance/construction costs, this reflects costs as reported by builders.

Table 24: Lifetime Electrification Cost Impacts Under Four Scenarios

Climate Zone	Scenario 1	Scenario 2	Scenario 3	Scenario 4
3	$7,348.34	$3,427.30	$3,021.34	$(899.70)
12	$8,011.41	$4,090.37	$3,684.41	$(236.63)
12 (SMUD)	$8,939.63	$5,018.59	$4,612.63	$691.59
13	$7,093.86	$3,172.82	$2,766.86	$(1,154.18)
7	$1,729.89	$(2,191.15)	$(2,597.11)	$(6,518.15)
9	$6,986.79	$3,065.75	$2,659.79	$(1,261.25)
10	$7,539.46	$3,618.42	$3,212.46	$(708.58)
Average	$6,807.06	$2,886.02	$2,480.06	$(1,440.98)

Source : ZNE CBA Report

Conclusions/Recommandations

The findings of this report are limited to a specific context: the homes analyzed were designed as ZNE. Analysis to determine the carbon emissions of these homes was outside of the goals of this analysis. Further, the comparative performance of the mixed-fuel and all-electric homes is limited to the ZNE context. This analysis does not demonstrate or establish the performance of either minimally code-compliant, or carbon neutral homes. This report also does not establish the marginal cost of a ZNE homes as against a minimally code compliant one.

Rapidly shifting California energy policy priorities have pivoted away from the long-standing goal of ZNE homes. While ZNE is more practically achievable than ever before, new legislation, such as SB 100 and AB 3232 are clearly making carbon emissions the driving metric for energy performance. In this new context it is important to highlight the information in this report that can provide meaningful insight into that ongoing conversation.

This analysis has provided a look into the potential annual performance of a ZNE home with or without battery storage, a difference of hundreds of dollars per year. Further analysis can and should be done to assess the marginal cost of batteries in code-compliant homes with minimally sized solar systems. Home battery storage technology is likely now at the beginning of the learning cost curve, and as a result there is the substantial likelihood of declining costs for this technology for some time to come. Additionally, this report found that the newly available EV2-A rate from PG&E could make a substantial difference in the annual performance of homes equipped with battery storage, but because the program is presently listed as a pilot, it is impossible to determine the long-term viability thereof.

This report provides the largest sample of natural gas infrastructure costs for new housing developments, and the results are significantly lower than the results found in other reports that have attempted to address the same question. Additionally, these cost determinations represent only large and medium single-family developments in otherwise undeveloped areas, infill and multifamily projects are likely to lower costs still.[87] This report also found significant variation in construction and appliance costs between all-electric and mixed-fuel homes. Responses indicate that these differences may be a learning issue in part, that HVAC equipment sizing for all-electric homes may have to be scaled up to meet consumer expectations, resulting in higher equipment costs, installation costs, and electric infrastructure (panel) sizing. These results, however, were limited, and further investigation is necessary to identify whether these differences are likely to be lasting, or if learning benefits may bring the costs down.

[87] While outside of the general scope of this report, interviews with infrastructure consultants conducted for this report provided anecdotal evidence that multifamily developments could see net revenue for the inclusion of natural gas based on the availability of allowances from natural gas utility providers.

CHAPTER 10: Financing Community Solar

Project Approach

This section provides an overview of the options and potential for financing community based solar systems. There are numerous reasons to support the development of such systems including: cost, scale, flexibility, control of demand response and simplicity. Community based solar systems meet the solar mandate of the 2019 Residential Building Energy Efficiency Standards (BEES) and remove the need for having rooftop solar on each home. Community solar systems retain the environmental benefit and potentially maximize the financial benefit by taking advantage of the economies of scale.

In order to assess the potential for these community solar systems this section reviews the practical and legal functionality thereof and discusses the relationship of the costs and benefits between special district (Mello-Roos) and utility community solar systems. The models for developing community owned solar systems are somewhat limited in both concept and practice. One of the reasons for this is that individual rooftop solar PV systems have reliably provided cost benefits. However, as the State moves into the 2019 code cycle (which went into effect January 1, 2020) there is a new mandate that requires all new homes to have renewable energy generation sufficient to offset onsite electrical consumption on an annual basis. This new mandate will increase the market demand for solar installations from just market viable locations to installations in more marginal locations. Additionally, the market will explore the potential for lower installation and maintenance costs associated with the scale of community solar systems.

State policy has been developed to provide alternative methods of financing for community improvements and services. California Government Code 53313.5(j) explicitly authorizes the use of so-called Mello-Roos financing to install community owned solar PV systems.

The key advantage of a community owned system is the ability to take advantage of economies of scale. Where a rooftop photovoltaic (PV) system may cost $3.50 to $4.50 per watt for 2 or 3 kW, a community scale system with 500 kW installed could cost less than $2 per watt.[88] While there is no doubt that there are significant gains to be had by taking advantage of economies of scale, there are significant hurdles that greatly increase the difficulties of installing such systems. Community scale solar systems are burdened by the need to deliver off-site power to the homes, whereas rooftop solar is

[88] U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018, pg. 26.

physically attached on-site. Community scale systems need to be managed and maintained, whereas rooftop systems are the responsibility of the homeowner, or often of the solar PV installer that has leased the system to the homeowner. Community scale systems need to be permanently associated with the homes they service for a minimum of 20 years in order to meet the energy requirements. Community scale systems need to be cost-effective to the homeowner, paid for in an equitable and code compliant manner, and the power generated needs to be credited proportionally to the energy requirements of each home.

Additional approaches to financing community scale energy systems include direct financing, whereby the developer of the community installs the system and adds that cost to the purchase price of the homes. Solar leases and power purchase agreements (PPA) are other financing possibilities. This report will analyze the potential barriers and benefits of the various options for establishing community scale solar systems.

