FINAL REPORT

Zero Energy Housing for Military Installations
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LIST OF ACRONYMS

BLCC	Building Life-Cycle Cost Program
Btu	British thermal unit
CBE	Center for the Built Environment
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalents
CTC	Concurrent Technologies Corporation
DoD	Department of Defense
DOE	Department of Energy
EO	Executive Order
ERV	energy recovery ventilator
ESTCP	Environmental Security Technology Certification Program
EUI	energy use intensity
FEMP	Federal Energy Management Program
FY	fiscal year
GHG	greenhouse gas
GSA	General Services Administration
GSHP	ground source heat pump
HVAC	heating, ventilation, and air-conditioning
IRR	internal rate of return
JNCO	Junior Non-Commissioned Officer
kBtu	thousand Btu
kWh	kilowatt-hour
LCC	life-cycle cost
LCCA	life-cycle cost analysis
LEED	Leadership in Energy and Environmental Design
MARR	minimum acceptable rate of return
MMBtu	million Btu
NCDC	National Climatic Data Center
NDCEE	National Defense Center for Energy and Environment
NREL	National Renewable Energy Laboratory
NIST	National Institute of Standards and Technology
NPV	net present value
O&M	operations and maintenance
PPV	public-private venture
PV	Photovoltaics
Q/A	quality assurance
RECS	Residential Energy Consumption Survey
SEER	seasonal energy efficiency rating
sf	square feet
SHGC	solar heat gain coefficient
TED	The Energy Detective
TMY	typical meteorological year
USGBC	U.S. Green Building Council
WUI	water use intensity
ZEH	zero energy home

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EXECUTIVE SUMMARY

This project evaluated the design approach and operational performance of two zero energy housing units compared to two typically designed (baseline) housing units. One net zero energy duplex consisting of two housing units was designed and constructed at Fort Campbell, Kentucky. A baseline duplex identical to the standard housing design in this neighborhood was also designed and constructed next to the zero energy duplex. These housing units were the same size, floor plan, and orientation, and housed families with similar characteristics to minimize differences between the housing units. Table ES.1 summarizes the location and housing unit characteristics.

Table ES.1. Location and Housing Unit Characteristics

Metric	ZEH and Baseline Housing Units
Location	Fort Campbell, KY
Climate zone	Mixed humid
Cost of energy[a]	7.9¢/kWh
Cost of water[a]	$1.58/kGal
Floor space per unit	2492 square feet
Bedrooms/Baths	4/2.5

[a] Utility costs were covered by Fort Campbell and not incurred to the homeowners.

The ZEH design included high levels of insulation, high performance windows, a ground source heat pump, an energy recovery ventilator, and low flow water fixtures. Renewable energy systems were photovoltaic panels located on the metal roof and solar hot water heating. One of the design constraints was to minimize perceived differences in housing equity between the families participating in the project and other Fort Campbell housing units. That constraint limited changes to the layout and floor plan that could have resulted in additional energy savings.

Performance monitoring of all four housing units was completed to compare the energy, water, operations, occupant satisfaction, and life-cycle cost of the ZEHs compared to the baseline housing units. A monitoring system was selected, installed, and calibrated to collect data from 50 monitoring points within each home. Performance was monitored for 17 months; one year of data (January 2011 through December 2011) was used for final data analysis and results. Whole-house energy use of all four housing units was also compared to similar homes at Fort Campbell (referred to as the Woodlands community), and national averages.

The ZEH and baseline home occupants were given an orientation prior to moving into the housing units to familiarize them with the unique features of the housing units and the project. Tips regarding how to reduce energy were provided to the occupants during this orientation. Real time energy feedback devices were placed in the housing units, and detailed monthly energy reports were provided to the occupants to inform them of opportunities for improvement. Monthly phone calls were held with the occupants to receive and provide feedback, and validate any unusual data observations (e.g., lower energy usage because occupants were on vacation).

Occupant engagement contributed to 15% less energy use in the baseline homes compared to the average home in Woodlands community. The zero energy homes (ZEHs) used on average 24% less energy than the baseline homes, but did not achieve net zero energy over the study period. Figure ES.1 summarizes the monthly energy performance of the Woodlands typical home, the average baseline, and the ZEH homes. The average solar production for the ZEHs is also shown.

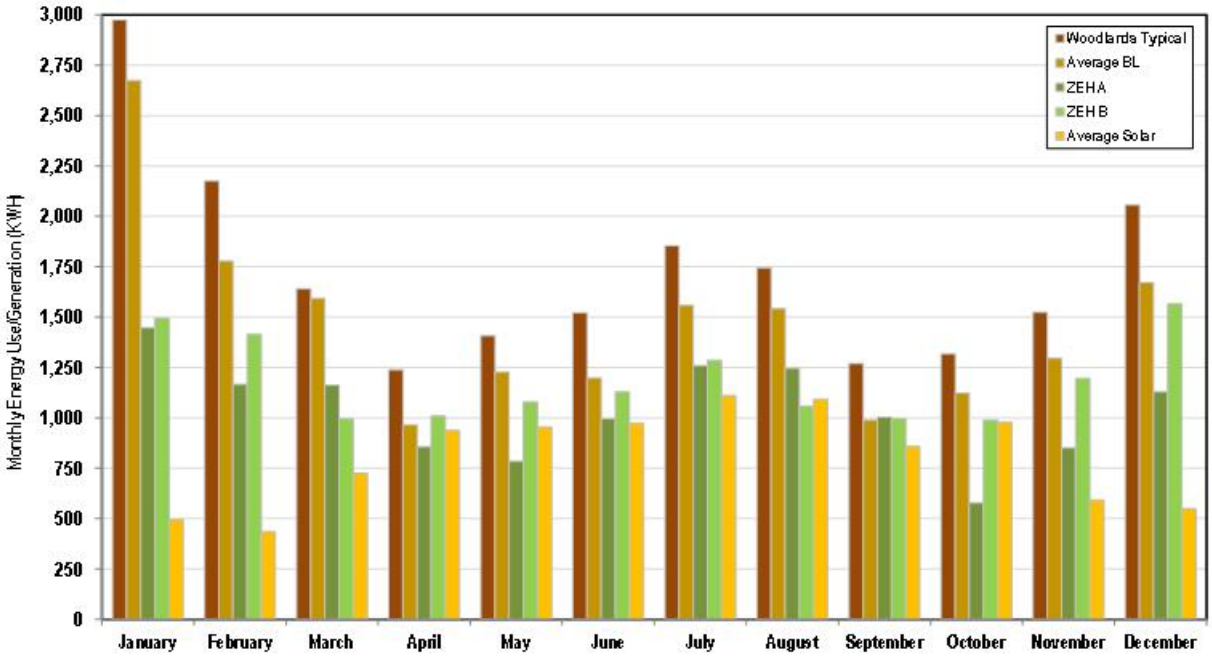


Figure ES.1. Monthly Energy Use Summary

The ZEH unit used 51% less water per person than the baseline unit. There was no notable difference in emergency maintenance activities between the ZEH and baseline units; both the ZEH units and the baseline units had about the approximately the same level of emergency maintenance needs. The technologies in the ZEH units did require more preventative maintenance. Multiple life-cycle cost scenarios were completed, but no scenario was life-cycle cost effective for this location for a variety of reasons including low energy costs and interest paid on the capital investment loan.

Findings from this project included:

- Feedback devices (real-time or monthly) appear to lower energy use. Occupants found that the real time feedbacks devices were effective in helping them use less energy and water.
- Achieving net zero energy may have been possible with more than one year's data to help occupants and maintenance staff better understand and use the systems in the housing units.
- Modeling assumptions may not reflect actual building characteristics and use, which can affect the ability to design for net zero energy.

- Cost-effective ZEHs are difficult to achieve, and are most likely to be cost effective in areas where energy costs are high and renewable resources are plentiful (e.g. California).
- Incorporating a more energy efficient envelope was the least costly design change for this duplex (compared to ground source heat pumps, solar hot water systems, or solar panels).
- Specialized maintenance costs can impact the cost effectiveness of a project.

1.0 INTRODUCTION

The Zero Energy Housing for Military Installations Environmental Security Technology Certification Program (ESTCP) project measured and compared the performance of net zero energy designed homes to typically designed homes (baseline homes). The project team tracked and provided input to the design; however, the emphasis of the project was on measuring the energy and water use of the housing units at Fort Campbell.

During the design, construction, and pre-occupancy phase, the ESTCP project team identified technical experts and provided input on the design approach—notably appliance and heating, ventilation, and air-conditioning (HVAC) technology selection, and energy modeling. A metering system to collect detailed energy consumption data was selected, installed, calibrated, and tested for functionality. In-home energy monitors were selected to provide real-time energy consumption feedback to occupants. Families with similar characteristics were selected through a survey and interview process. The families participated in an orientation prior to moving into the housing units to familiarize them with the components of the home and the project goals. Detailed energy use was monitored throughout the study duration, and the occupants were engaged through monthly energy summaries and focused support on how to reduce energy. Occupants provided input on the type of data that was most helpful to inform actions and decisions.

Energy use of the zero energy homes (ZEHs) was compared to the energy use of the baseline homes. Energy use of both the ZEH and the baseline homes was compared to the average energy use of the surrounding homes in the neighborhood. Water use, operations and maintenance (O&M), energy costs, occupant comfort, and greenhouse gas (GHG) emissions were also evaluated. Table 1 shows the project timeline from design through performance measurement.

Table 1. Project Timeline

	Phase	Dates
ZEH Design	Initial design and modeling	July 2008-August 2008
	Design charrette	August 2008
	Design and modeling	August 2008-January 2009
	Construction	March 2009-October 2010
	Occupant selection	August-September 2010
	Home Energy Rating	October 2010
Performance Measurement	Monitoring system installation and calibration	September-October 2010
	Occupant orientation and engagement	October 2010-March 2012
	Families move into the housing units	October 2010
	Data collection, normalization, and comparisons	October 2010-February 2012
	Data analysis conducted and final report written	March 2012-September 2012

The Fort Campbell ZEH project team consisted of the following members:

- U.S. Army Installation Management Command Southeast led the project development and acted as the principal investigator for the first two years of the task.
- The U.S. Department of Energy's (DOE) Pacific Northeast National Laboratory was the current principal investigator and the lead for performance measurement and analysis.
- National Defense Center for Energy and Environment (NDCEE) assisted with project development and design process coordination and provided technical support.
- Concurrent Technologies Corporation provided technical support throughout the task and conducted the life-cycle cost (LCC) analysis.
- Luckett & Farley participated as the architect of record.
- National Association of Home Builders Research Center provided technical support and assisted with the energy modeling.
- Campbell Crossing, LLC (formerly Fort Campbell Family Housing) provided technical support and included members from design, construction, maintenance, and HVAC installation.
- Lend Lease (formerly Actus Lend Lease) provided project management support and will be transferring results to other Actus Lend Lease military projects and the wider developer/construction industry.
- 7Group managed and facilitated the goal-setting workshop and design charrette and conducted the initial energy modeling.

1.1 BACKGROUND

Residential homes use more than 20% of the energy consumed in the U.S. (DOE 2011). With current construction methods, buildings account for 54% of sulfur dioxide emissions, 17% of nitrous oxide emissions, and 40% of carbon dioxide (CO_2) emissions (DOE 2011). These pollutants not only damage local air quality but are potentially creating climate change issues and health problems on an unprecedented global scale.

This project evaluated the performance of two net zero energy homes (ZEHs) at Fort Campbell, Kentucky. Net zero energy homes generate as much electricity as they consume from the grid through a combination of: (1) energy efficient design, (2) energy generation, typically with renewable energy sources, and (3) energy conservation practices by the homeowners. The issues validated were actual performance and cost compared to industry baselines and two conventional homes in the same subdivision. The benefits of ZEHs to the Department of Defense (DoD) are lower energy costs, increased energy security, and decreased pollution from energy production and use.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this project was to evaluate the performance of the design and construction of the Fort Campbell ZEHs to determine whether they are cost effective and practical. The intent

was to improve potential acceptance of zero energy concepts for other DoD and private sector projects and to significantly reduce the energy required from the utility grid. The project was designed to measure energy consumption, environmental impact, operational effectiveness, and LCC for ZEH.

The project involved incorporating two ZEHs within a residential development known as the Woodlands. The Woodlands is composed of 236 duplex buildings (each duplex includes two single family housing units) and 51 single family housing units, for a total of 523 individual units. The intent of this project was to incorporate necessary design requirements for zero energy without significantly modifying the floor plans and/or exterior elevations of the buildings. This approach took advantage of established costs and scheduling requirements available and allowed for a comparison to all of the duplexes in the Woodlands community.

Energy consumption, environmental impact, operational effectiveness, and LCC were measured for two typically designed housing units (one duplex) and two ZEHs (one duplex). Specific modeling/measurement methods included:

- Construction cost differentials between the ZEHs and typically designed housing units were tracked and documented during construction.
- Actual energy and water consumption and use patterns were monitored by installing meters and devices that recorded real-time data on energy and water use in 15 minute intervals. Data were collected on overall energy use for each home with additional data collected to capture individual loads for HVAC systems, appliances (kitchen and laundry), "fixed" lighting, and the remaining "plug loads" (lamp lighting, computers, entertainment, etc.). Monitors also collected data on humidity and temperature (indoor and outdoor).
- Energy costs were calculated based on total energy use.
- Energy generation from the photovoltaic (PV) panels and solar hot water were monitored.
- O&M costs were measured by tracking the job-hours and equipment costs required to maintain each home. O&M issues and any reported costs were documented through Fort Campbell's maintenance recording system. Interviews with building occupants and maintenance personnel also informed the O&M results.
- Occupant comfort was evaluated at all four housing units through monthly interviews throughout the monitoring period and a follow-on survey of occupants regarding their impressions of the housing units, comfort, and overall experience.
- Reduced carbon dioxide equivalent (CO_2e) emissions were calculated using a regional energy mix. CO_2e are a representative measure of the environmental impact of energy use, translating key GHG emissions into one metric.

1.3 REGULATORY DRIVERS

Executive Order (EO) 13423 set goals to improve energy efficiency and reduce GHG emissions through reduction of energy intensity by 3% annually through the end of fiscal year (FY) 2015, or 30% by the end of FY 2015, relative to a 2003 baseline. EO 13514 expands on the energy

reduction and environmental performance requirements of EO 13423 by setting a goal for each federal agency to establish an integrated strategy towards sustainability and make the reduction of GHG emissions a priority. The Energy Policy Act of 2005 specifically encourages the use of energy efficient buildings as a means for reducing GHG emissions. The Energy Independence and Security Act of 2007 requires that new federal buildings decrease their consumption of fossil fuels 55% by 2010 and 100% by 2030. Recently, DoD has set goals in their Strategic Sustainability Performance Plan to reduce scope 1 and 2 GHG emissions by 34%, and indirect scope 3 emissions by 13.5%.

2.0 TECHNOLOGY DESCRIPTION

The technology demonstrated has two components: (1) design and operation of a ZEH, and (2) performance measurement to evaluate the ZEH design. These two components are described in more detail in the following sections.

2.1 TECHNOLOGY OVERVIEW

Theory, Functionality, and Design of Zero Energy Homes

ZEHs are designed to generate as much energy as they use over the course of a year. The design process uses extensive energy modeling to identify the optimal mix of building systems to obtain a 50-70% reduction in energy use over a typical residential building. Renewable energy systems are used to provide the remaining energy use. Occupants are encouraged to operate the home in ways that support the net zero energy goal, and must be actively engaged in pursuing the energy goals for the home to achieve net zero energy. Figure 1 provides an overview of the zero energy methodology.

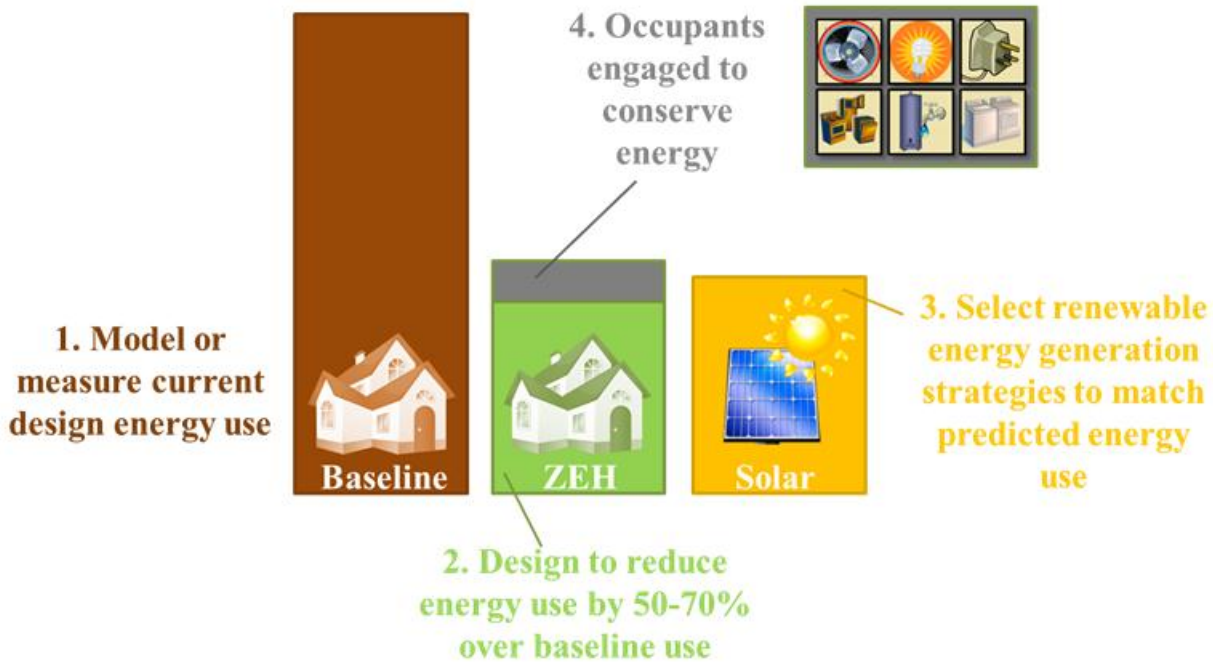


Figure 1. Zero Energy Methodology

A ZEH must be designed to use a fraction of the energy use required by a typical building so that the remaining power needs can be met by on-site renewable energy systems. The success of achieving a ZEH design depends on the ability to develop appropriate building-specific technology integration strategies. The building must be designed using a systems approach to enable synergies.

A key design strategy is to reduce environmental effects of site temperature, solar radiation, wind, cloud cover, and humidity. This is done primarily by reducing the heat transfer through the building envelope and controlling solar heat gain. Changes in materials and construction methods are used to reduce heat transfer while window location, overhangs, and specialty glazing are used to control solar gain.

Building energy use reductions are achieved through the increased efficiency of the heating, cooling, and hot water systems and the use of high efficiency appliances and lighting.

With a ZEH properly designed for reduced energy use, the remaining energy needs can be met with renewable energy production. Renewable energy systems typically include solar power generation, solar thermal capture, and wind power.

The final strategy required for a ZEH is occupant engagement and participation in operating the home in ways that support the net zero energy goal. Energy conservation practices should be employed by building occupants, as was done in this project.

Atypical weather can increase or decrease energy consumption and generation during a given year. Because a ZEH is designed for a "typical" weather year (as defined by modeling software), evaluating the home's performance over multiple years can be a better indicator of the success of achieving net zero energy.

Theory, Functionality, and Design of Performance Measurement

Whole building performance measurement evaluates existing sustainably designed buildings by documenting operational data to determine if the buildings perform as the design intended. To gather useful information, the operational data needs to be:

- Measured, not modeled;
- Relatively easy and inexpensive to collect;
- Representative of sustainable design principles, not just individual design strategies such as energy efficiency; and
- Translatable into cost values that could be shared with the financial decision makers to demonstrate performance in their language.

The operational data provides some basic information about a building's comparative performance with respect to sustainable design. The metrics collected include energy, water, maintenance, waste generation, indoor environmental quality, and transportation.

Chronological Summary of the Development of Zero Energy Homes

ZEH has been researched and studied in the following environments or settings:

- DOE supports Zero Energy Home initiatives through the Building America Program (http://www1.eere.energy.gov/buildings/residential/ba_index.html). The long-term goal

is to develop cost effective, production ready systems in five major climate zones[1] that will result in ZEHs that produce at least as much energy as they use annually by 2020. Specific research and development targets for the Building America ZEH initiative are to reduce whole-house energy use in new homes by an average of 50% by 2015 and 70% by 2020, as compared to the Building America Research Benchmark. The long-term objective is to achieve ZEH in the private sector by ensuring a positive or neutral cash flow for the homeowner, which means that the cost of performance improvements and on-site power production (e.g., PV systems) are offset by the utility savings when financed over the life of an average 30-year home mortgage. In this project, the Campbell Crossing loan acquired was a 40-year loan. The National Renewable Energy Laboratory (NREL) provides much of the research and technical support for DOE ZEH initiatives (http://www.nrel.gov/buildings/residential.html). The National Association of Home Builders Research Center also conducts research on ZEH, including support to NREL research efforts, and it maintains web-based resources for the home building industry. Two notable resources are Toolbase Services (http://www.toolbase.org/) and the Partnership for Advancing Technology in Housing (http://www.pathnet.org/).

- The NDCEE, operated by Concurrent Technologies Corporation (CTC), has performed energy modeling for the development of ZEH concepts at Fort Campbell, Kentucky, Schofield Barracks, Hawaii, and Fort Drum, New York as part of the Sustainable Installations Initiative. The modeling compared the baseline technologies at these locations with an alternative mix of technologies to maximize energy use reduction.

Chronological summary of performance measurement

- A whole building performance measurement protocol funded by the DOE Federal Energy Management Program (FEMP) was the basis for the performance measurement activity (Fowler et al. 2009). The protocol was published in 2005 and updated in 2009. Adaptations were made to tailor the process to the ZEH analysis. This protocol has been used to measure the performance of office buildings, barracks, education facilities, and courthouses. The protocol was adapted for this single family residence application.

- In 2007 and 2010, similar metrics were used to measure the performance of high performance federal office buildings and courthouses operated by the General Services Administration (GSA). The buildings were compared to industry standards and GSA targets.

- From 2005-2008 a subset of the metrics were used to measure performance of Navy barracks, offices, and education facilities.

- In 2011-2012, the metrics were used to measure and compare the performance of 14 Air Force buildings. Seven U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) buildings were compared to seven traditionally designed buildings.

- From 2008-2012, the protocol was used in the design, construction, and performance measurement of two fire stations at Fort Bragg, North Carolina, also an ESTCP project.

[1] Climate zones are defined in the Residential Energy Consumption Survey (RECS), available at http://www.eia.gov/consumption/residential/maps.cfm.

Potential DoD applications
DoD provides more than 300,000 family housing units, which combined use 11 trillion British thermal units (Btu) of electrical energy annually. In FY 2006 alone, this energy cost $254 million and represented 11% of DoD's total facility electrical use. Much of this electricity was generated by coal fired plants, which are responsible for generating 40% of U.S. mercury emissions. Electric energy used in DoD homes not only contributes to environmental challenges, but also creates serious energy security problems for our military installations. A 100% dependence on energy produced by finite resources and stressed electric power grids represents vulnerability in maintaining troop readiness. Potential DoD users of the ZEH findings include other Residential Communities Initiative partnerships, which represent approximately 160,000 homes. In addition, Lend Lease plans to apply selected lessons learned to the 38,000 homes they manage for the DoD and the 145,000 homes they manage worldwide. Lessons learned may also be applicable for other building types such as barracks, offices, or others.

2.2 TECHNOLOGY DEVELOPMENT

Design Approach
The approach used to design the ZEH was as follows:

- Identify design and technology integration strategies to achieve energy efficiency and on-site energy production necessary for a net ZEH.
- Conduct a workshop with the design team to set performance goals for the ZEH and identify specific technologies to achieve those goals.
- Conduct energy modeling to simulate energy use, and estimate costs and environmental impacts.

The design team began meeting via teleconference in July 2008. Initial meetings focused on establishing the performance goals, project requirements, and ZEH design approach. Campbell Crossing provided baseline data and initial energy modeling was conducted. In August 2008 a design charrette was held on site at Fort Campbell. During this charrette, the project status and requirements were discussed, performance goals were established, and integrated strategies and technologies were discussed. To guide the charrette discussion, the USGBC LEED for Homes checklist was used.

The design of the ZEH was a modification of an existing Campbell Crossing and Lend Lease standard duplex design. Starting with an existing floor plan limited the ZEH design options but meant the housing units would be identical to the occupants, which was an important consideration for Campbell Crossing and Lend Lease. A report detailing the charrette process and outcome is given in Appendix A. After the charrette, the team continued to meet via teleconference to refine the design.

Energy Modeling
As part of the design process, energy modeling was used to evaluate the expected performance. Energy modeling is a technique for estimating a building's energy requirements using a computer tool that simulates the interaction of building systems to estimate how the interactions

affect overall energy performance. Energy modeling is used at various stages of the design process—from conceptual design to construction documentation—by architects, engineers, and building owners. In the design stage, energy modeling provides insights that can contribute to more effective design decisions; energy modeling after final design is used to document results.

For this project, iterative energy modeling was done throughout the design process to estimate the expected energy use of the ZEHs so that the necessary energy efficiency technologies and renewable energy needed to achieve net zero energy could be determined. The energy modeling was conducted using EnergyGauge[2] software.

Baseline Design

A project requirement was that the ZEH had to be similar in appearance and function to the existing duplex. Data were collected to establish the parameters of this design and establish the baseline. The design plans for the baseline duplex were provided to the design team by Campbell Crossing. Information from these drawings was used to create the baseline model. The provided drawings included:

- Architectural site plans
- Unit floor plans
- Building floor plans
- Roof plans
- Exterior elevation
- Building sections
- Wall sections
- Interior elevations
- Structural drawings
- Mechanical, electrical and plumbing drawings

In addition, metered energy data were provided for six similar Fort Campbell units, each with a floor area of 2007 sf. One year of data was obtained (June 2007 - May 2008); annual electricity usage varied from 22,210 kWh (37.8 kBtu/sf) to 33,716 kWh (46.5 kBtu/sf) per unit. Average usage for the six units was 27,327 kWh (57.3 kBtu/sf) per unit. This information was used to inform the expected energy use for the baseline model and the associated performance objectives comparing the expected baseline energy use with the expected ZEH energy use.

ZEH Design

Energy savings from specific building components were analyzed to evaluate the energy design of the ZEH. During the design charrette, the design team determined which technology integration strategies should be evaluated using energy modeling for inclusion in the final design. Energy modeling was conducted with these recommendations; the modeling report containing

[2] EnergyGauge software is an hourly simulation program based on a DOE2 engine developed through DOE.

the post-charrette modeling process details is given in Appendix C which informed the final modeling assumptions.

Table 2 summarizes the final major design elements for both the typical home and the ZEH as well as the final modeling assumptions. The typical home energy model used a slightly more efficient cooling system than was included in the final design, and less efficient lighting systems and appliances than the final design; all other characteristics were the same. In the ZEH energy model, the window U-values were slightly lower and the solar heat gain coefficient (SHGC) was slightly higher compared to the final design. The R-value for floor insulation over the garage was also higher in the typical home model compared to the final design.

