Webpage Abstract

Current construction of site-built homes is dictated by a cost-first, sequential, disintegrated design and installation approach. In other words, the different trades and contractors try to reduce costs without giving enough consideration to how all the systems in the homes function together. This makes it difficult to cost-effectively achieve energy efficiency and comfort. Developing and refining principles and practices for new construction is a necessary step to achieve affordable newly constructed zero net energy (ZNE) homes and help the state achieve its aggressive greenhouse gas (GHG) reduction targets. This project demonstrated that affordable ZNE houses are achievable using low-cost construction techniques and on-site renewable. The project team built, commissioned, and collected field data from two affordable ZNE houses in Stockton, California, that demonstrated near-zero net annual energy use with on-site solar PV arrays. One of the homes was an all-electric home, and the other a mixed-fuel home (using both electricity and gas). Examples of cost savings from this approach include right-sized Heating, Ventilation and Air Conditioning (HVAC) and advanced framing methods that reduced lumber and windows by 60% compared to typical homes, reduction in heat pump size by 80%, and significantly reduced amount of plumbing pipes and ductwork.

FINAL PROJECT REPORT

Measure Results from Affordable Zero Net Energy Homes

Agreement Number: EPC-16-001

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Executive Summary

Background

Developing and refining new principles and practices for building construction is a necessary step to achieve affordable newly constructed zero net energy (ZNE) homes and help the state achieve aggressive greenhouse gas (GHG) reduction targets such as Assembly Bill 1279 (Statutes of 2022), which requires California to reduce statewide GHG emissions by 85 percent compared to 1990 levels by 2045. The goal of this project was to demonstrate that affordable ZNE houses are readily achievable using low-cost construction techniques and on-site renewable energy, in combination with high-performance measures and integrated project design and delivery approaches. Integrated project design and delivery refers to a collaborative approach to design and delivery where the trades assist during the design phase, and the designers work with the trades through the entire construction phase until the home is fully completed.

A key objective of this project was to collect at least 12 months of monitored field data from two newly built, affordable ZNE homes in Stockton, California. The ZNE homes utilized several energy efficiency measures, which were applied in a cost-effective manner. These measures included:

- Adaptive, Replicable, and Efficient Architectural Design
- Advanced Framing and High-Performance Enclosure
- High Performance Heating, Ventilation, and Air Conditioning (HVAC)
- Efficient Water Heating System Design
- Water Conservation
- Advanced Lighting
- Solar PV

The project built and commissioned two single-story, approximately 1,200-square-foot single-family homes. One of the homes is an all-electric home (AEH) and the other is a mixed-fuel home (MFH) including both electricity and gas.

Project Purpose and Approach

This project utilized low-cost construction techniques and on-site renewable energy in combination with high-performance measures and integrated project design and delivery approaches. The measures incorporate a wide variety of advanced technologies and construction techniques to achieve excellent energy performance and occupant comfort. The energy efficiency measures were selected to complement and enhance other measures. For example, advanced framing and highly insulated enclosures were combined with right-sized, high-efficiency HVAC equipment. The enclosure was designed to reduce the heating and cooling loads within the home, and the HVAC equipment capacity was designed to match the lower loads. This resulted in a comfortable home with lower capital costs of framing and equipment and lower energy utility costs.

Each house was designed to maximize the benefits and minimize the disadvantages of its respective fuel mix, incorporating advanced features in categories such as energy efficiency, indoor air quality, aesthetics, structural integrity, and cost-effectiveness. The construction emphasized affordability, utilizing standardized dimensions, low-cost foundation systems, and minimizing waste and debris.

The exterior walls were constructed with advanced, 2x6 framing, R-21 insulation in the cavities, and R-5 continuous insulation on the outside, resulting in an overall U-factor of 0.038 Btu/h-ft^2-°F for the opaque walls. The vented attic includes R-42 insulation at the ceiling and an exposed radiant barrier. The crawlspace foundation includes R-21 cavity insulation under the floor and continuous R-5 rigid insulation under the floor joists. Windows featured a low-E coating and an average U-factor of 0.27, and a solar heat gain coefficient (SHGC) of 0.24. The U-factor is an indicator of the amount of heat transfer through the window; a lower U-factor results in lower heat transfer. SHGC relates to the amount of solar heat that passes through the window. Finally, high-efficiency and right-sized HVAC equipment was included in these homes.

Project objectives included monitoring and evaluating the performance of both houses for a year and comparing the performance of the all-electric and mixed-fuel homes to guide future ZNE designs. The evaluation focused on:

- Whole-building energy use and energy contributed from the grid and by the photovoltaic system.
- Home performance relative to the overall ZNE goals.
- Electrical and gas end use measurement and assessment.
- Seasonal energy use for space heating, cooling, and water heating.
- Measurement of indoor comfort conditions, including temperature and relative humidity (RH).

Key Results

The annual energy use intensity (EUI) of the two homes were calculated using actual field data including energy consumption and solar generation. EUI is defined as the annual energy consumed per square foot of floor area. For Stockton (California climate zone 12), where the homes were constructed, a “good” EUI consumption is 16.6 kBtu/ft^2-year. Based on field measurements, the net EUI of the AEH home was -2.8 kBtu/ft^2-year, which means the total site renewable energy generation was higher than consumption and the ZNE goal was met. The net EUI of the MFH was 10.7 kBtu/ft^2-year and while the MFH did not meet the ZNE goal, it still showed a net EUI lower than a non-solar home and can be considered a good EUI for the Stockton climate zone.

Based on responses from homeowners to survey questionnaires, the team found that both homes (AEH and MFH) had lower setpoints for cooling and higher set points for heating than are typical, and both homeowners noted that they used their HVAC much more than they would have if they didn’t have solar. The MFH homeowners also periodically used extra space conditioning equipment like a portable electric space heater. Owners of both homes reported that they were happy with their systems and did not report any major comfort-related issues.

The MFH homeowners made modifications to the garage to add a bathroom, a small through-the-wall heat pump unit, and a mini fridge. These additions resulted in a significant increase in their overall energy consumption. However, since these additions were not part of the original design, they were excluded from the EUI calculations and end-use comparisons with the AEH. A comparison of the measured end-use energy consumption in the two homes indicated that the MFH consumed more energy than the AEH across all major end-use categories like space heating and cooling, water heating, appliances, and plug loads and lights. A clear takeaway of the findings is the importance of occupant behavior, and a home with solar installation can still accommodate very energy-intensive operational choices.

Several design decisions implemented in this project can enable cost reductions. Examples include 60% reductions in the amount of lumber and window area compared to industry standard homes of similar size, a reduction in the heat pump capacity from industry standard 3-4 tons to 0.75 ton in the AEH, compact plumbing design significantly reducing the piping material, and, finally, significantly reduced ductwork of about 50 feet compared to 300 feet in industry standard homes. These measures also enable lower energy consumption and utility bills. Affordability and cost-effectiveness were key aspects of this project. However, the exact price of the demonstration site homes could not be accurately estimated since many of the building components were donated, and volunteer labor was used to build the homes.

Knowledge Transfer and Next Steps

Knowledge transfer was a key factor for the success of this project and conveying the knowledge to home builders was particularly important. Ensuring home builders are familiar with the latest construction techniques and best practices so that the measures from this project may be implemented in future home developments. The project team conducted a number of training webinars to share practices and techniques used in this project. Training webinars were held in November 2020, and March 2023.

An e-book was developed, titled Real-World Zero Net Energy Homes for California, which condensed decades of industry experience on topics surrounding ZNE and high-performance homes. The e-book outlines cost-effective methods and designs for constructing new homes that can produce the same amount of energy as they consume over the course of a year. The e-book can be downloaded for free from this link - Real-World-ZNE-Homes-for-California-January.

A paper was published and presented at the 2018 Summer Study on Energy Efficiency in Buildings by the American Council for an Energy-Efficient Economy. This paper summarized the affordable ZNE design strategies used in the two homes and provided insights on creative approaches and challenges when trying to construct affordable ZNE homes.

For future installations, it is advisable to work with the homeowners to educate and inform them about how their energy bills and associated carbon footprint can be improved with modifications to their energy-use choices, even though they have a solar home. While the project team is not currently pursuing any new projects directly as an outcome of this project, the learnings of this project need to be broadly disseminated to stakeholders and policymakers. Broad implementation of the design and construction aspects of this project can provide significant benefits in terms of energy savings, GHG reductions, and cost savings for consumers. Additional development and demonstrations of tailored ZNE homes in different regions of California, with different climate types, snow loading, seismic requirements, etc., can be of value.

Introduction

Field measurements of site-built homes provide indisputable proof that the widespread approach of cost-first, sequential, disintegrated design and installation makes it difficult to cost-effectively achieve energy efficiency and comfort. In a cost-first scenario, the different trades and contractors try to reduce costs without giving enough consideration to how all the systems in the homes function together. In addition to energy efficiency measures, builders need new principles and practices that work, both economically and technically. Developing and refining these principles and practices for new construction is a necessary step to achieve affordable newly constructed zero net energy (ZNE) homes and help the state achieve aggressive greenhouse gas (GHG) reduction targets such as AB1279 (Muratsuchi, A., Garcia, C., et al., Chapter 337, Statutes of 2022), which requires California to reduce statewide GHG emissions by 85 percent compared to 1990 levels by 2045.

The goal of this project was to demonstrate that affordable ZNE houses are readily achievable using low-cost construction techniques and on-site renewable energy, in combination with high-performance measures, and integrated project design and delivery (IPD) approaches created from research and development (R&D) over the past two decades. IPD refers to a collaborative approach where the trades assist during the design phase and the designers work with the trades through the entire construction phase until the home is fully completed.

The objective of this project was to collect at least 12 months of monitored field data from two newly built, affordable ZNE homes built in Stockton, California. The innovation was to pilot the use of several energy efficiency measures in a cost-effective manner. These measures included:

- Adaptive, Replicable, and Efficient Architectural Design
- Advanced Framing and High-Performance Enclosure
- High Performance Heating, Ventilation, and Air Conditioning (HVAC)
- Efficient Water Heating System Design
- Water Conservation
- Advanced Lighting
- Solar photovoltaic (PV)

The project team, led by GTI Energy, worked with Habitat for Humanity of San Joaquin County (SJC-Habitat) to develop affordable ZNE strategies. The project built and commissioned two single-story, approximately 1,200-square-foot single-family homes in Stockton, California. One of the homes is an all-electric home (AEH) and the other is a mixed-fuel home (MFH) with electricity and natural gas. The two homes are otherwise identical in their basic design and incorporated a range of energy efficiency measures.

Figure 1 shows the location of AEH and MFH, which are located on 3213 Glenhaven Lane and 3237 Glenhaven Lane, respectively, in Stockton, California.

Figure 1: ZNE Homes

Source: Google Maps

The evaluation objectives were to monitor and compare the performance of the two homes over the course of a year, to inform future ZNE designs. Focal points of the evaluation included:

- Whole-building energy use and energy contributed from the grid and by the photovoltaic system.
- Home performance relative to the overall ZNE goals.
- Electrical and gas end use measurement and assessment.
- Seasonal energy use for space heating, cooling, and water heating.
- Measurement of indoor comfort conditions, including temperature and RH.

An additional goal was to compare the ZNE homes with the Title 24 2016 California Building Energy Efficiency Requirements. This was done via calibrated building energy modeling of the ZNE homes and comparable Title 24 2016 compliant homes.

Project Approach

Integrated Project Design

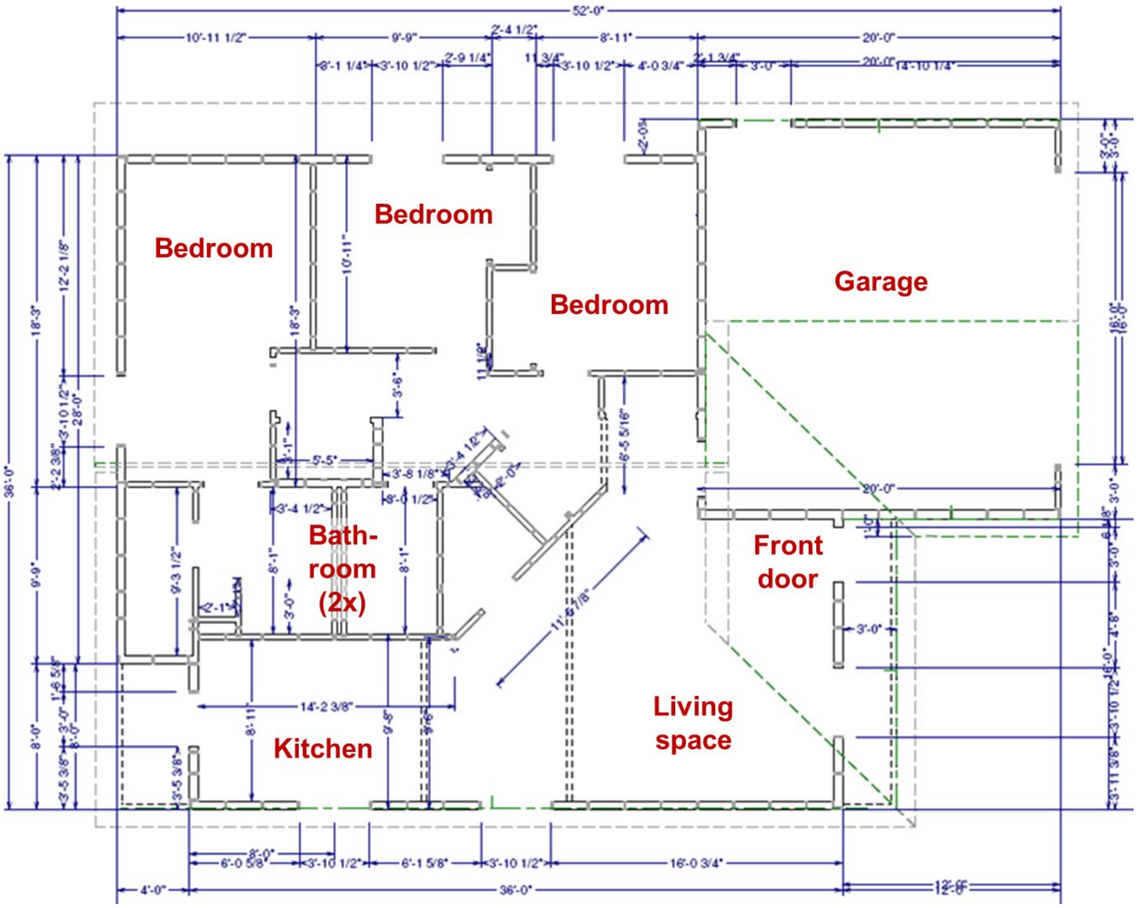
The measures included in the homes were meticulously selected to complement and enhance other measures. For example, the homes included a centralized water heating system that significantly reduced the amount of piping needed (enabled shorter piping runs). Reduced pipe lengths result in lower material and installation costs but also reduce heat loss from the water heating system to end uses like shower heads and sink faucets. A reduction in heat loss lowers utility costs while maintaining occupant comfort. Similarly, advanced framing practices included in this project reduce labor and material costs while enabling higher levels of insulation compared to conventional framing practices. Through advanced framing practices, heat losses through thermal bridging can be reduced, which can also reduce HVAC loads and improve occupant comfort.

Construction

SJC-Habitat constructed the AEH and the MFH with the same design and solar orientation on the same city block in Stockton, CA. Each home incorporated advanced features in categories such as energy efficiency, indoor air quality, aesthetics, structural integrity, and cost-effectiveness. The construction emphasized affordability, utilizing standardized dimensions, low-cost foundation systems, and minimizing waste and debris.