Project Results

Of the approaches to financing or establishing community scale solar systems, this section places a significant emphasis on the use of land secured financing, otherwise known as Mello Roos. While direct financing exists as an option, its barriers are potent enough to be considered overwhelming. Direct financing places the entire upfront burden of the cost of developing a community scale solar system on the developer of the community. Because the California Building Energy Efficiency Standards (BEES) require renewable energy to be attributed to every new home, the community solar system must be completed at the time the first home in a community is completed. And because it is necessary to build a community solar system all at once in order to take advantage of economies of scale, a developer would be forced to carry the burden of financing the development of such a system until all planned homes have been sold, and the builder will be left with carrying the burden of any remaining balance should any homes go unsold. And given the impact of the 2008 Recession, and the considerable number of developments that went unfinished, developers are extremely weary of carrying long-term, speculative debt.

While direct financing lacks practicality because of the risks and burdens placed on the developer, utility owned off-site systems have no development risk to the builder. The utility financed systems avoid most of the builder development barriers that a directly financed system would face. One significant example that has already been submitted to the CEC for approval are the Sacramento Municipal Utilities District (SMUD) offering the "Solar Shares" community solar program. Each home enrolled in the program must identify and permanently assign a specific quantity of SMUD's solar generating capacity to that individual home. The CEC requires through the building energy codes that a community solar system provide a net benefit to participating homeowners. In order to meet this requirement SMUD offers the simple stipulation that participants will receive a minimum annual credit of $10 for their participation, and that the renewable energy credits (RECs) associated with the solar attached to the home would be permanently retired.

The process for approving off-site community solar programs has met significant public and industry opposition. However, as strong as this opposition has been, the State has made it clear that the application satisfies both the State code requirements and the broader energy policy goals of increasing the total amount of renewable energy installed.

The primary opposition to SMUD's proposal has been the concern that such a program would discourage the development of rooftop solar installations, home energy storage, and negatively impact the rooftop solar installation industry through ratepayer financed competition. The effect on discouraging rooftop solar, and the negative impact on the solar installation industry is straightforward but is arguably a natural outcome of a competitive market, and not an issue the State has any responsibility to mitigate. The matter of discouraging home energy storage however has more significant merit from a state policy perspective. When a home has both rooftop solar and battery storage, that storage allows the homeowner to maximize the use of the energy generated by that system.

While SMUD's application has not yet been approved, its approval does appear likely, and will strongly inform the development of similar, utility financed renewable energy systems. It is not clear whether other utilities will be interested in following suit because developing community shared systems may limit a utility's ability to maintain profit margins. Community solar systems are required by code (BEES Section 10-115 (a)3) to produce dedicated energy savings benefits. However, the ability of a utility to sell solar energy directly to a homeowner, and thereby preventing the homeowner from installing their own solar system and generating their own power, increases the amount of energy the utility can sell.

Beyond the directly financed and utility approaches, the other most promising avenue for developing distributed energy systems is the land-secured, or Mello Roos approach.

Historically, land secured financing has been used to finance the basic infrastructure needed for new developments, such as roads and sewage treatment facilities. The funding is raised through the issuance of bonds by a special tax district known as a community facilities district (CFD). Owners of the properties that benefit from the infrastructure agree to a lien on the property that is repaid through a special tax. The taxes raised are used to pay debt service on and retire the bonds, which are secured using the property as collateral.

The Mello-Roos Community Facilities Act of 1982 describes a mechanism for financing facilities and services using special assessments within CFDs. It has been used to finance a wide variety of infrastructure projects in new residential development, as well as within existing communities. Through this mechanism, municipal bonds are issued to generate funding that can be invested into various forms of infrastructure. Mello-Roos.

districts are most often formed prior to division and sale of lots, so existing residents do not shoulder the burden; only benefiting property owners repay the debt through special assessments guaranteed by property liens. Typical infrastructure improvements used for CFDs include sewers, landscaping, roads, and other amenities needed to meet increased demands placed on local agencies as the result of new development.

Updates to the Title 24 BEES will put an increased emphasis on energy efficiency in new residential construction starting on January 1, 2020. Solar generation will be required to achieve code compliance and battery storage will become, for the first time, an energy code compliance option. Outfitting individual homes with rooftop solar and battery storage technologies can add to the per-unit cost of residential construction by thousands of dollars. These costs are incurred by homebuilders and then rolled into the purchase price of a new home, resulting in a higher initial purchase price for homebuyers. Moving to off-site community solar and storage allows the energy needed for energy code compliance to be purchased at a lower cost per kWh. Using a CFD to fund off-site community solar rather than using conventional financing can lower the cost of borrowing because CFDs offer municipal bonds that are tax exempt and have attractive terms based on a high likelihood of repayment, due to the lien attached to the properties in the CFD.

As 2019 BEES comes into play, offsite community solar will become increasingly attractive as a compliance method for new developments. As shown above, to be credited towards compliance the solar generation needs to be, among other things, dedicated, quantifiable, and verifiable. The use of a CFD provides an administratively straightforward path to establishing these attributes, due to the effective ownership of the generating facility by the houses in the CFD. This ownership is established by the existence of the CFD and maintained by the payment of the special tax.

While a Mello Roos based, community solar system has its advantages, there are, however, potential disadvantages of using land secured financing which also need to be considered:

- **Compliance**: Under the current code, offsite renewables must qualify with the Energy Commission as an approved Title 24 community solar system. This process is public and contentious. Using a CFD to fund community solar systems introduces administrative and legal complexities, such as insurance or access for maintenance.
- **Default**: The use of special taxes and a lien on the property to guarantee payment of the bonds creates a long-term obligation on, initially, the developer and, after purchase, the homeowner. If the development is not completed, or sales of houses are below expectations, the obligation to pay the special tax remains attached to the lots. This adds barriers to resale of the lots.
- **Bond market:** The issuance of bonds is a market dependent event. If financial markets change between the initial planning of the development and the

formation of the CFD and the issuance of the bond, changes in interest rates may make the bond repayments prohibitively expensive. Given the time required between initial planning for a new development and the beginning of construction, this is a risk for the developer. Using conventional methods, the financing of the solar would most likely be established in parallel with the financing of the development as a whole.