Table 2. Summary of Design Elements

Design Element	Typically Designed Home Energy Model	Typically Designed Home Final Design	ZEH Energy Model	ZEH Final Design
Heating system	Air source heat pump (8.45 HSPF[a])	Air source heat pump (8.45 HSPF[a])	GSHP[b] (4.0 COP[c])	GSHP (4.0 COP)
Cooling system	14 SEER[d]	13 SEER	GSHP (18.5 SEER)	GSHP (18 SEER)
Water heater	Electric element storage tank (energy factor of 0.92)	Electric element storage tank (energy factor of 0.92)	Solar thermal preheat collector with storage tank and back-up electric element (energy factor of >1)	Solar thermal preheat collector with storage tank (solar energy factor of 8.9) and back-up electric element (energy factor of >1)
Electricity production	Utility provided	Utility provided	Roof-mounted PV and utility tie / backup	Roof-mounted PV system and utility tie / backup
Window U-value	0.35	0.35	0.31	0.34
Window SHGC	0.33	0.33	0.32	0.31
Appliances	No Energy Star	Energy Star except clothes washer	Energy Star including clothes washer	Energy Star including clothes washer
Lighting systems	100% incandescent	100% fluorescent interior and exterior	100% fluorescent interior and exterior	100% fluorescent interior and exterior
Power supply control	None	None	None	None
Bath fan controls	None	None	Timer switches	Occupancy sensor-controlled, fixed time
Slab floor insulation	R-5 rigid	R-5 rigid	R-10 rigid	R-10 rigid
Slab vapor barrier	None	None	Extended under footing and turned up 4 inches	Extended under footing and turned up 4 inches
Exterior wall construction	2x4 metal stud	2x4 metal stud	2x6 wood stud	2x6 wood stud
Wall insulation	R-15 batt	R-15 batt	R-19+ cellulose or foam	R-19.8 spray foam
Floor insulation over garage	R-19	R-19	R-30	R-19.8
Ceiling insulation	R-49	R-49	R-60	R-60 blown in cellulose
Sheathing	R-0.5	R-0.5	R-5	R-5
Exterior overhangs	None	None	Extended roof, added to windows	1’6” truss extension; retractable awnings on

Design Element	Typically Designed Home Energy Model	Typically Designed Home Final Design	ZEH Energy Model	ZEH Final Design
				rear windows
Envelope sealant	None	None	At construction joints	Complete building envelope perimeter sealant
Advanced framing techniques	None	None	Additional stud materials needed to frame corners with sufficient room for insulation	Outside wall framed to allow insulation in corners.

[a] heating seasonal performance factor
[b] ground source heat pump
[c] coefficient of performance
[d] seasonal energy efficiency rating

A detailed comparison of the modeled energy use between the Campbell Crossing typically designed unit and the ZEH design is shown in Table 3.

Table 3. Comparison of Modeled Annual Energy Use for Typical Design, and ZEH Components

End Use	Campbell Crossing typically designed unit (kWh unless otherwise noted)	ZEH (kWh unless otherwise noted)
Cooling Energy	2182	746
Heating Energy	4597	1381
Ventilation Fan Energy	226	449
Hot Water Energy	3774	475
Clothes Washer	123	42
Dishwasher	240	67
Dryer	974	974
Lighting	2358	946
Miscellaneous	3377	3377
Range	706	706
Refrigerator	669	415
Total Electric	**19873**	**9578**
PV Supply	0	10340
Net Energy Use	**19873**	**-762**
Heat/Cool/Hot Water Energy (does not include fan energy)	**11201**	**2602**
Appliance, Lighting, and Miscellaneous Energy	**8447**	**6527**
Hot Water Use, gallons/day	**74**	**54**

The ground source heat pump (GSHP), energy recovery ventilator (ERV), and increased envelope insulation were notable differences between the typical design and the ZEH to make the home more energy efficient. Renewable energy systems included PV panels and solar hot water systems. These design components are described in more detail in Section 5.

The ZEH units received LEED Platinum certification in March 2011.

Occupant Selection
Engaging occupants to conserve energy is a vital component of achieving net zero energy in a ZEH. Occupants open to being part of the project and receiving feedback on their energy use was a pre-requisite for selection. Selecting occupants with extremely high or low historical energy use prior to moving into the new homes may have misrepresented the impact of receiving regular feedback regarding their energy use while living in the new homes. Therefore, occupants with historical average energy use were selected.

To control for variance caused by occupant behavior to the extent possible, families similar in size, typical daily occupancy, and electronic equipment were sought as occupants for the housing units.

Performance Measurement
The analysis technique used in this study was called "matched pairs." For building performance measurement, a matched pairs study compares two groups of similar buildings. In this case, the primary comparison was between the ZEH units and the typically designed units. The matched pair analysis was possible because the units serve the same function, are located in the same climate zone, are located in the same housing development, and are of the same size.

Energy and water use was evaluated, in addition to maintenance, air emissions, and occupant satisfaction.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages and limitations of ZEH and typical building design
ZEHs are a potentially more comfortable home with lower energy costs. ZEHs have the following intangible benefits, which make them attractive to both the military and the private sector:

- Energy security: ZEHs increase energy security, and mitigate mission risks posed by unpredictable availability of energy. On-site generation provides an essential redundancy to power provided by the local electric utility. ZEHs will have a dual source of energy providing power when their systems are down (e.g., occasional maintenance) or when there is a failure of the local electric utility.
- Cost predictability: Because ZEHs provide a large percentage of a home's electricity needs with renewable sources, price risks are significantly mitigated. Given the impact of seasonal and daily weather on the long term cost of electric energy, the volatility of the electric market will dwarf that of other commodities (corn, gold, pork bellies, etc.) that can be traded in an open market.
- Operational benefits: Increased building occupant comfort translates into increased family and soldier readiness. Increased DoD ability to operate in energy-shortage and high-energy-cost areas will ensure that major training bases remain affordable and available for soldier training.
- Reduced air emissions: Based on source energy and emission factors developed by Deru and Torcellini (2007), 70% energy savings for just one home at Fort Campbell could

reduce total emissions by about 50,591 pounds per year, with CO_2 emissions accounting for about 44,406 pounds per year.

Advantages and limitations of performance measurement

The advantages of performance measurement include more informed decision makers and stakeholders regarding the LCCs and benefits of sustainably designed buildings. In addition, performance measurement can identify operational concerns that may have been overlooked by building management but that, when addressed, can improve building performance.

Performance measurement can be limited by the amount and type of data available for analysis. Additional metering equipment may be required, which adds to the cost and can make the analysis difficult to replicate at a large scale. In addition, sufficient knowledge of building systems, energy systems, data management, and data analysis is often necessary to draw reliable conclusions, as was the case with the Fort Campbell ZEHs.

Major cost considerations of ZEHs

ZEHs can be LCC effective in places that have higher-than-average utility rates and abundant renewable energy opportunities on site. Previous performance measurement studies have shown that maintenance costs and activities are lower for high-performing commercial buildings compared with typically designed facilities (Fowler et al 2010). The ZEH design team considered maintainability for the features modified (as part of the integrated design approach). Potential maintenance differences with the solar hot water heater and the PV systems were tracked, along with all maintenance activities for both buildings.

Major cost considerations of performance measurement

Performance measurement can reveal opportunities to improve building performance as well as inform future building designs. These benefits can reduce operational costs.

The cost of performance measurement can vary according to the level of detail desired. Skilled knowledge of building systems is necessary, as well as data analysis and data management capabilities. Individuals with experience in performance measurement will be able to more effectively replicate the process at other buildings.

3.0 PERFORMANCE OBJECTIVES

The project compared a typically designed and constructed duplex that has been replicated for hundreds of residences on Fort Campbell to a ZEH duplex. The ZEH duplex is a modified version of the typically designed duplex that was built as a demonstration for this project. Each duplex consists of two units, and each individual unit was compared separately. In addition, the ZEH duplex was compared to the typically designed duplex.

There were two key components to this project. The first was to provide insight on integrated design strategies. To achieve this, sustainable design objectives were incorporated into the design of the ZEH units. Computer simulation was conducted to model the energy and water use of the ZEH design and the baseline units. Two methods were used to assess the design:

- Energy modeling
- National standards

The second project component was to evaluate the measured performance of the ZEH units and compare it to multiple baselines. Those baselines included the following:

- Measured performance of the *typically designed* units
- Average measured performance of similar *Woodlands residences* in 2011
- Average measured performance of similar *Ft. Campbell residences* in 2008
- *National standards*
- Expected performance based on the *design estimates*

The *typically designed units (Baseline units)* were the primary metric for comparison, using a "matched pairs" analysis. (Refer to Section 6 for detailed discussion on matched pairs analysis.) The typically designed units are the same size, same floor plan and are located next to the ZEH in the same housing development, with the same orientation. To accomplish this comparison, building performance data were collected, normalized, and analyzed to address each performance objective. The majority of the metrics were compared to the matched pair.

The average measured performance of the *Fort Campbell residences (the Woodlands),* also provided a comparison of housing units that are the same size, have similar floor plans, and are located at Fort Campbell. The data for these buildings were averaged, and normalized where the data were readily available. Historical data from 2008 for similar buildings constructed before the Woodlands were used during the design process for modeling comparisons and establishing performance objectives.

National standards used for comparison included the Residential Energy Consumption Survey (RECS). RECS is an energy survey of a nationally representative sample of residential housing units administered by the Energy Information Administration (EIA) every 3-5 years.

Design estimates included the energy models, documented design intent as appropriate, and manufacturer expectations or specifications.

Each objective is identified as either "Design, "Measured," or "Calculated," to clarify how the data were used in the analysis. The methodology reference for the performance measurement technique is discussed in the *Building Cost and Performance Metrics: Data Collection Protocol*, Revision 2 (Fowler et al. 2009).

Table 4 lists 14 specific performance objectives. The Design and Measured objectives involved data developed during this project. The Calculated objective was derived from measured data and eGRID emission factor information from the U.S. Environmental Protection Agency (EPA 2012). Note that each duplex has two housing units and that the performance measurements were taken for each individual housing unit.

Table 4. Design and Measured Performance Objectives

	Performance Objective	Metric	Data Requirements	Success Criteria	Results
	Quantitative Objectives				
DESIGN	1. Reduce modeled energy use of ZEH design compared to typically designed unit (*Energy*)	Modeled annual energy use per unit area	▪ Data on building components required to run energy models ▪ Modeled energy use of ZEH unit design ▪ Modeled energy use of typically designed unit[a]	ZEH model shows 50% less annual energy use (kBtu per square foot) than typically designed unit[b]	ZEH model showed 52% less energy use than typically designed unit
	2. Reduce modeled energy use of ZEH design compared to national standards (*Energy*)	Modeled annual energy use per unit area	▪ Data on building components required to run energy models ▪ Modeled energy use of ZEH unit design ▪ Average annual energy use provided as national standard[c]	ZEH model shows 60% less annual energy use (kBtu per square foot) than the national average	ZEH model showed 72% less energy use than the national average
	3. Modeled on-site energy generation is equal or greater than modeled energy use (*Energy*)	Modeled net energy use per year	▪ Data on building components required to run energy models ▪ Modeled energy use of ZEH design ▪ Modeled annual energy generation from PV panels and solar thermal	ZEH model shows energy generation (kBtu per year) is equal to or greater than design energy use[d]	ZEH model showed 8% more energy generation than design energy use

	Performance Objective	Metric	Data Requirements	Success Criteria	Results
	4. Reduce modeled potable water use of ZEH design compared to typically designed unit (*Water*)	Modeled annual water use per occupant	▪ Equipment specifications for building components required	ZEH design includes more efficient fixtures and fittings than typically designed unit[e]	Rated performance of ZEH toilets were 22% more efficient than the typically designed unit; lavatory faucets were 32% more efficient, and showers were 30% more efficient
MEASURED	5. Reduce measured energy use of ZEH compared to typically designed unit (*Energy*)	Measured annual energy use per unit area	▪ Metered whole building energy use of ZEH unit ▪ Metered whole building energy use of typically designed unit ▪ Average metered energy use of Fort Campbell unit complex[f]	ZEH shows 50% less energy use (kBtu per square foot) than a typically designed unit and Fort Campbell unit complex average	ZEH A: energy use was 29% less than average typically designed unit and 40% less than average Fort Campbell unit complex ZEH B: energy use was 19% less than average typically designed unit and 31% less than average Fort Campbell unit complex
	6. Reduce measured energy use of ZEH compared to national standard (*Energy*)	Measured annual energy use per unit area	▪ Metered whole building energy use of ZEH unit ▪ Average annual energy use provided as national standard for homes[g]	ZEH shows 60% less energy use (kBtu per square foot) than national average	ZEH A: energy use was 63% less than national average ZEH B: energy use was 58% less than national average
	7. Annual measured on-site energy generation is equal to or greater than annual measured energy use (*Energy*)	Measured net energy use per year	▪ Metered whole building energy use of ZEH unit ▪ Metered annual energy generation from PV panels and solar thermal	Annual ZEH energy generation (kBtu per year) is equal or greater than its energy use	ZEH A: energy generation was 79% of energy use ZEH B: energy generation was 67% of energy use
	8. Reduce measured HVAC system energy use compared to typically designed unit (*Energy*)	Metered HVAC system energy use per year	▪ Metered energy use of ZEH HVAC system ▪ Metered energy use of typically designed unit HVAC system	ZEH HVAC system shows 60% less energy use (kBtu per year) than the HVAC system in the typically designed unit[h]	ZEH A: HVAC system energy use was 26% less than average typically designed unit ZEH B: HVAC system energy use was 33% less than average typically designed unit

	Performance Objective	Metric	Data Requirements	Success Criteria	Results
	9. Reduce measured ZEH hot water energy use compared to typically designed unit (*Energy*)	Metered annual hot water use per occupant	▪ Metered energy use of ZEH hot water systems ▪ Metered energy use of typically designed hot water systems ▪ Number of typical occupants for each unit	ZEH hot water system shows 60% less energy use (kBtu per occupant per year) than hot water system of typically designed unit[i]	ZEH A: hot water system energy use was 39% less than average typically designed unit ZEH B: hot water system energy use was 3% less than average typically designed unit
	10. Reduce measured ZEH lighting, plug load, and appliance energy use compared to typically designed unit (*Energy*)	Metered annual energy use associated with lighting, plug load, and appliances	▪ Metered energy use of ZEH lighting, plug load, and appliances ▪ Metered energy use of typically designed lighting, plug load, and appliances ▪ Number of typical occupants for each unit	ZEH shows 10% less annual energy use (kBtu per occupant) for lighting, 10% less annual energy use for plug loads, and 20% less energy use for appliances compared to typically designed unit[j]	ZEH A: lighting energy use was 33% less than average typically designed unit ZEH B: lighting energy use was 16% less than average typically designed unit ZEH A: plug load energy use was 4% less than average typically designed unit ZEH B: plug load energy use was 3% less than average typically designed unit ZEH A: appliance energy use was 32% less than average typically designed unit ZEH B: appliance energy use was 19% less than average typically designed unit
	11. Reduce measured ZEH potable water consumption compared to typically designed unit (*Water*)	Metered annual water use per occupant	▪ Metered whole building water use for ZEH ▪ Metered whole building water use for typically designed unit ▪ Number of typical occupants for each unit	ZEH shows 30% less water use (gallons per occupant) than typically designed unit[k]	ZEH A water use was 51% less than Baseline B. Sufficient data were not available to compare ZEH B water use.

	Performance Objective	Metric	Data Requirements	Success Criteria	Results
CALCULATED	12. Reduce ZEH air emissions associated with measured electricity use (*Air Quality*)	Calculated emissions from energy generation sources using CO_2 equivalents as the indicator metric	▪ Metered whole building energy use for ZEH ▪ Metered energy generation from PV panels ▪ Metered whole building energy use for typically designed unit ▪ Utility specific emissions data	ZEH related net emissions (CO_2 equivalents per year) are 100% lower than typically designed unit	ZEH A: emissions were 85% less than the average typically designed unit ZEH B: emissions were 75% less than the average typically designed unit
	Qualitative Objectives				
MEASURED	13. ZEH maintenance is equal or less than typically designed unit maintenance *(Maintenance)*	Number of maintenance activities and time associated with these activities	▪ Number and hours of ZEH and typically designed unit preventative maintenance activities ▪ Number and hours of ZEH and typically designed unit emergency maintenance activities	ZEH maintenance activities are equal or less than the typically designed unit maintenance activities[l]	ZEH preventative maintenance activities were more than the typically designed unit. ZEH emergency maintenance activities were approximately the same as the typically designed unit.
	14. ZEH occupant satisfaction is equal to or higher than typically designed unit (*IEQ*)	Building occupant satisfaction feedback from occupant interviews	▪ Occupant satisfaction feedback from ZEH and typically designed unit regarding overall satisfaction with unit, and satisfaction with specific building features such as thermal comfort	ZEH shows equal or higher satisfaction as compared to the typically designed unit	ZEH satisfaction was equal to typically designed unit

[a] Modeled energy use for the typically designed duplex is 34.8 kBtu/sf per the NAHB Research Center. June 2008. Primary Energy and Sensitivity Analysis for Ft. Campbell J4B Model. Page 4.
[b] Basis for percent reduction success criteria: NAHB Research Center. Zero Energy Homes. A Brief Primer. Page 13. http://www.toolbase.org/PDF/CaseStudies/ZEHPrimer.pdf
[c] National average for duplexes is 46.7 kBtu/sf per the Residential Energy Consumption Survey. EIA. 2001. Residential Energy Consumption Survey (RECS). Table CE1-5.2u. Total Energy Consumption and Expenditures by Square Feet and Household Demographics, 2001. http://www.eia.doe.gov/emeu/recs/recs2001/ce_pdf/enduse/ce1-52u_sqft_demo2

The operational performance of the ZEHs was documented using the performance metrics and specific technologies or strategies were evaluated for their success in reducing the energy consumption of the ZEH.

3.1 QUANTITATIVE METRICS

Energy

Energy use is the most frequently tracked metric for high performance and sustainably designed buildings. Reducing energy consumption has a major effect on a building's environmental footprint, including carbon-related impacts. Because this project had the ultimate goal of achieving net zero energy consumption, the majority of the design objectives focused on energy systems.

Objective 1, reduce modeled energy use of ZEH design by 50% compared to typically designed unit, involved establishing design goals and participating in the design charrette to provide integrated design and energy efficiency design expertise. The value engineering process and construction practices also needed to be managed to avoid negatively affecting the design intent of the energy-related building features.

Since the ZEH unit design was adapted from a standard unit design used in the same housing development, the expected design energy performance of the ZEH unit was compared to the design energy performance of the typically designed unit. The energy use for the baseline and ZEH design building were estimated using an energy model, in this case EnergyGauge. The energy savings were derived by comparing the modeled energy use of the typically designed unit to the modeled energy use of the ZEH design. The energy efficiency improvements are typically found in the building envelope; lighting systems; HVAC systems; and internal loads such as appliance use. Detailed design specifications and energy modeling expertise were applied to realize this objective. The equation that was used to determine whether the metric met the success criteria follows:

> Percent Difference for Design Energy Savings = 100 * (1 – (Modeled Energy Use of Proposed Design in Btu per square foot / Modeled Energy Use of Design Baseline in Btu per square foot))

Objective 1 was met. The ZEH model showed 52% less annual energy use than the typically designed unit.

Objective 2, reduce modeled energy use of ZEH design by 60% compared to national standards, followed similar methodology to Objective 1. In this case, the modeled annual design energy consumption of the ZEH unit was compared to the national average reported in RECS 2001 of 46.7 kBtu/sf. The equation that was used to determine whether the metric met the success criteria follows:

> Percent Difference for Design Energy Savings = 100 * (1 – (Modeled Energy Use of Proposed Design in Btu per square foot / National Average Energy Consumption in Btu per square foot))

Objective 2 was met. The ZEH model showed 72% less annual energy use than the RECS 2001 national value.

Objective 3, modeled on-site energy generation is equal or greater than modeled energy use, involved comparing the modeled energy use as described in Objective 1, and the designed PV electricity generation. Over a period of 1 year, the ZEH unit should generate as much energy as it uses, so that at the end of the year the net energy use is zero. The energy generation of the PV panels was modeled using NREL's PVWatts performance calculator (http://rredc.nrel.gov/solar/codes_algs/PVWATTS/version2/). The equations used to determine whether the metric met the success criteria are as follows:

> Modeled Annual Net Energy Use = Modeled Energy Use of Proposed Design in Btu – Modeled Energy Generation of Proposed PV Panels in Btu
>
> Modeled Annual On-site Generation ≥ Modeled Annual Energy Use of Proposed Design

Objective 3 was met. The ZEH model showed the modeled PV energy generation was 8% more than the design energy use.

Objective 5, reduce measured energy use of ZEH by 50% compared to typically designed unit, involved metering energy use, normalizing the energy use by number of occupants, and comparing the normalized energy use of the ZEH unit to the typically designed unit. The meters captured energy use every 5 minutes for 17 months. The detailed 5-minute data were used to analyze the daily and weekly use of energy for each building. The data were summed into monthly and annual totals for summary analysis. 12 months of data (calendar year 2011) were used for the primary analysis period.

Both the ZEH unit and the typically designed unit used only electricity. The metered energy use was converted to British thermal units so that energy use for each building could be compared to national averages. The equations involved to convert electricity (kilowatt-hours) to British thermal units include:

> 1 kWh = 3,413 Btu
>
> Total building energy use = Btu

The total building energy use is commonly compared using the building conditioned size, creating a metric referred to as energy use intensity (EUI). The ZEH unit and typically designed buildings' energy use were compared using these normalized values. The following equations were used to normalize and compare the monthly energy use:

> ZEH unit EUI_{month} = ZEH unit monthly measured energy use/square footage of ZEH unit
>
> Average typically designed unit EUI_{month} = Average monthly measured energy use/square footage of the typically designed unit

The following equations were used to normalize and compare the annual energy use:

ZEH unit EUI_{annual} = ZEH unit summation of monthly measured energy use/square footage of the ZEH unit

Average typically designed unit EUI_{annual} = Average typically designed unit summation of monthly measured energy use/square footage of the typically designed unit

Percent difference of measured energy savings per square foot = 100 * 1 – (ZEH unit EUI/Average typically designed unit EUI_{annual})

The energy use analysis also considered other occupant activities that may have influenced building performance, including:

- Significant plug loads
- Systems usage (set points and frequency of use)
- Time without typical occupancy (vacations, deployment, etc.)
- Long-term visitors

Objective 5 was not met. ZEH A showed 29% less energy use than the average baseline home, and 40% less energy use than the average Woodlands complex home in 2011. ZEH B showed 19% less energy use than the average baseline home and 31% less energy use than the average Woodlands complex home.

One reason for the lower percent difference between the ZEHs and the typically designed units was that the typically designed units used less energy than expected. Both the average baseline home and the average Woodlands complex home in 2011 were more efficient than the average Fort Campbell home in 2008, using 48% and 39% less energy per square foot, respectively. The average baseline and average Woodlands housing units were also more efficient than the national average, using 48% and 39% less energy per square foot, respectively. These differences in the expected and actual energy consumption of the typically designed units were in part the result of recent Fort Campbell standards for more efficient lighting and appliances than the original baseline model and design contained.

Table 5 summarizes the performance comparison between the units, and illustrates how Objective 5 would have been met if the Baseline units' energy use was consistent with historical Ft. Campbell energy use in 2008 or national averages.

Table 5. ZEH Energy Performance Summary

Unit	Baseline	Woodlands 2011	Ft. Campbell 2008	RECS
ZEH A	-29%	-40%	-77%	-77%
ZEH B	-19%	-31%	-67%	-58%

Occupant habits, including thermostat setpoints and laundry use also affected the performance of the ZEH and baseline housing units.

Objective 6, reduce measured energy use of ZEH by 60% compared to national standard, followed a methodology similar to the one followed in Objective 2 and Objective 5. In this case, the annual metered energy consumption of the ZEH unit was compared to the national average reported in RECS 2001. The equation used to determine whether the metric met the success criteria is as follows:

> Percent Difference for Measured Energy Savings = 100 * (1 – (Metered Energy Use ZEH unit in Btu per square foot/National Average Energy Consumption in Btu per square foot))

Objective 6 was met. ZEH A showed 63% less energy use than the national average, while ZEH B showed 58% less energy use. The average ZEH consumption was 61% less than the national average.

The 2001 RECS formed the basis for the original comparison because these were the most recent data available during the design phase (2005 RECS data were not published until 2008). No regional values were reported in the 2001 data set, so the national whole home annual EUI of 46.7 kBtu/sf was used. RECS data from 2005 and 2009 have since been published (in 2008 and 2011, respectively). These data sets include data subsets by region, building age, and building size. These values, along with the original 2001 RECS dataset, are summarized in Table 6.

Table 6. Annual RECS EUI Comparison (kBtu/sf)[a]

Year	National	South Census Region	Constructed after 2000	South Census Region and Constructed after 2000
2001	46.7	-	-	-
2005	43.7	37	33.4	-
2009	45.5	41	37.1	35.5

[a] RECS data is available at http://www.eia.gov/consumption/residential/index.cfm.

The national EUI decreased 3% from 2001 to 2009. Buildings in the south census region constructed after 2000 had an average EUI that was 22% lower than the national average in 2009, and 24% lower than the national average in 2001.

Objective 7, annual measured on-site energy generation is equal to or greater than measured annual energy use, followed a methodology similar to that used in Objective 3 and Objective 4. In this case, the metered energy consumption of the ZEH unit was compared to the metered PV electricity generation. The equation used to determine whether the metric met the success criteria is as follows:

> Annual Energy Consumption = Metered Energy Use of ZEH unit in Btu – Metered Energy Generation of PV Panels in Btu
>
> Modeled Annual On-site Generation ≥ Modeled Annual Energy Use of Proposed Design

Objective 7 was not met. ZEH A's energy generation was 79% of its energy use, while ZEH B's energy generation was 67% of its energy use. One reason this design objective was not met was that the PV panels generated 6% less energy than predicted (which is within the range of expected variances between modeled and actual solar energy production). In addition, greater HVAC energy consumption than expected resulted in more energy consumption in the ZEHs.

Objective 8, reduce measured HVAC system energy use by 60% compared to typically designed unit, compared the metered HVAC system energy use in the ZEH unit to the metered HVAC system energy use in the typically designed unit. The equation used to determine whether the metric met the success criteria is as follows:

> Percent Difference for Measured HVAC Energy Savings = 100 * (1 – (Metered HVAC Energy Use ZEH unit in Btu per square foot/Metered HVAC Energy Use of typically designed unit in Btu per square foot))

Objective 8 was not met. ZEH A's HVAC system showed 26% less energy consumption than the average typically designed unit, while ZEH B showed 33% less energy consumption. The interior temperature setpoints in both the ZEHs and the baseline housing units tended to be higher than expected during the heating season and lower than expected during the cooling season. In addition, the ZEH interior temperatures tended to stay constant during the daytime heating season, while in the baseline housing units the temperature went down by a few degrees. This difference indicated occupancy variances (the occupants in the baseline housing units tended to be gone more often during the day than the ZEH occupants) and/or programmed temperature setbacks in the baseline housing units and not in the ZEHs.

Objective 9, reduce measured ZEH hot water system energy use by 60% compared to typically designed unit, compared the metered hot water system energy use in the ZEH unit to the metered hot water system energy use in the typically designed unit. The equation used to determine whether the metric met the success criteria is as follows:

> Percent Difference for Measured Hot Water Energy Savings = 100 * (1 – (Metered Hot Water Energy Use ZEH unit in Btu per square foot/Metered Hot Water Energy Use of typically designed unit in Btu per square foot))

Objective 9 was not fully met. ZEH A consumed 39% less hot water energy compared with the average typically designed unit, while ZEH B consumed 3% less hot water energy. Different laundry habits and variances in occupancy contributed to not meeting the objective.

Objective 10, reduce measured ZEH lighting (10% reduction), plug load (10% reduction), and appliance energy use (20% reduction) compared to typically designed unit, compared the metered lighting, plug load, and appliance energy use in the ZEH unit to the metered lighting, plug load, and appliance energy use in the typically designed unit. The equations used to determine whether the metric met the success criteria are as follows:

Percent Difference for Measured Lighting Energy Savings = 100 * (1 – (Metered Lighting Energy Use ZEH unit in Btu per square foot/Metered Lighting Energy Use of typically designed unit in Btu per square foot))

Percent Difference for Measured Plug Load Energy Savings = 100 * (1 – (Metered Plug Load Energy Use ZEH unit in Btu per square foot/Metered Plug Load Energy Use of typically designed unit in Btu per square foot))

Percent Difference for Measured Appliance Energy Savings = 100 * (1 – (Metered Appliance Energy Use ZEH unit in Btu per square foot/Metered Appliance Energy Use of typically designed unit in Btu per square foot))

Objective 10 was met for all end uses. The ZEHs showed 33% and 16% less energy use per occupant for lighting, 10% and 26% less energy use for plug loads, 32% and 19% less energy use for appliances.