Each single-family home is about 1,200 square feet, featuring three bedrooms, two bathrooms, and an efficient floor plan. Home features include an incredibly compact, centralized plumbing layout, with the longest hot water pipe measuring only 12 feet. The 24”-on-center framing and use of single 2x8 header framing resulted in a framing factor of 12% compared to 35% in typical single-family homes. The windows were proportioned to fit within the 24"-on-center framing modules and their area fraction was also reduced to about 12% versus 35% in typical single-family homes. The lower window fraction can reduce the component costs and improve the thermal performance of the enclosure, since windows typically allow greater heat transfer than the opaque, insulated sections of the walls. Figure 2 illustrates the floor plan used for both the AEH and MFH.

Figure 2: Home floor plan overview



Source: George Koertzen

The exterior walls utilized advanced, 2x6 framing, R-21 insulation in the cavities, and R-5 continuous insulation on the outside, resulting in an overall U-factor of 0.038 Btu/h-ft^2-°F for opaque walls. The vented attics were designed to contain R-42 insulation at the ceiling and an exposed radiant barrier. The crawlspace foundation had at least R-21 cavity insulation under the floor and continuous R-5 rigid insulation under the floor joists. High performance windows were selected, featuring low-E coating and an average U-factor of 0.27 and SHGC of 0.24.

This comprehensive approach to advanced framing, includes both tried-and-true techniques and some innovative framing methods that were developed during the evolution of the Dream Creek subdivision (*Habitat for Humanity of San Joaquin County, 2017*). Generally, these techniques traded redundancy, having many framing members, for resource efficiency, saving energy, lumber, and money. Using fewer framing members reduced the framing factor, which in turn reduced thermal bridging. Thermal bridging refers to higher conductivity paths in the enclosure, such as framing members, and reducing the thermal bridging improves the overall thermal performance of the enclosure. SJC-Habitat's approach was tailored to comply with the 2016 California Residential Code, which provides detailed instructions on how to frame a house in ways that do not require an engineer's review and stamp but is structurally stable, and the SJC-Habitat homes adhered to those prescriptive guidelines.

In addition to increasing the stud spacing from 16" to 24" on-center, this approach reduces unnecessary wood members and metal fasteners at all locations in the home, including upper and lower plates, window and door headers, truss bracing, wall intersections, and floor framing. These homes are in Stockton, which is not near a major earthquake fault, so the building code's structural requirements are less stringent than they would be for houses in the Bay Area or the Sierra Nevada region. Thus, some of the design aspects, if used in an area of higher seismic risk, may need to be altered to meet local building codes and standards. However, generally, these energy efficiency optimized designs could be utilized in several areas throughout California.

Equipment Selection

In addition to advanced framing, the heating and cooling equipment was sized for the ZNE homes, which were expected to experience lower heating and cooling loads than typical single-family homes. As a typical rule of thumb, heat pumps (HP) are sized as 1 ton capacity for every 500 ft^2 of home area, stepped up to the nearest higher tonnage and then 1 ton capacity is added to the calculated value. Therefore, for a 1200 ft^2 home, the HP tonnage would be 4 tons. In the AEH, a HP of much lower tonnage and high efficiency was selected to match the expected loads. In the MFH, a tankless water heater was selected, which would also serve as the heat source for space heating.

Field Monitoring

The project included monitoring and evaluating the performance of both homes for a year and comparing the performance of the AEH and MFH to guide future ZNE designs. The evaluation plan focused on:

- Whole-building energy use and energy contributed from the grid and by the PV system.
- Home performance relative to the overall ZNE goals.
- Electrical and gas end use measurement and assessment.
- Seasonal energy use for space heating, cooling, and water heating.
- Measurement of indoor comfort conditions, including temperature and RH.

The team established a set of measurement requirements, as described below.

Average occupancy was determined through an occupant survey, and behavior patterns were analyzed through end-use analysis. Electrical end-uses were monitored directly at the electrical panels, where end-uses were disaggregated. Each major appliance had its own breaker, while lighting loads were separated from plug loads. For the MFH, gas use was disaggregated by each end-use and measured with a dedicated gas meter.

Detailed monitoring was conducted on the domestic hot water (DHW) system in each home, including instrumentation to measure water temperature, flow rates, and power use, to quantify system efficiency. Efficiencies were compared against manufacturer specifications. In the MFH, the tankless water heater provided hot water for both DHW and space heating, so monitoring was conducted on the hot water loop to the fan coil to separate space heating from water heating energy use.

Weather data, including temperature and insolation specific to the house, was collected and used to put energy use in the context of environmental conditions and to calibrate measured results with modeled predictions.

Temperature and humidity data were collected in various rooms to evaluate heating and cooling distribution effectiveness. A smart thermostat with logging capability was installed in each house to monitor and understand the impacts of the occupants' choices of setpoints and operating modes (heating or cooling). Table 1 details the instrumentation and frequency of data collection.

Table 1: Monitored Systems and Instrumentation.

Performance Category	Monitored Items	Monitoring Instruments	Monitoring Frequency
Electrical consumption	HVAC, DHW, appliances, plug load circuits, lighting circuits	SiteSage with current transducers	1-minute data
Gas consumption	HVAC, DHW, appliances	SiteSage	1-minute data
DHW	Temperature, flows	Onicon energy meters, temperature sensors	5-second data, aggregated to 1-minute for analysis
HVAC	Temperature	Onicon energy meters	5-second data, aggregated to 1-minute for analysis
Indoor conditions and operation	Temperature and RH in various rooms, setpoints, modes	ecobee	5-minute data, aggregated to 1-minute for analysis
Weather	Dry bulb, solar radiation	Onsite weather station	5-second data, aggregated to 1-minute for analysis
Heat flux	Heat flow through North and West exterior walls	Heat flux sensors	5-second data, aggregated to 1-minute data for analysis
Solar generation	Electrical generation	SiteSage with current transducers	1-minute data

Source: Frontier Energy

The monitoring approach was tailored to the systems at each house, with some overlap of basic methods and devices. As outlined in Table 1, the following categories were monitored in both homes: electricity consumption, natural gas consumption, DHW, indoor conditions, HVAC operation, weather conditions, and solar PV generation.

Project partner, Frontier Energy, utilized a microcomputer-based data acquisition system that pushed collected data through an internet connection directly to the Frontier Energy secure FTP server every hour. The SiteSage and ecobee systems push data every minute to their cloud repositories through the cellphone modem's internet connection. Frontier Energy's monitoring server polled these systems' respective application programming interfaces and downloaded data daily to Frontier Energy's secure FTP server, to be stored with other site data. Frontier Energy's monitoring server performed automated data checks and generated an alert when values deviated from expected operating ranges (e.g., indoor air temperature is between 40 and 90˚F). Suspect data were evaluated to determine whether the ranges needed to be modified or if a sensor error or system failure had occurred; in the latter case, a service call was scheduled immediately. Frontier Energy's monitoring server also generated a weekly summary of collected data. Raw data were archived in comma-delimited text format, in files named by data source and date. Merged and concatenated data were stored in binary file format on the Frontier Energy secure FTP server, which automatically backed-up data every 8 hours.

Analysis Methods

Data was reduced and aligned on 1-minute steps using Python scripts. Computations were performed and plots developed to evaluate all relevant metrics. Detailed DHW system data were analyzed to calculate efficiencies, to compare against manufacturer specifications. The energy meters performed the necessary calculations of the energy added to the water by the water heater.

This is the result of the standard heat equation:

$$Q = c_p \rho V \Delta T$$

Where:
Q is the amount of heat added, kJ.
c_p is the specific heat, kJ/kg-K.
ρ is the density, kg/m^3.
V is the total volume flowed, L.
ΔT is the temperature difference between the hot and cold side, K.

The energy meter provided the temperature and flow rate variables to reproduce this calculation, though the energy meter automatically makes density and specific heat adjustments for temperature. The outputs of the energy meters were compared to separate thermal loads for DHW and the air-to-water heat pump at the mixed-fuel house.

In addition, energy use analysis, data were cleaned and aggregated into 5-minute or hourly data for ease of manipulation. A gas factor of 1.0 was used to translate from one hundred cubic feet (CCF) of natural gas to Btu. For ZNE analysis, gas end use consumption was converted from Btu to kWh for comparison with electric end uses by dividing by 3412; and in other cases, electricity consumption (or production) was converted to Btu by multiplying by 3412.

Building Energy Modeling

Building energy modeling using BEopt, version 2.8.0 (*BEopt: Building Energy Optimization Tool*) was performed. BEopt models of the ZNE homes built to match the home characteristics and calibrated against the monitored field data. Following calibration, the BEopt models were used to compare the energy performance of the ZNE homes to similar Title 24 2016 compliant homes.

Results

ZNE Homes Construction Details

The two ZNE homes featured a variety of advanced measures that complimented and enhanced other measures across the homes. As discussed in previous sections, the integrated project design and delivery approach allowed for collaboration across trades and home designs to deliver a final product with improved construction efficiency, lower waste, and cost savings. The following sections detail the construction techniques, designs and equipment used at each home.

Envelope Characteristics

Advanced Framing and Insulation

The constructed homes incorporated advanced framing building techniques that involved an initial time investment of thoughtful design and engineering considerations to reduce the amount of framing materials and labor in light wood-frame construction. This initial time investment yielded material and labor cost reductions along with substantial energy savings by reducing thermal bridging. The walls were built using 2x6 framing with R-21 batt insulation within the cavities and R-5 foam insulation between the framing and exterior sheathing.

Current industry standards utilize windows of standard sizes located according to plan with 16" on center studs. This project utilized advanced framing in their builds while integrating window placement as part of the framing process. The ZNE homes implemented thoughtful window sizing and placements to fit 24" on center framing, as shown in Figure 3. Windows with a U-factor of about 0.27 Btu/h-ft^2-°F and solar heat gain coefficient (SHGC) of 0.24 were used.

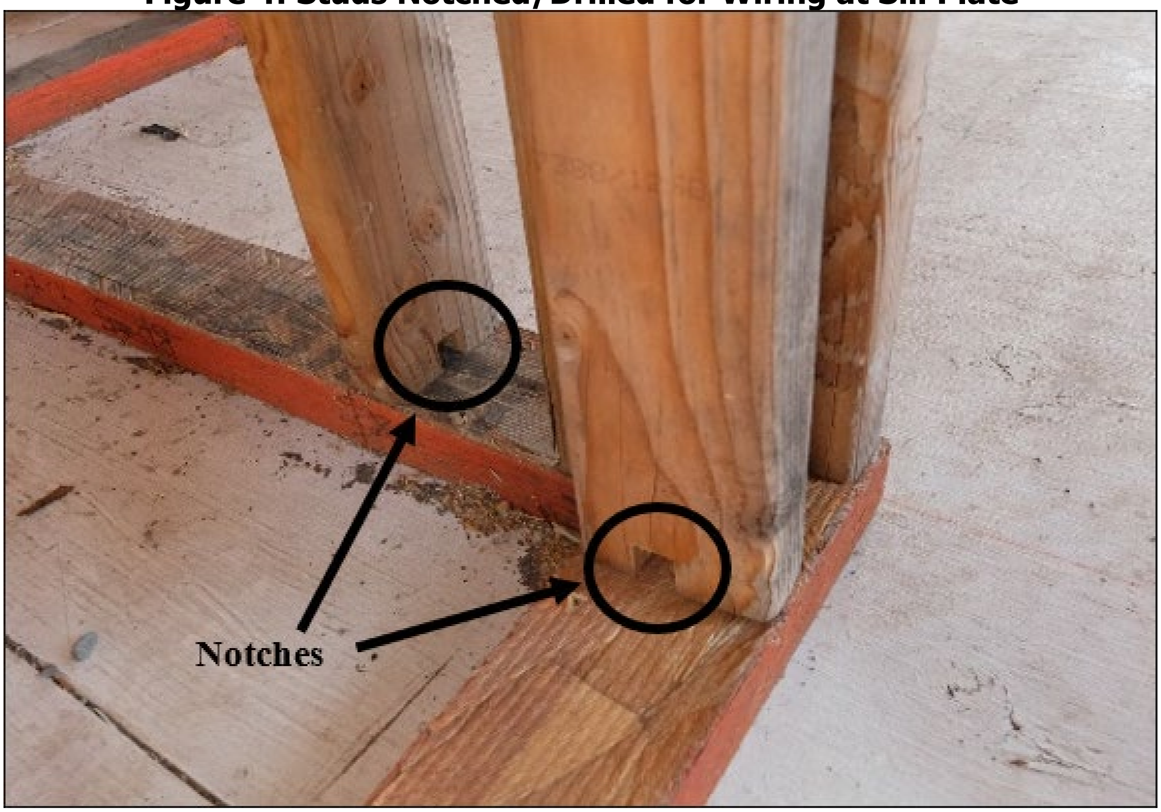
Figure 3: Advanced Framing During Construction Process.

Source: Frontier Energy

The 24”-on-center framing and use of single 2x8 header framing resulted in a framing factor of 12% compared to 35% in typical single-family homes. The windows were proportioned to fit within the 24"-on-center framing modules and their area fraction was also reduced to about 12% versus 35% in typical single-family homes.

Additionally, the studs were notched/drilled for wiring at the sill plate. In conventional framing techniques, holes are drilled at random heights to route wiring, which adversely impacts the performance of batt insulation within the wall cavities. Carefully drilling the studs at the sill plate to smoothly route wire avoids inhibiting the insulation, which minimizes the unwanted heat transfer between the interior conditioned space and the exterior environment. This technique is illustrated in Figure 4.

Figure 4: Studs Notched/Drilled for Wiring at Sill Plate



Source: Frontier Energy

Roof/Attic and Crawlspace

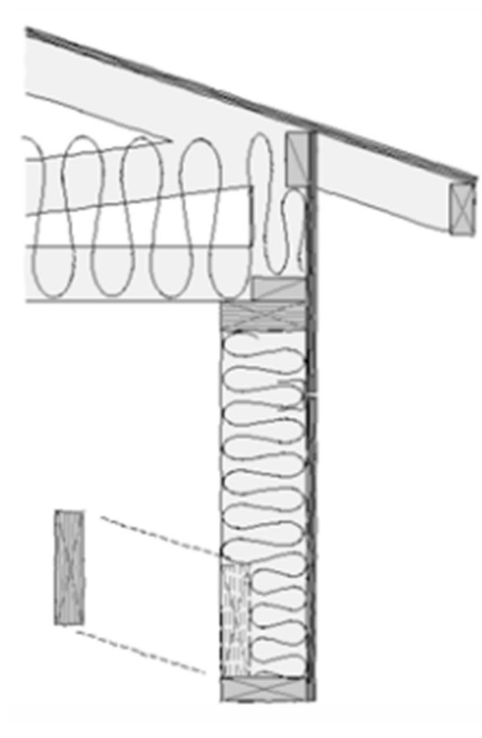
Figure 5 illustrates the truss framing and R-42 cellulose blown-in attic insulation. A raised-heel truss design allowed for deep insulation layering and permits insulation to extend out to the wall edge. The raised-heel design, as seen in Figure 6, avoids compromising the insulation effectiveness and R-value due to compression of the attic insulation over the top plate, which is often found in conventional truss designs.

Crawlspace was vented with R-21 cavity insulation in the raised wood floor above the crawlspace as well as R-5 rigid insulation under the floor joists.