- **Tax burden:** The special tax will appear on owners' property tax bills, which may be a deterrent to buyers. CFDs that provide direct benefits to the assessed property are also not eligible for state and local income tax deductions for individuals or households. The additional tax can lower the amount of the mortgage for which buyers can qualify, thereby limiting the pool of buyers. This applies not just to the initial sale, but also to subsequent resale (during the repayment period of the bonds), which can further deter buyers.
- **Public Opinion:** Mello Roos, as with any tax, is commonly seen in an unfavorable light. This political distaste may in many cases prove too much of a burden on home sales for developers when acting in highly competitive markets.

Conclusions/Recommendations

Community solar systems can provide significant advantages to homebuyers and homebuilders. These systems can help bring down renewable energy installation costs, particularly in areas where renewable systems are only marginally cost-effective. These benefits hinge on being able to take advantage of economies of scale and require significant upfront investments. Direct financing for community solar systems is less likely given the risk and debt burden a private developer would be likely to face. A Mello-Roos funded system helps avoid this risk by attaching the debt as a tax on the properties in question. Without having any existing examples of such a system in place, it is difficult to speak of a Mello-Roos funded system in any way other than speculative.

Utility offered community solar systems, as exemplified by the SMUD, do not offer any significant benefits to the homeowner. There is the minor financial benefit ($10/year), and the reduction in greenhouse gas emissions, but it is not clear whether either of these alone or together, are of sufficient value to change homebuyer preferences. The benefits for builders, and society at large, are however more significant, and more quantifiable. Such a community solar system would represent a large amount of new renewable energy and would free the builder from having to install solar for each home, either through purchase, lease, or PPA agreement. It would also eliminate the requirement of installing solar on each home and the associated water damage risk from roof penetrations when installing.

CHAPTER 11: Independent Measurement and Verification of Project Savings and Performance

Introduction

The primary goal of this task is to establish how the demonstration community homes perform as residential ZNE buildings. The emphasis on performance is an important distinction to make, as the 2013 Integrated Energy Policy Report (IEPR) TDV metric definition of ZNE (also known as "ZNE Code") applies only to the design and construction of the building before it is occupied.[89] Since this chapter is concerned with how the demonstration community homes performed while occupied, the research team approaches the measurement and verification analysis described herein as an assessment of whether the homes performed according to the ZNE Site definition (i.e., a building that offsets its annual energy use with renewable energy generated on-site).[90] Nevertheless, the results presented subsequently do not provide a conclusive assessment of ZNE performance (at the home or community level), as the research team did not have a full year of monitoring data available for any of the homes, and the annual requirement is an essential component of any ZNE performance designation.[91] Despite this limitation, the study team verified energy consumption and generation for each of the demonstrated homes within the community for a specific time frame. This effort is not representative of how the homes would perform with an entire year of data and is intended to only provide interim direction.

M&V Approach

The research team used circuit-level monitoring data to obtain whole-home consumption and generation data from the homes. Whole-home consumption was calculated by adding up the individual circuits in the home and is the same CURB data used in the Chapter 8 analysis.[92] The research team also used the CURB data for monitored generation, which was monitored on a single circuit in each of the homes. Following the Site ZNE definition, the research team summed consumption and

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89 Integrated Energy Policy Report, Pg. 37. The scope of work for this task directed the research team to use the TDV metric definition of ZNE from the 2013 Integrated Energy Policy Report to evaluate the ZNE status of the community. After a thorough review of the ZNE M&V best practices and relevant policy documents, the research team concluded that the use of TDV multipliers for the evaluation of home performance was not appropriate for this analysis. For more information on the use of TDV, see Appendix 3C.

90 For a detailed explanation of ZNE, see Appendix 3A

91 All ZNE designations that deal with performance (i.e., post-construction) require a full year of monitoring.

92 For more information on the circuit-level monitoring data, see Chapter 8

generation (when solar generation is produced, it is recorded as negative wattage in the CURB monitoring system) to obtain net energy consumption.[93]

As part of the M&V effort, the research team also incorporated modeled consumption to produce a comparison to anticipated net consumption compared to actuals to contextualize these results. Monitored consumption, generation, and net usage were compared to the CBECC-Res TMY models for each of the homes for a similar time frame to determine if there were any major differences between observed and predicted software (we discuss this in greater detail in Chapter 8).[94] As discussed subsequently, there are known limitations with using the CBECC-Res modeled data, specifically for predicted generation, but the research team felt it was still necessary to include it as a reference point for what a typical home is expected to produce and consume within the analysis period.

The research team anticipated more than a year of data from over 10 homes. However, the home energy use monitoring was delayed due to slower-than-expected sales[95] and construction[96] of the ZNE homes, which in turn resulted in significantly less data than expected. The research team found it necessary to further limit the dataset to include homes with five weeks of continuous occupancy before November 2019, to ensure the homes could be compared across consistent monitoring periods. Table 25 summarizes the six selected homes that are included in this preliminary M&V analysis, along with some basic attributes of the properties.