Water

Objective 4, reduce modeled potable water demand of ZEH design compared to typically designed unit by using more efficient fixtures and fittings, involved establishing design goals and participating in the design charrette to provide integrated design and water efficiency design expertise. Additionally, this objective involved following through the design and construction process to ensure the value engineering process and construction practices did not negatively impact the design intent of the water-related building features or their second order impacts on hot water load.

Water savings were derived by comparing the modeled water use of the baseline design building to the modeled water use of the ZEH unit design. The water efficiency improvements are typically realized by using low flow fixtures. Detailed design specifications were needed for this objective to be met. The equation used to determine whether the metric met the success criteria is as follows:

Percent Difference of Design Fixtures and Fittings = 100 * (1 – (Specified Water Use of ZEH Fixtures and Fittings in gallons per unit of use/ Specified Water Use of typically designed fixtures and fittings in gallons per unit of use))

Objective 4 was met. ZEH design fixtures and fittings were 22 to 32% more efficient than the typically designed fixtures and fittings.

Objective 11, reduce measured potable water use by 30% compared to typically designed unit, involved metering water use and normalizing the water use by number of occupants and square footage. The normalized values from the typically designed unit were compared to the normalized water use of the ZEH unit. The domestic water meters captured water use every 5 minutes for 17 months. The detailed 5-minute data were used to analyze the daily and weekly use of water for each building. The data were summed into monthly and annual values for summary analysis. 12 months of data (calendar year 2011) were used as the primary analysis period.

Water use is commonly normalized using the number of building occupants, creating a metric referred to as water use intensity (WUI). Similar to energy use, water use can be analyzed for various timeframes to better understand domestic water use. The following equations were used to normalize and compare the annual water use:

> ZEH unit WUI = ZEH unit summation of annual measured potable water use/number of building occupants
>
> Typically designed unit WUI = Typically designed unit summation of annual measured potable water use/number of building occupants

Objective 11 was met. ZEH A used 51% less energy than Baseline B. Insufficient quality water use data were available for ZEH B, so a comparison could not be made.

Air Quality

Objective 12, reduce ZEH air emissions associated with measured electricity use by 100%, was calculated given the regional power generation mix that provides power to the respective units. The GHG emissions were calculated using EPA eGRID emission factors and provided in kilograms of carbon dioxide equivalents per unit of energy use (kg CO_2e/MMBtu). The equation that was used to determine whether the metric met the success criteria is as follows:

> Percent Difference of Air Emissions = 100 * (1 – (Calculated air emissions of ZEH unit/Calculated air emissions of typically designed unit))

Objective 12 was not met. Calculated air emissions of ZEH A were 85% less than emissions of the baseline housing units. Calculated air emissions of ZEH B were 73% less than the baseline housing units.

3.2 QUALITATIVE OBJECTIVES

Maintenance

Objective 13, ZEH maintenance is equal to or less than typically designed unit maintenance, involved compiling the number of preventative and emergency maintenance activities of each ZEH unit and comparing them to the typically designed units. It was expected that the ZEH would have the same level of maintenance as the typically designed unit. The equations that were used to determine whether the metric met the success criteria are as follows:

> Annual Measured Maintenance = Measured Maintenance Activities of ZEH unit in total number – Measured Maintenance Activities of typically designed unit in total number
>
> Ratio of Service related Maintenance to Total Maintenance (by number) = Number of Service related Maintenance activities/Measured Maintenance activities in total number
>
> Annual Measured Maintenance = Measured Maintenance Activities of ZEH unit in total hours – Measured Maintenance Activities of typically designed unit in total hours

Ratio of Service related Maintenance to Total Maintenance (in hours) = Hours of Service related Maintenance activities/Measured Maintenance activities in total hours

Objective 13 was not met. ZEH emergency maintenance activities were about the same as they were for typically designed units, but the ZEH-specific technologies resulted in more preventative maintenance activities than the typically designed units. Cleaning and replacing the energy recovery ventilation system filters was the primary preventative maintenance activity in the ZEHs that was not performed in the typically designed units. As noted in Section 7, this maintenance component had a high cost impact relative to the energy savings.

Occupant Satisfaction

Objective 14, ZEH occupant satisfaction is equal to or higher than typically designed unit, involved interviews with the building occupants of the ZEH units and the typically designed units. Originally, the Center for the Built Environment (CBE) occupant survey was to be used because it offered a database of buildings for comparison. However, the CBE survey questions and corresponding database are structured for commercial building occupants and most of the questions do not apply for residential applications. Therefore, occupant satisfaction was qualitatively evaluated based on monthly interviews with the occupants and a final set of questions after the monitoring period was complete. The questions that were asked covered overall building satisfaction and thermal comfort.

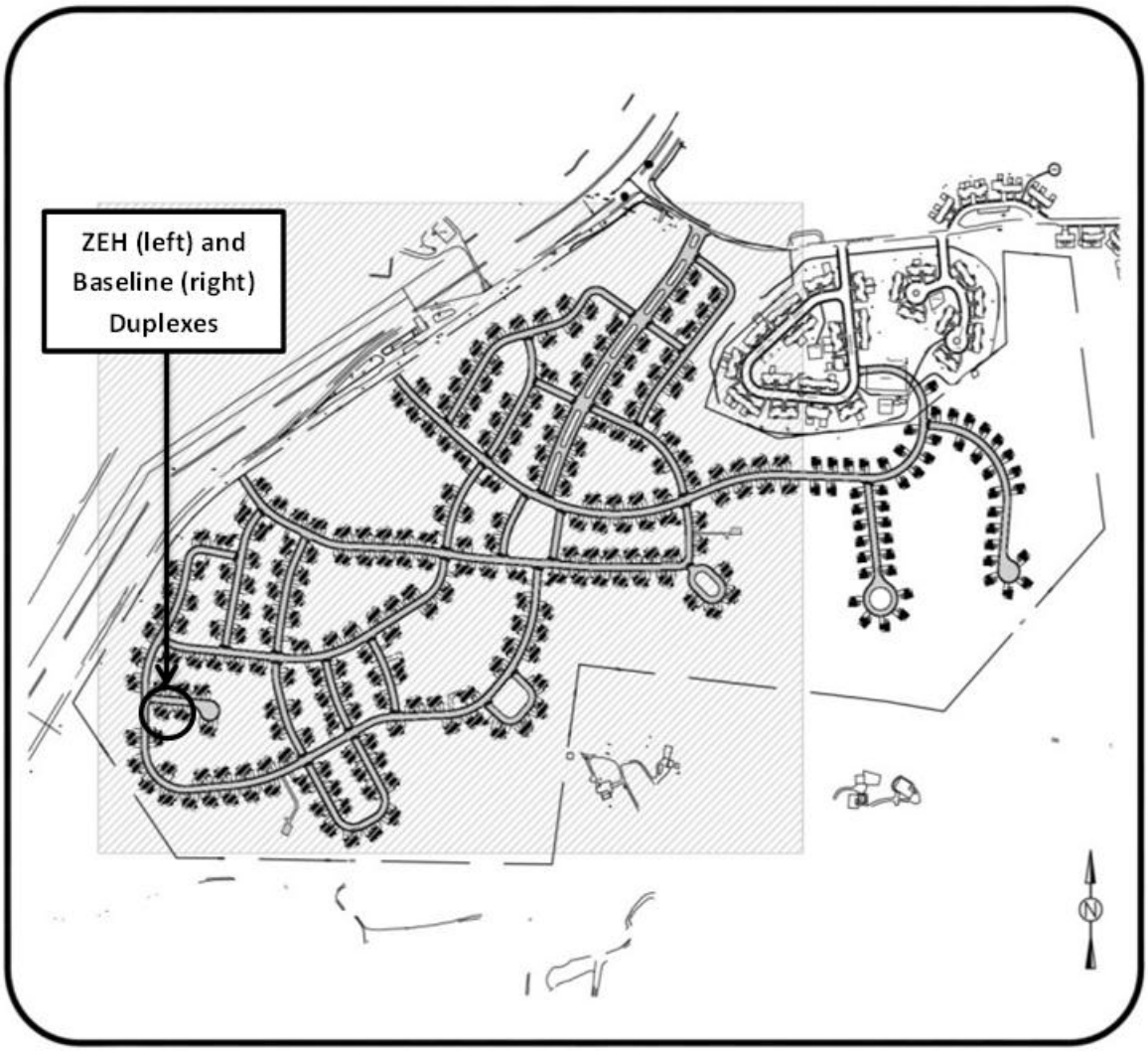
The occupant satisfaction metrics were also analyzed in relation to other performance metrics, for example thermal comfort and energy performance.

Objective 14 was met. Monthly interviews and the results from the final set of questions indicated that there was no notable difference in satisfaction between the occupants of the ZEH and typically designed units.

4.0 FACILITY/SITE DESCRIPTION

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The housing units used in this study are located in the Woodlands subdivision of Fort Campbell. Fort Campbell is located on the border of Kentucky and Tennessee in the hot-humid climate zone.[3] The Woodlands is adjacent to the installation, located southeast of post. In total, the subdivision includes 470 new Junior Non-Commissioned Officer (JNCO) and Senior Non-Commissioned Officer (SNCO) housing units, with construction completed October 2011. Figure 2 shows the Woodlands neighborhood site plan.



SITE MAP

Figure 2. Woodlands Site Plan (Luckett & Farley)

[3] Climate zones are defined in the RECS, available at http://www.eia.gov/consumption/residential/maps.cfm.

Figure 3 shows the location of the Woodlands neighborhood development in relation to the main cantonment area of Fort Campbell.

Figure 3. Orthophotographic Map of Installation and Subdivision

The Woodlands neighborhood development is managed by Campbell Crossing LLC, which is operated by Lend Lease.

The average cost of electricity in 2011 was 7.9¢/kWh. The average cost of water was $1.433 per thousand gallons from January through September 2011, and $1.58 per thousand gallons from October through December 2011. The occupants did not pay any energy or water bills; utility costs for the housing units were covered by Campbell Crossing.

Fort Campbell has an average yearly solar potential for a flat collector tilted at 37°of 4.8 $kWh/m^2/day$ (NASA 2010).

4.2 FACILITY/SITE CONDITIONS

The housing units are located next to each other in the same subdivision and orientated the same way. The location and orientation of the housing units did not affect the demonstration.

The weather seemed to have an effect on the monitoring equipment. The monitoring equipment failed twice. Both of these events were preceded by a thunderstorm, and the monitoring systems had to be replaced. Section 5 discusses the monitoring systems in more detail.

The weather also impacted the GSHP technology. The colder-than-usual temperatures in November 2010 helped identify that the GSHP well field was not deep enough to prevent freezing, as the ZEH A system broke down from frozen pipes and had to be reset. Note that this event was outside of the monitoring period for data comparisons. It is uncertain if this was an isolated incident or if the efficiency of the system during other times of the year was also affected.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

Pre-demonstration activities included contributing to the design by providing energy modeling and technical assistance on specific technologies, facilitating the design charrette, identifying and purchasing monitoring equipment, developing performance criteria, and selecting and training occupants of the ZEH.

Operational testing included the following:

- Testing of the building envelope and HVAC systems was conducted by a Home Rater prior to occupation. These tests are required for LEED certification and Energy Star certification, and are similar to commercial building commissioning. The tests included blower door testing and HVAC performance verification.
- Installing and calibrating energy and water monitoring equipment at the ZEH units and the typically designed units during construction and prior to occupation
- Collecting and verifying the performance data, and performing preliminary analysis for all four housing units from October 2011 through February 2012 (calendar year 2011 was used as the primary analysis period)

Post-demonstration activities included analyzing and summarizing the data, and communicating the findings from March 2012 through September 2012.

5.2 BASELINE CHARACTERIZATION

The baseline comparisons, as described in section 3.0, include *energy modeling*, and *national standards* for the design, and the following for the building performance measurement:

- Measured performance of the *typically designed* units
- Average measured performance of similar *Woodlands residences*
- *National standards*
- Expected performance based on the *design estimates*

To control for variance caused by occupant behavior to the extent possible, the following similarities between families were sought:

- Willingness to participate in the demonstration project
- Number of adults
- Number of children
- Specific hours of the day the home will be normally occupied (based on job and school schedules of occupants)

- Number of days in the coming year the military member is expected to be in the field or on temporary duty
- Number of days in the coming year the military member is expected to be deployed
- Special needs that will affect energy use (medical equipment, hobbies, etc.)
- Monthly energy use for past year, if available
- Number and type of electronic equipment owned and frequently used (televisions, computers, etc.)

Families were invited to apply to be part of the study, and interviews were conducted to determine suitability. The characteristics of the families selected are listed in Table 7.

Table 7. Occupant Family Characteristics

Characteristic	Baseline A	Baseline B	ZEH A (first family)	ZEH A (second family)	ZEH B
Number of adults[a]	2	2	2	2	2
Number of children	2	2	2	2	2
Hours home during the day	2-4	0-3	3-6	Not Recorded	3-6
Electronics	Televisions: 3 Computers: 2	Televisions: 4 Computers: 2	Televisions: 4 Computers: 2 Freezer	Televisions: 4 Computers: 1 Laptops: 2 Freezer Alarm system	Televisions: 4 Computers: 2

[a] Varied during the course of the study due to deployed spouses.

At the beginning of the study, the enlisted member from each of the four families was deployed. Each enlisted family member returned home at different times in 2011. Table 8 shows the number of regular occupants per month, and the yearly average used for data normalization.

Table 8. 2011 Regular Occupants per Month

Month	Baseline A	Baseline B	ZEH A	ZEH B
January	3	3	3	3
February	3	3	3	4
March	3	3	3	4
April	3	3	3	4
May	4	3	4	4
June	4	3	4	4
July	4	3	4	4
August	4	3	4	4
September	4	4	4	4
October	4	4	3	4
November	4	4	3	4
December	4	4	3	4
Average	**3.9**	**3.3**	**3.4**	**3.7**

In October 2010, prior to moving into the housing units, the ZEH and baseline families participated in a 1-day occupant training program. The training included an overview of the goals and objectives of the ZEH project, the families' influence on the success of the project, and

proper equipment usage. The training also provided a synopsis of the real-time metering equipment so that the families understood how to monitor and control their electricity usage. The primary real-time metering device was an in-home energy monitor, called The Energy Detective, or TED (Figure 4). This device, about the size of a typical cellular phone, showed both the real time whole-house energy use and the cost. The device also tracked cumulative energy use per day and per month, as well as the highest and lowest power load recorded during a given day.

Figure 4. The Energy Detective (TED)

ShowerMinders were also installed in all showers (Figure 5). These devices measured how long the shower was turned on; a green light turned on during the first 5 minutes; from 5 minutes to 8 minutes the light turned yellow, and after 8 minutes the light turned red. The device did not directly affect the water flow.

Figure 5. ShowerMinder

In addition to the October 2010 orientation, monthly written feedback on energy and water use was provided to the occupants, and discussed with them over the phone. The purpose of this interaction was to help both the occupants and the ESTCP team understand the underlying factors for specific consumption patterns. Additional details on the monthly reports are included in the Operational Testing section.

A final survey was distributed after the monitoring period concluded to understand what elements of the study were most helpful and influential in changing occupant behavior (example survey included in Appendix F). All of the families noted that the TED was one of the most effective elements that influenced their behavior. Many families also indicated that the other real-time feedback device, the ShowerMinder, was an effective tool. One family mentioned using kitchen timers in their new home because they had become so used to the ShowerMinder helping them reduce their shower times. The monthly energy reports and call with the ESTCP team was also noted as an element that affected energy use.

The project plan was to have the same four families live in the housing units for the duration of the demonstration period, but extenuating circumstances resulted in a family change in one of the ZEHs in September 2011, and a family change in one of the baseline housing units in December 2011. When turnover of occupants occurred, the new occupants were given a training program similar to the October 2010 orientation. This took place during the New Occupant Orientation given to all residents prior to occupancy.

5.3 DESIGN AND LAYOUT OF ZEH TECHNOLOGY COMPONENTS

The starting point for designing the ZEH was the existing typically designed duplexes that Campbell Crossing currently builds. The constructed ZEH and baseline housing units are pictured in Figure 6.

Figure 6. Street View of Baseline (left) and ZEH (right) Housing Units

This two-story duplex provides homes for two families. Each family has four bedrooms and 2,007 square feet of living space with 2.5 bathrooms on a slab foundation (no basements). The ZEH duplex floorplan is shown in Figure 7 The baseline floorplan (Figure 8) is nearly identical to the ZEH plan; the main difference is that the solar hot water tank was placed in the powder

room closet in the ZEHs, while the hot water tanks were placed in the mechanical rooms in the baseline units.

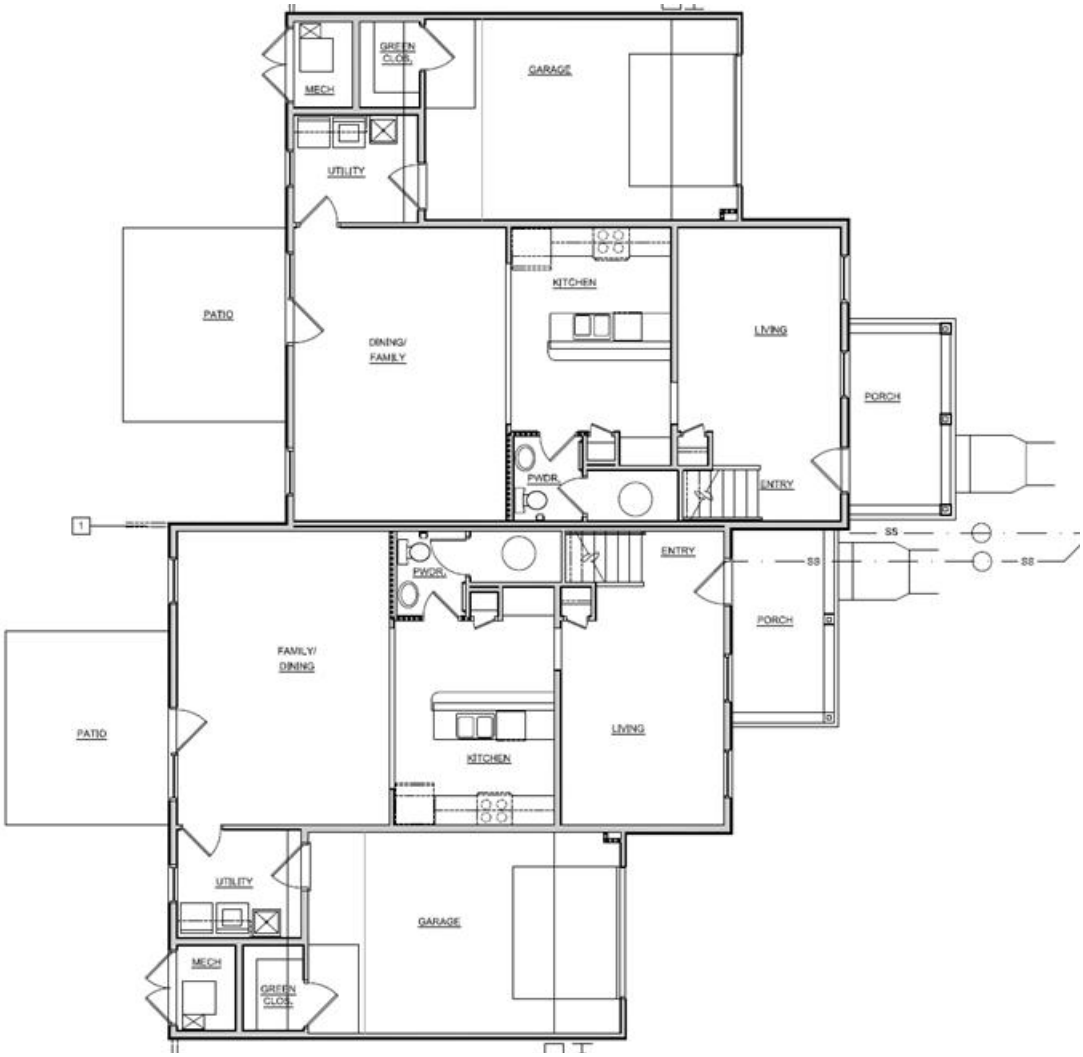


Figure 7. ZEH Duplex Floor Plan (First Floor)

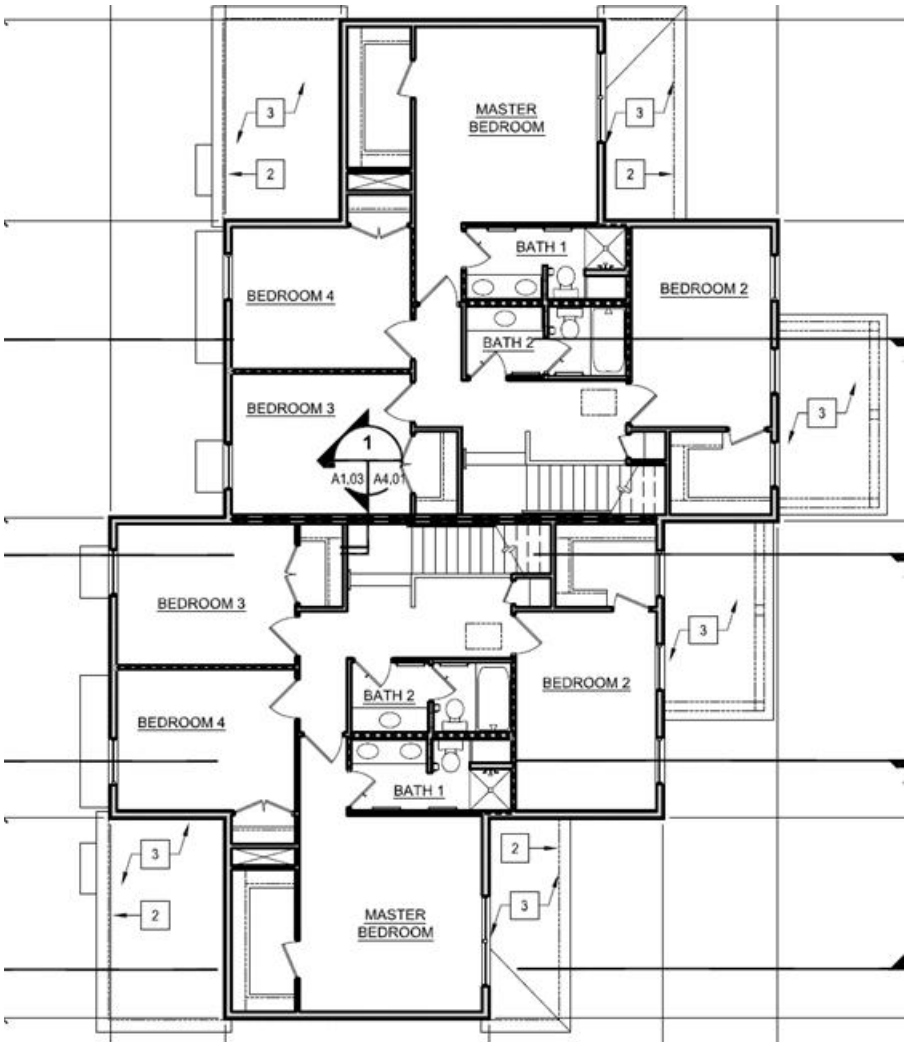


Figure 8. ZEH Duplex Floor Plan (Second Floor)

Campbell Crossing is a production builder and Campbell Crossing did not want these demonstration homes to cause equity issues, thus constraints were placed on the ZEH design. First, no alteration of the street exterior was allowed—the ZEH had to have the same look and feel as the other housing units on the street. Second, the ZEH had to be built within the existing footprint and provide the same square footage of living space, number of bedrooms, and bathrooms. Third, both the ZEH and the baseline control housing units had to be placed within the existing development plan. Finally, only GE appliances could be considered, as the builder has a nationwide contract with GE.

The major differences in technology components between the baseline duplex and the ZEH duplex were the PV array and the solar water heater, both of which went on the roof at the back of the house, in keeping with the desire to have a standard street view. The original hip and gable roof shown below on the left (Figure 9) was redesigned to the flatter "shed" roof shown on the right, in order to have sufficient space for the PV equipment. This roof redesign resulted in a lower cost roof that was easier to build. The original intent was to have the roofs extend over the porches to add space for the solar water heater collectors; however, this was not needed as the

solar water heater collectors were put over the utility rooms. Therefore, the porch roofs were not included in the ZEH.

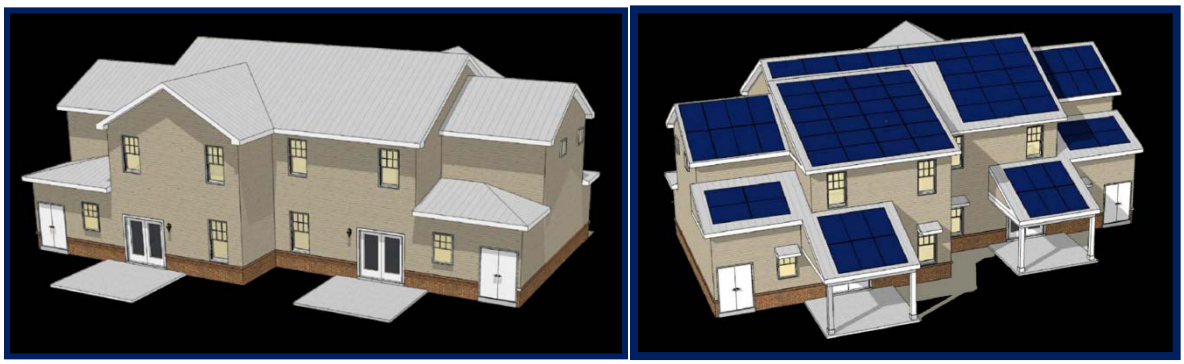


Figure 9. Rear View of ZEH (Original Roof on Left and Redesigned Roof on Right)

Post-construction, Campbell Crossing provided the "as-built" drawings to the ESTCP team, and these were reviewed to determine if any design elements were modified during construction. During this review, three design modifications related to building envelope were noted:

- The U-value of the installed windows on the ZEH was 0.34 instead of the specified 0.31. The U-value measures the ability for heat to flow through the window; the lower the U-value, the greater its resistance to heat flow and therefore the better its insulating properties. The typical unit had a 0.35 U-value; therefore, the ZEH windows did not vary greatly from the typical unit. The estimated modeled energy impact of the higher U-value was 1% or less of whole home energy use.
- The R-value of the insulation on the floor over the garage varied from design. The R-value measures the thermal resistance of a building material; the higher the R-value, the better the insulation's effectiveness (it is the inverse of the U-value). The ZEH design had a value of R-30 whereas the typical unit was R-19. According to the building contractor, a conservative estimate of the insulation installed over the garage floor is R-19.8 instead of the specified R-30.
- All ductwork was to be in conditioned space according to the design; however, some ductwork was placed in the unconditioned attic. This ductwork was routed as close as possible to the bottom of the lower cord of roof trusses and covered with blown insulation to comply with Energy Star requirements, the standard practice in other Campbell Crossing housing units.

These changes were likely to have affected the heat transfer to and from the house. In addition, two design elements, controlled power strips and high efficiency appliances, were specified in the design, but the constructed ZEH did not have controlled power strips. Both the baseline and the ZEH housing units had Energy Star-rated refrigerators, stoves, and dishwashers installed, as is standard in Fort Campbell housing units. The ZEH housing units were provided with high efficiency clothes washer and dryers, while the baseline housing units were not.

The ZEH design specifications included the following performance criteria:

Appliances and Lighting: Appliances included in the housing units were a high efficiency dishwasher, clothes washer, and refrigerator. In addition, hardwired fluorescent lighting was installed. The Campbell Crossing typically designed unit also had a high efficiency dishwasher, refrigerator, and lighting. The only appliance difference between the ZEH and the typically designed unit was the clothes washer and dryer.