Figure 5: Attic Space Showing Deep Blown-In Insulation

Source: Frontier Energy

Figure 6: Raised Heel Truss Design Avoiding Compression of Attic Insulation

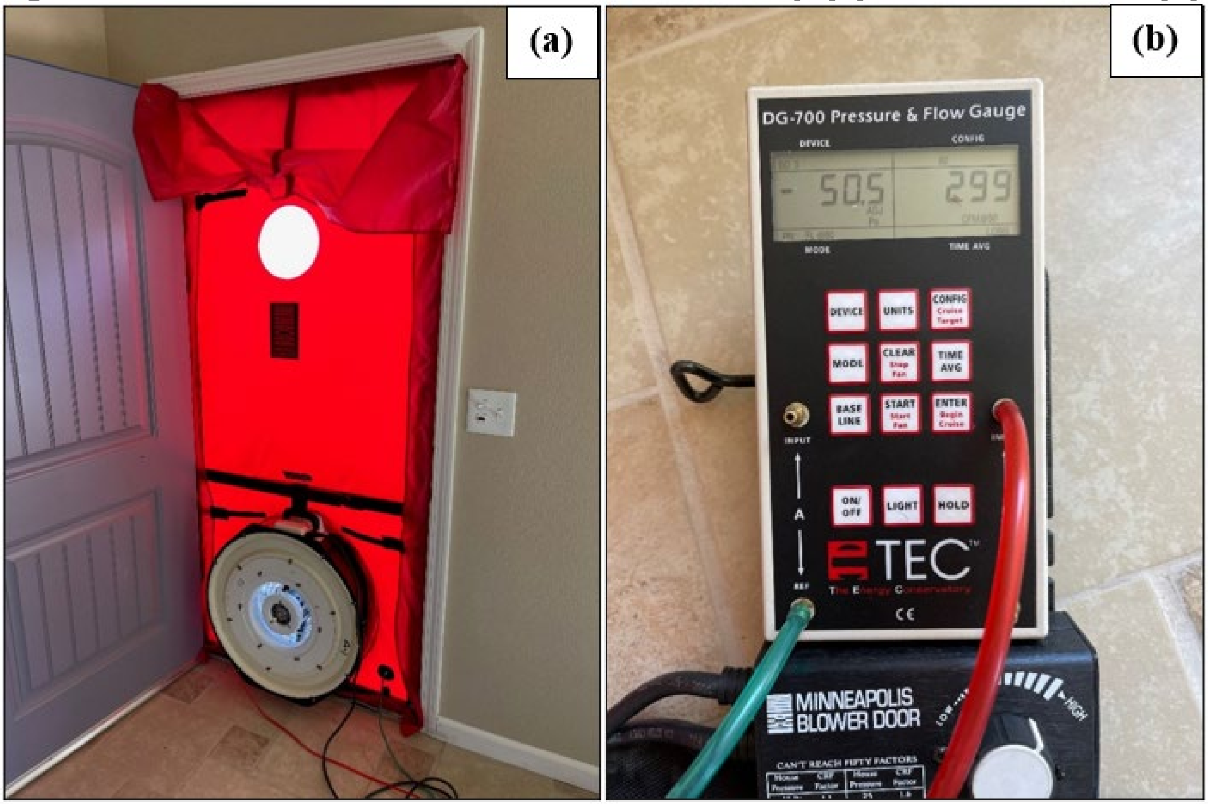


Source: George Koertzen

Air Tightness

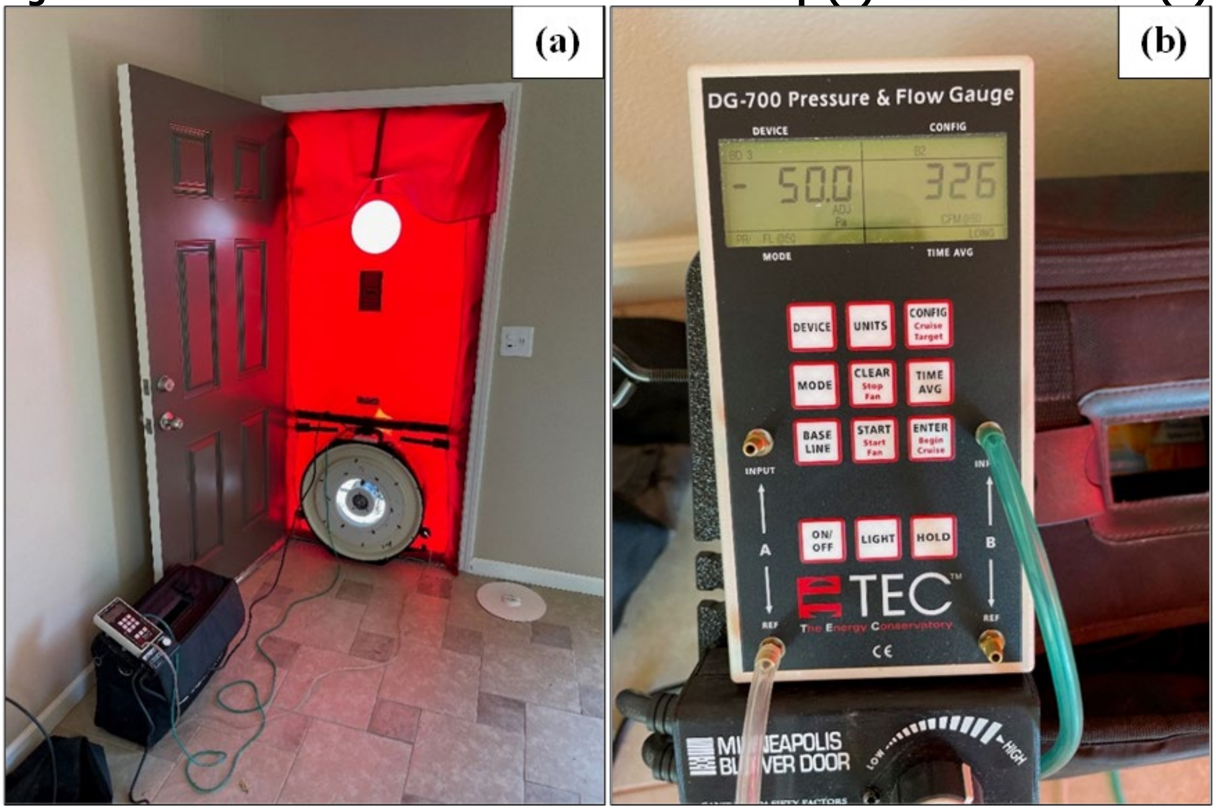
Effective air sealing methods were used to minimize air leakage in and out of the homes, which minimizes unwanted transfer of heat. The envelopes of both homes performed extremely well under blower-door testing, which is used to test the airtightness of the exterior envelope of a building. The AEH shows a 1.94 ACH50 score and the MFH scored 2.11 ACH50, as shown in Figure 7 and Figure 8. ACH50 refers to air changes per hour at a pressure differential of 50 Pascals across the building envelope. For reference, the industry standard for homes is 4-5 ACH50.

Figure 7: All Electric Home Blower Door Test Setup (a) and Test Results (b).



Source: Mike MacFarland

Figure 8: Mixed Fuel Home Blower Door Test Setup (a) and Test Results (b).



Source: Mike MacFarland

Table 2 summarizes the main characteristics of the high-performance envelope with advanced framing.

Table 2: High Performance Envelope Features

Framing	2x6 and 24” on center
Framing factor	12%
Wall insulation	R-21 cavity and R-5 exterior insulation
Attic insulation	R-42 blown insulation
Crawlspace insulation	R-21 floor and R-5 rigid insulation
Air tightness	1.94 – 2.11 ACH50
Windows	U-factor = 0.27 Btu/h-ft^2-°F; SHGC = 0.24

Source: GTI Energy

HVAC Equipment

As important as the envelope, the heating, cooling, and hot water equipment are integral to overall home energy efficiency. A “just-right” design is necessary to avoid problematic and wasteful characteristics of oversized and undersized equipment designs. The AEH featured a 3/4 ton ducted mini-split heat pump boasting a 12.5 heating seasonal performance factor (HSPF) (or heating efficiency) and 24.5 seasonal energy efficiency ratio (SEER) (or cooling efficiency). Figure 9 illustrates the final installation of the outdoor unit, which is installed above the ground with direct routing into the attic. This helps prevent incidents of copper wiring theft and soiling of the equipment by critters. The unit’s compact design allowed for this placement without expensive structural reinforcement. Moreover, the right-sized HP can meet the home's heating and cooling needs in an inexpensive and efficient manner.

Figure 9: All-Electric Home's Installed Heat Pump

Source: Frontier Energy

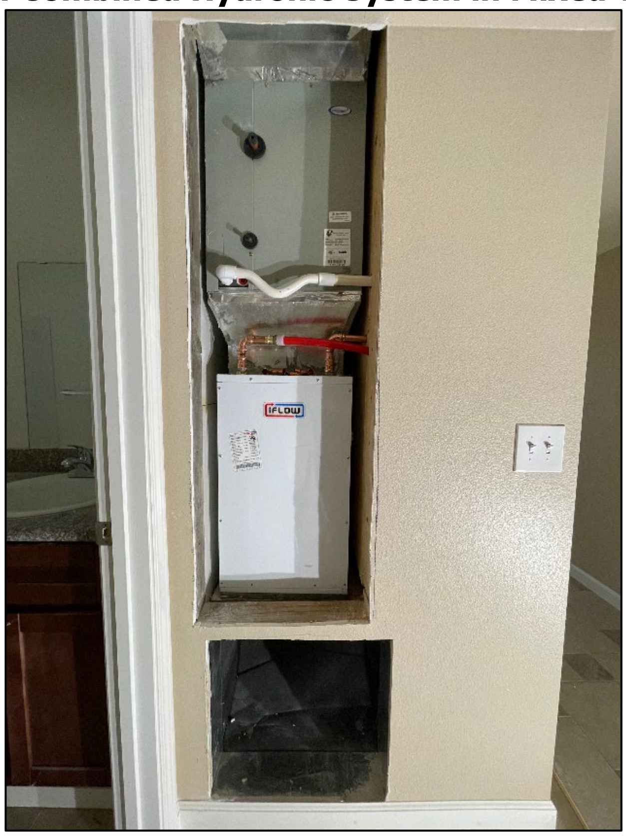
To effectively deliver fresh and filtered air throughout the house, all the ducts were routed into the thermal envelope in a dropped ceiling in the hallway, instead of having them in the unconditioned attic. Figure 10 shows the distribution manifold within the conditioned space.

Figure 10: HVAC Duct Distribution Manifold

Source: Frontier Energy

The MFH featured a combined hydronic air handler that uses hot water from the tankless water heater to heat the air, along with a 1.5-ton, split-system air conditioner. The ZNE homes have relatively small heating loads, and the centralized placement of the combined hydronic unit allows for very short duct runs with everything inside of the thermal envelope. Figure 11 illustrates the compact space-saving size and centralized location of the air handler and A/C coil of combined hydronic system. The tankless water heater is located just behind the wall to the right of the air handler, next to the washer/dryer, as shown in Figure 12.

Figure 11: Combined Hydronic System in Mixed-Fuel Home



Source: Frontier Energy

Figure 12: Tankless Water Heater and Washer/Dryer

Source: Frontier Energy

Table 3 summarizes the equipment specifications for the two ZNE homes.

Table 3: AEH and MFH Equipment Specifications

AEH	Measure	Specification
Heating/Cooling	Ducted mini-split heat pump	Fujitsu 3/4 ton (AOU9RLFC) 12.5 HSPF; 24.5 SEER; Heating coefficient of performance (COP) = 4.14; Cooling COP = 4.25
Water Heating	Split system HPWH	Sanden 43gal tank (GAUS-160QTA) Sanden HP (GUS-A45HPA) 3.75 Uniform Energy Factor (UEF); Heating COP 80/47/17°F = 5.5/4.2/2.8
Ventilation	Fresh air supply fan	Panasonic FV-15NLFS1
MFH	**Measure**	**Specification**
Heating/Cooling	Combined-hydronic system	Air Handler: iFlow IFLH-16000W Condensing Unit: Trane 1.5 Ton (T4TTL6018A1000A) w/ ADP coil (TG35636D175B2222AP) Energy efficiency ratio (EER) = 12.45 Hot Water Source: DHW system
Water Heating	Tankless water heater	Navien Condensing, Natural Gas, 0.97 UEF (NPE-180S)
Ventilation	Fresh air supply fan	Panasonic FV-15NLFS1

Source: Frontier Energy

Solar Photovoltaic

Photovoltaic arrays of 5 kW direct current capacity were installed on the roofs of both the AEH and MFH.

Plumbing

An often-forgotten energy savings measure is efficient and thoughtful plumbing design. Conventional DHW systems consist of branch distribution designs with relatively long and large diameter main lines feeding into smaller branches that flow directly to plumbing fixtures. Due to lengthy travel distances, traditional designs result in energy and heat losses in the system. Designing a piping layout from the hot water source with minimal travel distance to faucet outlets avoids unnecessary heat losses, water pressure losses, and potential water leaks. Because hot water can quickly reach its destination, less energy and water will need to be utilized. The material and labor costs, along with maintenance costs, are also reduced due to the thoughtful water heating system design implemented in this project. The homes utilize Manabloc manifold water distribution systems, as illustrated in Figure 13. The average distance to a water fixture is 8 feet, with the longest being just 12 feet. Figure 12 illustrates the proximity of the tankless water heating source to a hot water fixture, the clothes washer. Additionally, with the Manabloc, each plumbing fixture has a shutoff switch and can be shut off individually when repairs or replacements are needed.

Figure 13: (A) Compact Water Manifold Block Within Drywall Cavity and, (B) Installation Within the Framing.

Source: Frontier Energy

Ventilation

Ventilation can greatly impact the indoor air quality and efficiency of homes. Four basic mechanical whole-house ventilation systems that are widely used are exhaust, supply, balanced, and energy recovery. An exhaust ventilation system depressurizes and exhausts air from the home through intentional and passive vents. Supply ventilation systems pressurize the home using fans to force outside air into the building through vents. Balanced ventilation systems represent a combination of both exhaust and supply ventilation systems, where the rate of indoor air removal and supply of outside air into the building are approximately equal, making this a more reliable approach. Recently, energy recovery ventilation (ERV) systems have been found to be more energy efficient through their controlled means of ventilation. The ERV system is a type of balanced system but uses warmer exhaust air during winters to partially heat the incoming fresh (cold) air and vice versa during summers, thereby reducing the energy losses via exhaust air and increasing the overall home efficiency.
Since both homes have such tight enclosures, a balanced ventilation approach is ideal. The original design included ERVs but were switched to a fresh air supply fan (Panasonic FV-15NLFS1) with a MERV 13 filter. These air supply fans were donated to this project and helped in reducing the cost of the homes. To incorporate these donations, the builder adopted a combined exhaust and supply ventilation system. The air supply fan (supply ventilation system) is plumbed to provide fresh, filtered air in the return ducts of the two HVAC systems. This helped ensure fresh and good quality indoor air while allowing the bathroom and kitchen exhaust fans (exhaust ventilation system) to operate at high efficiency.

Lighting

All lighting in the homes used high-efficacy light emitting diodes.

MFH Garage Additions

During a site visit by a project team member at the beginning of the measurement and verification (M&V) period, it was observed that the MFH homeowners added a bathroom, a small through-the-wall heat pump unit and a mini fridge in the garage. The garage energy consumption in the MFH needed special consideration due to these modifications and it being used as conditioned space even though the garage lacked exterior insulation. The garage modifications and usage resulted in an unnaturally high additional energy load in the MFH. For the purposes of ZNE performance evaluation, the MFH garage energy consumption was excluded from analysis and reporting in most instances, as noted in following sub-sections.