Table 25: Summary of Demonstration Community Homes

Home ID	Model (Floor Plan) Identifier	Square Feet	Bedroom Count	PV Size [kW]	Monitoring Period
B	Residence 240	2,361	4	6.615	Sept. 25 - Nov. 18, 2019
L	Residence 210	2,019	4	6.615	Sept. 25 - Nov. 18, 2019
M	Residence 210	2,019	4	6.615	Sept. 25 - Nov. 18, 2019
J	Residence 210	2,019	4	6.615	Sept. 25 - Nov. 18, 2019
K	Residence 210	2,146	4	5.985	Sept. 25 - Nov. 18, 2019
O	Residence 260	2,544	5	6.615	Oct. 1 - Nov. 18, 2019

Source: CURB Monitoring Data and TMY Models

Study Limitations

As noted above, home energy use monitoring was delayed as the result of larger economic trends within the California housing market which resulted in significantly less data than expected. Given these delays and associated data issues, the research team

[93] Although utility billing data is the preferred source for measurement and verification of energy consumed, the research team was unable to obtain it for this analysis.
[94] For more information on the CBECC-Res TMY models, see Chapter 8
[95] Sales were affected by regional economic trends as well as lower-cost options for conventional (non-ZNE) homes in the surrounding areas.
[96] Construction was delayed by ongoing skilled labor shortages and delayed ground-breaking due to the extremely wet winter of 2018-2019.

identifies the following limitations to serve as a guide for interpreting analytical choices made and results presented in this chapter. The team outlines these below:

- **Generalizability of Results Given Data Coverage:** The research team limited the dataset to include homes with a minimum of five weeks of continuous occupancy before November 2019. This period coincides with the fall shoulder season (i.e., the months between summer cooling and winter heating) where space heating and cooling is substantially less compared to other times of the year. Because space heating and cooling is a substantial portion of the overall energy consumed by a home over a typical year, the research team cannot assume that the monitored energy usage that occurred during this period is typical of what they would see over a larger monitoring period. Given that the M&V analysis is focused on a narrow sample (n=6) over a narrow period during a shoulder season, the results depicted herein are not generalizable to the entire demonstration community (n=20 at the time of this report) nor to the annual ZNE performance for the six homes within this group.
- **Gas consumption data not included:** The demonstration community homes were designed as all-electric ready, and as built use natural gas only for cooking. The research team did not have access to gas consumption data from the utility and is, therefore, unable to include it in the M&V analysis.
- **Predicted Generation Data**: CBECC-Res provides predicted generation with TMY weather assumptions. Since actual radiation data for this period was not available, the research team was unable to replace the TMY weather assumptions with actual weather data to better approximate predicted generation.[97]

Key Findings and Results

The following results reflect preliminary findings for a subset of demonstration community homes that cover a limited period. As summarized in Table 26, none of the homes produce zero net energy during the period of study for both observed and modeled data. Similarly, both the observed and modeled findings indicate over-generation for each of the homes (except for "O" which did not have its solar system turned on until November 17th) with the generation at the sample community level almost doubling that of the community-level consumption. The research team is aware of the PV systems being oversized and has specific recommendations surrounding this in the subsequent section. Additionally, the monitored net performance of the homes is substantially more variable than the model assumes. Figure 30 displays the comparison

[97] The research team requested time-series predicted generation data that used to price solar contracts as this is a more accurate prediction of generation than the CBECC-Res models. However, this data was ultimately not provided due to its sensitive/proprietary nature.

of monitored to modeled consumption and generation for the sample demonstration community.

Table 26: Summary of Monitored Home-by-Home and Community Scale Consumption, Generation and Net Usage (all usage in kWh)

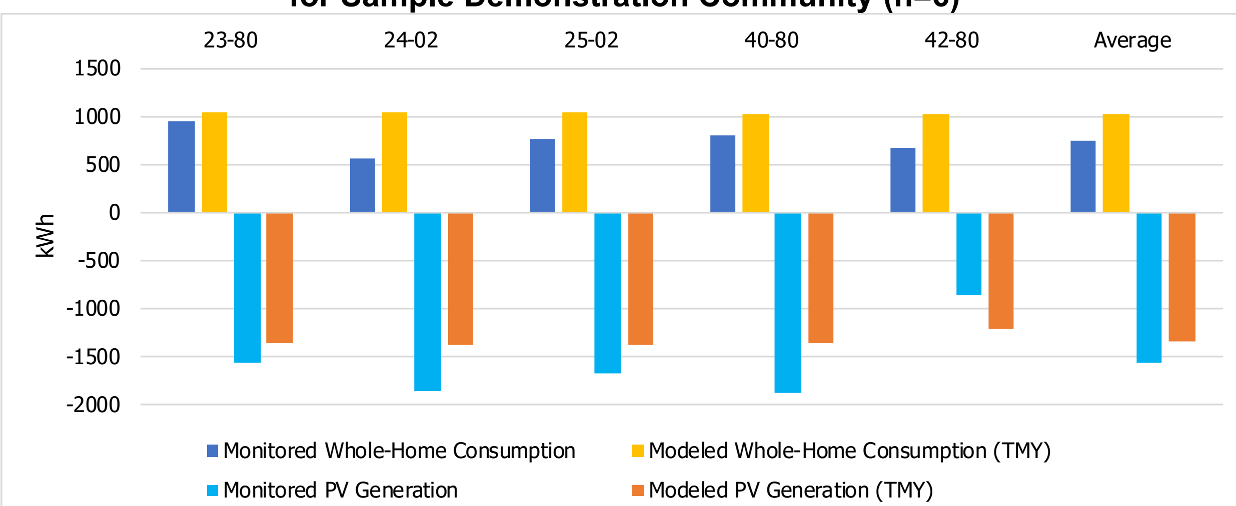
Home ID	Monitored Whole-Home Consumption [a] *(A)*	Monitored PV Generation [b] *(B)*	Monitored Net *(A + B)*	Modeled Whole-Home Consumption (TMY) *(C)*	Modeled PV Generation (TMY) *(D)*	Modeled Net *(C+D)*
B	948	-1566	-618	1,033	-1359	-326
L	562	-1864	-1302	1,043	-1386	-343
M	755	-1668	-913	1,032	-1386	-354
J	793	-1880	-1087	1,022	-1364	-342
K	666	-860	-194	1,021	-1219	-198
O	974	-1	973	1,001	-1192	-191
Sample Demonstration Community Total	**4,698**	**-7,839**	**-3,141**	**6,152**	**-7,906**	**-1,754**

[a] Represents the sum of all circuits (excluding "Main") from CURB.