Building Envelope: The building envelope was 2 x 6 inch wood stud walls insulated to R-19 (using spray foam), with sheathing rated at R-5. As noted above, the floor over the garage was designed to be insulated to R-30, but was below R-20. The attic was insulated to R-60. Sealing of the top plates, walls, and cavity were specified to be completed during construction. The windows were to have a max U-value of 0.31 and a max SHGC of 0.32; actual values were U-value = 0.34 and SHGC = 0.31. Slab floor installation was R-10 with a vapor barrier extended under the footing and turned up 4 inches. Advance framing techniques were used to allow the building corners to be completely insulated. In addition, exterior overhangs were included by extending the roof and adding retractable window awnings on the rear windows. The awnings automatically extend during summer to minimize solar heat gain, and retract during winter to maximize solar heat gain. This was done to reduce the heat gain through the windows. These design elements were undertaken to reduce the energy use and size of the heating/cooling system.

Heating/Cooling System: HVAC was supplied by a ground source heat pump of very high efficiency (18 SEER and 4.0 COP). All ductwork was to be in conditioned space; ductwork in attic routed close as possible to the bottom of cords of roof trusses and covered with blown insulation to comply with Energy Star requirements. All ducting was sealed and insulated during construction. A ventilation air heat recovery unit was also installed.

Hot Water: A 120-gallon solar heating system with 96 square feet of collector area and a solar energy factor of 8.9 was installed. The system has backup electric heat. A centralized water manifold distribution system was installed to cut down on distribution losses. In addition, all hot water lines were insulated both below and above slab.

Photovoltaic System

After the predicted energy use reduction, there was a remaining modeled energy use of approximately 10,000 kWh per year per unit for the ZEH design. Using location and weather data for Fort Campbell it was determined that a PV system sized at approximately 7,425 watts per unit (14,850 watts total) would be required to provide sufficient energy. The PV system was designed with 3 strings of 11 panels in series. Each unit has thirty-three 225-watt panels. The layout of this system on the duplex roof is given in Figure 10. As noted above, to provide the sufficient space for the PVs, the roof was redesigned. The gable and hip roofs were replaced with shed roofs. Porch roofs were intended to be added as drawn below providing more space for PV panels, but were not needed. Retractable awnings were installed instead to capture shading benefits in the summertime.

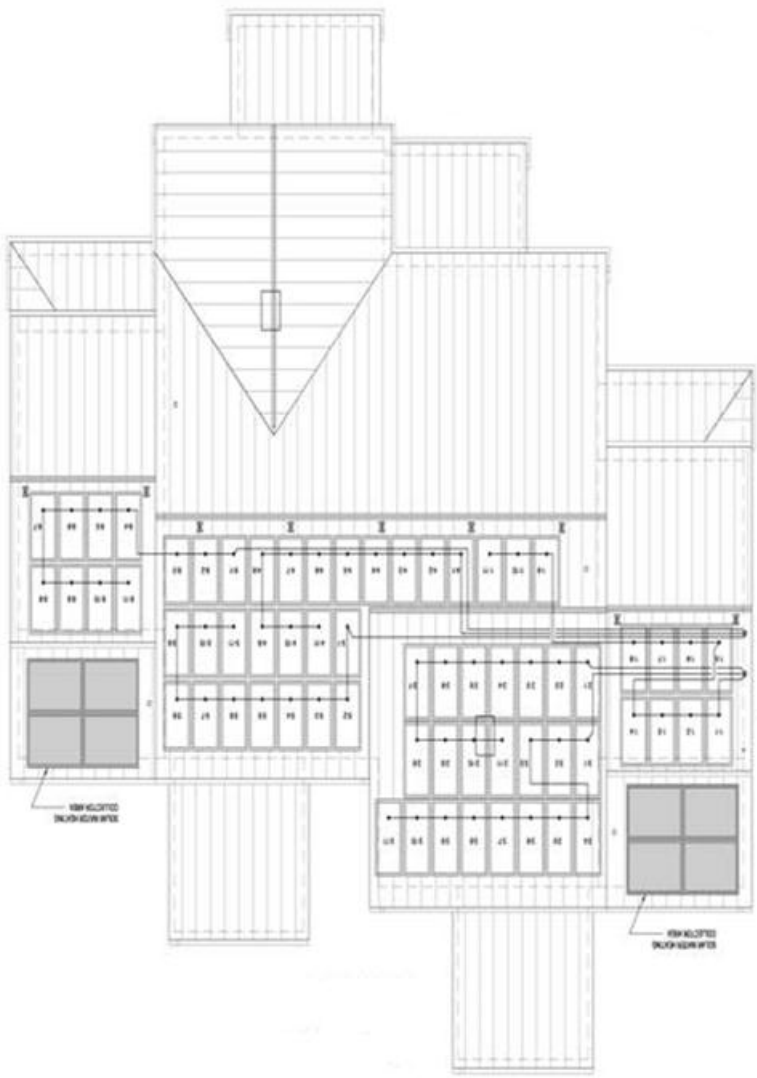


Figure 10. PV System Layout on Duplex Roof

Construction of the housing units was completed in September 2011. Home energy performance testing and monitoring equipment installation and testing was performed in September and October 2011, and the housing units were occupied by the end of October 2011.

Figure 11 shows the final rear view of the ZEHs and the baseline housing units.

Figure 11. Rear View of the Baseline (left) and ZEH (right) Housing Units

5.4 OPERATIONAL TESTING

Operational testing consisted of three phases: home energy rating prior to occupancy; monitoring system installation and calibration; and data collection, normalization, and comparisons after the families moved into the housing units (Table 9).

Table 9. Operational Testing Phases and Dates

Phase	Dates
Home Energy Rating	October 2010
Monitoring system installation and calibration	September - October 2010
Families move into the housing units	October 2010
Data collection, normalization, and comparisons	October - December 2011

Home Energy Rating Prior to Occupancy

Campbell Crossing hired Home Energy Concepts Corporation to conduct a home energy rating, required for LEED certification. This was completed after construction, but prior to occupation. As part of this process, the mechanical system and building shell features were tested and performance was verified. In addition, a blower door test was conducted on each of the ZEHs to determine infiltration rates. ZEH A had an infiltration rate of 1168 CFM at a pressure difference of 50 Pascals (CFM50) and the ZEH B had a rate of 1157 CFM50. Based on design, the infiltration rate was expected to be half of this value, specifically 595 CFM50.

Duct leakage to the outside was 44 CFM for ZEH A and 48 for ZEH B. These rates are close to design intent (40 CFM). The test report also noted that the energy recovery ventilation system was balanced and operating at 80 CFM. Based on design, it was estimated that a ventilation rate of 60 CFM was needed. The actual system therefore introduced one third more air than is needed. This would theoretically increase the energy use of the HVAC system, but it is within typical operating parameters and has a relatively small impact on energy use in comparison to other variances such as infiltration.

Based on these test results, it appeared that the building envelope was not as tight as designed. This is likely, in part, due to the design changes, but it is also possible that proper sealing was not completely achieved during construction. Campbell Crossing had initially intended to hire a

company to oversee construction, but did not do so, which may have affected the quality of the construction. The housing units still achieved a low Home Energy Rating System (HERS) index of -5, meaning they were rated to generate more energy than they would consume (a rating of 0 indicates no net energy is consumed; a rating of 100 indicates a standard new home).

Monitoring System Installation and Calibration of ZEH and Typically Designed Units

All monitoring equipment was installed in September 2010, after construction but prior to occupancy. The tables that follow outline the parameters, installation, and data collection guidance for the monitoring devices that measured each performance objective. The ESTCP project team used the data collection protocols outlined in *Building Cost and Performance Metrics: Data Collection Protocol*.

Table 10. Baseline Unit Metering Procedure

Performance Objective	Building Consumption Parameter	Brief Description of Installation and Data Collection Guidance
5 and 6. Reduce measured energy use (*Energy*)	Total building electric	Installed metering device to capture total building electricity use Provided electricity use data in 5-minute intervals to the data acquisition system
8. Reduce measured HVAC system energy use (*Energy*)	HVAC electric	Installed electric metering device(s) to capture total heating and cooling equipment energy use (including ventilation) Provided electricity use data in 5-minute intervals to the data acquisition system
9. Reduce measured hot water energy use (*Energy*)	Hot water electric	Installed electric metering device(s) to capture hot water heater energy use Provided electricity use data in 5-minute intervals to the data acquisition system
10. Reduce measured lighting, appliance, and plug load energy use (*Energy*)	Lighting electric	Installed electric metering device to capture lighting electricity use Provided electricity use data in 5-minute intervals to the data acquisition system
	Appliances electric	Installed electric metering device to capture appliance electricity use Provided electricity use data in 5-minute intervals to the data acquisition system (separate metering for each major appliance requested)
	Plug load electric	Installed electric metering device to capture plug load electricity use Provided electricity use data in 5-minute intervals to the data acquisition system (separate metering for each room requested)
	Indoor and outdoor temperature	Installed temperature monitors in living room, family room, and upstairs hallway of both units. Installed one outdoor temperature monitor to represent outdoor temperature of both units Provided space temperature data in 5-minute intervals to the data acquisition system
	Indoor and outdoor relative humidity	Installed relative humidity monitors in family room of both units. Installed one outdoor humidity monitor to measure outside air humidity at the duplex. Provided humidity data output in 5-minute intervals to data acquisition system

Performance Objective	Building Consumption Parameter	Brief Description of Installation and Data Collection Guidance
11. Reduce measured potable water use (*Water*)	Potable water	Installed whole-building water meter, and connected to the data acquisition system Provided whole building water volume data in 5-minute intervals to the data acquisition system.
Data acquisition system	Transmit and store all data captured by devices listed above	Installed in garage of each unit Provided data acquisition system that collected all of the metered points in the building. This system collected water volume, electric usage, temperature, and humidity information.
Visual data display	Energy and water data visualization for occupants	Placed on the computer desk adjacent to the kitchen where the occupants could easily see their consumption. Provided a real-time display that showed the a) Real-time consumption, b) Cumulative daily and monthly consumption, and c) Daily high and low power draw for electricity

Table 11. ZEH Unit Metering Procedure

Performance Objective	Building Consumption Parameter	Brief Description of Installation and Data Collection Guidance
5 and 6. Reduce measured energy use (*Energy*)	Total building electric	Installed metering device to capture total building electricity use Provided electricity use data in 5-minute intervals to the data acquisition system
7. Measured on-site energy generation (Energy)	Total building electric	Installed metering device to capture total building electricity generation Provided electricity use data in 5-minute intervals to the data acquisition system
	Solar hot water thermal contribution	Installed flow and temperature sensors before and after the holding tank to measure the energy content of the solar hot water used by building occupants Provided time series flow and temperature data in 5-minute intervals to the data acquisition system.
	PV panels	Installed electricity metering devices to measure the electricity production from the PV panels.

Performance Objective	Building Consumption Parameter	Brief Description of Installation and Data Collection Guidance
		Provided electricity production data in 5-minute intervals to the data acquisition system
8. Reduce measured HVAC system energy use (*Energy*)	HVAC electric	Installed electric metering device(s) to capture total heating and cooling use (including ventilation) Provided electricity use data in 5-minute intervals to the data acquisition system
9. Reduce measured hot water energy use (*Energy*)	Hot water electric	Installed electric metering device(s) to capture electricity used for hot water generation Provided electricity use data in 5-minute intervals to the data acquisition system
10. Reduce measured lighting, appliance, and plug load energy use (*Energy*)	Lighting electric	Installed electric metering device to capture lighting electricity use Provided electricity use data in 5-minute intervals to the data acquisition system
	Appliances electric	Installed electric metering device to capture appliances electricity use Provided electricity use data in 5-minute intervals to the data acquisition system (separate metering for each major appliance would be preferred)
	Plug Load electric	Installed electric metering device to capture plug load electricity use Provided electricity use data in 5-minute intervals to the data acquisition system (separate metering for each room would be preferred)
	Indoor & Outdoor temperature	Installed temperature monitors in living room, family room, and upstairs hallway of both units. Installed one outdoor temperature monitor to represent outdoor temperature of both units Provided space temperature data in 5-minute intervals to the data acquisition system
	Indoor & Outdoor relative humidity	Installed relative humidity monitors in family room of both units. Installed one outdoor humidity monitor to measure outside air humidity at the duplex. Provided air temperature data output in 5-minute intervals to data acquisition system (if the buildings are next to each other, only one outdoor temperature monitor is needed)
11. Reduce measured potable water use (*Water*)	Potable water	Installed whole-building water meter, and connect to the data acquisition system Provided whole building water volume data in 5-minute intervals to the data acquisition

Performance Objective	Building Consumption Parameter	Brief Description of Installation and Data Collection Guidance
		system
Data acquisition system	Transmit and store all data captured by devices listed above	Installed in garage of each unit Provided data acquisition system that collected all of the metered points in the building. This system collected water volume, electric usage, and temperature information.
Visual Data display	Energy & water data visualization for occupants	Placed on the computer desk adjacent to the kitchen where the occupants could easily see their consumption. Provided a real-time display that showed the a) Real-time consumption, b) Cumulative daily and monthly consumption, and c) Daily high and low power draw for electricity

Table 12. Baseline and ZEH Unit Metering Procedure

Performance Objective	Parameter	Type of Information Collected	Location
12. Reduce air emissions associated with measured electricity use	Carbon dioxide equivalents	Energy use and utility power generation data	Calculated based on energy use measurement and publicly available utility information
Qualitative Performance Measures			
13. Duplex maintenance	Maintenance activities	Number of preventative and emergency maintenance activities and hours of the ZEH units and typically designed units	Documentation collected by Fort Campbell maintenance personnel
14. Occupant satisfaction	Overall unit satisfaction	Monthly feedback regarding general satisfaction with the home and the systems in place.	Typically designed unit and ZEH unit occupants were interviewed.

In October 2010, the ESTCP team tested the monitoring equipment to check that all meters were tracking energy consumption at expected levels and patterns. Additional details on the equipment testing and calibration process can be found in Appendix E.

Data Collection, Normalization, and Comparison

The families moved into the housing units in October 2010. The period used for data normalization and comparison was January through December 2011. Data from October through December 2010 were not included in the monitoring period because of data loss in ZEH B from equipment failure that was likely caused by lightning storms. This equipment failure event required coordination with subcontractors to send and install new equipment, and Fort Campbell personnel to schedule time with the family to access the unit and reinstall the equipment.

In June 2011, the monitoring system failed again in ZEH B and Baseline A, once more likely due to severe weather. New equipment was again installed, although not all water flow meters and indoor temperature sensors regained functionality. Additional details on the monitoring points can be found in the Sampling Protocol section.

In addition to the data collection equipment installed in the housing units, the housing units were metered by the utility company that provides electricity to all housing units in the Woodlands neighborhood. This metered monthly whole-house energy consumption provided additional data points for the ESTCP team for analysis and comparison.

The collected data were used to develop monthly energy reports that were shared with the families. The first page of the report (Figure 12) included daily energy consumption. Each day was color coded to indicate the level of energy consumption. The color coding was based on the expected monthly consumption according to modeled data: green indicated days where energy consumption was below the target; yellow indicated days where energy consumption exceeded the target by up to 25%; and red indicated days where energy consumption exceeded the target by more than 25%. On red days, the two end uses with higher than typical energy consumption were highlighted with an icon so the family could recognize what may have contributed to the higher energy consumption. For example, Figure 12 shows that on Thanksgiving (November 24) the highest end uses were plug loads and kitchen appliances. Displaying the daily consumption in the form of a calendar allowed the families to more easily compare their energy consumption with their schedule and identify events that may have influenced their energy use (e.g. vacations, visitors, severe weather).

The second page of the report (Figure 13) provided more detailed energy consumption by end use so the families could see how individual end uses affected their energy consumption. The four lowest energy consumption days were highlighted in green and the four highest consumption days were highlighted in red. The monthly energy comparison allowed each family to see how their consumption compared to the other housing units in the study, and the other housing units in the neighborhood ("Average Woodlands"). Daily solar output data were provided to the ZEH families. Energy tips changed monthly and served as reminders on ways to reduce energy use.

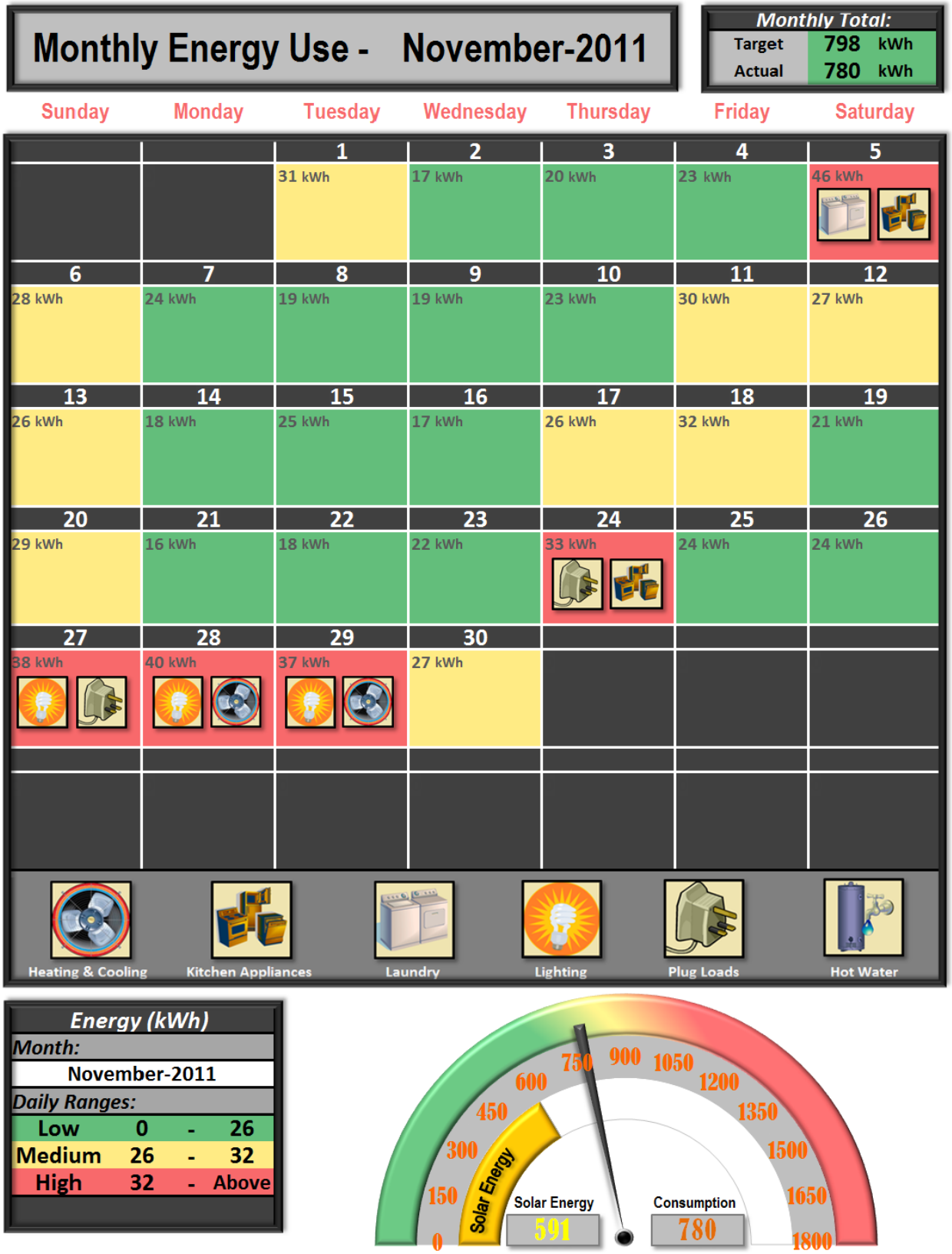


Figure 12. Monthly Energy Report Example, Page 1

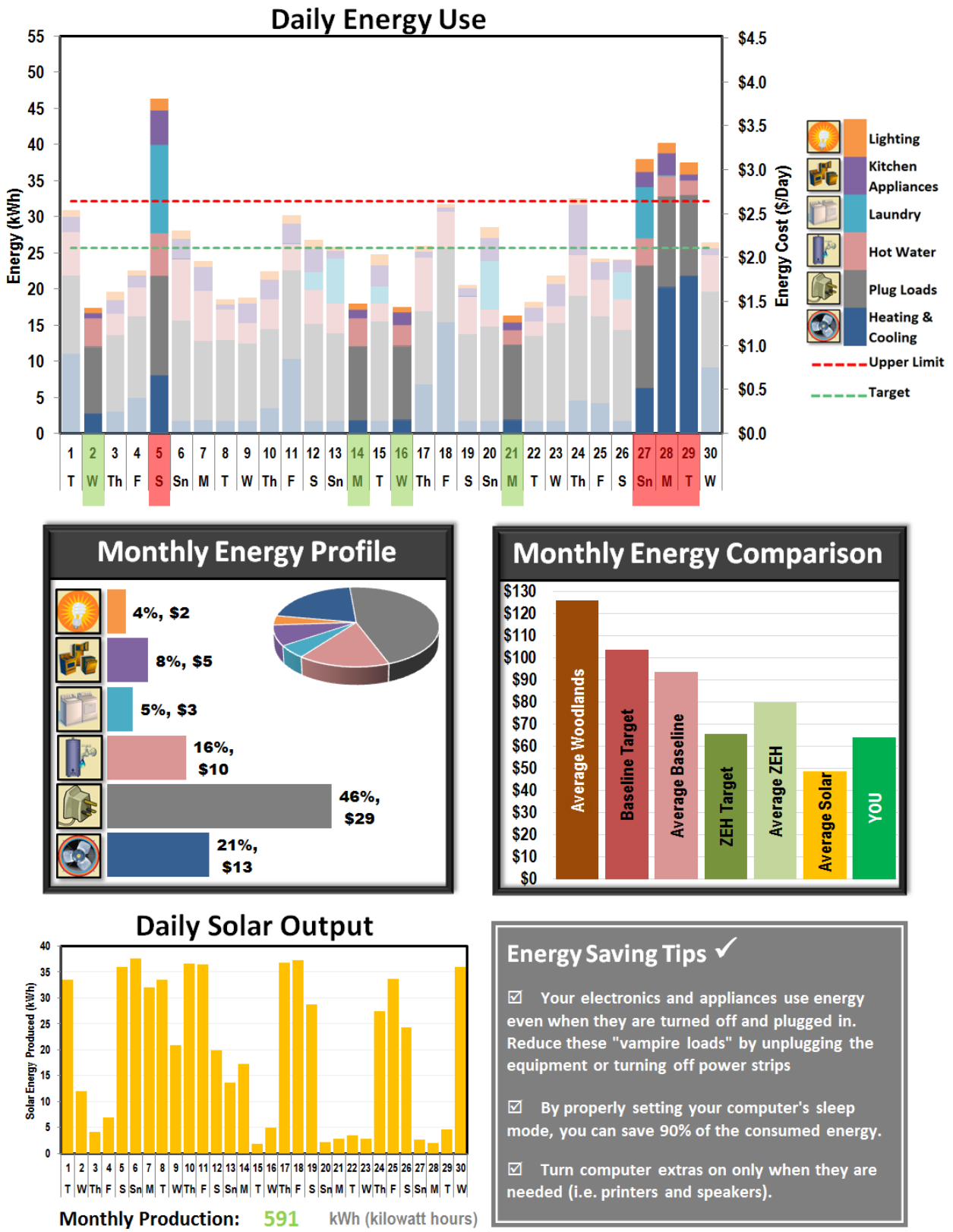


Figure 13. Monthly Energy Report Example, Page 2

After the monitoring period concluded, the monitoring system was left in the homes in case Campbell Crossing wished to continue providing more detailed energy reports to the occupants. The ESTCP team worked with Lend Lease to transfer knowledge on collecting, analyzing, and communicating the detailed monitoring data. The goal was for the Lend Lease team to continue delivering more detailed energy data to the occupants. A methodology had been established for transferring data from the online database where it is stored to a workable spreadsheet. Training was provided regarding the data analysis and communication strategies used. Time and resource constraints have limited the Lend Lease team's ability to continue to provide the detailed monthly analysis.

5.5 SAMPLING PROTOCOL

This section describes the samples that were collected during each phase of the project. Table 13 and Table 14 summarize the number and types of samples collected.

Table 13. Baseline and ZEH Unit Monitoring Samples

Performance Objective	Parameter	Number and Type of Samples	Sample Method	Schedule
5, 6, and 7. Reduce measured energy use (*Energy*)	Total building electric	5-minute data were collected 24 hours/day, 7 days a week for 12 months. Some data were lost during periods where monitoring equipment was not operational	Data acquisition system was used to collect and distribute data to analysis team	1/2011 through 12/2011
	Solar hot water thermal contribution			
	PV panels			
8. Reduce measured HVAC system energy use (*Energy*)	HVAC electric			
9. Reduce measured hot water energy use (*Energy*)	Hot water electric			
10. Reduce measured lighting, appliance, and plug load energy use (*Energy*)	Lighting			
	Plug load			
	Appliances			
	Indoor and outdoor temperature			
	Indoor and outdoor relative humidity			
11. Reduce measured potable water use (*Water*)	Potable water			

Table 14: Baseline and ZEH Unit Other Performance Metrics

Performance Objective	Parameter	Number and Type of Samples	Sample Method	Schedule
Qualitative Objectives				
13. Unit Maintenance	Maintenance activities	Annual documentation of maintenance requests and preventative maintenance performed by site personnel	Email request for data sent to site maintenance personnel	1/2011 through 12/2011
14. Occupant	General	Monthly feedback	Monthly feedback was	

Satisfaction	building	collected. Final survey questions distributed electronically, and written and verbal responses were received	collected through phone calls. Final survey questions distributed through email and responses received through email and phone calls	

A branch circuit power meter installed at the energy panel gathered interval electricity data on the building systems. Measurements of temperature, relative humidity, and water consumption were metered individually and fed to the data acquisition system. Additional detail on all monitoring points was provided on multiple mechanical drawings too numerous to include here.

Figure 14 shows the installed monitoring equipment in one of the units. The panel on the left is the data acquisition system; the panel on the right is the electric panel with individual current transformers on each end use to record electricity consumption.

Figure 14. Photo of Installed Monitoring Equipment

During the monitoring period, data were routinely uploaded by the ESTCP team and checked for consistency. Monthly energy reports were developed using these preliminary data and shared with the families as described in the Baseline Characterization section. After the monitoring period was completed, all collected data were further analyzed using the quality assurance (Q/A) process described in Appendix E. Final results, including normalized data, were compiled and recorded.

As discussed in the Operational Testing section, some data were lost at various times during the year because of equipment failure. Table 15 summarizes the total metering points installed and operational in October 2010 compared with the metering points that were functional at the end of the monitoring period in December 2011.

Table 15. Summary of Metered Points at Installation and End of the Monitoring Period

Unit	Energy		Flow		Environment		Total	
	Oct 2010	Dec 2011	Oct 2010	Dec 2011	Oct 2010	Dec 2011	Oct 2010	Dec 2011
Baseline A	37	37	2	0	5	1	44	38
Baseline B	37	37	2	2	6	6	45	45
ZEH A	40	40	3	2	7	7	50	49
ZEH B	40	40	3	0	8	1	51	41
Total	154	154	10	4	26	15	190	173

The metering points that were dropped affected Baseline A and ZEH B, and included water flow data and interior temperature data.

In addition to the major equipment failures experienced in October 2010 and June 2011, data were occasionally missing at various times. The amount varied from a few 5-minute intervals to multiple days of lost data. The causes for these occurrences were not always identifiable. Potential reasons were internet connectivity issues or equipment errors. To account for these missing data points, a Q/A process was developed to remove erroneous data points and fill in missing data. This Q/A process is explained in further detail in Appendix E.

The ESTCP team also analyzed whole house metered data provided by the local utility, Minol. The submetered data collected by the ESTCP team did not always match Minol data. This difference in metered data is not unusual as metered values can vary depending on the meter type and characteristics (Fitzpatrick and Murray 2011). ESTCP meters were not calibrated to Minol meters because Minol data were provided a month or more after the real-time energy consumption. For more information, refer to Appendix E.

Fort Campbell uses Minol data for official records and provides these data to residents across the installation, so Minol data were used for the annual and monthly total energy use comparisons in this report. The energy data collected by the ESTCP meters were used for more detailed comparisons of smaller time scales and submetered energy uses. Table 16 summarizes the data sources used for comparisons.