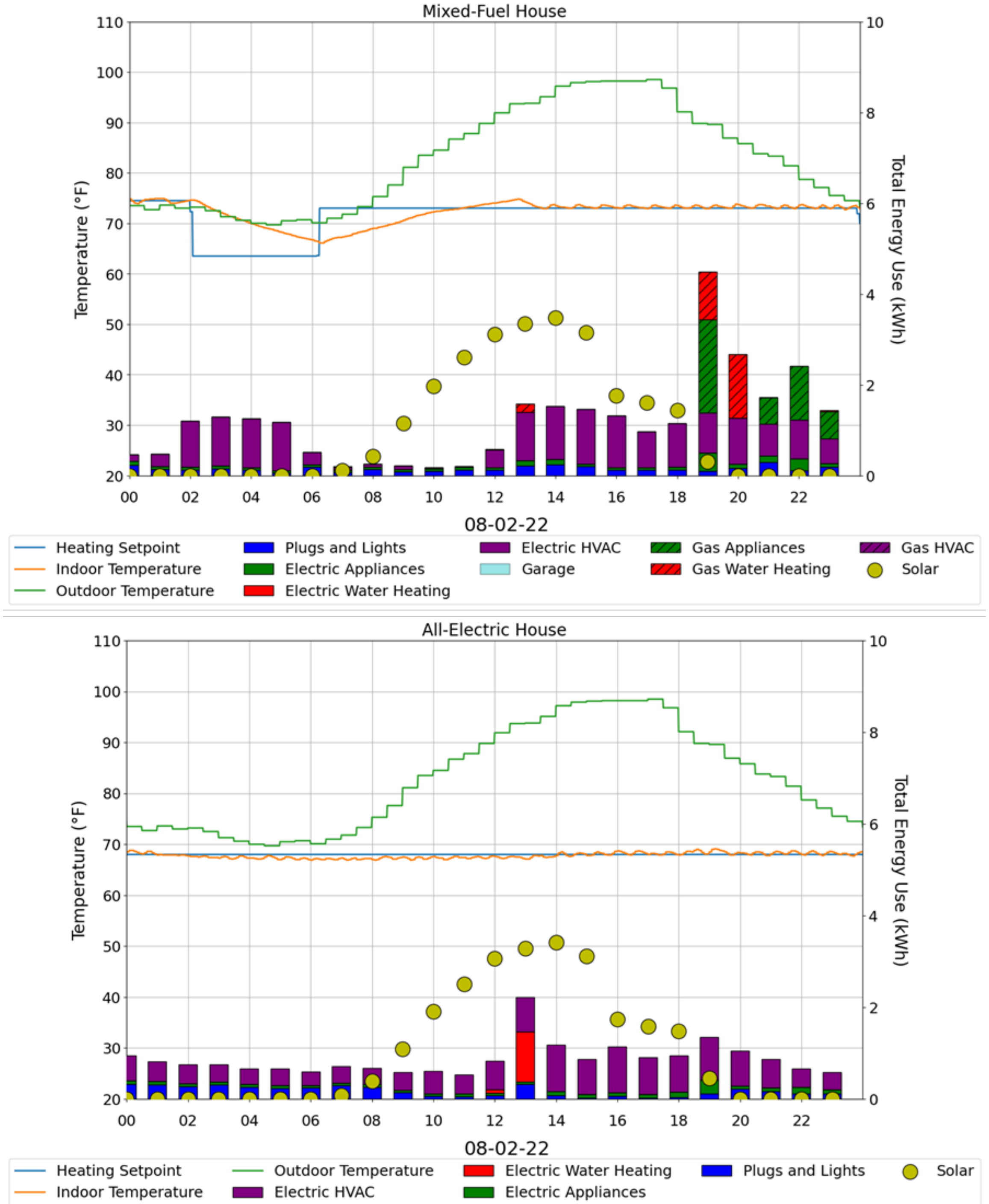
Furthermore, the MFH homeowners left the connecting door between the garage and the main home open at times. While the impact due to the connecting door being left open could not be quantified, it is expected to increase the overall heating and cooling loads and HVAC energy use in the MFH.

Field Monitoring and Analysis Results

Sample Daily Monitored Data

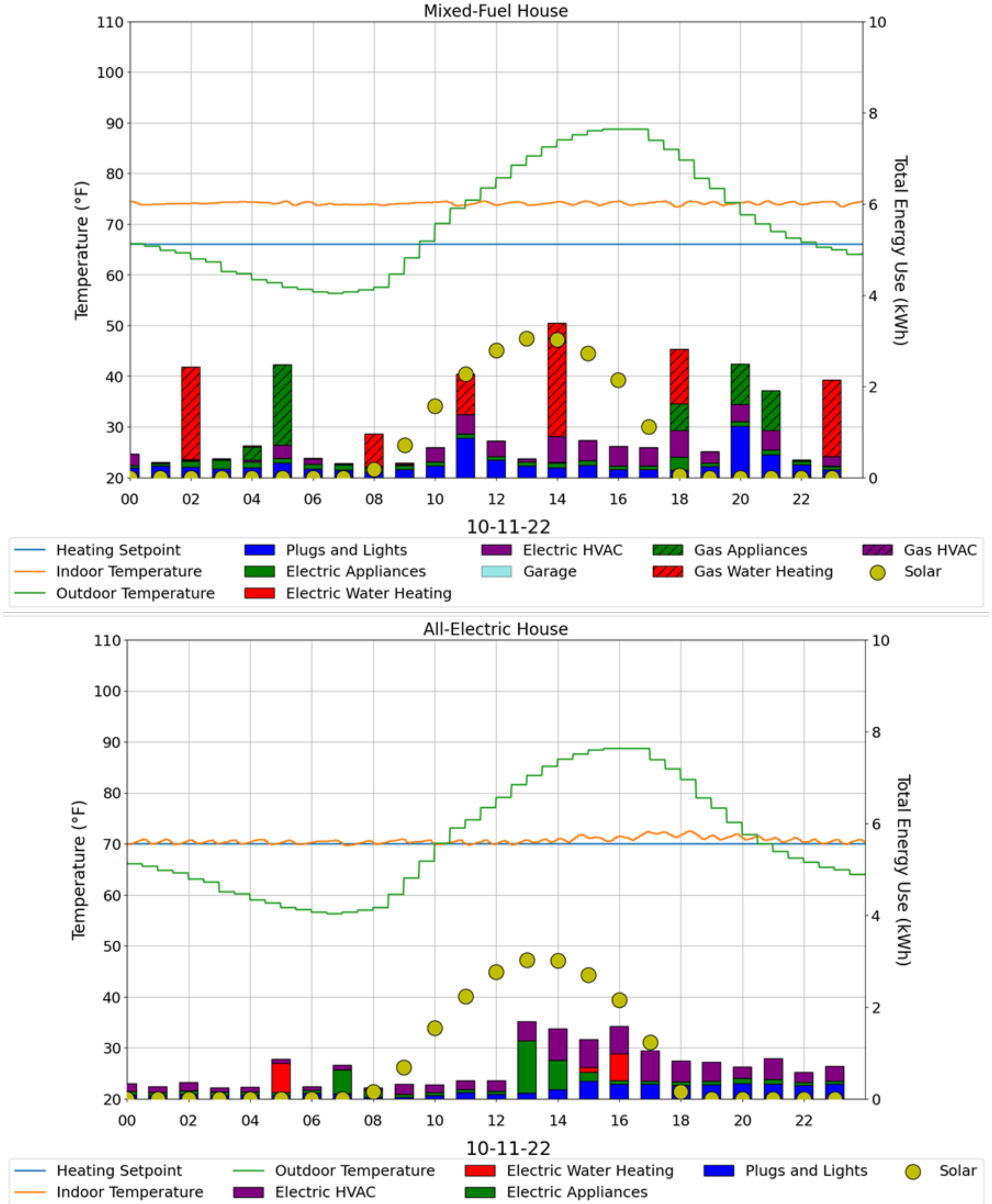
Figure 14, Figure 15 and Figure 16 show sample 24-hour temperature, energy consumption and solar generation data during August 2022, October 2022 and January 2023 from the MFH and the AEH. The energy consumption due to the garage additions in MFH are discernible in the 24-hour energy use data, most noticeably during January 25, 2023. End uses that consumed gas are shown with cross-hatching.

Figure 14: Sample 24-Hour Data During August 2, 2022. Top – MFH, Bottom - AEH.



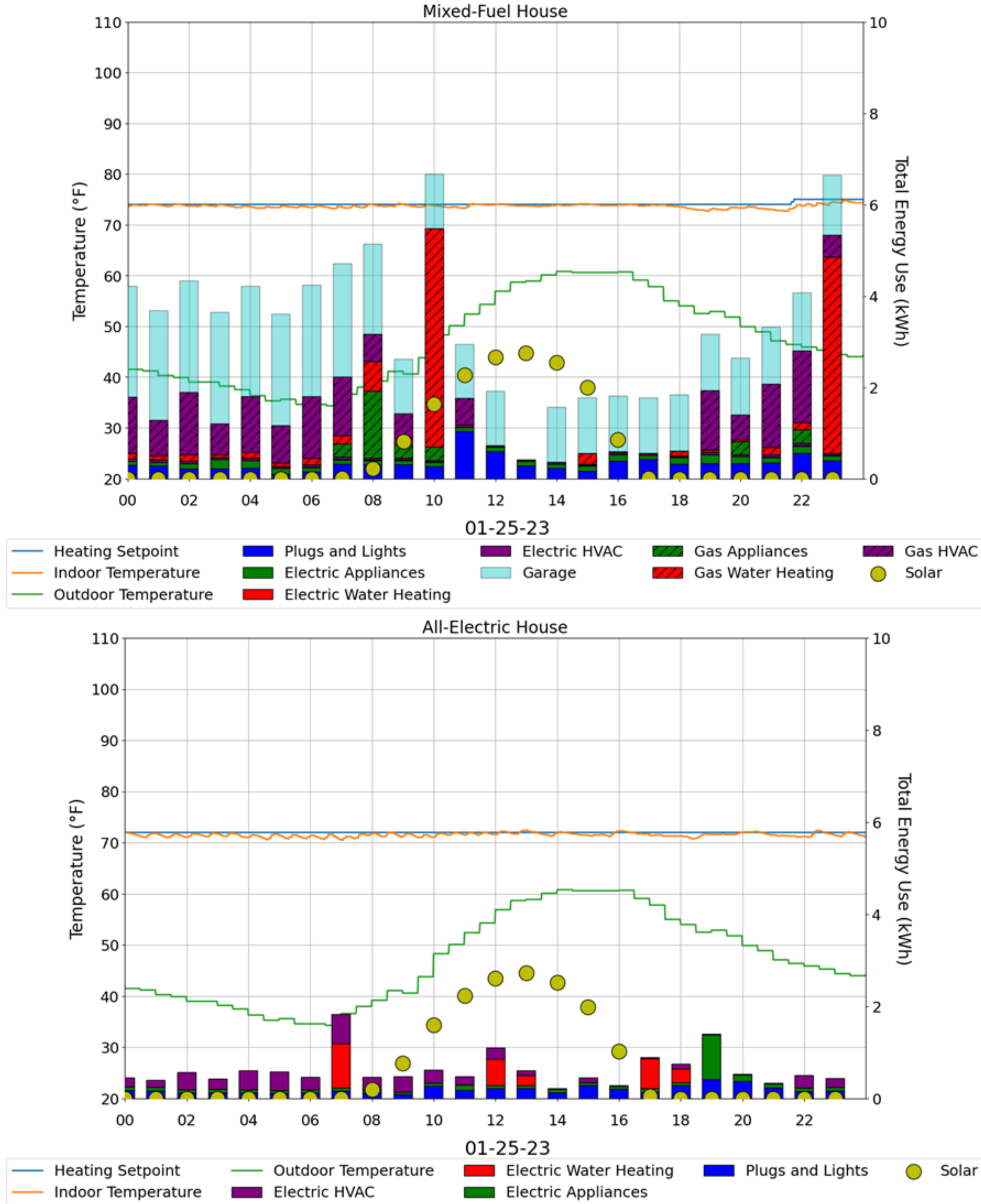
Source: Frontier Energy

Figure 15: Sample 24-Hour Data During October 11, 2022. Top – MFH, Bottom - AEH.



Source: Frontier Energy

Figure 16: Sample 24-Hour Data During January 25, 2023. Top – MFH, Bottom - AEH.

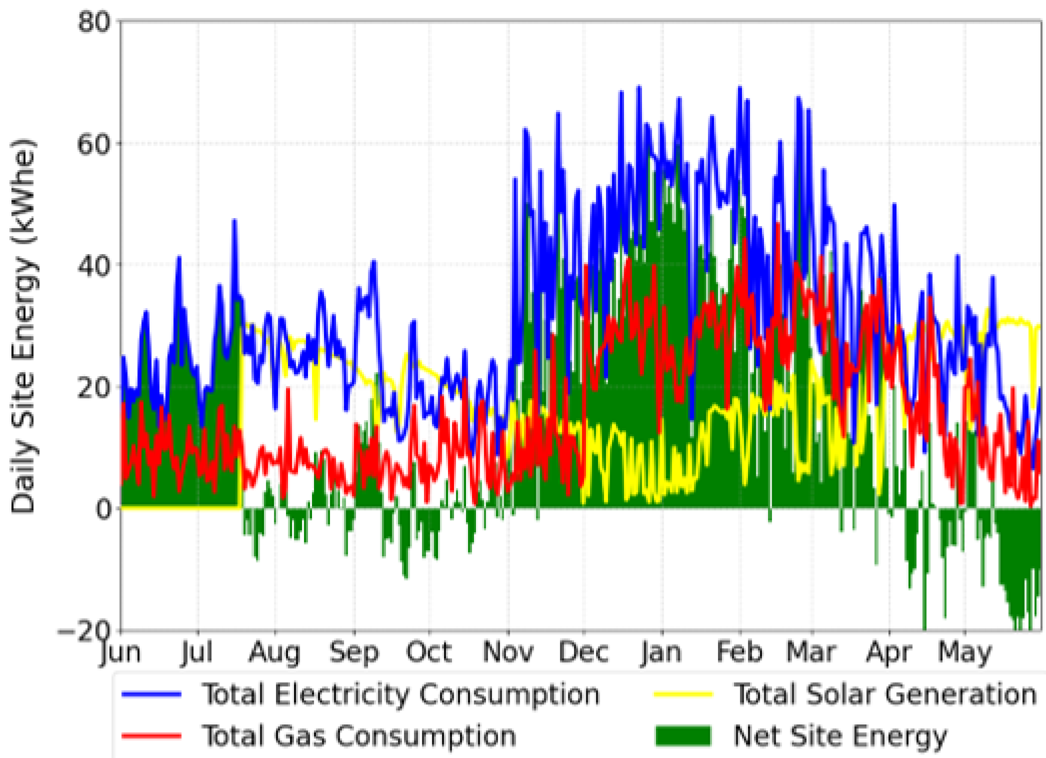


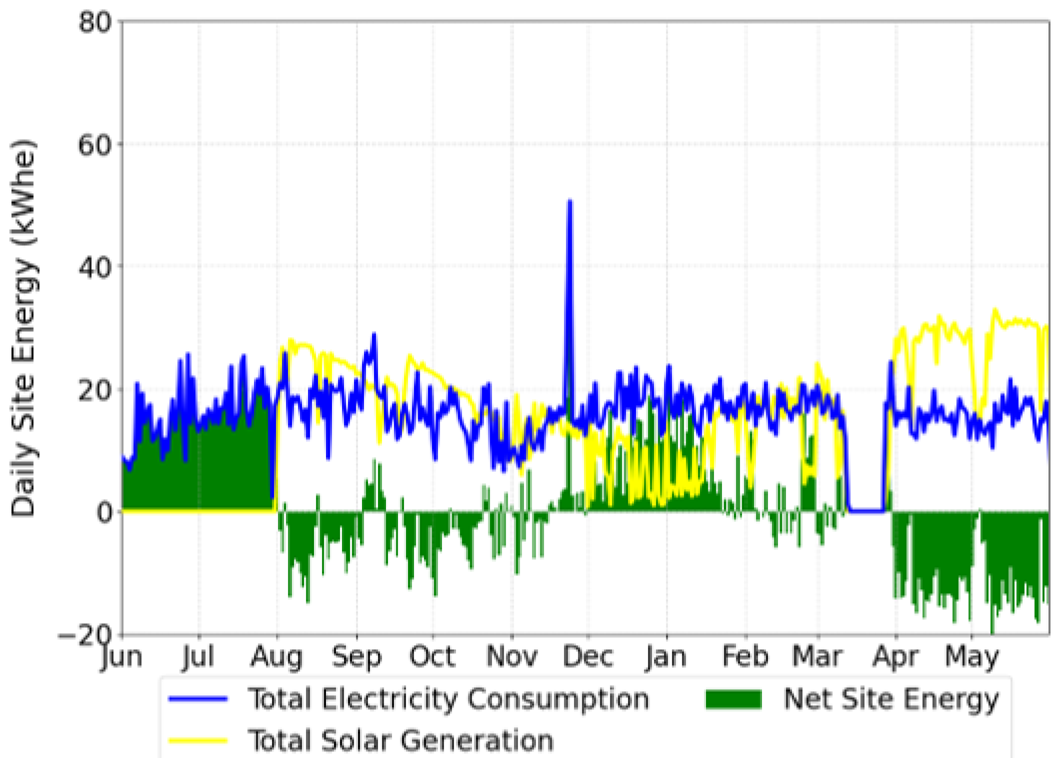
Source: Frontier Energy

Energy Consumption by End-Use

Additionally, Figure 17 shows the overall energy consumption per day by the two homes, including total electricity consumption, total gas consumption, solar production, and net electricity consumption (positive) or production (negative). PV generation did not start until mid-to-late July 2022 in the two homes.