[b] Represents the sum of the "Solar" circuit from CURB.

Source: CURB Monitoring Data and TMY Models

Figure 30: Monitored versus Modeled Whole-Home Consumption and Generation for Sample Demonstration Community (n=6)



This shows that the modeled whole-home consumption and PV generation are systematically larger for the 6 homes in the sample. Note that O is not included in the figure due to lack of generation.

Source: CURB Monitoring Data and TMY Models

Conclusions and Recommendations

As mentioned above, a full year of monitored generation and consumption data is necessary to determine if a home or community achieved Zero Net Energy. Since the research team had less than two months of data, it is hard to draw any useful conclusions about ZNE—or how the homes might perform over a year.

However, as discussed in Chapter 4, the team's refined and updated CBECC models indicate that the PV systems (which were sized using a different energy modeling program and before the addition of a few additional energy savings measures), were likely oversized. Although the source of the deviation may vary between homes, the fact that all ZNE homes used less energy than predicted by CBECC during the same period indicates that the magnitude of PV oversizing may be even higher.

Although the electric utility performs annual an annual true-up known as Net Energy Metering and provides a credit to the consumer for any generation more than their home's annual consumption, the amount the utility pays for each kWh of excess generation is exceptionally low. Whether the ZNE homebuyer purchased the PV system outright—or like most homeowners—opted for a zero-down lease agreement, the equivalent price they pay for power is usually lower than the retail price, but far higher than the utility credit for each kWh of excess generation. It is not in their financial interest for homeowners to consistently over-generate on an annual basis.

And, since lifestyle and behavioral variation create such large disparities between the amount of power each homeowner uses annually, it is exceedingly difficult to find a one-size-fits-all method for modeling and sizing PV to Zero Net Energy. Instead, the solution may be to stop short of full ZNE—much in the way the CEC has when determining how much PV new homes need for compliance with the 2019 Title 24 Standards.

CHAPTER 12: Benefits to Ratepayers

The advancement of Zero Net Energy homes offers the potential for numerous benefits. This project has delivered distinct benefits across numerous categories related to the development of ZNE homes. To best appreciate these benefits, it helps to first contextualize the purpose and promise of ZNE buildings generally. ZNE means that a building generates as much energy as it consumes over a year. Typically, this is achieved through high-performance construction standards, high-efficiency appliances, and onsite solar power generation. It takes the combination of these elements to achieve ZNE cost-effectively. ZNE was adopted as a policy goal by the State of California to achieve the combined goals of stabilizing the electric grid and reducing greenhouse gas emissions. When measuring building energy performance California uses a weighted metric that normalizes electricity and natural gas and incorporates the hourly "costs of energy to the consumer, the utility system, and to society." This metric uses localized weather data to more accurately reflect the energy use associated with a given building. California's use of TDV for measuring energy efficiency has been crucial in maximizing the effectiveness of the energy infrastructure in the state. TDV cost increases with demand on the utility system, reaching its highest values when demand on the electric grid is at its peak in summer evening hours.

ZNE offers benefits to the homeowner through reduced utility bills, and a higher efficiency, more comfortable home. ZNE offers benefits to the public at large by reducing the burden on the electric grid and reducing the emission of greenhouse gases. This project shows the benefits of ZNE through the construction of dozens of new ZNE homes, simplifying the process of producing ZNE homes, and significantly reducing the costs associated with building ZNE homes.

Grid Reliability

One of the key goals of both TDV and ZNE is to increase grid reliability. In the early 2000's California suffered a series of devastating rolling blackouts costing untold millions in economic damage. There were many causes and responses to that series of events, not least of which was the first and only recall of a sitting governor. One of the lasting policy changes from the rolling black outs has been the use of TDV for assessing the impact of building energy use under Title 24, California's building energy code. The purpose of using TDV is the acknowledgment that energy used during different times of the day has different values. A kWh consumed from the electric grid at 6:00 AM is not equivalent to one consumed at 7:00 PM. At times of the day when energy demand is low, such as early morning hours before many businesses open, there is substantial surplus energy available on the grid. At times when demand is high, such as 7:00 PM in July, when many businesses are still open, and home cooling demands are high, the demand on the grid is near its peak. At this peak the system is near its total capacity, if the system were to go beyond its capacity, some customers would be forced to go without power, as many did in the early 2000s. By valuing energy consumed at peak demand higher than energy consumed at low demand, the State encourages technologies that can reduce or avoid energy consumption at peak demand times.

This report has given a thorough analysis of many different building features, their costs, and their effects on TDV energy consumption. One interesting technology studied was the deployment of heat pump water heaters enabled with internet of things (IoT) controls and a heating schedule designed to avoid peak energy demand periods. This approach involved a partnership with Rheem, the water heater manufacturer, and education and outreach to the homeowners about the effect and parameters of the schedule being applied to the water heaters. Initial results indicate substantial promise in the ability of these water heaters to provide thermal energy storage procured while solar power generation is high, and energy demand is low, which lasts through peak demand periods of the day.