Table 16. Summary of Data Sources

Time Period	Metric	Data Source
Annual and Monthly	Total Energy Use	Minol meters
Daily and Hourly	Total Energy Use	ESTCP meters
Monthly, Daily and Hourly	Submetered Energy Use	ESTCP meters

5.6 SAMPLING RESULTS

This section includes a summary of the sampling results collected and analyzed. Data summaries are provided instead of the raw data due to the large amount of data collected (5-minute intervals for a 12-month period for over 150 separate monitoring points).

Energy Use

Table 17 through Table 20 summarize the monthly energy use for each baseline and ZEH unit. Table 21 includes the monthly Minol data recorded and provided to the ESTCP team. The Minol data formed the primary basis for analysis as described in Section 5.5. Differences between the submetered end use data and the Minol data were likely due to meter calibration, accuracy, and missing data.

Table 17. Baseline A Sub-metered Data (kWh)

Meter Name	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11[a]	Aug-11[a]	Sep-11	Oct-11	Nov-11	Dec-11
Miscellaneous	206	227	304	299	362	290	NR	NR	311	328	333	491
Lighting	53	71	56	72	101	62	NR	NR	95	109	101	128
Dishwasher	0	0	0	0	1	0	NR	NR	0	0	0	0
Dryer	82	97	94	65	138	65	NR	NR	81	106	107	154
Clothes Washer	5	6	7	5	10	5	NR	NR	7	9	7	11
HVAC	2138	950	501	210	289	400	NR	NR	140	186	310	569
Range	21	15	17	20	41	9	NR	NR	24	20	28	59
Refrigerator	28	28	32	32	42	31	NR	NR	38	35	34	41
Water Heater	246	194	171	168	231	122	NR	NR	153	174	218	358

[a] NR indicates no recorded data due to meter malfunction.

Table 18. Baseline B Sub-metered Data (kWh)

Meter Name	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11
Miscellaneous	330	256	278	233	319	329	375	383	221	316	342	167
Lighting	102	99	79	85	95	89	92	101	67	105	104	96
Dishwasher	5	9	9	6	5	4	5	3	2	2	7	2
Dryer	102	106	136	103	178	101	83	162	101	122	124	96
Clothes Washer	2	2	3	1	3	2	1	4	2	3	3	2
HVAC	1248	767	603	211	194	516	689	669	275	162	225	632
Range	26	31	30	13	26	17	13	28	25	26	43	12
Refrigerator	37	31	36	37	37	34	31	39	32	37	39	27
Water Heater	341	331	463	256	332	215	177	359	296	380	439	330

Table 19. ZEH A Sub-metered Data (kWh)

Meter Name	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11
Miscellaneous	293	267	359	328	300	322	342	359	349	243	419	447
Lighting	59	53	73	68	53	66	71	68	95	29	30	31
Dishwasher	11	9	15	12	9	12	10	15	16	5	15	15
Dryer	56	40	68	55	53	62	56	60	78	25	39	38
Clothes Washer	6	5	8	5	5	6	5	6	8	2	2	2
HVAC	736	526	312	124	97	344	604	468	182	87	113	389
Range	10	5	16	13	14	16	12	18	18	10	25	29
Refrigerator	33	27	32	32	30	32	32	34	37	25	25	24
Water Heater	169	142	208	164	138	127	113	128	141	86	113	128

Table 20. ZEH B Sub-metered Data (kWh)

Meter Name	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11[a]	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11
Miscellaneous	274	283	282	327	329	346	NR	321	327	325	348	402
Lighting	75	72	61	80	72	88	NR	89	109	69	92	105
Dishwasher	8	12	12	14	11	11	NR	9	14	11	14	17
Dryer	54	93	68	86	89	93	NR	85	93	79	95	93
Clothes Washer	3	6	5	6	6	6	NR	6	7	5	6	6
HVAC	566	457	261	110	176	330	NR	269	135	173	250	518
Range	16	21	14	18	15	15	NR	7	10	17	23	29
Refrigerator	31	32	33	39	43	46	NR	41	39	33	41	39
Water Heater	202	374	263	296	296	250	NR	181	235	234	296	354

[a] NR indicates no recorded data due to meter malfunction.

Table 21. Minol Data (kWh)

Home	Jan-11	Feb-11	Mar-11	Apr-11	May-11	Jun-11	Jul-11	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11
Baseline A	2,603	1,580	1,179	899	1,172	1,042	1,533	1,248	926	1,015	1,168	1,857
Baseline B	2,747	1,975	2,007	1,034	1,282	1,356	1,583	1,834	1,054	1,234	1,421	1,485
ZEH A	1,447	1,167	1,162	859	785	995	1,260	1,246	1,002	579	850	1,129
ZEH B	1,493	1,414	996	1,010	1,078	1,129	1,285	1,056	995	989	1,196	1,565

Water Use

Table 22 summarizes the monthly water use in gallons for the baseline and ZEH housing units.

Table 22. Monthly Water Consumption (gallons)

	Cold Water				Hot Water			
Month	**Baseline A**	**Baseline B**	**ZEH A**	**ZEH B**	**Baseline A**	**Baseline B**	**ZEH A**	**ZEH B**
11-Jan	3,021	3,414	2,618	NR	1,501	1,879	1,334	NR
11-Feb	3,154	3,165	2,149	NR	1,165	2,020	1,102	NR
11-Mar	4,724	5,269	3,471	2,910	1,067	3,007	1,734	NR
11-Apr	6,290	3,021	2,856	3,887	1,202	1,726	1,451	NR
11-May	8,573	3,956	2,338	4,030	1,881	2,550	1,216	NR
11-Jun	6,446	4,083	2,715	4,282	1,114	1,888	1,355	NR
11-Jul	NR	2,893	2,500	NR	NR	1,653	1,179	NR
11-Aug	NR	7,760	2,953	NR	NR	3,919	1,517	NR
11-Sep	NR	5,243	3,602	NR	NR	2,940	1,630	NR
11-Oct	NR	5,416	1,296	NR	NR	3,440	629	NR
11-Nov	NR	7,582	1,716	NR	NR	3,476	930	NR
11-Dec	NR	7,669	1,691	NR	NR	2,265	978	NR

Occupancy Variances

Notable occupancy-related events were recorded during monthly interviews with occupants. To maintain occupant privacy, detailed information (exact number of visitors, exact duration of visits) was not explicitly requested. Table 23 records months where regular occupancy changed (e.g., spouse returned from deployment), the family hosted visitors, were absent from the home (e.g., vacation), or moved. The number of people in the home (visitors or regular occupants) most affected hot water use, as discussed in section 6. When the families were on vacation and absent from the home, energy use decreased as expected.

Table 23. Summary of Notable Occupancy-related Events in 2011

Family	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec	2011 Approx Weeks Absent	2011 Approx Weeks with Visitors
ZEH A				O, V	A	A	A, V		M	M		V	7	3
ZEH B		O	A		V	V	O	O		A		A	2	2.5
Baseline A				O		A, V	V					V	2	5
Baseline B			V					O	A, V			M	2.5	1

O = Occupancy change; V = Visitors; A = Absent; M = Move

6.0 PERFORMANCE ASSESSMENT

6.1 STATISTICAL ANALYSIS

The analysis technique used in this study is called "matched pairs." For building performance measurement, a matched pairs study compares two groups of similar buildings. In this case, the primary comparison was between the ZEH units and the typically designed units. The matched pair analysis was possible because the units served the same function, were located in the same climate zone, were in the same housing development, and were the same size.

An additional comparison was made between each housing unit in the duplexes to observe if the effect of occupant behavior on the building performance was greater than the effect of the improved building design. ZEH housing unit A was compared to the ZEH housing unit B, and the typically designed housing unit A was compared to the typically designed housing unit B. The units were also compared to an average of the other units in the neighborhood.

Because the analysis contained only two residences for each building design, the statistical robustness was limited, and identified differences between the two building types may not be representative results.

Five-minute metered data were collected for multiple end uses, whole building energy use, and water usage. The level of data collection allowed for the summary analysis as well as detailed end-use analysis to understand how the units performed and how the occupants operated the individual housing units over time.

On-going data analysis occurred as the data were received. For example, sudden increases or decreases in the energy data were first reviewed to assess whether the building equipment was operating as expected. If the data analysis did not provide a plausible explanation for unexpected data, the occupants were contacted to better understand the information.

6.2 DATA NORMALIZATION

The performance metrics were normalized as appropriate to allow for a comparison between the matched pairs and to other similar buildings. The primary building characteristics used to normalize the performance data were unit size and number of duplex occupants. Although the units are the same size, square footage was used to normalize energy use, water use, and maintenance activity for comparison to industry standards. The number of occupants included a count of regular housing unit occupants, and was used to normalize water use and energy use. Changes in occupant weekly schedules, such as long vacations, deployment, or overnight visitors, were also used to inform the data analysis.

6.3 SPECIFIC ANALYSES OF THE MEASURED PERFORMANCE OBJECTIVES

6.3.1 Energy

The objectives to *reduce measured energy consumption* and *confirm measured energy generation* were used to compare the energy performance of the units. Energy use includes

electricity for the typically designed unit and electricity use and renewable generation for the ZEH. The electricity consumption was converted from kilowatt-hours to British thermal units over a time interval. Unit energy use was normalized by gross square footage when comparing to Woodlands units and national averages.

As illustrated in Figure 15, both ZEHs used more energy than the amount of solar energy generated over the course of the year. The ZEH units did not achieve net zero energy in 2011 because the units used more energy than expected, and less energy was generated by the PV panels than expected.

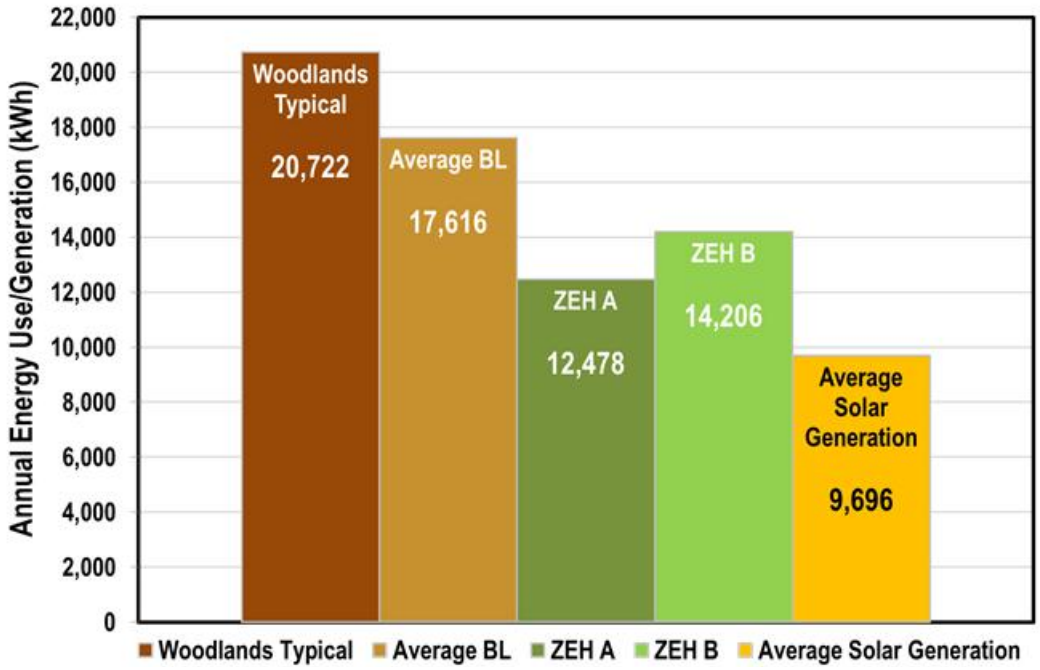


Figure 15. Annual Total Energy Use

The ZEHs did consistently use less energy than the baseline housing units and the average Woodlands home (Figure 16). The baseline housing units also consistently used less energy than the average Woodlands home. This difference between the average baseline home energy use and the average Woodlands home was notable, indicating that providing detailed energy use information (especially with the real-time energy devices such as TED) likely influenced the families' energy use patterns.

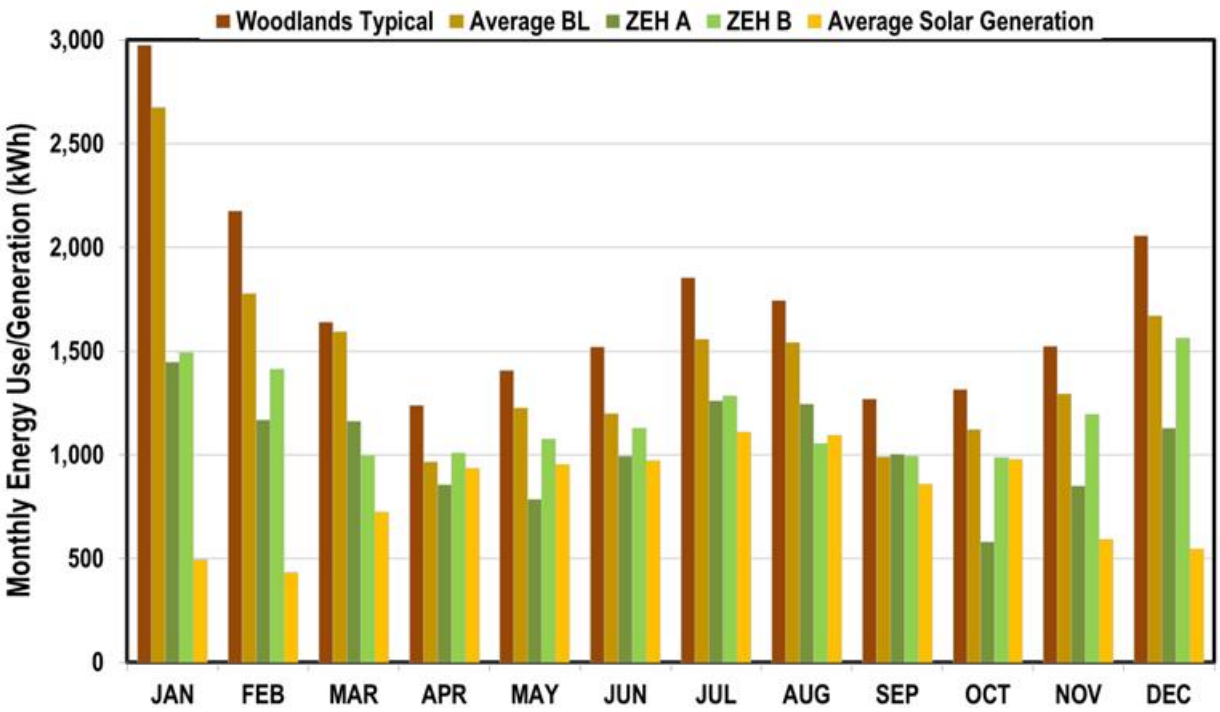


Figure 16. Monthly Total Energy Use

The Woodlands housing units also consumed less energy than originally expected. Date from 2008 provided by Lend Lease indicated that similar housing units at Fort Campbell consumed an average 27,327 kWh per unit, or 46.5 kBtu/sf which is in line with 2001 RECs data. In comparison, the average Woodlands consumption in 2011 was 20,722 kWh per unit, or 28.4 kBtu/sf which is 20% less than 2009 RECs data for the south census region homes constructed after 2000. While many factors may have influenced this change in energy consumption, the trend could be consistent with more efficient lighting and appliances in Lend Lease's standard home design and increased awareness of energy efficiency goals.

Consistent with the typical ZEH approach, the solar panels were sized to produce as much energy as the housing units were modeled to consume. Many assumptions were required to create this modeled energy consumption, including technology performance, frequency of use, and interior and exterior temperatures. Successfully reaching net zero energy depends on how closely the assumptions matched the actual use patterns.

As discussed in Section 2, the original model included less efficient kitchen and lighting in the baseline home than was actually installed. Accordingly, the actual baseline consumption for these end uses was less than expected (Figure 17). Differences between the modeled and actual consumption was the most noticeable for HVAC energy use. The ZEH housing units consumed 40% more HVAC energy than the model predicted. Various factors affected HVAC energy consumption, such as interior temperature setpoints, building envelope tightness, and exterior environmental conditions. Modeling estimates indicated that differences between modeled and actual interior temperature setpoints resulted in 30% more HVAC consumption than expected, and higher infiltration rates resulted in 20% higher consumption. These variances are discussed in more detail in the following subsections.

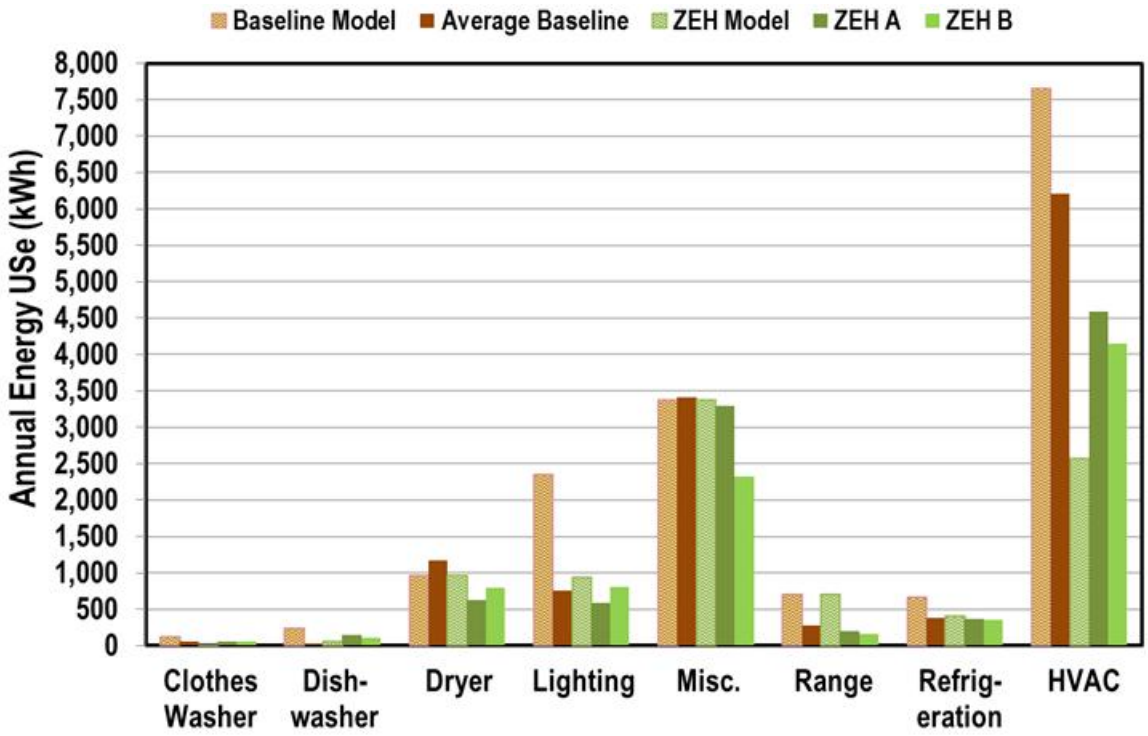


Figure 17. Modeled and Actual End Use Comparison

Figure 18 summarizes the performance of the ZEHs compared to the average baseline unit, the average Woodlands home, the typical home in 2008 (when the homes were designed), and the modeled energy use of the ZEHs and the baseline units. The ZEHs and the baseline units did not perform as the model predicted, but the ZEH units peformed better than the baseline units, the average Woodlands home, and the average Ft. Campbell home in 2008.

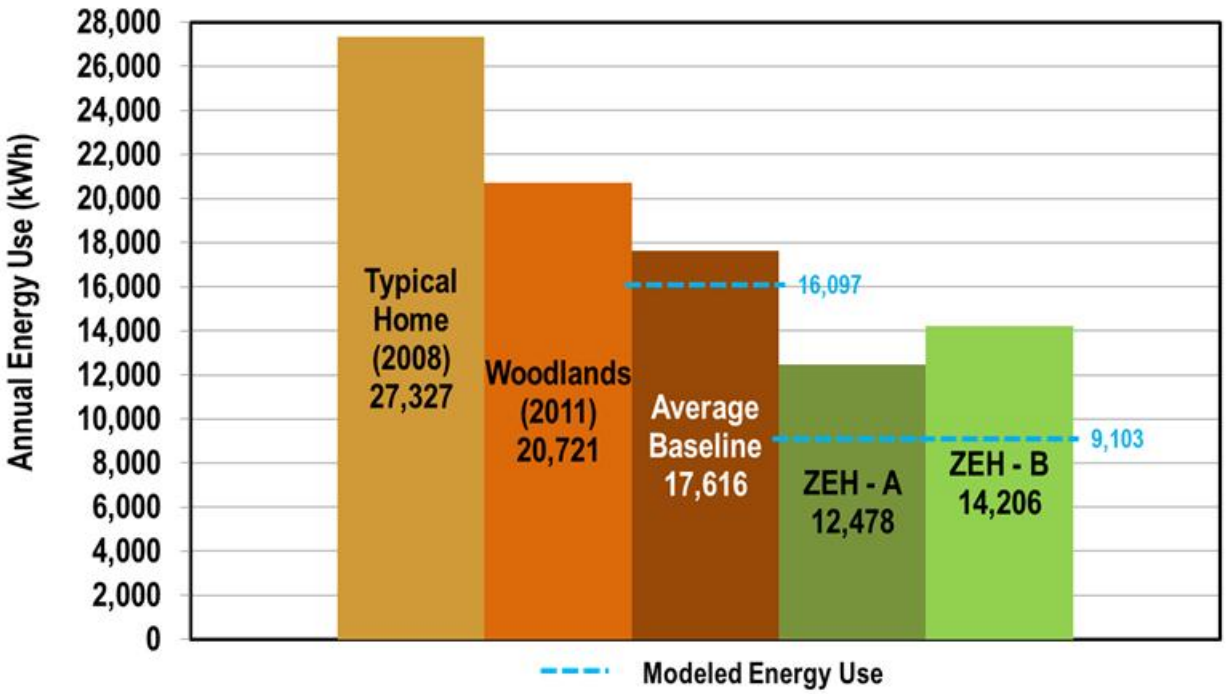


Figure 18. Modeled and Actual Energy Use Comparison

Interior Temperature

Indoor temperature sensors were installed in the living room, family room, upstairs hallway, and garage for each home. Data were available for all 12 months in ZEH A and Baseline B. Temperature data for ZEH B and Baseline A were available for interior spaces (other than the garage) from January through June 2011.

The setpoints assumed in the model were a maximum 76 °F for cooling and a minimum 71 °F for heating. The measured interior temperature of the housing units was typically lower than the modeled 76 °F. Figure 19 shows the average interior temperature recorded in the living room for ZEH A. ZEH A Family 1 maintained a fairly constant 72°F for the nine months they lived in the unit (Figure 19). ZEH A Family 2 moved into ZEH A in October, and preferred cooler temperatures. The lower interior temperature setpoint resulted in lower HVAC energy consumption during the heating season compared to wintertime months for Family 1.

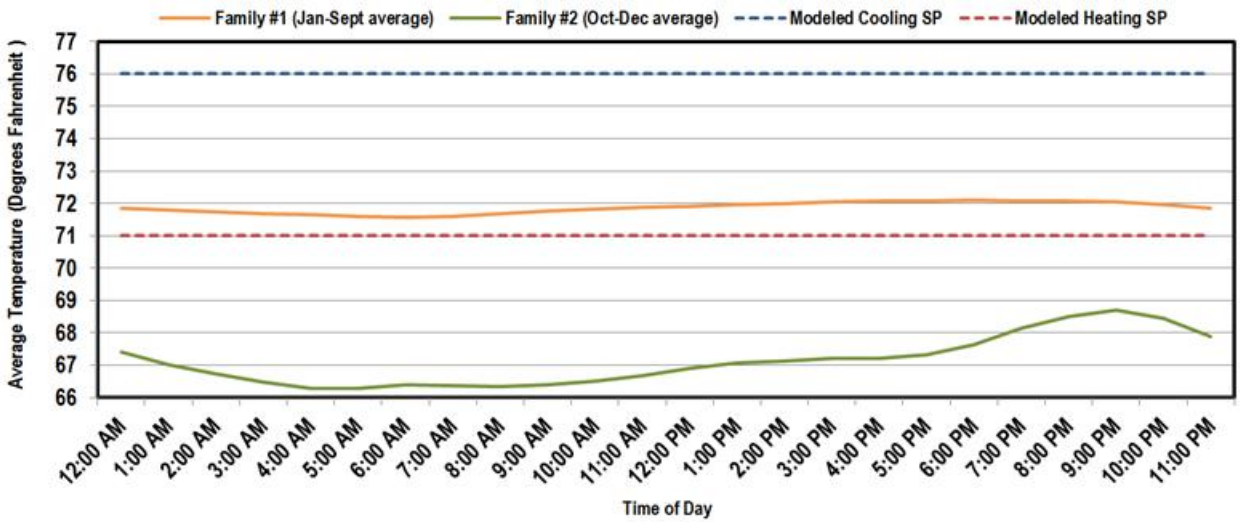


Figure 19. Sample ZEH Average Temperature

During winter, the average hourly temperatures in the baseline housing units varied during the day compared to the nighttime hours, indicating some temperature setbacks (Figure 20). In contrast, ZEH temperatures were reasonably constant (Figure 19). According to occupant feedback, there was typically someone home during the day in the ZEHs, whereas the occupants in the baseline housing units were typically absent during the day. This difference in occupancy patterns likely influenced the temperature setbacks present (or not) during the day, and thus daytime energy consumption.

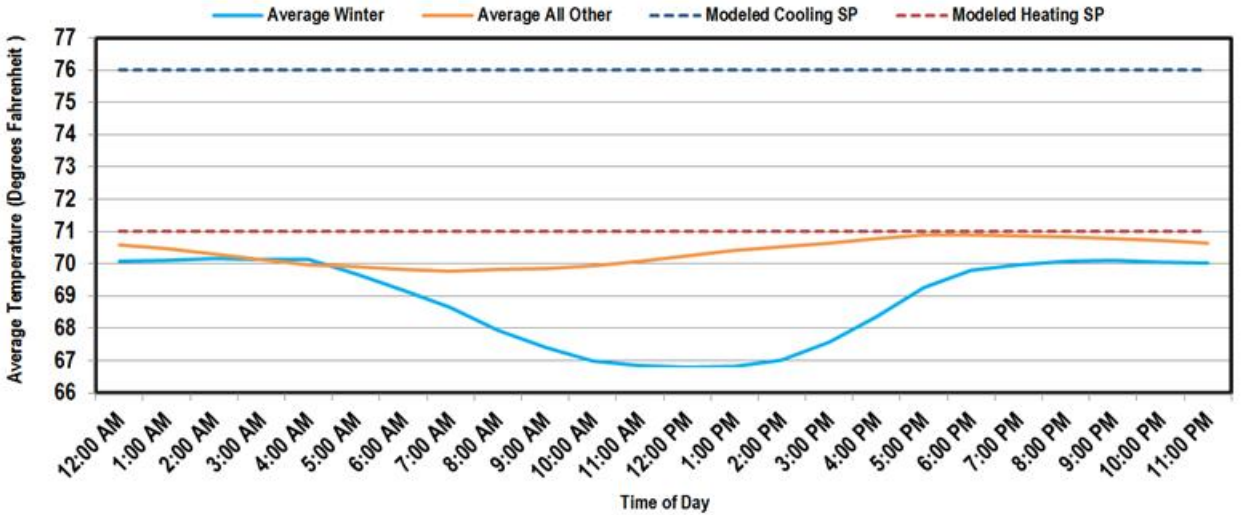


Figure 20. Sample Baseline Average Interior Temperature

During summer, daytime and nighttime temperatures were fairly constant in all four housing units. Indoor temperatures for ZEH A were typically lower during the winter than the other ZEH and the baseline housing units. Indoor temperatures for Baseline A were typically higher during the summer than the ZEH units and the other baseline units. Indoor temperatures for Baseline B were on average lower in winter (less energy consumed) and summer (more energy consumed) than the other housing units.

Relative Humidity

Notable differences between the relative humidity measured in the ZEHs and baseline housing units were not identified (Figure 21). The relative humidity remained below 70% in all the housing units except in June, when ZEH B and Baseline A recorded values slightly higher than 70%. Indoor relative humidity data were not available for ZEH B and Baseline A for July through December.