Figure 17: Energy Consumption and Net Site Energy. Top – MFH, Bottom - AEH.

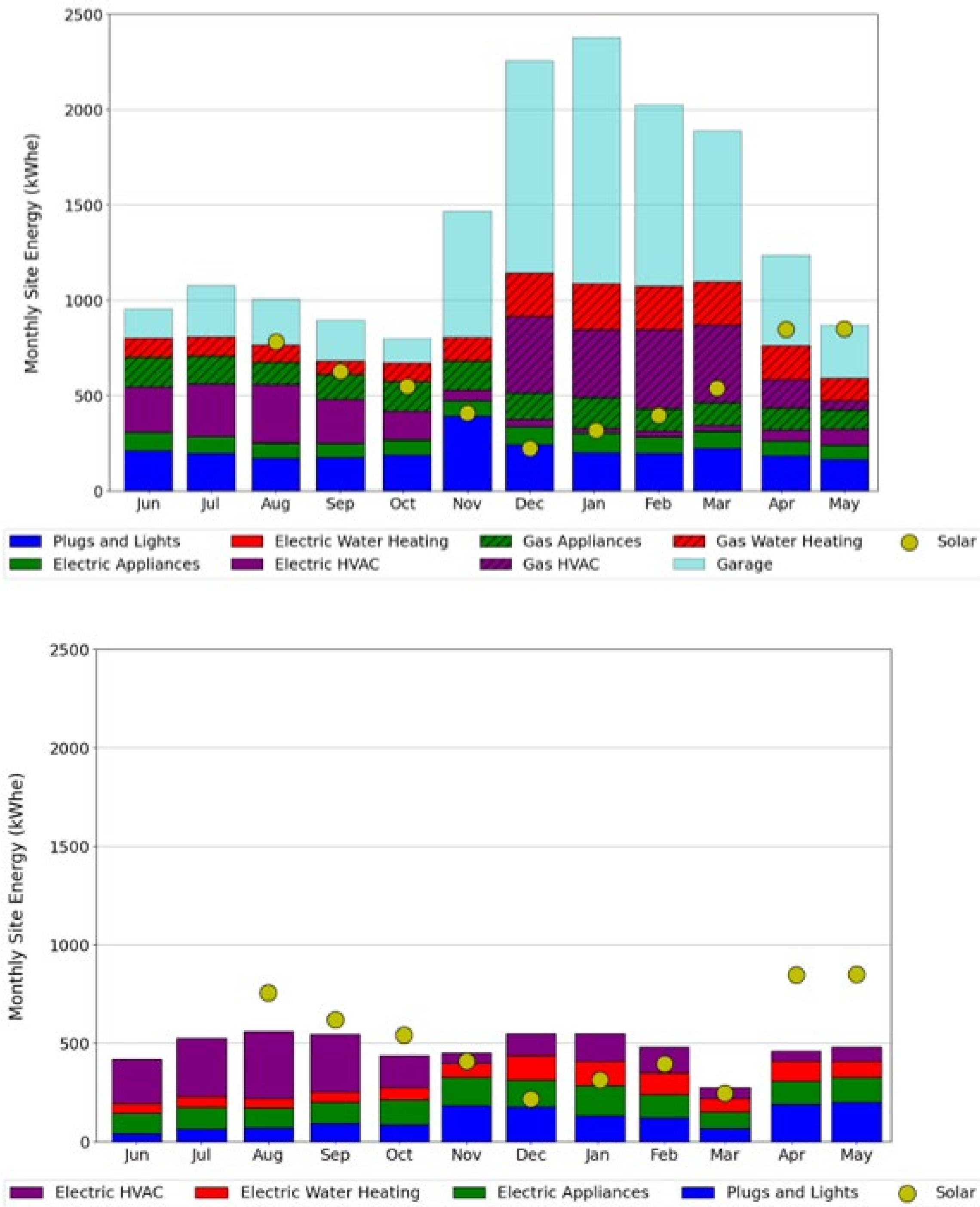




Source: Frontier Energy

Figure 18 shows the monthly energy consumption of the homes by end use. The monthly energy consumption graphs show that the energy consumed in the MFH garage is quite large.

Figure 18: Monthly Energy Consumption by End-Use. Top – MFH, Bottom – AEH

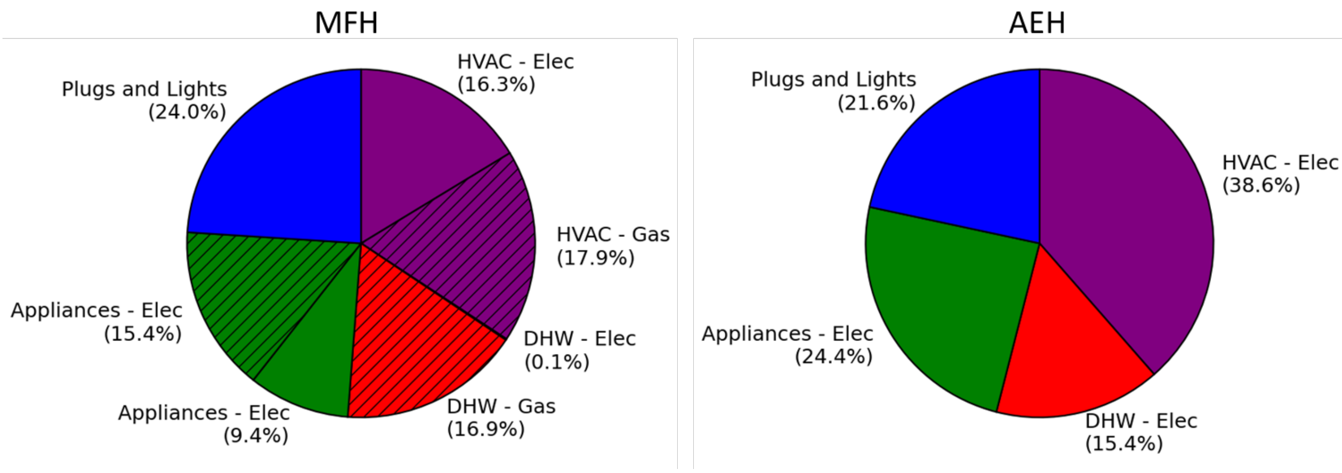


Source: Frontier Energy

In December 2022, the MFH occupants reported that they were not able to achieve their set-point for heating. A visit to the home identified that the valve between the water heater and the fan-coil unit had not been opened, so that they were not receiving any space heating. This can be seen clearly on the MFH plot in Figure 18, as the gas used to heat water for HVAC showed a sharp increase in December. The MFH water heater continued consuming gas for DHW.

Figure 19 compares the different end uses, as a percentage of whole-home energy consumption. The energy consumption in the garage is neglected. The breakdown by end uses is similar for each home.

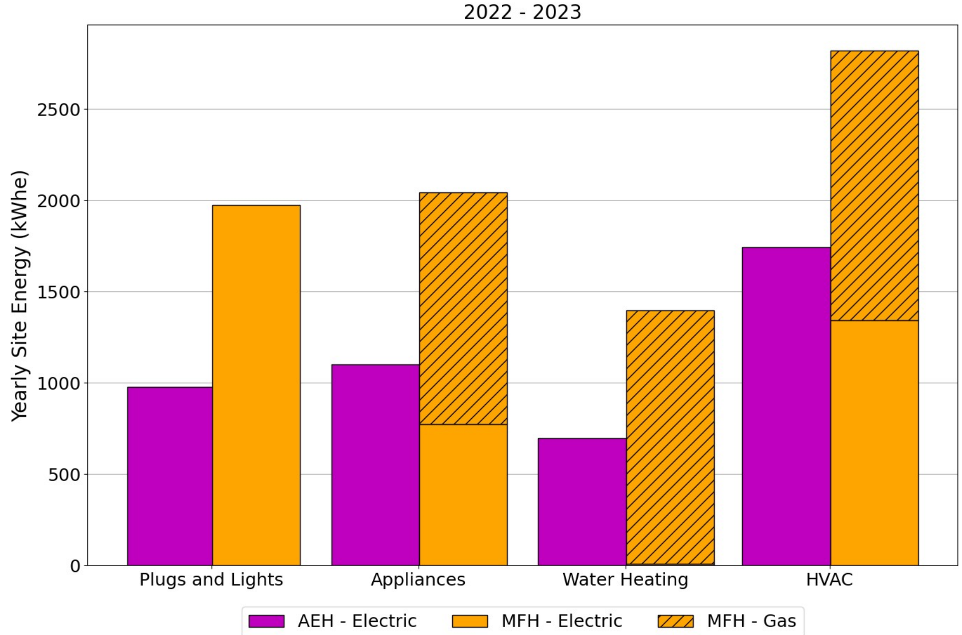
Figure 19: Comparison of End-Uses. Left – MFH (without garage), Right – AEH.



Source: Frontier Energy

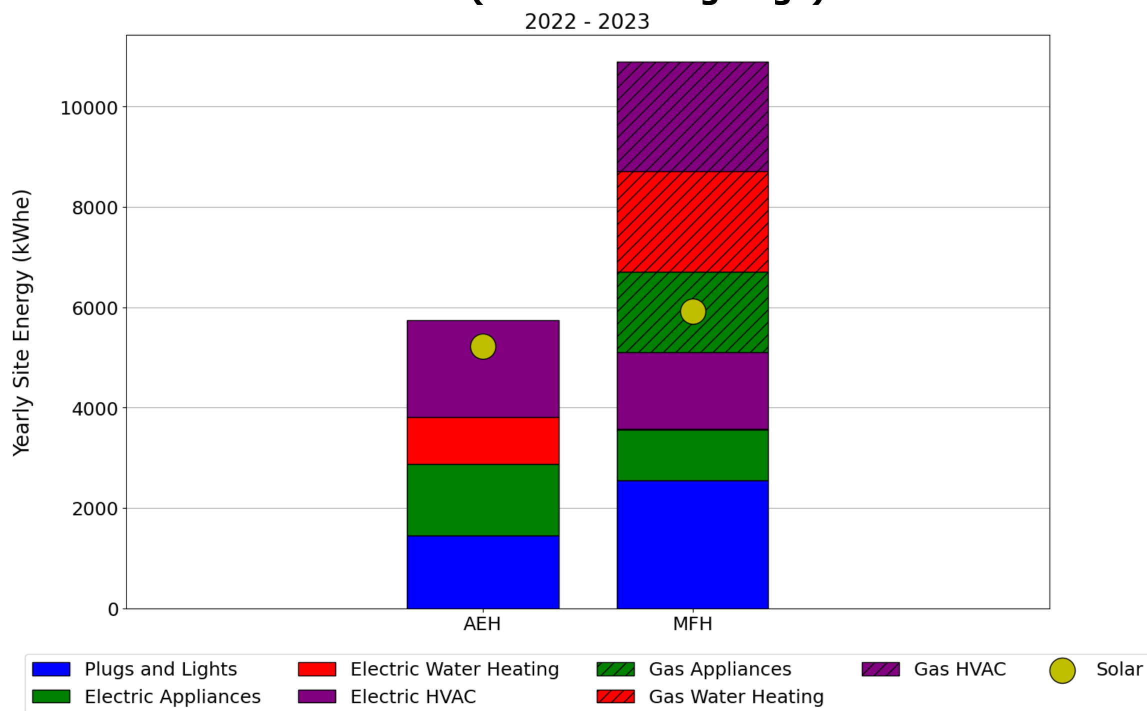
Figure 20 compares the energy consumption by end use across both homes. Consumption for the MFH is higher than that in the AEH across end uses. Note that this does not show the impact of PV production. Figure 21 shows this comparison in a different format and includes solar production. Again, it is evident that energy consumption in the MFH is much higher in all categories. These charts do not include the energy consumption for the MFH garage.

Figure 20: Energy Consumption of Homes, June 2022 through May 2023 by End-Use and Fuel (without MFH garage).



Source: Frontier Energy

Figure 21: Total Energy Consumption of Homes, June 2022 Through May 2023 by End-Use (without MFH garage).

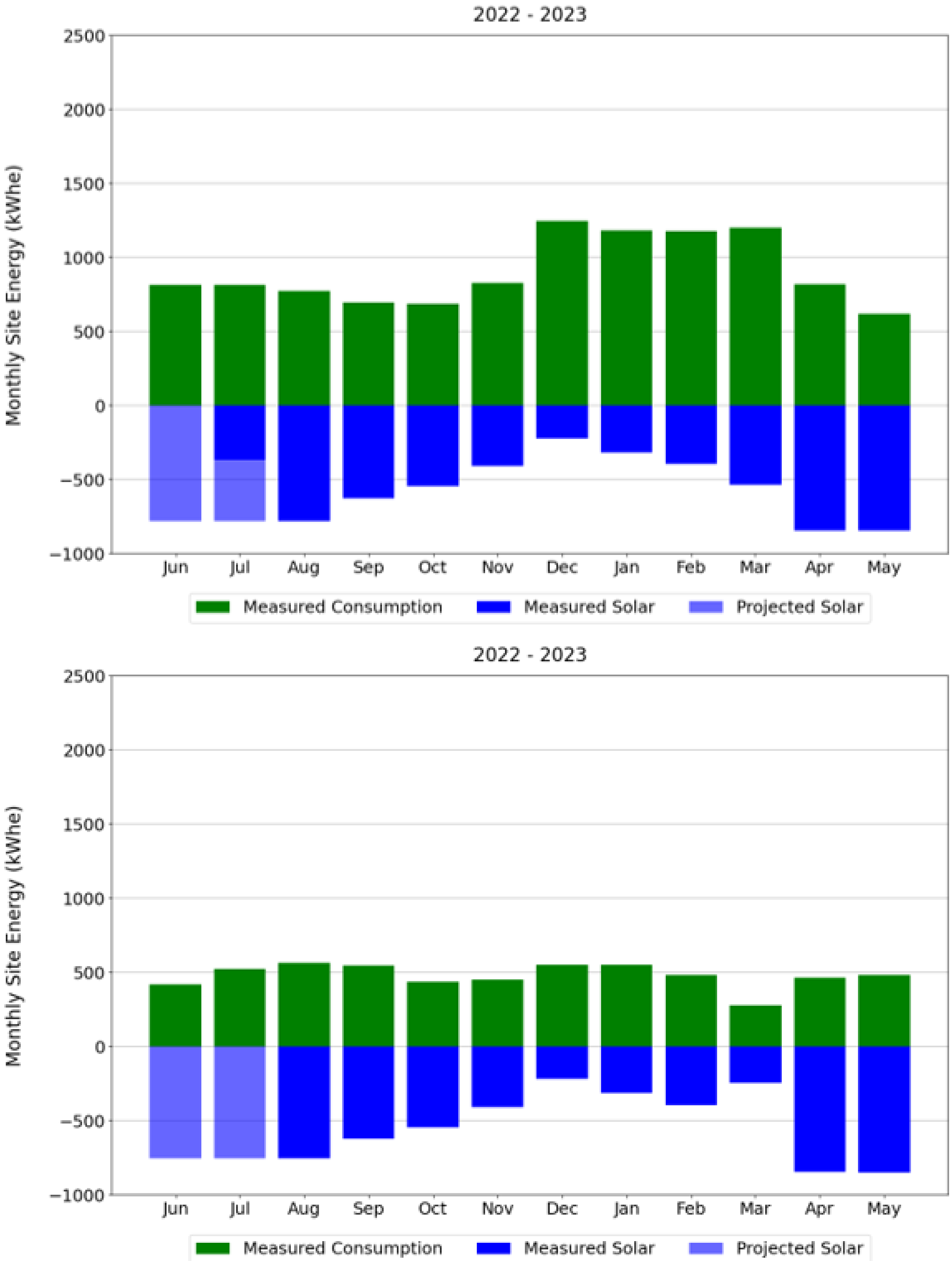


Source: Frontier Energy

Figure 22 shows the monthly energy consumption and solar production for a year to enable assessment of ZNE goal achievement. The estimated solar generation for the period before which solar data became available (June and part of July 2022, shown with lighter shading) were extrapolated by looking at production in similar months. The data for the MFH in Figure

22 does not include the energy consumed in the garage.