Cost Savings

This project has led to, directly or indirectly, substantial cost savings in several areas. Directly, this project has supported the construction of dozens of homes with annual utility cost a mere fraction of typical homes, with annual utility bills measuring in the hundreds instead of thousands. This project has helped to reduce the cost of ZNE, and energy-efficient homes generally, by analyzing and prioritizing energy measures based on their cost-effectiveness. By working with builders and other stakeholders this project has helped to reduce the cost of constructing ZNE, providing step-by-step guidance covering the costs of learning new practices, such as compact hot water distribution, to encourage their further adoption.

By supporting the development of IOT connected and TDV water heating schedules this project has helped to not only reduce utility bills but also to display the market value of similar practices.

By creating and demonstrating circuit-level energy use monitoring this project has shown best practice approaches to energy tracking, enabling informed user behavior, and providing field-based performance samples of many high-performance building features.

Emissions

This project has given substantial consideration and effort to understanding and reducing greenhouse gas emissions from buildings. This project supported the construction of nearly all-electric homes.[98] The ZNE homes as built have projected

[98] The homes constructed in the ZNE community use electricity for all primary purposes, however most of the homes use natural gas for cooking appliances. Cooking is a negligible portion of total home GHG emissions.

annual emissions of less than 1/10th of a typical mixed-fuel home built to 2016 code standards. Table 27 below displays the difference in emissions based on the fuel source and compares basic code-compliant homes against ZNE ones.

Table 27: Overview of CO_2 Emissions by Primary Fuel for Baseline Code Compliant and ZNE Homes in Climate Zone 13

Type	kWh	Therms	2016 Code kg CO_2	ZNE kg CO_2
Mixed-Fuel	6,455	418	3,861	1,615
All-Electric	11,139		2,460	289

Source: CBECC Modeling Results

The table shows the dramatic effects of both ZNE and the removal of natural gas on total emissions. The remnant amount of emissions in the all-electric ZNE home comes from the emissions associated with consumption of electricity from the electric grid. As California moves towards decarbonization of its electric grid, all-electric homes will also move towards zero emissions, whereas the emissions from mixed-fuel homes, whether ZNE or not, will remain relatively flat.

Using these figures, the research team estimates that this project avoids 253,647 kg of CO_2 emissions per year. In addition, this research provides valuable support for the development of future low and zero-emission homes, making it abundantly clear that an all-electric ZNE home dramatically outperforms a code-compliant, mixed-fuel home with respect to emissions.

Benefits of Experience

One of the largest benefits of this project is also one of the most intangible. The benefits of learning, practice, and experience are crucial to any economic transition. Market actors, like homebuilders, are generally risk-averse, seeking to maintain reliable profits as easily as possible. A significant shift in construction and procurement practices requires a significant adjustment, one that requires time and effort. This project was designed to minimize that disruption to every extent possible and to maximize the ability to share the value of lessons learned as widely as possible.

This project has studied and provided detailed data on market and cost performance for ZNE, and all-electric homes. This research delineates which aspects of ZNE and all-electric homes are most interesting, and which provide the largest barriers. This analysis supports the common anecdote that gas cooking appliances are strongly preferred, and that greater effort needs to be made to inform the public about the benefits of induction cooking. This research has shown that primary heating appliances are only a secondary concern and that homebuyers are not deterred by heat pump HVAC and water heating systems. This research has also shown that buyers are willing to pay a premium for high-performance homes and that there is some level of knowledge regarding the benefits of reduced utility bills.

This project has created and modeled easily replicable construction approaches that advance building efficiency without adding substantial complexity. By adopting compact design approaches early in the construction process, the builder can employ high-efficiency compact distribution systems for HVAC and hot water without drastic changes to past practices.

Health

Indoor air quality (IAQ) in homes is important because people breathe more and take in more air pollutants at home than at any other location. On average Americans spend roughly two-thirds of their lives inside their homes. The air pollutants in our homes come from various sources including but not limited to outdoor air; the materials used to construct, finish, and furnish our homes; our pets; activities such as cooking; and products that are used for cleaning, personal care, and hobbies.

Since the mechanical systems that create comfort conditions typically use a substantial portion of the total energy used in a home, designs for efficient low-energy homes must include efficient heating and cooling systems, good insulation, and airtight shells to reduce uncontrolled outdoor air infiltration. However, lower infiltration also means less dilution and slower removal of indoor contaminants; it thus becomes necessary to bring in outdoor air through mechanical means. Mechanical ventilation systems require additional energy to operate and must be carefully designed and sized to avoid unnecessary increases in overall energy consumption.

In addition to measuring the IAQ performance of these homes, the project also employed a relatively novel tactic to address one of the most common issues with home ventilation systems. While all new homes are outfitted with ventilation systems, these systems often go under used, or entirely unused. Because most systems are enabled by simple on/off toggle switches, once a system is turned off, it tends to remain off unless the occupant has a clear understanding of the benefits of ventilation. And because there is no perfectly reliable way to ensure the education of each occupant, a ventilation system that is resilient to an uneducated occupant will outperform a basic one. Therefore, the homes built under this project were enabled with a smart ventilation control system. This system allows the user to temporarily disable it for times when outdoor air quality is particularly poor, such as when fall fires cause smoky air, but the system will return to operation after 24 hours without further action from the occupant.

Future Value

This project has produced practical ZNE homes and shown that today California can build homes to meet future energy and climate change goals. These homes are prewired for electric vehicle chargers and home battery storage. These homes have connected, real-time energy use monitoring that can inform policy makers and building designers about building performance at a more granular level and on a greater scale than ever seen.

This project has demonstrated that the home of the future is well within our reach, something that current builders are capable of with only limited support, with most of the technology available off the shelf today.