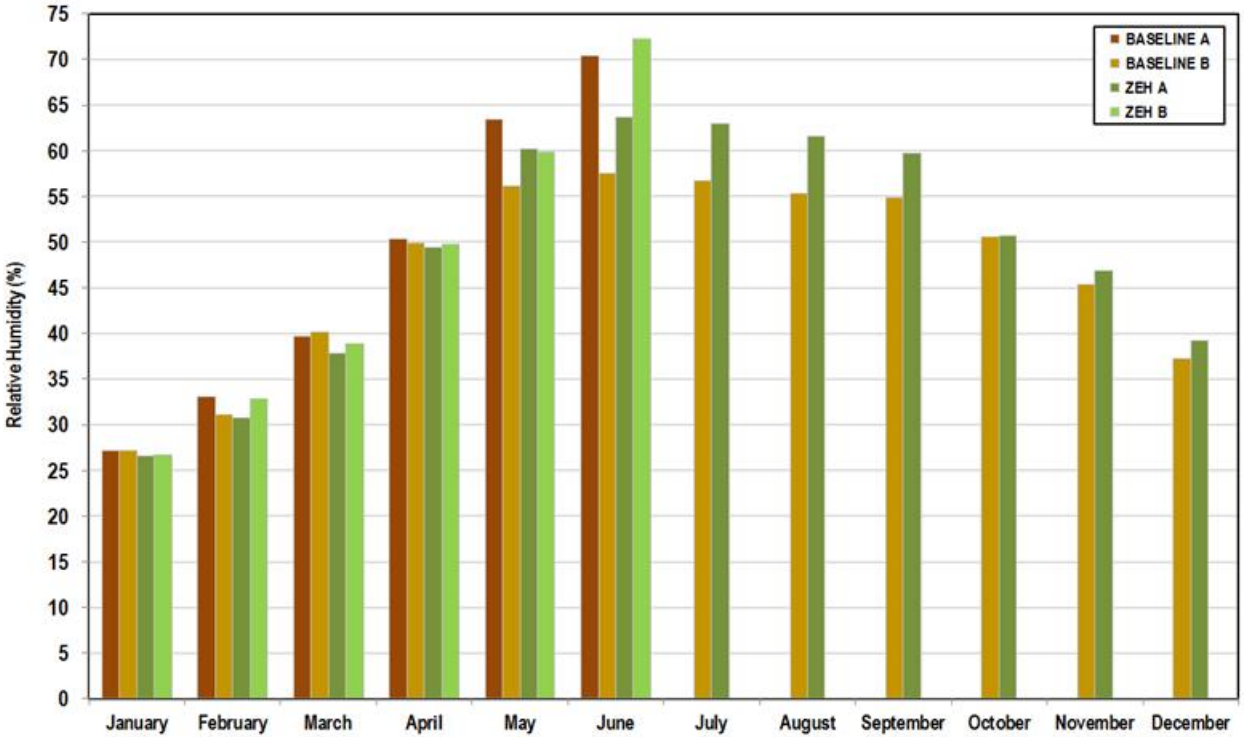


Figure 21. Average Monthly Relative Humidity

Outdoor Temperatures

Figure 22 shows the average monthly temperatures recorded by the National Climatic Data Center (NCDC) at a station adjacent to the Fort Campbell airstrip, the typical meteorological year (TMY) used in the modeled data, and the exterior temperature sensors at the housing units in 2011 (ZEH-B). Temperatures were slightly above average throughout the year, but not enough to expect a large effect on overall energy consumption compared to modeled energy use.

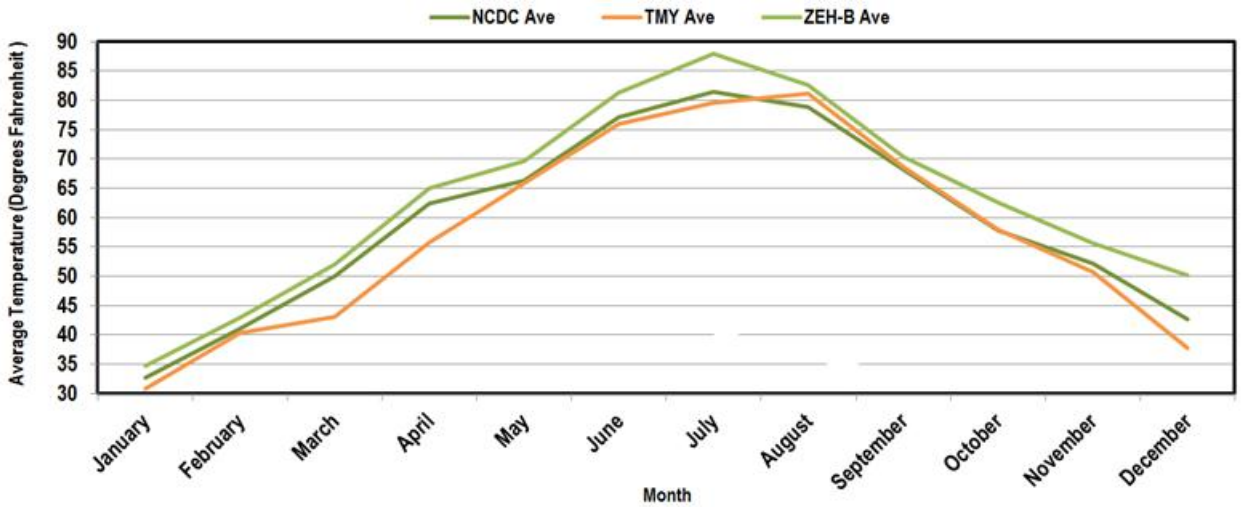


Figure 22. Average Typical Monthly Temperatures Compared to Average 2011 Temperatures

PV Panels

In addition to the housing units consuming more energy than expected, the solar panels also produced 6% less energy than expected (Figure 23). As with energy modeling of building energy use, modeled solar energy generation often varies slightly from actual generation because of variables associated with modeling, including insolation, temperature, inverter behavior, wiring and its associated losses, module performance, and shading. Other comparisons of PV models and actual performance illustrate that 6% is within the range of observed variation of 5-11% (Cameron et. al 2008).

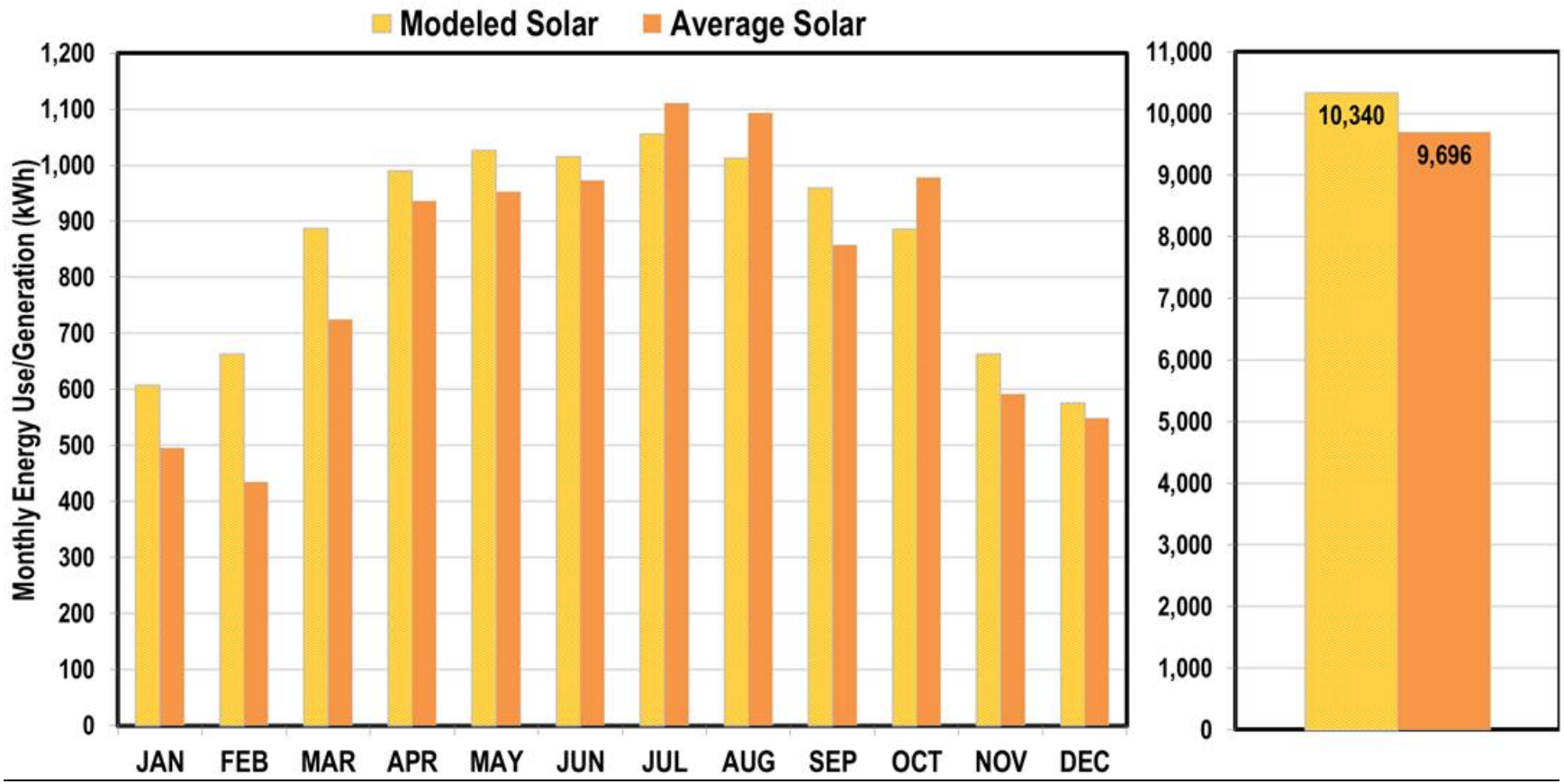


Figure 23. Modeled and Actual Solar Energy Production

Solar Hot Water

To collect data necessary to calculate the amount of solar energy delivered to the occupants by the solar hot water system, a flow meter was installed and two temperature sensors placed on the inlet and outlet of the hot water holding tank inside the home. However, the contact between the temperature sensors and the water flow was not sufficient to collect accurate temperature data. In addition, the lightning storms mentioned in previous sections led to some dropped temperature sensors. The metering equipment subcontractor informed the ESTCP team that the solar hot water system's water temperature monitoring points could have affected the system failure, so the team decided not to risk losing the entire monitoring again by trying to restore the solar hot water system monitoring points. As a result, insufficient data were available to determine conclusively the amount of solar energy delivered by the solar hot water system. The backup electric heater's electricity use was consistently recorded, and, along with the hot water flow, was used to compare hot water performance between the ZEHs and baseline units. ZEH A and Baseline B were used for comparison because hot water flow data were not consistently available for ZEH B and Baseline A.

The solar hot water comparison showed that on average, Baseline B used 131 watts per gallon of hot water delivered, while ZEH A used 112 watts per gallon of hot water delivered, a difference of 14%. Figure 24 shows the monthly power per gallon comparison between ZEH A and Baseline B.

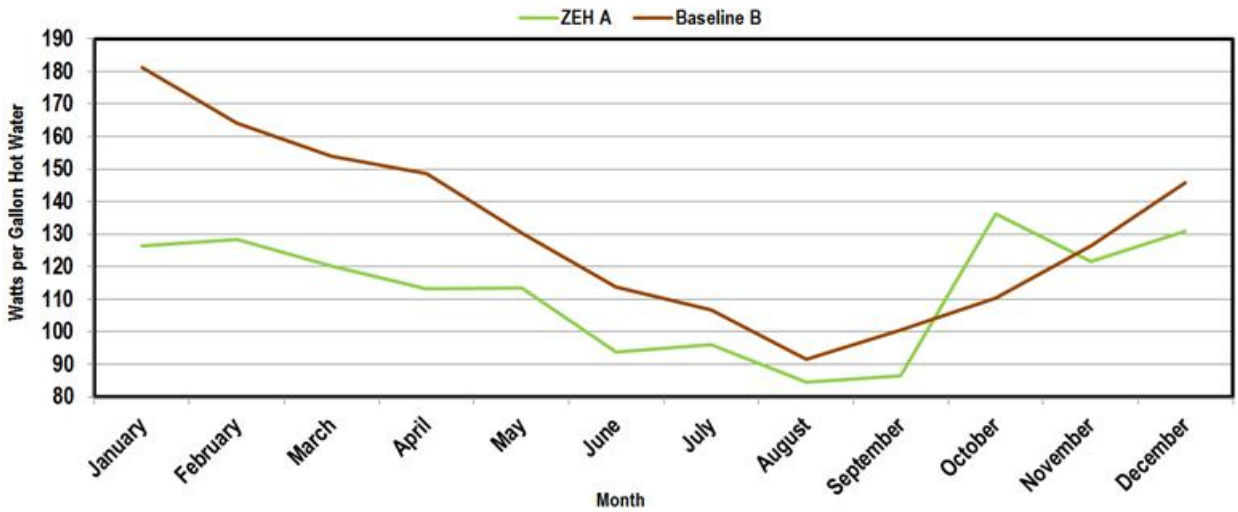


Figure 24. Monthly Hot Water Comparison

ZEH A consistently used less power per gallon of hot water consumed than Baseline B (except in October when usage decreased because the ZEH family moved so the home was empty for half of the month), indicating the contribution of the solar hot water heater. However, Baseline B also used more water on average than ZEH A (Figure 25). It is unclear if the solar hot water system or the lower volume of hot water used compared to Baseline B contributed more to the lower energy use per gallon of hot water consumed in ZEH A.

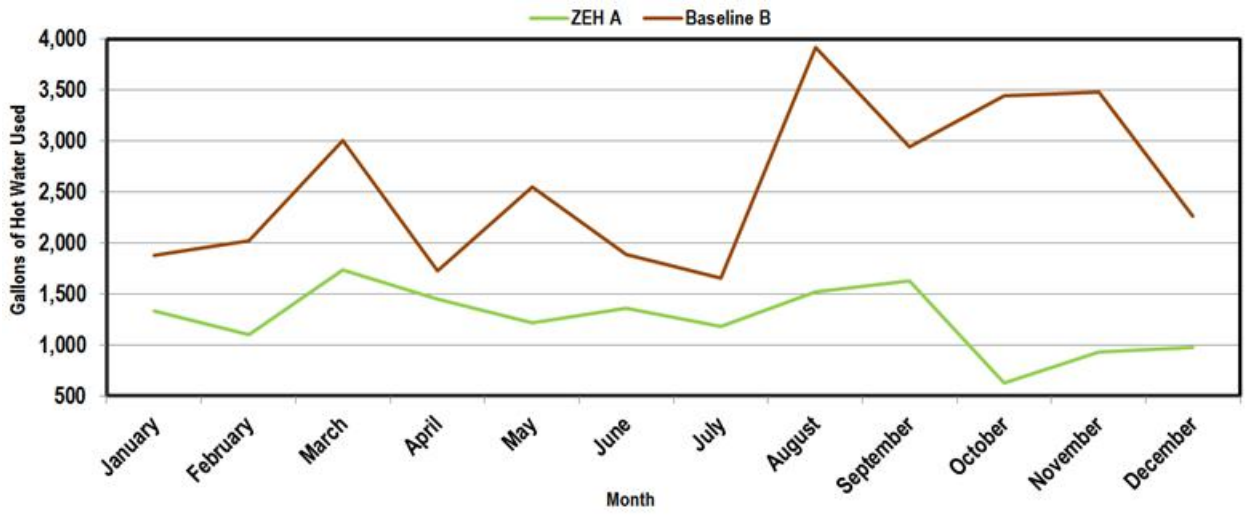


Figure 25. Monthly Hot Water Consumption

While the data indicate that the solar hot water system reduced hot water electricity use in ZEH A compared to Baseline B, without sufficient metering in place, conclusions cannot be made about the amount of total hot water energy use provided by the solar hot water system.

Occupant Interaction

Although the ZEHs did not reach net zero energy, the families did respond favorably to the information provided throughout the project. Laundry use was one area where occupants modified behavior as a result of the information provided in the monthly reports. Figure 26 shows a month of data from early in the monitoring period for one of the housing units. The ESTCP team noted that laundry use occurred almost daily in this home (there were only two days during the month without laundry use). When this observation was discussed with the family, the feedback from the family was that one of the children in the home did small loads of laundry daily to have the ideal outfit for school the next day. After the parent reviewed these data and saw the multiple loads of laundry, the parent used the monthly data report to communicate the unnecessary energy use to the child.

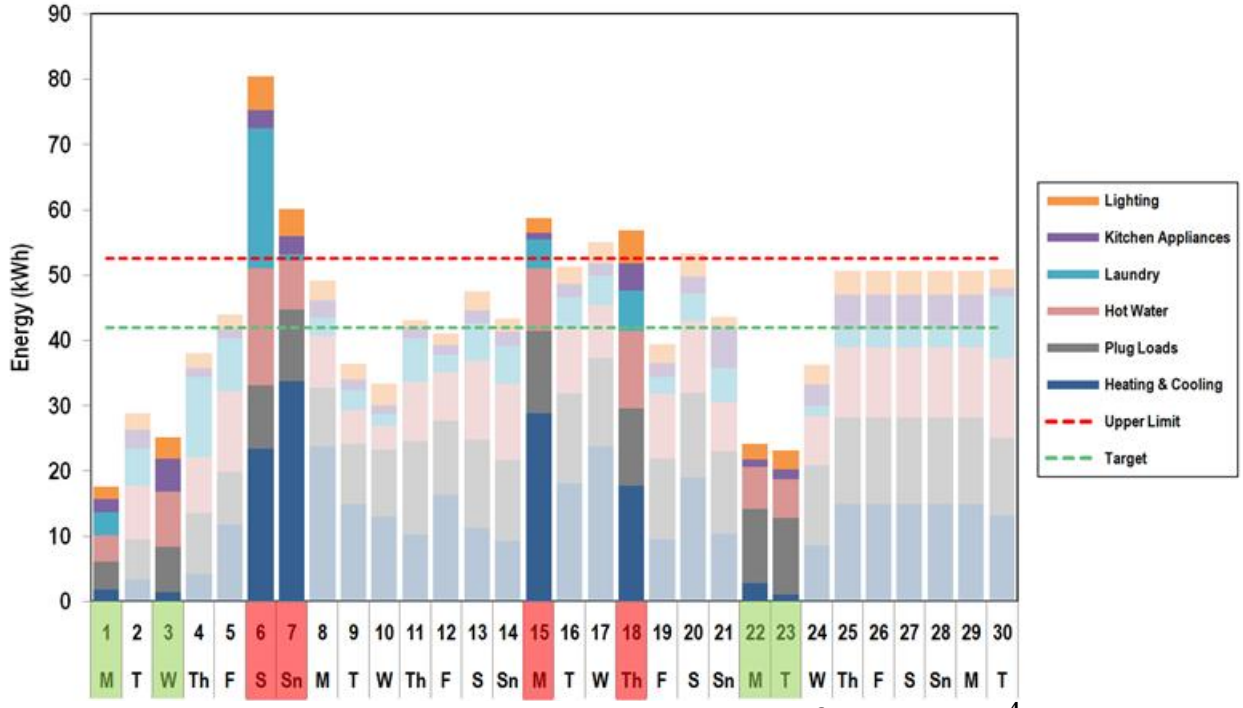


Figure 26. Example Daily Laundry Use, before Feedback[4]

The next month (Figure 27) shows that laundry use changed from almost daily to a few times per week.

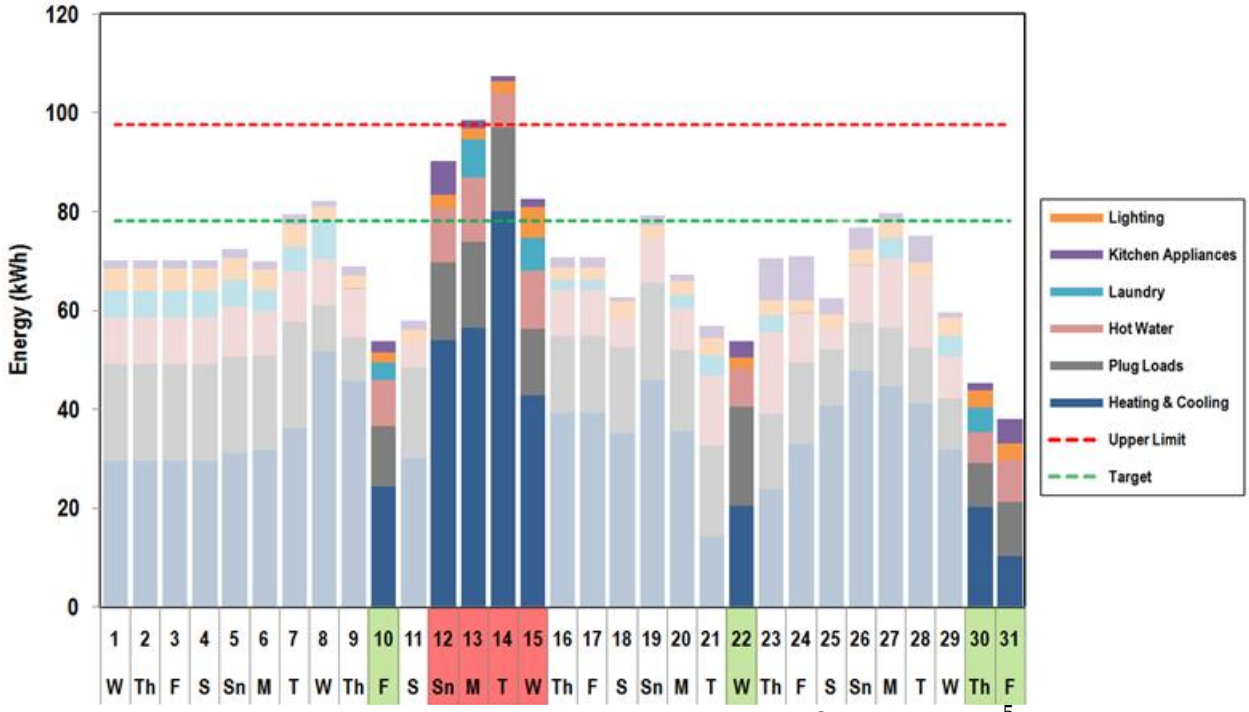


Figure 27. Example Daily Laundry Use, after Feedback[5]

[4] The energy data for the days 25-29 of this month were interpolated according to the Q/A methodology described in Appendix E.

6.3.2 Water

The objective to *reduce measured potable water consumption* was used to examine the quantity of water used by unit occupants for domestic uses. Domestic potable water use was collected as gallons of use over time. The number of regular occupants was used to normalize the water use per unit occupant. In addition to measuring water use per regular unit occupant, the number of visitors and length of visit were used to allow for a normalized comparison of the domestic water use between the units. Water use and cost was normalized by square footage as well.

Water flow data were not available from June through December for Baseline A and ZEH B; therefore, data from Baseline B and ZEH A formed the basis for the water consumption analysis.

ZEH A consumed 51% less water per person than Baseline B in 2011. The ZEH A family was gone more weeks during the year than the Baseline A family, and had more weeks with visitors.[6] Accounting for vacation and visitors, ZEH A consumed 48% less water per person than Baseline B. ZEH A consumed 41% less gallons per square foot than Baseline B.

Table 24 summarizes the water use results for Baseline B and ZEH A.

Table 24. 2011 Water Use Summary

Unit	Regular Occupants (number of people)	Vacation Weeks	Weeks with Visitors	Water Use per Regular Occupant, Not Including Vacations or Visitors (gal/person/day)	Water use per Occupant, Including Vacations and Visitors (gal/person/day)	Water Use per Unit of Floor Area (gal/sf)
Baseline B	3.4	3	1	74.0	76.2	30.6
ZEH A	3.3	7	3	36.0	39.3	18.1

6.3.3 Maintenance

The objective *reduce housing unit maintenance* examined the operational impact of sustainable design features. The maintenance metric compared (planned) preventative maintenance with (unplanned) repair-related maintenance (e.g., emergency service calls). The scheduled maintenance activities were reviewed to determine if the same level of maintenance was occurring at all housing units. The rate and reason for service calls were compared between the units and to the preventative maintenance records. Maintenance calls related to occupant habits rather than building performance (e.g., broken doors, broken window blinds) were not included in the analysis.

Table 25 indicates the number and hours of preventative and emergency maintenance calls in 2011 for each home.

[5] The energy data for days 1-4 of this month were interpolated according to the Q/A methodology described in Appendix E.
[6] Conservatively assumed one more person in the home during the periods with visitors.

Table 25. 2011 Maintenance Activity Summary

	Baseline A	Baseline B	ZEH A	ZEH B
Preventative				
Number of calls	0	0	2	2
Total annual hours	0	0	1.75	1.75
Emergency				
Number of calls	2	2	2	1
Total annual hours	1	1.5	2	0.7

ZEH emergency maintenance activities were about the same as both typically designed units, but the ZEH-specific technologies resulted in more preventative maintenance activities than the typically designed units. Cleaning and replacing the energy recovery ventilation system filters was the primary preventative maintenance activity in the ZEHs that was not performed in the typically designed units.

Post Monitoring Period Maintenance Activities

Maintenance records were also received for the months following the monitoring period. Some preventative maintenance activities for the renewable energy systems and the HVAC systems occurred in the ZEHs during these months. These activities are noted below, but are not included in Table 25.

Energy recovery ventilators (ERVs)

As was seen during the monitoring period, the ERVs require more frequent filter changes. The ERVs were thus an added maintenance item in the ZEHs as they are not present in the baseline housing units. Maintenance staff determined that the pre-filter needs monthly cleaning (typically takes 30 minutes) and the main filter needs to be replaced annually (typically takes 30 minutes).

Solar hot water systems

Additional maintenance was also required on the solar hot water panels. Fort Campbell maintenance personnel were not familiar with required maintenance after the buildings were constructed, and it was determined that an additional 4-8 hours of training immediately after the buildings are constructed would improve understanding of the system's maintenance needs. The glass coverings on the solar collectors were streaking, likely due to calcium deposits. The manufacturer cleaned the panels per Fort Campbell's request, but the streaking began again soon after the cleaning. The manufacturer's finding was that streaking was caused by the heat buildup from the high capacity systems, and that the streaking only affects aesthetic appeal and not system efficiency; however, this was not independently verified.

Geothermal systems

In July 2012, the geothermal system in one of the ZEHs stopped operating properly. To continue cooling the home while the maintenance staff determined the cause, window air conditioning units were installed temporarily. Maintenance staff eventually determined that the systems simply needed to be reset to continue proper operation. Additional training when the buildings were first constructed on the system maintenance needs could have resulted in more rapid repair, without requiring window air conditioning units to be installed.

6.3.4 Air Quality

The objective to *reduce air emissions due to reduction in measured electricity use* provided an indicator of the reduced environmental impact of the ZEH unit. Carbon dioxide equivalents (CO_2e) were calculated, as the indicator metric of GHG emissions, using the power generation emission for the region serving the duplexes (the SERC Tennessee Valley, or SRTV region) as reported in EPA's eGRID database. The regional factors were used instead of the local utility factors for consistency with current federal GHG reporting guidance (CEQ 2012).

Because the ZEH and baseline housing units use electricity for all energy needs, the percent difference in GHG emissions between the two housing units was similar to the difference in energy consumption. ZEH A net emissions in 2011 were 1,617 kg CO_2e, and ZEH B net emissions were 2,894 kg CO_2e, or 85% and 73% lower than the average baseline home, respectively.

6.3.5 Occupant Satisfaction

The objective *measured occupant satisfaction* examined occupant impressions of the individual housing units. The occupant satisfaction survey results for the housing units were compared to one another. Originally, the CBE occupant survey was to be used because it offered a database of building occupants. However, the CBE survey questions and corresponding database are structured for commercial building occupants and most of the questions did not apply for residential applications (Table 26). Therefore, occupant satisfaction was qualitatively evaluated based on monthly interviews with the occupants and a final set of questions after the monitoring period was completed. The questions covered overall building satisfaction and thermal comfort.