Figure 22: One Year Performance of Homes. Top – MFH (without garage), Bottom - AEH.



Source: Frontier Energy

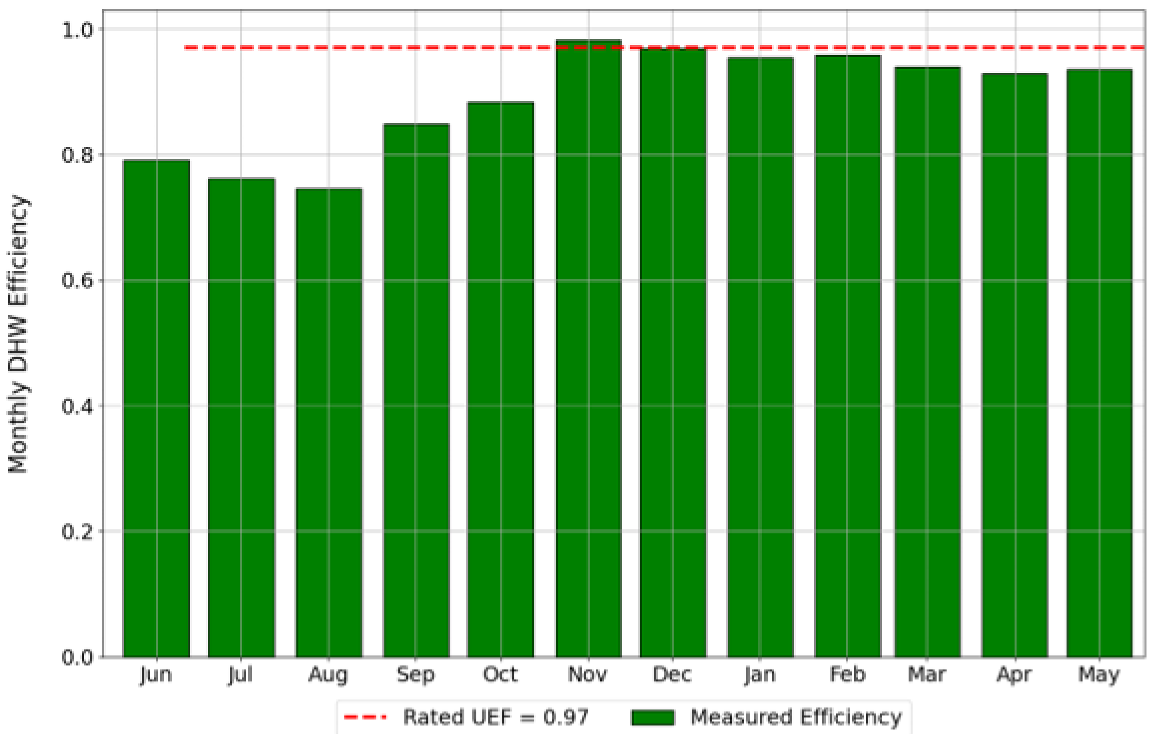
DHW Analysis

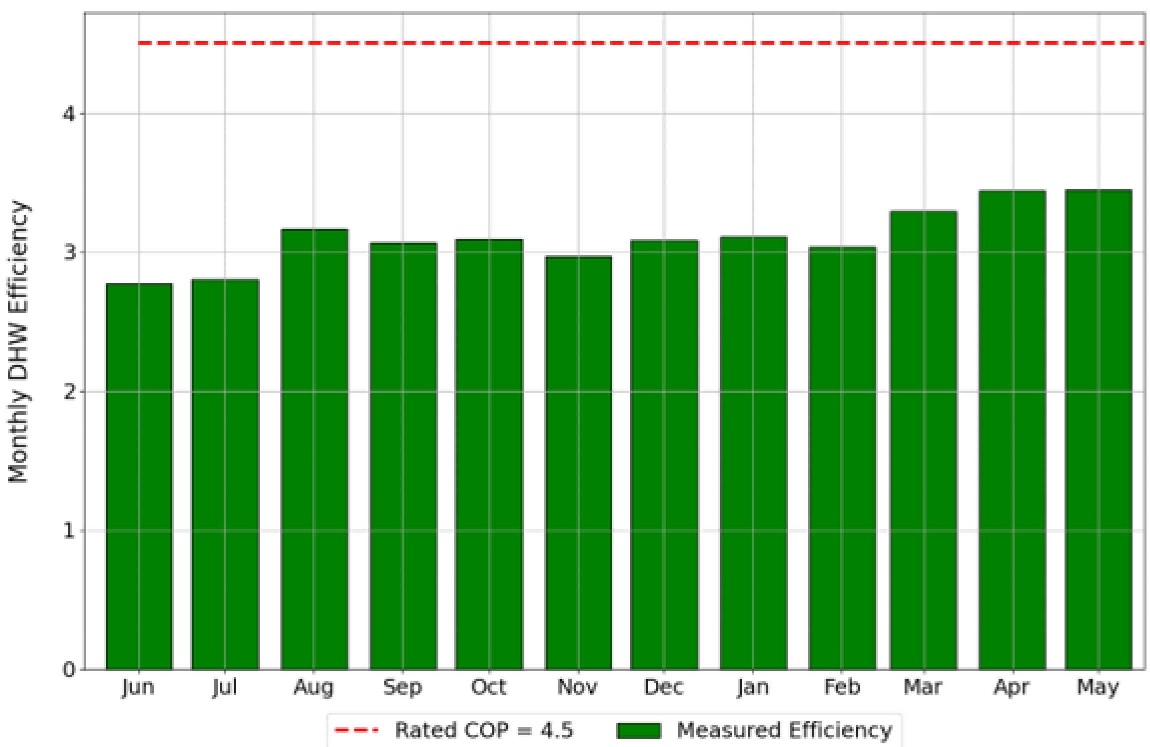
Figure 23 shows the monthly hot water system efficiency of both homes compared to the rated efficiency from the manufacturer's specifications. For both homes, system efficiency is defined as the total thermal energy delivered to the loads - DHW for the AEH and DHW + Fan Coil for the MFH - divided by the total energy consumed for electricity plus gas, in site units.

At the AEH, the Sanden HP had a rated average mid-season COP of 4.5. For the MFH, the Navien gas-fired tankless water heater had a rated UEF of 0.97. UEF is slightly different than a simple average efficiency, but it is more difficult to measure in a field study, and it still provides an adequate frame of reference of the expected efficiency of this system.
The air-to-water HP at the AEH had an average measured efficiency for the year of 3.13. This is about 30.4% lower than the manufacturer's mid-season rating.

The hot water system at the MFH had an average measured efficiency of 0.94, which is just 3.1% below the UEF. The efficiency and UEF are not directly comparable, but it is a useful benchmark. The slight dip in efficiency during summer months may be because the system is also used for heating, and the total delivered capacity is lower during the summer months, lowering the overall operational efficiency.

Figure 23: Monthly DHW Performance. Top – MFH, Bottom – AEH.

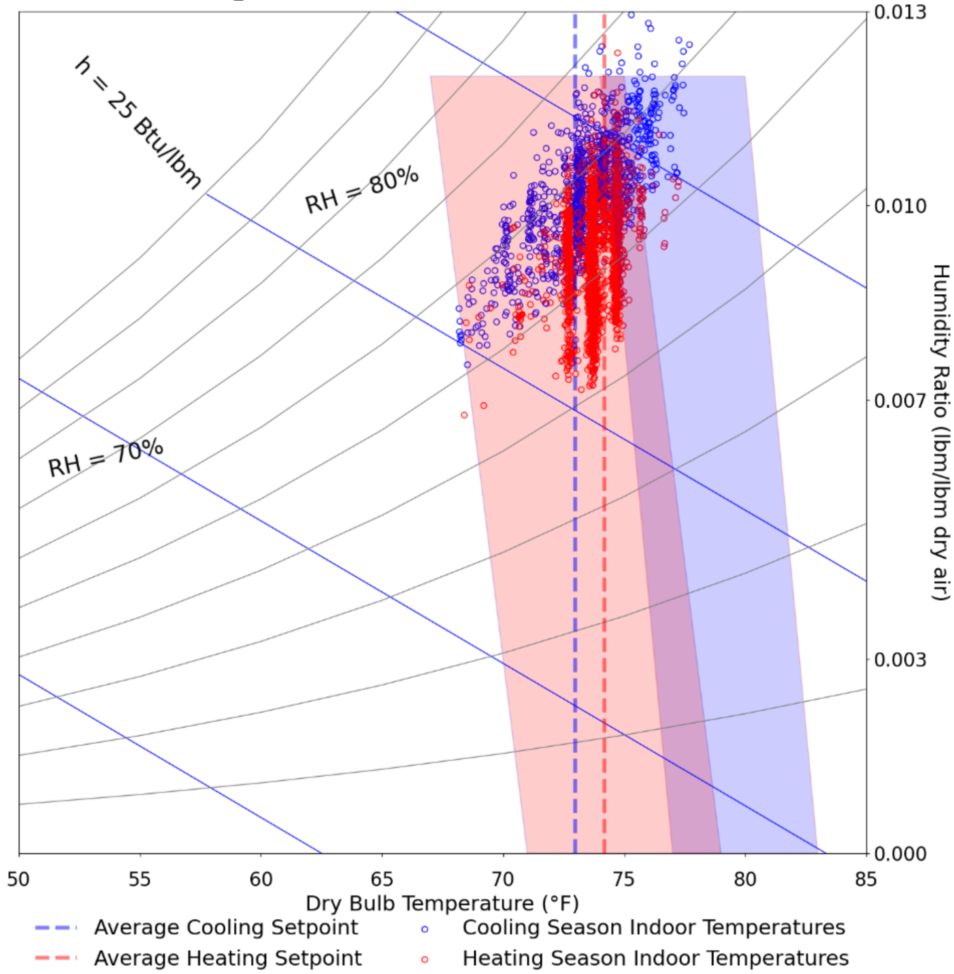




Source: Frontier Energy

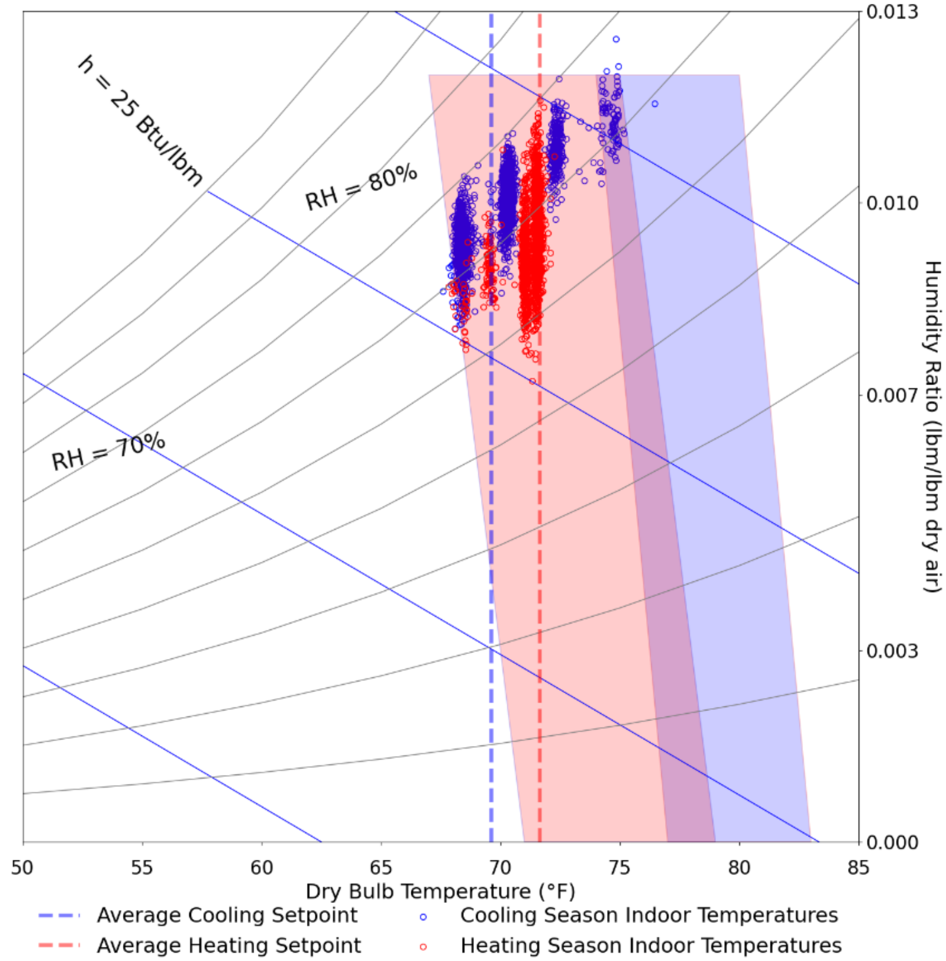
Occupant comfort through space conditioning was also a focal point. Figure 24 and Figure 25 show hourly average indoor temperatures and RH in the two homes. Points in blue indicate hours when cooling took place, and points in red indicate hours when heating took place. The charts also show the average temperature setpoints when the systems were operating - as blue and red vertical dotted lines. These data are plotted on a psychrometric chart and are superimposed on a graphical representation of the ASHRAE Comfort Zones for summer and winter. These charts indicate that in summer, both homes had setpoints and resulting temperatures significantly below the Comfort Zones. The MFH seemed not tightly controlled while the AEH had a very tight distribution. In winter, setpoints and resulting temperatures were well within the comfort zones and tightly controlled. These results suggest that occupants chose to use the air conditioning (cooling) more than one might otherwise expect.

Figure 24: Comfort Chart for MFH.



Source: Frontier Energy

Figure 25: Comfort Chart for AEH.



Source: Frontier Energy

Homeowner Surveys

To gather more insight into how the occupants used their homes, the project team sought responses to survey questionnaires to ask about summer and winter operation and indoor comfort conditions. Two surveys were performed – Summer 2022 and Winter 2022-23 - and the responses are listed separately. The Questionnaire template from the Summer 2022 survey is provided in Appendix A.

Summer 2022 Survey

Both homes had similar occupancy, typically three occupants, and similar usage - the AEH had occupants who stayed home with a young child during the day, and the MFH had one person working from home.

There were differences in behavioral patterns. The MFH did 10 loads/week of laundry using warm water vs. 6 loads/week in the AEH using cold water. The AEH reported more showers per week but of shorter duration for a similar cumulative weekly time period as the MFH. The AEH had a refrigerator or freezer in garage. Only the MFH reported using operable windows for cooling. In addition to the large renovation in the garage that entailed adding a bathroom and window heat pump unit, the MFH reported using a space heater in the master bedroom, day and night.