CHAPTER 13: Tech Transfer

Publications

As a demonstration project, one of the primary purposes was simply to *show* the public and other builders that ZNE can be achieved at scale. To spread awareness of effort and accomplishment—and to help ensure that buyers were aware of the benefits and opportunity to buy one of the homes—the team pursued and achieved extensive media coverage for the project. The team included a public relations firm that issued press releases, coordinated interviews, and organized events. The press releases were highly effective in drawing the attention of local, regional, and national publications. Some used the content of the press releases word-for-word, while others requested interviews and wrote original content. Below is a partial list of media coverage and publications, including links to the online version of articles:

Green Home Builder Magazine, The Featured Interview: Andrew McAllister, Commissioner of the California Energy Commission, 2/6/19: https://greenhomebuildermag.com/the-featured-interview-andrew-mcallister-commissioner-of-the-california-energy-commission/

Professional Builder, Green means go in the home building, Net-Zero Now, 2/15/19: https://www.probuilder.com/net-zero-now

Builder & Developer Magazine, BUILDERmedia, Builder Bytes Weekend Edition Eblast, Net-zero energy homes have arrived – and are shaking up the US housing market, 2/15/19: https://bdmag.com/net-zero-energy-homes-have-arrived-and-are-shaking-up-the-us-housing-market/

Cnbc.com, Net-zero energy homes have arrived — and are shaking up the US housing market, 2/14/19: https://www.cnbc.com/2019/02/14/homes-that-produce-their-own-energy-might-be-the-future-and-california-is-inching-closer.html

Msn.com, Why California's new solar mandate could cost new homeowners up to an extra $10,000, 2/17/19: https://www.msn.com/en-us/news/other/why-californias-new-solar-mandate-could-cost-new-homeowners-up-to-an-extra-dollar10000/ar-BBTHMez

Housingwire.com, California pushes people to splash out on zero-energy homes, 2/15/19: https://www.housingwire.com/articles/48205-are-zero-energy-homes-the-new-wave-in-housing

Mpamag.com, Are zero-energy homes the new wave in housing?, 2/15/19: https://www.mpamag.com/news/california-pushes-people-to-splash-out-on-zeroenergy-homes-159420.aspx

Economy Solutions Blog, Net zero-energy homes will transform US real estate market, 2/15/19: http://economy-solutions.blogspot.com/2019/02/net-zero-energy-homes-will-transform-us.html

Facebook.com, IS IT TIME TO GO GREEN IN 2019?, 2/13/19: https://www.facebook.com/1443913582567019/posts/2080742842217420 (Reach: 480)

Builderonline.com, California Builder, Energy Consultant Plan Net Zero Community, 9/06/18: https://www.builderonline.com/land/local-markets/california-builder-energy-consultant-plan-net-zero-community_o

Greenhomebuildermag.com, De Young Properties & ConSol Announce Largest Single-Family Zero Net Energy Community in California, 9/06/18: https://greenhomebuildermag.com/de-young-properties-consol-zero-net-energy/

Jdsupra.com, New energy-efficient home tract in north Clovis is largest of its kind in California, 10/13/18: https://www.jdsupra.com/legalnews/sustainable-development-update-october-49855/

Green Home Builder Magazine, Zero Net Energy Is At The Heart Of New Clovis Community, Community of the Year, Vol. 13, Nov./Dec. 2018: https://penpubinc.com/magazine/online/2018/GHB/NovDec/

Abc30.com, Clovis to soon be home to state's largest 'zero net energy' community, 9/13/18: https://abc30.com/realestate/states-largest-zero-net-energy-community-coming-to-clovis/4234910/

The Chamber Review, Central California Leads the State in Zero Net Energy Homebuilding at Scale with Largest Single-Family Community and 100+ Zero Net Energy Homes in Clovis, Pg. 38-39, 9/1/18: https://view.joomag.com/the-chamber-review-september-october-2018/0076930001536940233

The Chamber Review, Good News From Clovis Chamber Members, Pg. 24, 9/1/18: https://view.joomag.com/the-chamber-review-september-october-2018/0076930001536940233

The Chamber Review, About ConSol, About De Young's Zero Energy Footprint, Pg. 40, 9/1/18: https://view.joomag.com/the-chamber-review-september-october-2018/0076930001536940233

Fresnobee.com, New energy-efficient home tract in north Clovis is largest of its kind in California, 10/05/18: https://www.fresnobee.com/news/local/article219454140.html

Thebusinessjournal.com, De Young Announces Largest Net Zero Housing Development, 9/06/18: https://thebusinessjournal.com/deyoung-announces-largest-net-zero-housing-development/

Events

Conferences and Forums

The team also presented portions of the research at conferences and forums throughout the state. Below is a partial list:

Getting to Zero Forum, Oakland CA, October 2019;

CABEC, Monterey CA, April 2019;

Path to ZNE, Fresno CA, November 2018;

ACEEE Summer Study, Asilomar CA, August 2018

Getting to Zero Forum, Pittsburg PA, April 2018

EPIC Symposium, Sacramento CA, February 2018;

PCBC, San Diego, June 2017;

Supply Chain Innovations Supporting ZNE, Berkeley, March 2017

Meet the Experts

To help educate potential buyers about the key energy-saving features of the homes, several key team members joined the builder and manufacturer reps for a "meet the experts" event at one of the model homes in Clovis, CA. In addition to new prospective buyers, several buyers that already purchased one of the ZNE demonstration homes and came to learn about the operation and features.

Project Data

Due to the loss of the first two builder partners involved with the project, and the subsequent delays that the final builder encountered when selling and building the ZNE homes, limited data or analysis was available to share during the project term. So, although the team was effective in gaining media coverage and highlighting the project, there were few opportunities to share the results of the project with builders or other industries.