Table 26. CBE Survey Topics Compared to Collected Information

CBE Survey Topic	Information Collected
General building description questions	N/A - building layout/description known
General building occupancy questions (hours in the building, hours in different spaces, hours doing different types of activities)	Collected typical hours in the home in screening questionnaire.
Satisfaction with:	
Unit layout, including privacy and storage	N/A
Furnishings	N/A
Thermal comfort, including user control over specific features and satisfaction with temperature	N/A
Air quality (e.g., stuffy/stale air, cleanliness, odors)	General information collected during interviews
Lighting, including controls, amount, glare, reflections, contrast	N/A
Acoustic quality	N/A
Cleanliness and maintenance	Some maintenance information collected during interviews
Bathroom, kitchen, shared areas, laundry, computer rooms	Laundry collected during interviews
Specific features including:	
Thermostats	General information collected during interviews
Window blinds	Not collected
Hot water supply	General information collected during interviews
Vending machines	N/A
Water-efficient fixtures	General information collected during interviews
Electrical plugs	N/A
Informational materials (how to use)	General information collected during interviews
General satisfaction	General information collected during interviews

The occupant satisfaction metrics were also analyzed in relation to other performance metrics, for example thermal comfort and energy performance. Monthly interviews and the results from the final set of questions indicated that there was no notable difference in satisfaction between the occupants of the ZEHs and typically designed units.

7.0 COST ASSESSMENT

Costs were considered throughout the entire design, construction, and monitoring process. For this demonstration, the goal was to optimize the building efficiency level (to meet net zero) at the most cost effective level, while maintaining an equitable design to the current Campbell Crossing duplex design. These parameters guided the design process. Design elements under consideration were prioritized by anticipated cost and payback based on the technical expert knowledge.

The approach used for the cost assessment was life-cycle cost analysis (LCCA). This is a commonly applied tool in the high performance building industry. The National Institute of Standards and Technology (NIST) defines LCCA as "an economic method of project evaluation in which all costs arising from owning, operating, maintaining, and ultimately disposing of a project are considered to be potentially important to that decision" (NIST 1996). LCCA allows stakeholders to quantify the tradeoff of higher initial costs against reduced future cost obligations.

LCCA adds a dimension to evaluating building project costs that in the past had not been included in common practice. The driver for applying LCCA to building projects was the need to accurately measure investments in energy-saving equipment and strategies. LCCA differs from conventional construction cost analysis because it goes beyond limiting the analysis to initial or "first" costs associated with land acquisition, building design, and construction costs. LCCA expands the analysis scope to include operational, maintenance, and eventual disposal costs of a building. In other words, a LCCA takes into account all the costs associated with acquiring, owning and disposing of a building (NIBS 2010).

In high performance building, initial costs for energy-saving equipment and strategies may be high, but this initial investment is often offset by reduced operating costs throughout the life of the building. LCCA allows building owners to look beyond initial investment costs when evaluating building designs.

LCCA is a recommended practice of the USGBC's LEED building certification program and the National Institute of Building Sciences' Whole Building Design Guide (NIBS 2010). LCCA is the basis of the approach that was used to measure the economic impact of implementing ZEHs at Fort Campbell, Kentucky.

This project was undertaken because the military is interested in determining the impact associated with the construction of energy efficient homes. Data from this project will assist the military with measuring the expected ZEH benefits of lower energy costs, increased energy security, and decreased pollution from energy production. Although calculating impact of energy efficient housing on an Army- or military-wide basis is outside the scope of this project, the life-cycle cost differentials of constructing and operating the two ZEHs at Fort Campbell were calculated.

7.1 COST MODEL

As part of this demonstration, the Building Life-Cycle Cost Program (BLCC) 5.3-08, developed by NIST, was evaluated to determine appropriateness for use on this project. Typically, BLCC software is used to evaluate alternative designs that have higher initial costs but lower operating-related costs over the project life than the lowest-initial-cost design. It is especially useful for evaluating the costs and benefits of energy and water conservation and renewable energy projects. The LCCs of two or more alternative designs are computed and compared to determine which has the lowest LCC and is therefore more economical in the long run. BLCC also calculates comparative economic measures for alternative designs, including net savings, savings-to-investment ratio, adjusted internal rate of return (IRR), and years to payback.

It was decided not to use BLCC5 because it factors in funding mechanism as part of its analysis. Campbell Crossing, as the public-private venture (PPV) funding the ZEH, has a unique funding mechanism and neither the software nor communication with NIST provided enough clarity as to the whether the funding mechanism could be handled appropriately with the software. Instead, the Whole Building Design Guide published by the National Institute of Building Sciences was reviewed and determined to be adequate guidance for the ZEH demonstration goals. In addition, the analysis followed the requirements of NIST's Life-Cycle Costing Manual for the Federal Energy Management Program Handbook 135 (NIST 1996).

Identifying and collecting the appropriate data is an integral aspect of the LCCA. To determine the benefit for the military of investing in ZEH, all costs relevant to the decision needed to be identified, collected, and accurately analyzed. The LCCA results are highly dependent on the quality of the data collected. Inaccurate or insufficient data will result in an inadequate analysis. Therefore, it is crucial to properly identify the required data and to collect accurate data. Using the guidance mentioned above, critical cost items and data collection requirements were identified. Working with Campbell Crossing, a data collection process was drafted and communicated to the appropriate construction personnel. Data was collected throughout the construction process.

This section discusses the cost items that were included in the LCCA. A description of each relevant cost item is given, along with detail on the approach used to analyze the cost item, and sources for the data are delineated. If the cost item was not considered relevant to this analysis, the rationale for exclusion is given. Only differential costs between the baseline housing units and ZEHs were included in the analysis, as these were the only costs made available for proprietary reasons. Where data were not available, it was estimated based on engineering judgment.

Cost Category: Investment Related

Investment-related costs include those associated with the financial investment of the project such as financing, land acquisition, community infrastructure, construction, replacement and residual costs. Land acquisition and community infrastructure costs were treated as sunk costs for this analysis and excluded. It should be noted however, that if ZEHs were constructed on a large scale, additional infrastructure costs related to optimal house orientation (to take advantage of solar benefits) may be incurred.

Although there are additional costs associated with the design of a ZEH, these costs were excluded as they were considered costs that occurred in the past and could not be recovered for the purpose of this analysis. Building replacement will not be required within the analysis periods (25 and 40 years); therefore, no building replacement costs were included. However, the costs for equipment or materials needing replacement during the study period were captured. Because Campbell Crossing's physical assets resort back to the military at the end of their 50-year contract, residual costs are not included in the analysis.

Table 27 summarizes the investment costs that were excluded from the LCCA.

Table 27. Excluded Investment Costs and Rationale

Investment Cost Category	Rationale
Land acquisition	Sunk cost
Community infrastructure	Sunk cost
Design	Sunk cost
House replacement	Outside of analysis period
Residual	Property reverts to military at lease end

Design costs were not included for several reasons. The research nature of this project involved activities that would not normally be conducted under a typical military housing design project such as test plan development and the monitoring of energy, water and detailed incremental costs. In a non-research project scenario these costs would be incurred one time and then hundreds of units would be built using this standard design, reducing the design cost per house. Capturing design costs was therefore not pursued as any incremental cost increase in design of the ZEHs in this project would not be representative of future design costs.

Construction costs were included and are the largest contributor to overall ZEH costs. These costs include equipment and materials procurement costs, and labor related to construction.

Cost Item: Technology and Equipment

A major strategy for ZEHs is the inclusion of energy efficient technologies and equipment. Energy reductions for the ZEHs were achieved through the increased efficiency of the heating and cooling systems and internal load equipment such as appliances. This cost item also includes the solar equipment.

Specific technology and equipment for which differential costs were captured are given in Table 28. These costs were obtained from Campbell Crossing. Labor for PV and solar hot water system installation was included.

Table 28. Installed Technology and Equipment Items and Differential Costs Included in LCCA

Equipment	Cost Differential
Geothermal Heating/Cooling System Equipment and Installation	$19,200
Water Heater Equipment	$12,818
Water Heater Installation	$7,073
PV System Equipment	$54,647
PV System Installation	$30,153
Metal Roof	$25,783
PV and Solar Water Heater Joint Mounting Equipment – Installation	$11,063
PV and Solar Water Heater Joint - Commissioning	$5,000

Cost Item: Construction Materials

Specific energy efficiency strategies are achieved by replacing or adding construction materials. These materials are used to reduce the heat transfer through the envelope and to reduce solar heat gain. As part of this project, ZEH design elements were identified prior to construction that were anticipated to require additional materials and subsequent costs, and were reviewed with Campbell Crossing at that time. Not all material costs were provided to the ESTCP team, however, therefore material costs were included in the LCCA when provided. Costs for design elements such as windows, appliances, lighting systems, and power supply and bath fan controls were not provided.

Specific construction materials for which differential costs were captured are given in Table 29.

Table 29. Material Cost Items

Design Element	Cost Differential
Slab floor insulation	$2,170
Slab vapor barrier	No costs provided
Exterior wall construction	$17,016
Wall insulation	$14,230
Floor insulation over garage	No costs provided
Ceiling insulation	No costs provided
Sheathing	No costs provided
Exterior overhangs	No costs provided
Envelope sealant	No costs provided
Advanced framing techniques	No costs provided
Wider Doors	$284

The differential costs for the major material items were obtained from Campbell Crossing. As indicated in the table, some differential material costs were not collected by Campbell Crossing or were not released to the team because they were considered proprietary. Although labor for additional construction activities beyond the equipment and technologies was requested, a cost estimate was not provided by Campbell Crossing. These missing cost differentials are not as significant as the equipment and technology cost differentials and therefore are not considered essential to the cost analysis.

Cost Item: Operation, Repair and Maintenance Costs
Non-fuel operating, repair and maintenance costs were included in the analysis. This included labor and equipment costs incurred for routine maintenance or repair. Maintenance records for the demonstration period were provided and reviewed with Campbell Crossing.

Cost Item: Utility Costs
Both the baseline units and the ZEHs are all-electric housing units. Utility pricing was based on measured kWh and gallons of water used. Electric pricing did not include summer and winter differentials, block rates, time-of use charges, and demand charges.

Cost Item: Training Costs
An orientation session was held with the occupants before they moved into the housing units. The session provided an overview of the project and the occupants' influence on the outcomes, in addition to information on energy conservation, optimal operation of their housing units, and unusual equipment in the housing units. An occupant user guide to reducing energy use was developed and provided to the occupants. Monthly energy reports were developed and shared with the families to illustrate progress towards the goals of the project. Feedback was obtained and documented from all demonstration occupant families about the overall satisfaction with the housing units and perceived comfort of their indoor environment. Costs associated with the one-time orientation and the monthly reports were included in the analysis.

Summary of Cost Items
Below is a summary of all cost items and any data interpretation, scaling, and normalization that was used for the LCCA. Table 30 summarizes the cost elements and data that were tracked.

Construction Labor and Material Costs:

> **Description**: The final cost differential for construction between the typical and ZEH units.
> **Data:** Construction costs documented by the building contractor and the ESTCP team.
> **Data interpretation, scaling, and normalization:** Campbell Crossing provided an "economies of scale" factor. This factor was based on their building knowledge and experience and represents the decrease in costs anticipated if the ZEH were built on a large scale as is typical of a military housing project. As this factor is already built into the typical design, it was used to reduce the actual ZEH costs to provide a more realistic analysis of future building cost instead of this one-time demonstration project. Campbell Crossing estimated this economy of scale to be 10%. Therefore the differential investment costs used in this analysis was 90% of the actual investment costs.

Energy Costs:

> **Description**: The cost of electric energy used in each home, and generated by the ZEH.
> **Data:** Electrical usage and generation was monitored continuously with the exception of any disruptions as noted previously. Average electric rate was provided by Campbell Crossing. Time-of-day rates were not applicable.
> **Data interpretation, scaling, and normalization**: None required.

Water Costs:

Description: The cost of water used in each home.
Data: Water use was monitored continuously with the exception of any disruptions as noted previously. Average water rate was provided by Campbell Crossing.
Data interpretation, scaling, and normalization: None required.

Maintenance:

Description: The cost of routine and emergency repair of building components and systems.
Data: Work orders for each maintenance activity for each building were evaluated and costs calculated based on pay rates, labor hours, and costs of supplies/replacement equipment.
Data interpretation, scaling, and normalization: Maintenance actions were evaluated to determine cause and documented if unrelated to technologies and envelope modifications.

Occupant Training:

Description: The cost of interacting with the building occupants and providing information on how to most efficiently operate their housing units and save energy.
Data: The cost of the ESTCP team interacting with building occupants and providing monthly feedback. Also included were the costs to develop an occupant user guide to energy conservation, considered a first cost because it would not need to be replicated even if new occupants moved into the housing units.
Data interpretation, scaling, and normalization: None required.

Table 30. Summary of Project Cost Elements

Cost Element	Data Tracked During the Demonstration	Costs (per duplex – 2 ZEH units)	Cost per Unit
Differential construction labor and material costs with economy of scale factor	Documented construction cost differential for ZEH; includes PV arrays and solar water heater		
Technology and equipment	Ground source heat pump heating/cooling system, photovoltaic arrays, solar water heater, metal roof – equipment and installation	$165,737	$82,869
Construction materials	Insulation, exterior wall construction, and wider doors	$33,701	$16,850
Economy of scale factor		10% discount	$89,747
Energy	Metered annual electricity costs	$600 per year	ZEH A: $207 ZEH B: $370
Water	Metered annual water costs	$142.22 per year	$71.11
Maintenance	Documented maintenance costs per home based on frequency and type of required maintenance as well as labor and material per maintenance action		
Water heater pump/controls	Pump 10-year life, intermittent control repairs	$400 every 10 years	$200 every 10 years
PV inverter	15-year life	$8,600 every 15 years	$4,400 every 15 years
Metal roof extended life	Cost avoidance of replacing shingled roof every 20 years	($5,000) every 20 years	($2,500) every 20 years
ERV maintenance	Annual filters and cleaning	$912 every year	$456 every year
Occupant training	Training development and implementation costs		
One-time material development costs	Labor and materials	$4,400	$2,250
Training development	Labor	$10,500	$5,250
Occupant interaction	Labor	$24,000	$12,000
Financing	Loan payments (annual)	$11,432	$5,716

7.2 COST DRIVERS

The PV system used to generate energy for the zero energy housing is the most critical cost driver. For this demonstration project, the PV system accounted for almost 50% of the cost differential of the ZEHs. However, as noted later in this report, there has been a decrease in PV costs over the last several years. Some industry experts expect this trend to continue, with the potential for costs to decrease to about half (based on $/watt) of what that they were when this demonstration took place. Some sort of renewable energy system is needed to generate the energy required for a net zero house, and in many locations PV systems are the most practical from an available space perspective, though not necessarily a cost effective technology to meet

this requirement. The efficiency of the PV system is largely based on geographic location and orientation. If sufficient solar radiation or a proper orientation is not available at the proposed site, the economics of using PV systems will be affected.

Fort Campbell is in an area with a moderate solar resource, receiving an average yearly solar potential for a flat collector tilted at 37°of 4.8 kWh/m^2/day (NASA 2010). The homes were orientated so that the PV systems could be placed on the south-facing roof, and to maintain similar front exteriors as the other homes in the neighborhood.

The GSHP used to heat and cool the ZEHs was also an important cost driver. Geographic location needs to be considered when determining the value of this technology. GSHPs are more cost effective in locations where there are both high winter heating and high summer cooling loads. In addition, suitable soil conditions are critical for GSHPs to be cost effective, and must be evaluated prior to making a decision on this technology. GSHPs were included in these designs as a demonstration technology of interest by developer.

This project used small scale renewable systems to achieve net zero design because the buildings were small scale, and only one duplex was analyzed. If net zero energy on a community or site level was desired instead, a larger scale renewable energy project (e.g., ground mounted PV or geothermal-generated energy) could be more cost effective depending on the site characteristics.

One of the significant recurring maintenance costs was the monthly filter cleaning and annual filter replacement for the energy recovery ventilator. The site estimated the cost at almost $500 per year per house. Industry quotes indicate that ERV replacement filters are available for $10-$50. General practice does not involve regular replacement of these filters, so this information was shared with the site so that they can reduce maintenance costs.

7.3 COST ANALYSIS AND COMPARISON

Analytical Approach and Model Components

The NIST Life-Cycle Costing Manual (NIST Handbook 135) for FEMP details the LCC methodology and criteria established by FEMP for the economic evaluation of renewable energy (and energy and conservations) projects in federal buildings (NIST 1996). The approach detailed in Handbook 135 was used to estimate the life-cycle cost of the ZEH building at Fort Campbell.

The financial analysis conducted for this project was based on a discounted cash flow analysis. Cash inflows and outflows were calculated on an annual basis and the financial indicators were derived from these using a defined analysis period and discount rate. The singular captured benefit of the ZEH is a reduction in electricity usage and consequently energy savings. One cost avoidance was included in the analysis, which was the elimination of the 20-year roof replacement for the shingled roof of the typical home.

Cash outflows included capital expenditures to construct the ZEHs (and associated debt charges) and to develop and execute the occupant interaction program. The loan amounts were considered outflows in the form of interest and principal payments at the end of each year.

Electricity costs and fixed operating and maintenance costs were considered outflows, as was major equipment and component replacement.

To measure the financial viability of this project, the net present value (NPV) financial indicator was derived from the discounted cash flow analysis and was used as the performance measure for investment opportunities. The IRR was evaluated but could not be calculated because there was no return on investment. These financial indicators account for the time value of money, and discount the future capital investments or annual cost benefits to the current year.

Financial analysis parameters were obtained from various sources, including Campbell Crossing, research, and communication with equipment vendors; data sources are noted in the report and cost model.

Model Parameters and Major Assumptions

A spreadsheet-based discounted cash flow analysis model was developed to conduct the financial analysis. The model uses numerous input variables, which were derived from a wide range of sources. The outputs of the model are commonly used financial indicators. The values of the input parameters directly influence the financial analysis results; changing these input parameters would alter the financial indicators that were calculated by the model. Therefore, significant effort was expended to identify or estimate the expected value of each input. The value and data source for each input parameter is provided in this report section. Several scenarios were conducted to model potential situations and model parameters that are key drivers for the financial results. A sensitivity analysis (systematic change in input parameter value to evaluate impact on output) was conducted along with the scenarios and is detailed in the following sections.

Cost Inputs and Major Assumptions

Debt

Campbell Crossing provided only the differential costs between construction of a typical duplex and the ZEHs. Therefore, only these costs were used as the capital expenditures and the loan amount. The model inputs and financial assumptions to calculate the debt associated with this project are summarized together in Table 31. Each of these terms is defined in detail following the table.

Table 31. Debt Parameters and Assumptions

Data	Value	Source
Loan Origination Date	5/1/2007	Campbell Crossing
Loan End Date	5/1/2046	Calculated
Loan Term	40	Campbell Crossing
Interest Rate	5.667%	Campbell Crossing
Loan Amount	$179,494	Differential between typical and ZEH (with economies of scale)

- **Loan Origination Date** is the date at which the loan was taken out.
- **Loan End Date** is the date at which the loan obligation is fulfilled.
- **Loan Term** is the length of time allowed by the lending agency for the loan repayment.

- **Interest Rate** is the rate that is charged for the use of the money. This is a nominal interest rate.
- **Loan Amount** is the amount used in the model as the capital expenditures. This amount represents the differential costs that Campbell Crossing spent on the ZEH duplex above a typical duplex (with economies of scale).

Global

Global parameters and assumptions are summarized in Table 32. These parameters are those that apply to the overall analysis, such as rates and study period. Each of these terms is defined in detail following the table.

Table 32. Global Parameters and Assumptions

Data/Assumption	Value	Source/Notes
Base Year, Occupancy	2010	Actual occupancy October 2010
Interest/Discount/Escalation Rate	Nominal	Chosen convention
Discount Rate	3.9%	FEMP 100 CFR 436/Handbook 135
LCCA Study Period	Two scenarios: 25 and 40 operating years.	40 years plus planning/construction – maximum allowed by FEMP
Reporting Year	2012	All financial indicators are reported in 2012 dollars.
Electricity Rate	$0.079/kWh (2012)	Campbell Crossing
Electricity Escalation Rate	Various as detailed below	U.S. Department of Commerce
Taxes	None	Campbell Crossing is a PPV with the Army and pays no taxes
Salvage Value	None	Campbell Crossing

- **Base Year, Occupancy** is the year in which the housing units were first occupied. This signifies when operating and maintenance costs begin.
- **Interest/Discount/Escalation Rate** are all given in or converted to nominal rates. This was done to coincide with the nominal loan rate.
- **Discount Rate** was used in the analysis to discount future costs and benefits back to the 2012 date. For this analysis, the nominal discount rate provided in the Handbook 135 annual supplement of 3.9% was used (NIST 2011).
- **LCCA Study Period** is the number of years for which the cash flow analysis was completed. One scenario used a 25-year study period as this is a typical period for which buildings are evaluated. FEMP allows a maximum study period of 40 years; therefore, this period was used in a separate scenario to coincide with the loan term. FEMP provides for longer studies than 40 years if planning and construction periods are included. For this analysis, Campbell Crossing reported that the loan was taken in 2007 and therefore 2007 through the occupation date of 2010 was used as the construction period. Therefore the 25-year service study ran from 2007 through 2034 (3 years planning plus 25 occupation years for a total of a 28-year total study period). The 40-year service study period, ran from 2007 through 2049 for a 43-year total study period
- **Electricity Rate** is the actual rate paid by Campbell Crossing in 2012.

- **Electricity Escalation Rate** was calculated using the U.S. Department of Commerce projections for electricity in the industrial sector for Census Region 3, which contains both Kentucky and Tennessee, where Fort Campbell is located. These escalation rates are located in Table Ca-3, as found in the Energy Price Indices and Discount Factors for Life Cycle Cost Analysis 2011 (NIST 2011). These indices and discount factor multipliers are based on energy price projections developed by the Energy Information Administration of the U.S. Department of Energy. These rates were used for 2012 forward, and previous appropriate versions of the reports were used for earlier years with occupancy (2010 and 2011; references provided in the cost model). These indices were only provided through year 2041; for this analysis, the 2041 rate was used for all subsequent years. The projected fuel price indices represent the escalation of electricity, not accounting for general inflation. Thus, these escalated price indices produce estimated electricity prices in real dollars. Because the loan interest rate is a nominal rate, these escalation rates were converted to nominal in the model.
- **Taxes** for this project were not included in the analysis because Campbell Crossing is a PPV with the Army and does not pay taxes.
- **Salvage Value** is the estimated value of an asset at the end of its useful life. According to Campbell Crossing, there is no mechanism in place for the valuation process of these privatized projects as it is early in the contract period. Therefore, no salvage value was used, but this value is not considered necessary to estimate the cost impact of the ZEH.

Demonstration Data

Demonstration data used in the analysis are summarized in Table 33. These data were measured during the one-year demonstration period.

Table 33. Demonstration Data

Assumption	Value	Source
Baseline Energy Consumption per house	17,617 kWh	Average based on meter readings
ZEH A Energy Consumption	12,481 kWh	Meter reading
ZEH A Energy Production	9,866 kWh	Meter reading
ZEH B Energy Consumption	14,206 kWh	Meter reading
ZEH B Energy Production	9,525 kWh	Meter reading

Financial Analysis Results

The model developed for this analysis contains all the assumptions and calculations that were used in the analysis; the model is located in Appendix A, Cost Model.

Discounted Cash Flow Analysis

The discounted cash flow analysis was conducted by summing the cash inflows (electricity savings, cost avoidance[7]) and outflows (capital costs, operating and maintenance costs, and debt costs) detailed above. Table 34 provides a snapshot cash flow for key years for both the 25- and 40-year analysis. Electricity costs were escalated and all costs discounted, as described above, to 2012 dollars. The entire discounted cash flows for the 25- and 40-year study are located in Appendix G.

[7] Cost avoidance is due to ZEH metal roof life exceeding typical shingle roof life.

Table 34. Cash Flow Summary – Key Year Snapshot, 2012 Dollars

Cash Flow	Reporting Year (2012)	Final Study Year for 25-year analysis (2034)	Final Study Year for 40-year analysis (2049)
Debt Cost	($11.432)	($11,432)	$0
Electricity Savings	$2,158	$2,314	$2,381
O&M	($937)	($1,141)	$4,705
Net Cash Flow	**($4,764)**	**($10,260)**	**$4,705**

There is a negative cash flow throughout the 25-year study period and until the loan is paid off in year 2046 of the 40-year analysis. A positive cash flow is realized in both studies in the years where a cost avoidance is realized due to the extended life of the ZEH metal roof in operating years 20 and 40 (2029 and 2049).

Net Present Value

Net present value is the difference between the capital investment and the present value of future annual cost benefits associated with the project. NPV is the standard method to appraise long-term projects using the time value of money. If the NPV is positive, then the investment return is acceptable and the project would add value to the organization. The NPV was calculated by summing the annual cash inflows and outflows and then discounting these costs and revenues into 2012 dollars using the discount rate. The NPV of the 25-year study is ($257,657) and for the 40-year study it is ($212,586); these are 2012 dollars. This indicates the value of the project, which is negative for both study periods. In other words, it cost more to build and operate the ZEH than was recovered in electricity and water savings.

Financial Internal Rate of Return

The internal rate of return is used to measure the profitability of an investment. If the IRR is greater than the discount rate, then the project return is acceptable. For this project, the IRR could not be calculated because there was a negative return on investment.

Dollars per kBtu of Energy Saved

Dollars per kBtu of energy saved was calculated two ways: 1) dividing the first year investment cost by the cumulative energy savings over the LCCA period and 2) dividing the first cost by the average annual energy savings. Note that dollars per kBtu of energy saved does not account for accrued interest or O&M costs.

Simple Payback

Simple payback was calculated by dividing the first year investment cost by the average annual savings; note that simple payback also does not account for accrued interest or O&M costs.

Savings to investment ratio

Savings to investment ratio was calculated by dividing the present value of the cumulative savings over the 25 or 40 year term by the present value of the investment costs including interest paid on the loan and O&M costs.

Scenario Analyses

This cost model assumes a base scenario in which various assumptions were used as indicated in the section above. It is also useful to consider different scenarios where data are evaluated in different ways and key variables are altered to determine the impact.

Individual Unit Scenario

As noted previously in this report, the electricity consumption and production varied for the individual units. Therefore, a discounted cash flow was developed for each individual house. All parameters were consistent with the base scenario. Capital expenditures and O&M costs were allocated evenly between the two houses and the actual energy consumption and production for each house was used (see Table 33). The study period was 25 years.

Net Present Value

The NPV of the 25-year study for ZEH A is ($127,397) and for ZEH B is ($130,259) in 2012 dollars. This indicates the value of the project, which is negative for both. It is clear from these results that ZEH A performed better; in fact, it had both lower energy consumption and higher energy production. However, the variance is minimal and the return on investment is negative even for the better performing house.

Energy Efficient Duplex Scenario

Independent of the net zero energy goal of this demonstration project, the objective was to investigate a more cost effective, practical approach for the design and construction of housing with the intent of achieving a significant reduction in the energy required from the utility grid. To further evaluate progress toward this objective, an energy efficient duplex scenario was analyzed. The cost of PV equipment and the PV energy production was removed from the analysis. This scenario provides an estimate of the financial benefit of implementing the energy efficient features of the ZEH design. In addition, half of the commissioning costs were excluded from this scenario. The solar hot water heater was included as this can be a cost effective technology and further investigation for military housing is recommended. No roof modification costs were included because the modifications and associated costs, if any, are not known.

Net Present Value

The NPV of the 25-year study for the energy efficient duplex is ($99,711) in 2012 dollars. This indicates the value of the project is still negative, although the negative cost effectiveness diminished over that of the ZEH.

Energy Efficient Duplex without Solar Hot Water Scenario

This scenario evaluates the impact of the efficient envelope and the GSHP by replacing the solar water system with a domestic water system. The solar hot water system has high investment costs and efficiency can vary according to the characteristics of the system, use patterns of the occupants, and the building location. The solar hot water system costs were removed from the cost model. The differential energy usage was calculated using the measured electricity usage for the domestic water heater in the baseline home and the solar hot water heater electricity usage in the ZEH.