The AEH reported a cooling setpoint of 71°F, while the field monitoring recorded 68-70°F). MFH reported 74°F, while the monitoring recorded 73°F. Homeowners at both homes noted in personal conversations how excited they were to have solar homes, as it allowed them to use their HVAC systems much more than they were used to.

When asked about their household's goal for using heating and cooling equipment, AEH selected "We try to be frugal, but we want to be comfortable too" and MFH selected "We use the heater and AC as much as we need it to be comfortable." When asked to describe their thermostat setpoint, AEH selected "A compromise between comfort and controlling energy bills", and MFH selected "Entirely to be Comfortable."

Both homes reported that they really liked their systems, and while the MFH home did report experiencing discomfort, they said that it did not rise to the level of a problem.

Winter 2022-23 Survey

The occupancy profiles were similar to the previous survey. AEH had occupants who stayed home with a young child during the day and the MFH had one person working from home.

Compared to summer 2022, occupants of the AEH increased laundry loads from 6 to 14 per week and changed from cold water to warm water. The MFH reduced laundry loads from 10 to 5 loads per week and changed from warm to hot water. The MFH increased from 2 to 5 dishwasher loads per week, while the AEH initially did only one load per week, and then stopped using the dishwasher. MFH reported a similar number of baths/showers as the AEH, but of longer duration, so water heating energy consumption for the MFH was expected to be higher. The AEH continued using a refrigerator or freezer in the garage.

Regarding use of heating and cooling equipment, AEH still selected "We try to be frugal, but we want to be comfortable too." While the MFH originally selected "We use the heater and AC as much as we need it to be comfortable" for the summer, they switched to "We try to be frugal, but we want to be comfortable too" for the winter. MFH reported using a space heater in the master bedroom, day and night. The MFH reported using operable windows for cooling.

Regarding comfort, MFH occupants reported that they never experienced discomfort. The AEH reported that they never or almost never experienced discomfort in any rooms. When asked to describe their thermostat setpoint, both AEH and MFH selected "Entirely to be Comfortable" for the winter. The AEH reported a heating setpoint of 72°F and the MFH reported a heating setpoint of 74°F, both of which were validated with monitoring). Table 4 and Table 5 summarize the homeowner responses of both homes to the two surveys.

Table 4: Occupancy and Use of Appliances.

	AEH Summer	AEH Winter	MFH Summer	MFH Winter
Occupants, typically	3 typically, including someone home with child.	3 typically, including someone home with child.	3 typically, at least one works from home.	3 typically, at least one works from home.

Laundry	6 loads per week, cold water, no line drying.	14 loads per week, warm water, no line drying.	10 loads per week, warm water, no line drying.	5 loads per week, hot water, no line drying.
Dishwasher	1 load per week	Stopped using.	2 loads per week.	5 loads per week.
Baths/ showers	28 per week, avg 5 min.	27 per week, avg 10 min.	6 per week, avg 25 min.	20 per week, avg 20 min.
Garage refrigerator/ freezer	Yes.	Yes.	None.	None.

Source: Frontier Energy

Table 5: Use of Space Conditioning Systems.

	AEH Summer	**AEH Winter**	**MFH Summer**	**MFH Winter**
Goal	Try to be frugal but want to be comfortable too.	Try to be frugal but want to be comfortable too.	Use HVAC as much as needed to be comfortable.	Try to be frugal but want to be comfortable too.
Extra conditioning equipment	None.	None.	Room/Window AC, almost never used. Opened windows quite a bit.	Room/Window heating unit, never used, portable electric space heater used only when really needed ("I'm always cold so I used it to warm my room").
Discomfort	Never or almost never.	Never or almost never.	Discomfort often in most rooms, but not a problem.	Never or almost never.
Thermostat	Turned on and off very infrequently; Setting 71°F most of the time.	Turned on or up when feeling cool. Never turned off except once during Thanksgiving. Setting 72°F most of the time.	Turned on or up when feeling warm, off or down when feeling cool. Setting 74°F most of the time. Programmed: 70° (unoccupied), 74° (evening), 73° (sleeping). Very confident in programming.	Turned on or up when feeling cool, off or down when feeling warm. Setting 74°F most of the time.
Thermostat choice	A compromise between comfort and controlling energy bills.	Entirely to be comfortable.	Entirely to be comfortable.	Entirely to be comfortable.

Liked most	Home was so cold.	That we were warm all winter long and the energy bill was low.	"System works super good."	Getting used to having a heating system.

Source: Frontier Energy

Energy Use Intensity and ZNE Verification

Table 6 presents the energy use intensity (EUI) for the two homes using measured data for the period June 2022 – May 2023. EUI is defined as the annual energy consumed per square foot of floor area. The EUI calculations excluded the MFH garage. For each home, values are shown for consumption and production, as well as for the net consumption or generation. It is noted that for California climate zone 12, where Stockton is located, a "good" EUI consumption is 16.6 kBtu/ft^2-year (*Arup, 2012*).

The MFH EUI was much higher than expected and the net consumption considering solar generation was also high, although the net EUI is lower than a typical non-solar house and lower than a good EUI for Stockton. The AEH consumption EUI was average and, when solar generation is considered, the net consumption was negative, showing that the ZNE goal was met by the AEH.

Table 6: Total Annual Energy Use Intensity for the MFH (without the garage) and the AEH.

Mixed Fuel Home			All Electric Home		
Consumption	**Production**	**Net**	**Consumption**	**Production**	**Net**
30.8	-20.2	10.7	16.3	-19.1	-2.8

Source: Frontier Energy

It needs to be emphasized that substantial behavioral differences between the two homes were observed. The difference between the EUI of the AEH and the MFH is not a reflection of the different fuel sources used in the two homes.

BEopt Modeling

Model Calibration

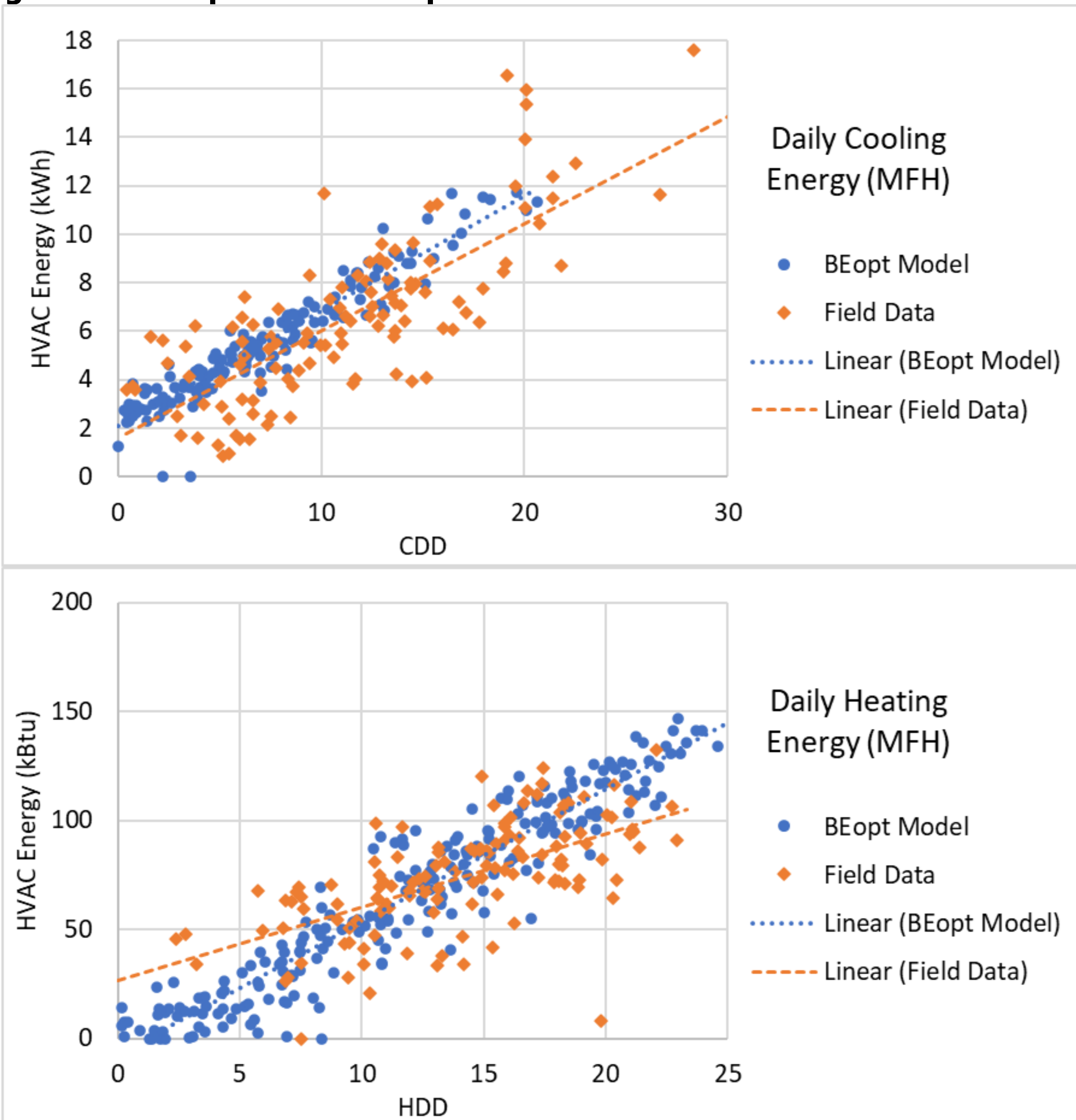
BEopt models of the two ZNE homes were created to match the characteristics of the as-built homes as closely as possible with respect to the construction, equipment specifications and lighting. The heating and cooling set points were selected to match those from the field monitoring. The modeled hourly heating and cooling energy consumption results were generated and aggregated to daily values, which were then compared to aggregated daily field monitored data from the two homes.

Figure 26 and Figure 27 compare the BEopt model results with field data for the MFH and AEH, respectively. The daily cooling energy use values were plotted against cooling degree day (CDD) values, while the daily heating energy use values were plotted against heating degree day (HDD) values. Degree days indicate how cold or warm a location is and are proportional to the expected heating and cooling energy consumption. A degree day is calculated as the difference of the mean daily outdoor temperature with a standard temperature of 65°F. The more extreme the outside temperature, the higher the number of degree days and greater the need for space heating or cooling.

The CDD and HDD values for the field data were calculated using the measured on-site outdoor temperatures. The BEopt models used a standard, built-in weather file for California climate zone 12, which is representative of Stockton weather, and the CDD/HDD values were calculated using the weather file data.

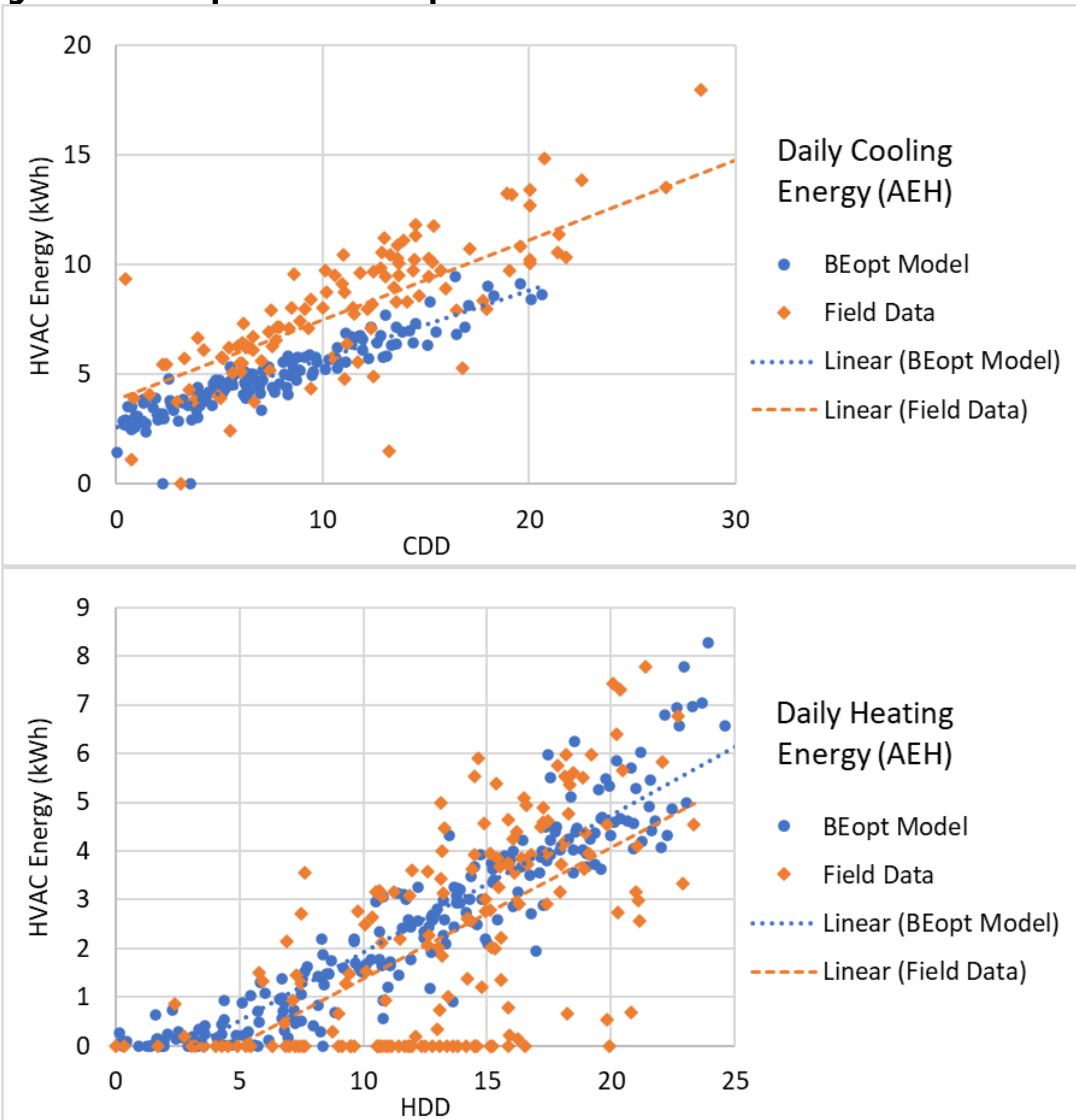
Reasonable agreement between the BEopt model results and field data were observed. In the case of the AEH BEopt model, the SEER of the mini-split heat pump needed to be lowered to 20 to get a good match with the daily cooling energy field data.

Figure 26: Comparison of BEopt Model Results with Field Data for the MFH.



Source: GTI Energy

Figure 27: Comparison of BEopt Model Results with Field Data for the AEH.



Source: GTI Energy

Comparison with 2016 Title 24 Building Energy Standards

Following calibration of the BEopt models of the as-built ZNE homes, these models were compared to Title 24 2016 homes of the same size and construction. Additional BEopt models for the Title 24 homes were created. For the comparative modeling, typical heating and cooling set points of 68°F and 78°F were assumed. Both the ZNE and Title 24 models used the standard weather file for California climate zone 12.

Table 7 lists the key differences between the models of the ZNE and Title 24 homes. The envelope, HVAC and water heater specifications for the Title 24 homes were taken from the 2016 Building Energy Efficiency Standards for Residential and Nonresidential Buildings (2016 Building Energy Efficiency Standards Reference Ace Tool).

Table 7: Key Differences Between the BEopt Models of the ZNE and Title 24 Homes.