Conclusions and Recommendations

One of the primary purposes of this project was simply to "demonstrate" that ZNE homes could be constructed at-scale, and to that end, the project was effective, in large part due to extensive media coverage. As the largest ZNE communities in California, the two subdivisions that served as the demonstration site are groundbreaking and noteworthy. However, without a focused effort to publicize the projects, it is unlikely that they would garner much attention from the media. In this case, the project team included a Public Relations firm that issued press releases, organized events, and coordinated interviews for articles. As such, the authors recommend that any future EPIC demonstration project of this scale include a PR group.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AC (Air Conditioning)	A system for cooling a room, building, or vehicle.
AER (Air Exchanges Rates)	The number of times that air gets replaced in a space every hour.
AMY (Actual Meteorological Year)	The weather data from a specific location for a specific year.
Btu (British thermal unit)	A unit of heat, defined as the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit.
CASE (Codes And Standards Enhancement)	Recommendations to support the California Energy Commission’s efforts to update California’s Building Energy Efficiency Standards (Title 24) to include new requirements for various technologies.
CBECC (California Building Energy Code Compliance)	The California Energy Commission’s approved public domain compliance software.
CFIS (Central Fan-Integrated Supply)	A ventilation system consists of an outdoor air intake duct connected to the return side of the air handler with a fan cycling control to make sure the fan runs a programmed minimum amount of time.
CHF (California Homebuilding Foundation)	An advocacy group for the homebuilding industry in California.
CIRB (Construction Industry Research Board)	A service provided by CHF that publishes residential, commercial, and energy-efficient building permit statistics for all California jurisdictions.
CO_2 (Carbon Dioxide)	A colorless, odorless gas produced by burning carbon and organic compounds and by respiration.
CSE (California Simulation Engine)	A general-purpose building simulation model developed primarily to perform required calculations for the CBECC-Res software.
CT (Current Transformer)	A type of transformer that is used to reduce or multiply an alternating current.

Term	Definition
CZ (Climate Zone)	Geographical area of distinct climate.
DR (Demand Response)	Providing electricity customers with the ability to choose to respond to time-based prices and other incentives by reducing or shifting electricity use, particularly during peak demand periods.
EDR (Energy Design Rating)	A score to express the energy performance of a home. A score of 0 would represent a home with zero total TDV energy consumption and a score of 100 would represent a 2006 IEXX-compliant home.
EEM (Energy-efficient Mortgage)	A mortgage that credits a home's energy efficiency in the mortgage itself, allowing borrowers to finance cost-effective, energy-saving measures as part of a single mortgage and stretch debt-to-income qualifying ratios on loans thereby allowing borrowers to qualify for a larger loan amount and a better, more energy-efficient home.
EPIC (Electric Program Investment Charge)	A charge to electricity customers of PG&E, SDG&E, and SCE used to support investments into clean energy technologies that provide benefits to the ratepayers.
ERV (Enthalpy Recovery Ventilation)	An energy recovery process of exchanging the energy (heat and moisture) contained in normally exhausted building or space air and using it to treat the incoming outdoor ventilation air.
GHG (Greenhouse Gas)	A gas that contributes to the greenhouse effect by absorbing infrared radiation
HRV (Heat Recovery Ventilation)	An energy recovery process of exchanging the heat contained in normally exhausted building or space air and using it to treat the incoming outdoor ventilation air.
HVAC (Heating, Ventilation and Air Conditioning)	The system used to provide heating and cooling services to buildings.
IAQ (Indoor Air Quality)	The air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants.
kW (kilowatt)	A measure of 1,000 watts of electrical power.

Term	Definition
kWh (kilowatt-hour)	A measure of electrical energy equivalent to a power consumption of 1,000 watts for 1 hour.
MELs (Miscellaneous Electric Loads)	Electric loads resulting from electronic devices not responsible for space heating, cooling, water heating, or lighting.
MLS (Multiple Listing Service	A suite of services that real estate brokers use to establish contractual offers of compensation (among brokers) and accumulate and disseminate information to enable appraisals
NEEA (Northwest Energy Efficiency Alliance)	A non-profit organization that works to accelerate energy efficiency in the Pacific Northwest through the acceleration and adoption of energy-efficient products, services and practices.
$PM_{2.5}$ (Particulate Matter)	Atmospheric particulate matter that have a diameter of less than 2.5 micrometers.
PG&E (Pacific Gas & Electric)	Utility company that provides electricity and natural gas to the majority of northern California
PV (Photovoltaic)	Relating to the production of electric current at the junction of two substances exposed to light.
SCE (Southern California Edison)	Utility company that provides electricity to the majority of Southern California
SDGE (San Diego Gas & Electric)	Utility company that provides electricity and natural gas to San Diego County and southern Orange County.
TDV (Time Dependent Valuation)	A code compliance metric meant to incorporate the societal and environmental impacts into the cost of energy during a given hour of the year.
Therm	A unit of heat equivalent to 100,000 Btu (29.3 kWh)
TMY (Typical Meteorological Year)	A collation of weather data for a specific location for a one-year period, where the data are averaged over several years (at least 12).
TOD (Time of Day)	Electricity prices that vary depending on the time in which the energy is consumed. This is the terminology used by SDGE.

Term	Definition
TOU (Time of Use)	Electricity prices that vary depending on the period in which the energy is consumed. This is the terminology used by PG&E and SCE.
UVA (Unvented Attic)	Attic assembly where air-impermeable insulation is applied directly to the underside of the structural roof deck and is tied into the insulation located in the walls so that the roof system becomes part of the insulated building enclosure.
VA (Vented Attic)	Attic assembly where air-impermeable insulation is applied at the attic floor and is tied into the insulation located in the walls so that the attic space is not part of the insulated building enclosure.
ZNE (Zero Net Energy)	Zero net energy consumption, meaning the total amount of energy used on an annual basis is equal to the amount of renewable energy generated. Can be in terms of site, source, or TDV energy.

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