	ZNE	Title 24 2016
Wall insulation	R-21 cavity + R-5 exterior	R-19 cavity
Attic insulation	R-42	R-19
Central air conditioner (MFH)	16 SEER / 13 EER	14 SEER / 12 EER
Space heating and water heater (MFH)	Condensing, 98% AFUE tankless water heater	80% AFUE furnace; Tankless gas water heater, 0.82 energy factor
Mini-split heat pump (AEH)	20 SEER / 12.5 HSPF	14 SEER / 7.4 HSPF
Water heater (AEH)	3.75 UEF HPWH	Electric standard, 0.92 energy factor

Source: GTI Energy

Table 8 compares the heating, cooling, and hot water annual energy use between the ZNE and Title 24 2016 home models. The models estimate a 48.2% reduction in the ZNE AEH compared to its Title 24 counterpart. In the case of MFH, the natural gas consumption for space and water heating in kBtu was converted to kWh using the conversion factor of 1 kWh = 3.412 kBtu. The modeled cooling energy use was estimated to be 4% higher in the ZNE MFH compared to the Title 24 MFH. While this is counter-intuitive, the ZNE MFH has much higher insulation in the exterior walls and roof compared to the modeled Title 24 MFH, which could serve to trap the internal heat generation by occupants, appliance, etc. and increase the cooling load. Since the modeled ZNE home had an air conditioner that is only slightly more efficient than the Title 24 MFH (SEER 16 vs. 14), it is possible for ZNE home cooling energy consumption to be higher. The total modeled site energy use, in kWh, was lower for the ZNE MFH by 21.4% compared to the Title 24 MFH.

Table 8: Comparison of Modeled Annual Heating, Cooling and Hot Water Energy Use in the ZNE and Title 24 2016 Homes.

	ZNE AEH	Title 24 2016 AEH	ZNE MFH	Title 24 2016 MFH
Cooling (kWh)	311	386	428	411
Heating (kBtu)			7,153	10,260
Heating (kWh)	351	830	2,096	3,007
Hot Water (kBtu)			9,283	11,094
Hot Water (kWh)	1,393	2,748	2,720	3,251
Total (kWh)	2,055	3,964	5,244	6,669
Percent Reduction	48.2%		21.4%	

Source: GTI Energy

Cost-effectiveness

Since many of the building components were donated and volunteer labor was used to build the ZNE homes, it is difficult to accurately estimate the as-built cost of these homes. Furthermore, the integrated design process and advanced construction methods used are not standard industry practices. Hence, a direct cost comparison between these ZNE homes and typical single-family homes is not possible.

However, there are significant opportunities for both capital and operational cost reductions in the ZNE homes, which can contribute to the overall cost-effectiveness and affordability. As noted in previous sections the framing factor and area fraction of the windows were both reduced to about 12% of the total wall from the industry standard of 35%, which is a 60% reduction in lumber and windows. These reductions can lower material costs and reduce the envelope generated heating and cooling loads, with associated reductions in energy bills. The AEH heat pump was sized to be ¾ ton compared to a 4-ton unit that would be typically installed in a similar sized home; an 81% reduction in size.

Based on personal communications with a member of the design and construction team, the amount of wall sheathing material needed for the ZNE homes was 20% lower than typical homes. Also, the ductwork in the ZNE homes was about 50′ compared to 300′ in typical homes. The plumbing pipes were designed to be extremely compact resulting in lower material costs, reduced heat losses and lower amount of wasted water (due to faster access to hot water from faucets and shower heads).

If all or some of these measures become standard industry practice, they can result in significant cost savings in single family homes.

Knowledge Transfer

Knowledge transfer was a key factor for the success of this project and conveying the knowledge to home builders was particularly important. Ensuring home builders are familiar with the latest construction techniques and best practices so that the measures from this project may be practiced in future home developments.

Published Documents

An e-book was written by the project team members, titled Real-World Zero Net Energy Homes for California, which condensed decades of industry experience on topics surrounding ZNE homes (*Real-World Zero Net Energy Homes for California 2020*). The e-book outlines cost-effective methods and designs for constructing new homes that can produce the same amount of energy as they consume over the course of a year. This information was gleaned from a 10-year process of planning, designing, building, and monitoring the performance of houses in the Zero Net Energy Dream Creek neighborhood in Stockton, California. Dream Creek is a 14-home development project led by the San Joaquin County Habitat for Humanity organization, with George Koertzen as the Principal Designer and Construction Project Manager. This project team of California design, construction, and engineering experts provided additional technical commentary and advice to builders. The e-book is available for purchase on Amazon and a free online version is available at the GTI Energy website (Real-World-ZNE-Homes-for-California).

A conference paper was also published at the 2018 Summer Study on Energy Efficiency in Buildings by the American Council for an Energy-Efficient Economy (*Leslie et al., 2018*). This article summarized the design strategies used to meet ZNE performance affordably in the two homes and provided insights on creative approaches and challenges when trying to apply cost-effective solutions to real-world affordable new construction.

Trainings and Webinars

As part of the knowledge transfer goals, the project team conducted a number of training webinars to share practices and techniques used from this project. The first round of builder training presentations was held on November 5, 12, and 19, 2020. The following presentations were made:

- High Performance Mechanical Systems for Affordable Zero-Net-Energy Homes, Mike MacFarland, Energy Docs Home Performance Contractor
- Zero Energy/Electricity/Emissions Homes, Design Part 1: Fundamentals, Ann Edminster, Design Avenues
- Zero Energy/Electricity/Emissions Homes, Design Part 2: Nuts & Bolts of Achieving ZNE on Budget, Ann Edminster, Design Avenues
- High Performance Building Enclosures for Zero Energy Homes Parts 1 & 2, Steve Easley

The final round of training webinars was held during March 21 and 24, 2023, and included the following presentations:

- Affordable Zero Net Energy Homes, Final Training Webinar Part 1: Fundamentals, Ann Edminster (Design Avenues)
    - George Koertzen was elevated to panelist status and provided additional details on the design and construction process.
- Affordable Zero Net Energy Homes, Final Training Webinar Part 2: Project Outcomes & Lessons Learned, Ann Edminster (Design Avenues) and Kristin Heinemeier (Frontier Energy)

Details of these training webinars are contained at the GTI Energy webpage (GTI Energy Affordable ZNE).

Conclusion

Current construction of site-built homes is dictated by a cost-first, sequential, disintegrated design and installation approach, where the different trades and contractors try to reduce costs without considering how all the systems in the home function together. This makes it difficult to cost-effectively achieve energy efficiency and comfort. Developing and refining principles and practices for new construction is a necessary step to achieve affordable newly constructed ZNE homes and help the state achieve aggressive GHG reduction targets. This project demonstrated that affordable ZNE homes are achievable using low-cost construction techniques, on-site renewable energy and high-performance IPD approaches.

Monitoring of the two ZNE homes showed two very different energy usage patterns. The MFH had much higher consumption than the AEH. While the homes had similar end use breakdowns, each end use consumption in the MFH was about twice that of the AEH. HVAC and appliances were the largest end-uses, with the remainder fairly evenly split between DHW and plug loads and lights.

Both homes had lower setpoints for cooling and higher set points for heating than is typical, and they both noted that they used their HVAC much more than they would have if they didn't have solar. Owners of both homes reported that they were happy with their systems and did not report any major comfort-related issues. The AEH had fairly low energy consumption, projected to be somewhat below that of other homes in the area over a year. In addition, its solar production was significant, and it is projected to have a negative net energy consumption over its first year of operation. While the MFH had very high consumption, with the contribution of its solar production, its annual energy use is projected to still be significantly below that of similar-sized industry standard homes.

The MFH homeowners made modifications to the garage, to add a bathroom, a small through-the-wall heat pump unit and a mini fridge in the garage. These additions significantly increased their overall energy consumption. Since these additions were not part of the original design, they were excluded from the ZNE analysis and calculations. It is noted that the differences in the monitored energy performance of the two homes were primarily driven by behavioral differences of the homeowners and is not a direct reflection on the different fuel sources in the two homes.

A clear take away of the M&V findings is the importance of behavior, and perhaps that with installation of solar, a home can still accommodate very energy-intensive operational choices. For future installations, it may be advisable to work with the homeowners to educate and inform them about how their energy bills and associated carbon footprint can still be improved with modifications to their energy-using choices, even though they have a solar home.

Building energy modeling of the ZNE homes and comparison with Title 24 2016 homes of the same construction and footprint showed savings of 23.7-48.2% in heating, cooling, and hot water energy consumption.

This project demonstrated several benefits for the state of California:

- Cost-effectiveness and affordability: Examples of cost savings include right-sized HVAC and advanced framing methods that reduced lumber and windows by 60% compared to typical homes, reduction of HVAC heat pump size by 80%, and significantly reduced amount of plumbing pipes and ductwork.
- Environmental benefits: Reduced HVAC loads and energy consumption of these two ZNE homes will result in lower greenhouse gas emissions. The energy consumption of the AEH was measured to be 16.3 kBtu/ft^2-year, reduced to an annual net EUI of -2.8 kBtu/ft^2-year with solar. The MFH was an example of high energy consumption behavior, but with solar, it showed a net EUI of 10.7 kBtu/ ft^2-year.
- Consumer appeal: These high-performance homes provided acceptable occupant comfort and high occupant satisfaction, based on monitored data and survey responses.

While the project team is not currently pursuing any new projects directly as an outcome of this project, the learnings of this project need to be broadly disseminated to stakeholders and policymakers. Broad implementation of the design and construction aspects of this project can provide significant benefits in terms of energy savings, GHG reductions and cost savings for consumers. Additional development and demonstrations of tailored ZNE homes in different regions of California, with different climate types, snow loading, seismic requirements, etc., can be of value.

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Project Deliverables

The project includes the following deliverables:

- Final Report Outline (Draft & Final)
- Draft Final Report
- Final Report
- ZNE Pilot Test Houses Design Details
- CPR #1 Report
- Monitoring Plan (Draft & Final)
- Construction Details Report (Draft & Final)
- Measurement and Verification Report (Draft & Final)
- Real-World Zero Net Energy Homes for California
- Training Materials - Affordable ZNE
- Summary of Training Classes Conducted - Affordable ZNE
- Kick-off Meeting Benefits Questionnaire
- Mid-term Benefits Questionnaire
- Final Meeting Benefits Questionnaire
- Initial Fact Sheet (Draft & Final)
- Final Project Fact Sheet (Draft & Final)
- Presentation Materials (Draft & Final)
- High Quality Digital Photographs
- Photo Waiver and Release Form
- Technology/Knowledge Transfer Plan (Draft & Final)
- Technology/Knowledge Transfer Report (Draft & Final)

Appendix A: Sample Survey Questionnaire

1. **During the following periods on a typical weekday, how many people are in your home in each age category?**

			Young Children (0-5)	*Older Children (6-13)*	*Teens (14-17)*	*Adults (18-60)*	*Seniors (> 60)*
2:00 am	-	6:00 am					
6:00 am	-	10:00 am					
10:00 am	-	2:00 pm					
2:00 pm	-	6:00 pm					
6:00 pm	-	10:00 pm					
10:00 pm	-	2:00 am					

2. **How many loads of laundry are washed in your home in a typical week?**
   ________________________loads/wk

3. **What temperature water do you usually use for your clothes washer?**
   (Check the response that is closest). ○ Cold ○ Warm
   ○ Hot

4. **Do you dry at least some of your laundry outside on a clothesline or rack?**
   ○ Yes ○ No

5. **Do you use an automatic dishwasher?**
   ○ Yes ○ No

- **If so, about how many loads of dishes do you clean in a typical week?**
  ____________________________loads/wk

6. **How many baths or showers are taken in your home in a typical week?**
   ________________baths/showers/wk

7. **Do you use a refrigerator or freezer in the garage?**
   ○ Yes ○ No

8. **Do you have any appliances or devices that you suspect might use a lot of energy (for example, a heater for a reptile cage, or car charger)? Please describe how much energy it uses or how often you use it.**

____

____

FOR THE REMAINING QUESTIONS, THINK ABOUT THIS PAST SUMMER—THE SUMMER OF 2022 …

9. Which best describes your household's goal for using cooling equipment last summer?
(Select only the one that is closest)

- ○ *We try to use the equipment as little as possible.*
- ○ *We use the equipment as much as we need it to be comfortable.*
- ○ *We try to be frugal, but we want to be comfortable too.*

10. How often (if ever) did your household use the following types of cooling equipment to keep cool and comfortable this summer? *(please select the best description, for each row)*

	We didn't have this equipment.	*Used it just about all summer.*	*Used it quite a bit.*	*Used it only a few days or nights, when really needed.*	*Almost never used it.*	*Never used it.*
Central AC system.	O	O	O	O	O	O
Room/window air conditioner.	O	O	O	O	O	O
Ceiling, table, or floor fans.	O	O	O	O	O	O
Whole-house fan.	O	O	O	O	O	O
Window fans.	O	O	O	O	O	O
Opened windows to cool off	O	O	O	O	O	O
Other (please specify:__________________).	O	O	O	O	O	O

11. This summer, how often did your household feel uncomfortably hot in each of the following rooms, and if so, how much of a problem was it? *(For each room, select the one answer that best describes how you felt)*

	Often, and it WAS a problem.	*Often, but it was NOT a problem.*	*Sometimes, and it WAS a problem.*	*Sometimes, but it was NOT a problem.*	*Never or almost never.*
Living Room	O	O	O	O	O
Kitchen	O	O	O	O	O
Family Room	O	O	O	O	O
Largest Bedroom	O	O	O	O	O
Smallest Bedroom	O	O	O	O	O
Other Important Room (specify)	O	O	O	O	O

____
____

12. What did your household like MOST about your primary cooling system last summer?

13. What did your household like LEAST about your primary cooling system last summer?

14. Last summer, if you ever came home to a hot house, how long did it usually take to get it to a comfortable temperature?

_________ minutes

15. How did your household mostly control your cooling equipment this summer? Choose which of the following four approaches *best* describes your strategy.
(Please check only one of the four approaches and answer the questions that follow.)

O *We turned cooling equipment on or off, or up or down, as needed.*

We typically turned it **ON** *or* **UP** *for the following reasons: (Please check all that apply)*

- ☐ *When we woke up.*
- ☐ *When we returned home.*
- ☐ *When we started to feel uncomfortably warm.*
- ☐ *When we became so uncomfortably hot we had to turn it on.*
- ☐ *Other (please explain):*

We typically turned it **OFF** *or* **DOWN** *for the following reasons: (Please check all that apply)*

- ☐ *When we left home for the day.*
- ☐ *When we went to bed.*
- ☐ *When things cooled off outside and we could do without cooling.*
- ☐ *When we started to feel uncomfortably cool.*
- ☐ *As soon as possible to save energy, even though we were still somewhat uncomfortably warm.*
- ☐ *Other (please explain):*

O *We used a thermostat to set one temperature, and left it there most of the time.*

What was that temperature, typically?
Which of the following best describes that temperature?

Comfortable	*Mostly Comfortable*	*Balanced*	*Mostly Energy-Saving*	*Energy-Saving*
O	O	O	O	O

O *We used a thermostat to set one temperature for the day, but then manually changed to an* ***energy-saving setting**** *for the night or for when no one was at home.*

What was the typical temperature setting in the morning as you prepared to leave?
What was the typical temperature setting when no one was home?
What was the typical temperature setting during the evening?
What was the typical temperature setting when people slept?
How often (times/week) did you typically switch it to this energy saving setting?

O *We programmed the thermostat so that different temperatures were automatically maintained at different times of the day and night, or used a "smart" thermostat.*

What was the typical temperature setting in the morning as you prepared to leave?
What was the typical temperature setting when no one was home?
What was the typical temperature setting during the evening?
What was the typical temperature setting when people slept?
How confident were you that it was programmed correctly?

Very confident.	*Somewhat confident.*	*Not very confident.*	*Not at all confident.*	*I don't know.*
O	O	O	O	O

Examples of energy-saving settings include increasing the thermostat's temperature setting or turning the equipment down or off.