Net Present Value

The NPV of the 25-year study for the energy efficient duplex without solar hot water was ($67,005) in 2012 dollars. This indicates the value of the project is still negative, although it was more cost effective than the ZEH scenario.

Energy Efficient Envelope Only Scenario

A scenario including only the energy efficient envelope and no additional equipment (i.e., no PV, no solar hot water, no GSHP, and no ERV) was also evaluated. GSHPs can also be an expensive technology, and depending on environmental conditions at a site, may not be cost effective. For this scenario, estimated modeled energy usage of the air source heat pump was used instead of estimated GSHP energy use. Only the material cost differentials were included.

Net Present Value

The NPV of the 25-year study for the energy efficient duplex without solar hot water and without an open-loop GSHP was ($28,686) in 2012 dollars. This indicates the value of the project is still negative, although this scenario had the least negative cost impact of all those evaluated.

Minimum Acceptable Rate of Return Scenario

The FEMP-recommended discount rate was used for these analyses, as this is the recommended rate for use with government energy projects. As mentioned previously, military housing is unique in that it is operated by a PPV. Therefore, funding mechanisms are quite different. Under this scenario, the impact of the discount rate was investigated to mimic more closely how a private company would evaluate a similar project. Private companies use a minimum acceptable rate of return (MARR) as the metric for project acceptance. In other words, the investment opportunity would be worthwhile if its rate of return is greater than the MARR. Campbell Crossing's MARR is proprietary; therefore, a range estimate was used based on values often used by private companies. A lower bound of 10% was analyzed along with an upper bound of 15%. All other data remained the same; the study period was 25 years.

Net Present Value

The NPV of the 25-year study for the variable MARR scenario is ($212,586) for the 10% MARR and ($201,079) for the 15% MARR in 2012 dollars. This indicates the value of the project is still negative and would not be an acceptable project from an economic standpoint.

Impact of Reduced PV Costs Scenario

PV costs have decreased over the last several years. Industry experts expect this trend to continue. In addition, discussions with the PV vendor indicated that the 10% economies of scale factor provided by Campbell Crossing underestimates the cost reduction that would be realized with widespread implementation of PV. To further evaluate the economic impact on the project due to reduced PV costs, another scenario was analyzed using a cost decrease of 50% for the PV system.

Net Present Value

The NPV of the 25-year study for the decreased PV system cost scenario is ($209,266) in 2012 dollars. This indicates the value of the project is still negative and therefore the project is not cost effective.

Table 35 summarizes the LCCA scenario results for the first six scenarios.

Table 35. LCCA Scenario Results

Cost Element	Base Case 40-year Analysis	Base Case 25-year Analysis	MARR 10%	MARR 15%	Individual Unit Scenario ZEH A	Individual Unit Scenario ZEH B
LCCA Lifetime	40	25	25	25	25	25
First Cost	$ 179,494	$ 179,494	$ 179,494	$179,494	$ 89,747	$ 89,747
Annual Energy Savings (kBtu)	8,188	8,188	8,188	8,188	4,397	3,791
Average Annual Savings	$ 2,252	$ 2,252	$ 2,252	$ 2,252	$ 1,209	$ 1,043
Average Annual Cost	$ 1,395	$ 1,252	$ 1,252	$ 1,252	$ 626	$ 626
Monthly Energy Savings (kBtu)	682	682	682	682	366	316
Monthly Energy Savings	$188	$188	$188	$188	$101	$87
Present Value of Annual Savings	$ 50,246	$ 38,702	$ 38,702	$ 38,702	$ 20,782	$ 17,920
$/kBtu Saved Annually	$ 0.55	$ 0.55	$ 0.55	$ 0.55	$ 0.51	$ 0.59
$/kBtu Saved Cumulatively	$ 22	$ 22	$ 22	$ 22	$ 20	$ 24
Simple Payback (years)	80	80	80	80	74	86
SIR	0.14	0.13	0.11	0.09	0.14	0.12
25-year NPV	40 year NPV: ($298,847)	($257,657)	($212,586)	($201,079)	($127,397)	($130,259)

Table 36 summarizes the LCCA scenario results for the remaining four scenarios.

Table 36. LCCA Scenario Results, Continued

Cost Element	Energy Efficient Duplex	Energy Efficient Duplex (no Solar Hot Water)	Energy Efficient Envelope Only	Reduced PV Costs
LCCA Lifetime	25	25	25	25
First Cost	$ 72,741	$ 47,611	$ 30,331	$ 141,334
Annual Energy Savings (kBtu)	2,505	2,237	1,800	8,188
Average Annual Savings	$ 689	$ 615	$ 495	$ 2,252
Average Annual Cost	$ 1,090	$ 1,018	$ -	$ 1,179
Monthly Energy Savings (kBtu)	209	186	150	682
Monthly Energy Savings	$57	$51	$41	$188

Present Value of Annual Savings	$ 11,840	$ 10,574	$ 8,507	$ 38,702
$/kBtu Saved Annually	$ 0.73	$ 0.53	$ 0.42	$ 0.43
$/kBtu Saved Cumulatively	$ 29	$ 21	$ 17	$ 17
Simple Payback (years)	106	77	61	63
SIR	0.10	0.13	0.21	0.16
25-year NPV	($99,711)	($67,005)	($28,686)	($205,861)

Assessing Non-Direct Cost Impacts – Future and Contingent Liability, Internal Intangibles and External Intangibles

When conducting a cost analysis, there are often implementation impacts for which dollar values cannot be assigned (often referred to as non-monetized impacts). The inability to quantify these impacts frequently causes them to be excluded from the analysis. This analysis indicated that implementing ZEH at military installation would result in an increase in direct costs to the military. However, some of the non-quantifiable impacts are expected to be positive. These impacts were considered qualitatively. Replacing grid electricity with renewable energy has benefits independent of what was captured in this analysis. These include the following:

- ***Indirect benefits*** associated with cost savings at the enterprise level could allow for a percent of the budget once appropriated to utility bills to be spent elsewhere.
- ***Contingent liability*** could be reduced by installing PV systems because having a renewable energy system onsite could enhance energy security. The DoD could also be better positioned to comply with emerging policies that require a certain amount of renewable energy to be a part of the portfolio and/or policies that regulate GHGs.
- ***Future liability*** associated with electricity price volatility could also decrease.
- ***Internal intangible*** benefits could be seen in the form of organizational branding, since becoming more sustainable is viewed positively by the public and private sectors. As the organization communicates its efforts to be more socially responsible, its organizational image could benefit.
- ***External intangible*** benefits from displacing electricity from the grid with electricity from a PV system could include positive impacts on public health, worker safety, climate stabilization and air pollution. Both domestically and internationally, a significant portion of grid electricity is generated by coal-fired power plants; therefore, displacing grid electricity with electricity from a PV system would reduce GHGs, particulate matter, and mercury emissions and thus have positive impacts on human health and the environment. Better air quality could also reduce the societal burden associated with increased emergency room visits for asthma attacks and other respiratory illnesses that are correlated with elevated levels of air pollution. Ecosystem benefits could result from less mining and mountain top removal practices, reducing the runoff and waste streams associated with coal mining.

Cost Summary

With electricity costs of 7.9 ¢/kWh, design modifications to an already efficient home such as the standard Campbell Crossing design are difficult to justify, as illustrated by LCCA results where no scenario evaluated was cost effective. Items that could help a project achieve cost effectiveness include the following:

- Higher cost of energy, such as in California or eastern states.
- Lower technology costs. The 10% economy of scale factor used in this analysis may be conservative. With more widespread adoption of ZEH design and construction techniques in both the DoD and private sectors, material, technology, and installation costs may decrease even more in the future.
- Presence of rebates or other incentives. No incentives for using more efficient technologies were available for this project; however, many states, utilities, and municipalities offer incentives that can increase the economic practicality of a project.
- Improved home design. The design constraints in this project (the same floor area and layout as the standard Campbell Crossing design) may have hindered the cost effectiveness of the project.
- Alternative financing. Interest accrued over the 40 year loan term is more than twice the total loan amount. Cost-effectiveness would increase if all capital costs were paid in year one.

8.0 IMPLEMENTATION ISSUES

Occupant engagement contributed to 15% less energy use in the baseline housing units compared to the Woodlands community. The ZEH housing units used on average 24% less energy than the baseline housing units, but did not achieve net zero energy during the study timeframe. The ZEH unit used 51% less water per person than the baseline unit. Low flow water fixtures and other water efficiency strategies likely influenced this savings. There was no notable difference in emergency maintenance activities between the ZEH and baseline units; both the ZEH units and the baseline units had about the approximately the same level of emergency maintenance needs. The technologies in the ZEH units did require more preventative maintenance, specifically the ERV filter required regular cleaning and annual replacement. This preventative maintenance component resulted in monthly and annual costs that impacted the cost effectiveness.

Lessons Learned

Lessons were learned throughout each stage of this project: building design and construction, energy monitoring, and occupant interaction and behavior change.

Building design and construction

- More extensive design changes (e.g. smaller footprint, different layout) may result in additional opportunities for cost effective design.
- Design elements are not always carried through into construction, and may not be noticeable changes in the as-built drawings.
- If design elements change after the building is modeled and the renewable energy system is sized, the actual energy use may not be consistent with what the renewable system can provide.
- Verify that construction techniques to seal the building are completed as intended throughout building construction process so that infiltration is minimized.
- Achieving net zero energy may be more cost effective and practical in areas where cost of energy is higher, or where incentives for renewable energy or energy efficiency strategies are available.

Monitoring system design and installation

- Design the metering plan with some overlap and/or correlated data points so it is possible to compare the total building energy use with an expected total energy use. Design circuits with only like loads if possible, and maximize the number of metered circuits serving electricity outlets in a building. Arrange sensors and monitoring system such that a single sensor or line failure has a minimum impact on the system as a whole. This was successfully performed for this demonstration.
- Commission monitoring systems to enable useful and reliable conclusions regarding building performance. Commissioning activities include checking that panels are properly labeled, meters are measuring approximately the expected level and profile of

energy use, and testing remote data collection process. Include monitoring system technical experts in the process to assist with troubleshooting as needed. This was successfully performed for this demonstration.

Data collection and analysis

- Back up local storage devices to allow data storage redundancy over the course of any extended network connectivity issues that may occur.
- Develop a robust and extensible system to store the building data and test the system with very large amounts of trial data. Perform basic data validation as it is retrieved; compare data with expected use range and patterns. Use multiple data streams to provide multiple opportunities for checking data. This was successfully implemented on this demonstration project.
- If data collection and analysis occurs off site, ensure local assistance at the site will be available to perform troubleshooting as needed, and include them in monitoring system installation and commissioning so they are familiar with monitoring devices.

Behavior change/occupant interaction

- Real-time energy feedback devices were the most useful to occupants in changing behavior.
- Engage occupants to provide the most useful information to reduce energy use. Responding to occupant feedback on the type of information they wished to see was specifically noted by occupants as something they appreciated.
- Saving money motivates behavior change. Even though occupants did not pay energy bills, lowering cost of energy was noted as a driver to reduce energy use.
- Large behavior changes may be required to achieve net zero energy, depending on the initial occupant preferences. For example, one ZEH family preferred cooler indoor temperatures during the winter, leading to lower thermostat settings and lower energy use with minimal behavior change. Another ZEH family preferred warmer indoor temperatures; achieving the same lower energy use would have required a notable change in behavior. Interior temperature setpoints were not outside typical operating ranges at around 72°F, but they were significantly different than the modeled assumptions of 68°F during heating seasons and 76°F during cooling seasons, resulting in an estimated 30% increase in HVAC energy use compared to the modeled estimate.
- Focus behavior change on most impactful areas. At times, families focused on actions that had a relatively small impact on overall energy use, such as turning off lights or reducing laundry use, instead of larger impact areas such as lowering the thermostat to reduce heating energy use.

Study Limitations

There were some project characteristics that limited the performance of the housing units, including design limitations, low energy costs, short monitoring periods, limited data points, and monitoring challenges.

Design elements were limited to the square footage and layout standard to all Campbell Crossing housing units to allow comparable data and provide the same housing environment for the ZEH occupants compared to other families. More comprehensive design changes such as modifying the floor space or layout may have resulted in a more cost effective design.

Energy costs were relatively low compared to average residential energy costs, which meant the savings from the more efficient features in the ZEH did not have the same impact that they may have had in other parts of the country or for private residences. In addition, no incentives for using more efficient technologies were available for this project; however, many states, utilities, and municipalities offer incentives that can increase the economic practicality of a project.

The monitoring period was relatively short. A longer monitoring period may have also shown different weather patterns and thus different energy use and energy production.

Differentiating between occupant preferences (indoor temperature, laundry habits, hot water use) and technology performance was difficult with only four data points (two ZEH, two baseline). More data points may have resulted in more defined trends in end use data. The Woodlands community data were useful to provide additional data points for comparison of whole home energy use. Dropped monitoring points at various times throughout the year resulted in less available data for analysis, which added to the limitations in identifying trends.

Findings that may be especially useful to influence future DoD policy include:

- Occupant feedback technologies, systems, and strategies have an impact on reducing energy use.
- ZEH designs may be more successful and cost-effective in areas such as California where energy costs are higher, renewable energy resource potential is greater, and designs are more adaptable.

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APPENDICES

APPENDIX A: DESIGN CHARRETTE REPORT

Ft. Campbell ZEH Charrette Report.pdf

APPENDIX B: PRELIMINARY ENERGY MODELING REPORT

PreliminarySimulation Report.pdf

APPENDIX C: POST-CHARRETTE ENERGY MODELING REPORT

Round2-FtCampbellZEHmodelling.doc

APPENDIX D: POINTS OF CONTACT

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APPENDIX E: DATA QUALITY ASSURANCE METHODOLOGY

The data received from the Fort Campbell homes had a number of data quality issues. These issues were identified and dealt with using an excel macro for improved consistency and repeatability, followed by manual evaluation for specific issues such as extreme values.

E.1 OVERVIEW OF DATA RECEIVED

Data received were categorized according to the following five types: actual data, missing data, interpolated data, overridden data, and data jogs. Unknown data resulted from any non-numeric values reported from the meter or when a value was simply not reported for one or more timesteps. When unknown data were identified, there were three options for the next piece of data. These are described in Figure E.1.

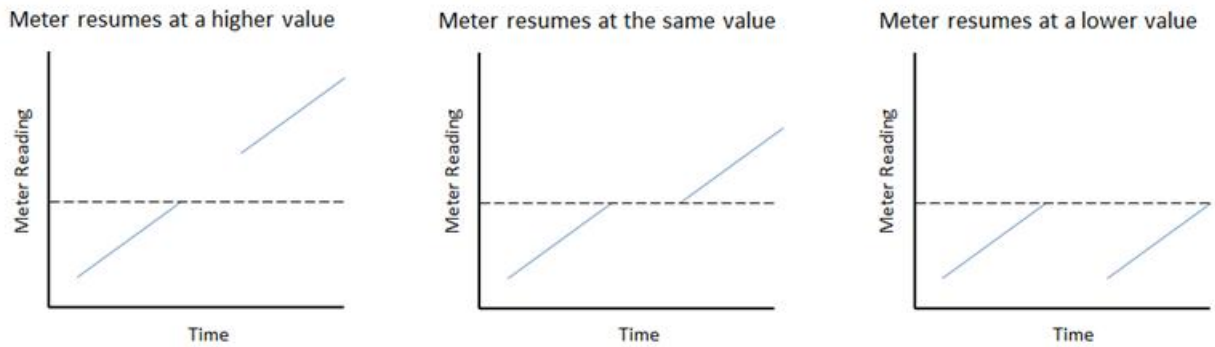


Figure E.1. Meter Options when Data Are Unknown (blue line indicates data)

In each case, a decision was made with how to treat the unknown data. Other than a negative usage step, it was difficult to determine if these values were actually faulty or if they merely reflected some atypical behavior of the building's occupants and/or systems. In the first two cases, all data are considered valid and were labeled as interpolated. This label indicated the data may be questionable. Further analysis was performed with the data to ensure the interpolated data conveyed realistic meter values across the period. In the third case, the data were simply considered to be lost. The point at which the data resumes is considered to be a jog, while all preceding unknown data points are categorized as missing. The resumed point is labeled as a jog for analysis and is used to calculate the usage after the next known good meter reading. No usage can be calculated from the jog because a previous usage value is unknown. A descriptive summary of each data type is presented in Table E.1.

Table E.1. Data Types Identified

Data Type	Data Provided at Time Step	Description	Inclusion in Calculations
Data	Yes	Data are congruent with previous data points	Yes
Jog	Yes	Data interpolation shows a negative consumption.	No
Interpolate	No	Usage was inferred based on a linear extrapolation of meter values between the two known points	Yes
Missing	No	Usage was not inferred because the usage would have been negative through the unknown period.	No
Override	Yes	Data were provided or calculated at the time step but it was determined to be erroneous	No

E.2. EUI CALCULATION AND AVERAGING

Calculating the EUI for a building over a given time period is a simple task if the data are congruent and consistent across the period. However, if data points are missing, it is possible to understate the building consumption across the period if adjustments are not made to account for the data gaps.

There are three ways of calculating the consumption of a building with questionable data. The first is to simply subtract the final metered data point from the initial metered data point. This process does not take any meter events into consideration throughout the period. If there are gaps in the data, the validity of the EUI data cannot be determined.

The second method is to create a hypothetical reading that only includes incrementally positive values from the original meter. Gaps can be interpolated using the approach described above, and a general idea of the consumption of a building can be determined. This case helps ensure consumption will not be significantly overstated, but does offer risk of understatement from missing data and jogs because the new variable only allows the meter to go in a positive direction and fills all missing gaps with zero consumption. In the case of a missing data point, this method would assume consumption was zero and would not extrapolate any consumption across the missing time period.

The third approach, and the approach used in this analysis, involves creating the artificial reading as described in the second method, but maintains missing values as missing data as opposed to zero consumption. These missing points are not included in a calculated average consumption over the time period of interest. Finally, this average is multiplied by the number of periods in the time of interest. Through calculation of the average consumption the system automatically fills any missing data periods based on the overall trend of the period of interest. This is generally performed on an annual basis but a shorter time period can lead to higher accuracies by capturing seasonal usage trends. Given a time period of interest (t), and a set of usage values (U), it is possible to determine the average consumption across the period (AC). The total consumption across the period is defined as AC*t. Figure E.2 provides a graphical representation.

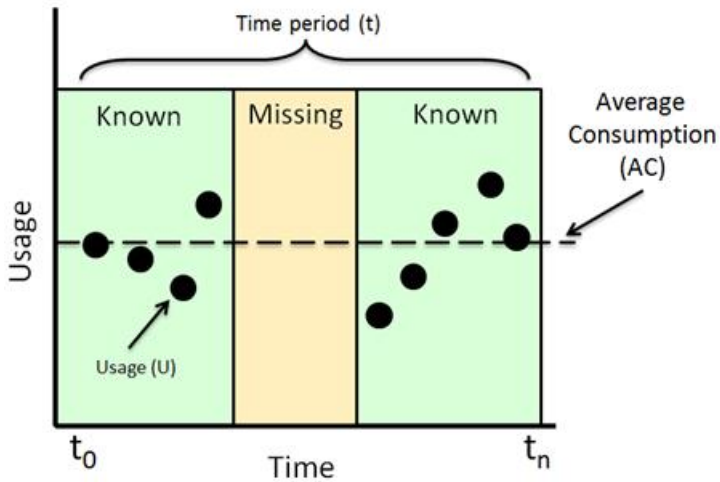


Figure E.2. Graphical Example of Data Conditioning

In the second approach the consumption over the time period would be defined by summation of usage within time period t. This may miscalculate the usage stated previously. The third approach determines the average usage (AC) and multiplies it by the duration of interest. An example is presented below to illustrate the effect of the two methods using hypothetical data. The time period analyzed can vary. For EUI calculations, the average was calculated over a month interval. Data were also analyzed on a daily and hourly basis.

This example shows hypothetical data for 24 time steps. The Meter Reading column shows the value as it might be originally received from Ft Campbell. The hypothetical usage is presented in the far right column. The hypothetical usage was used to guide the generation of the meter reading column and is presented for comparison, but is never part of the data and is shown here as a hypothetical comparison. The Meter Reading column is used to calculate the Calculated Usage, which is simply the difference between the current and last known meter reading. The Conditioned Usage column averages any necessary points and fills them across missing time periods. Each type of reading is categorized in the Data Type column. The final column shows the theoretical meter readings that would generate the initial meter reading column. This column is not known for analyzed data and is simply provided here as a comparison. Through this table it is possible to understand how the conditioning process was performed.

In this example, the third approach shows an average hourly consumption of 5.14. When this average is multiplied by the number of time steps in the period of interest (24), the consumption is predicted to be 124 meter units. The hypothetical data used to generate the example showed a consumption of 122 meter units (sum of the Actual Usage column). Simply summing the usage across the period, without the clearly erroneous data, produces a consumption of 108 meter units. Using the averaging technique in the third approach produces a deviation of 1.6% compared to 11.4% with simple summation as outlined in the second approach.

Table E.2. Data Conditioning Example

Time	Meter Reading	Calculated Usage	Conditioned Usage	Data Type	Theoretical Usage
0	**0**	**-**	**-**	**-**	**-**
1	4	4	4	Data	4
2	9	5	5	Data	5
3	17	8	8	Data	8
4	25	8	8	Data	8
5			3.75	Interpolate	4
6			3.75	Interpolate	3
7			3.75	Interpolate	3
8	40	15	3.75	Interpolate	5
9	48	8	8	Data	8
10	53	5	5	Data	5
11	61	8	8	Data	8
12			4	Interpolate	4
13			4	Interpolate	3
14			4	Interpolate	3
15	77	16	4	Interpolate	6
16	82	5	5	Data	5
17	88	6	6	Data	6
18	7000	6,912		Override	4
19	57	-6,488		Jog	6
20	63	6	6	Data	7
21	5066	5003		Jog	3
22			5.5	Interpolate	4
23	5077	11	5.5	Interpolate	7
24	5080	3	3	Data	3
	Average	326	5.14		5.08
	Sum	5535	108		122

This approach only applies to usage values for continuously increasing meters such as water and electricity. No filling was performed on temperature data because inferences between points had a low likelihood of validity as the gap size increased. Exterior temperature values were averaged between the four buildings and NOAA data was used to fill in any additional gaps.

E.3 DATA PROCESSING

The general data analysis and approval process is described in Figure E.3. The diagram shows many data inconsistency errors being addressed in step K. The continued repetition of this step, followed by all downstream analysis, ensures a log of changes is maintained. This makes it possible to evaluate the effect of adjusted data points on the final EUI values for the building.

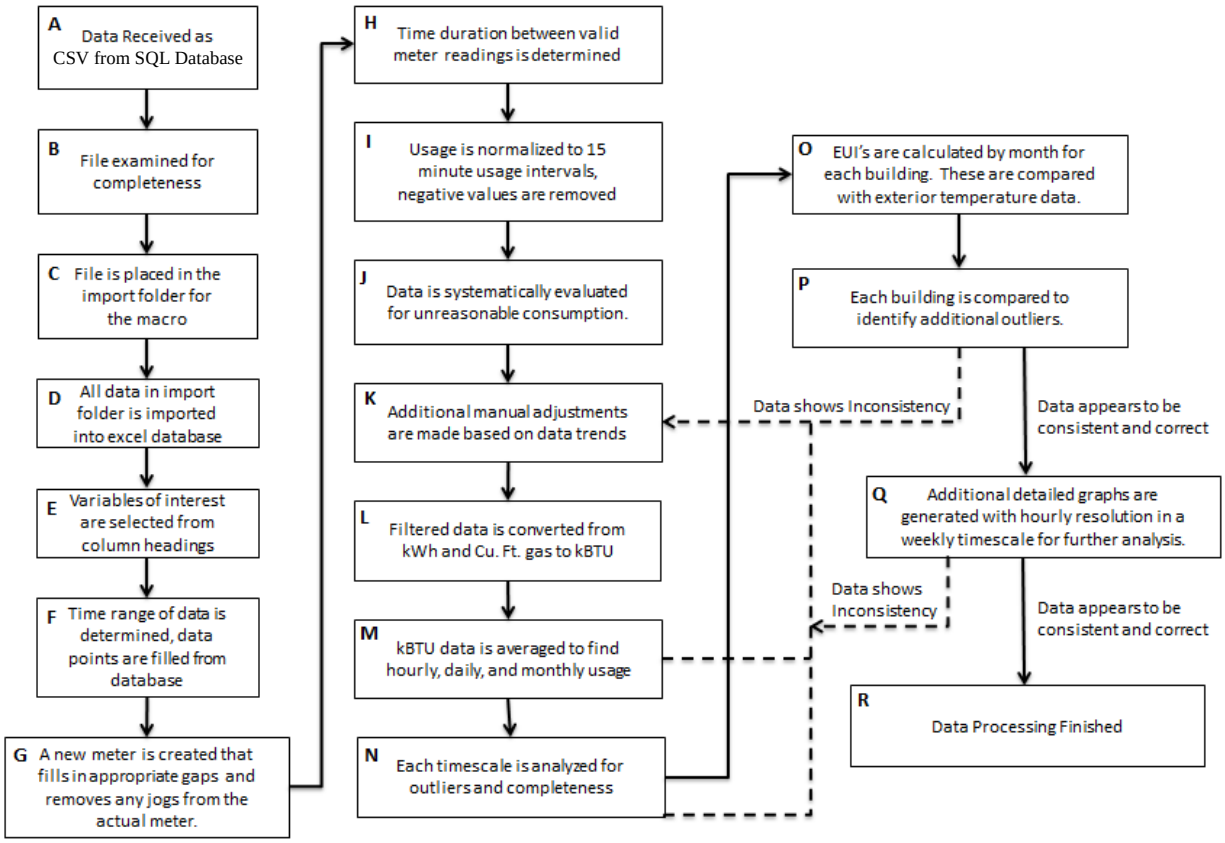


Figure E.3. Process flow for data analysis and approval

Step A: Receiving data
The data is stored in a SQL database. Queries are written to extract the appropriate data from the database in a CSV file.

Step B: File is examined for completeness
After the spreadsheet has been created, the data is checked to ensure that it is in the proper format, covers the desired time period, and doesn't contain any extraneous information.

Steps C/D: File transfer and importing
A macro has been developed to import all data in a folder. This folder only includes approved data based on the previous step. The next macro is then run which imports all data from all files placed in the folder. This ensures a complete database is built for analysis.

Step E: Variables of interest are selected
The XLS file contains many extra pieces of data that are not necessary for the current level of analysis (e.g. power factor). At the completion of the import, the macro lists all available variables. The user selects the appropriate variables, generally energy and environmental variables, for further processing.

Step F: Time range is determined

After importing, the earliest and latest time are recorded. These times generate the time steps for the complete new meter. Regenerating these intervals ensures all skipped data points are identified and adjusted. For example, it is possible that there is a missing hour from the meter; by creating a new set of time intervals, this data gap is immediately obvious.

Step G: Filled meter is created

The filled meter contains the most complete set of data possible. If a data point is missing, the last known valid point will be substituted in its place. These data form the basis for further analysis.

Steps H/I: Time duration is determined

This important step allows for interpolating of data across large gaps. By recreating a complete set of time intervals, it is much simpler to determine the duration between the current and last known good data point. This total duration serves as the denominator for the usage calculation. The usage is then multiplied by 0.25 to ensure the time step (5 minutes) is correct. This usage forms the basis for averaging.

In the example there is a meter reading at 8:15 and 9:00, but there are no data at 8:30 and 8:45. The Filled Meter column copies the last known meter reading until a new meter reading is provided, hence 110 is filled from 8:15 through 8:45. When data are missing, it is necessary to determine the total span for the gap. This span is measured in the Time Step column. When both data points are available, the time step is 15 minutes or ¼ of an hour. When a Meter Data point is not available, the time is incremented by an additional 15-minute or ¼ of an hour. This increased time step is important because it becomes the denominator to normalize the usage. In the example below, the usage at 9:00 would initially be shown as 30-meter units, which is substantially higher than the other usage values shown. By interpolating it over the entire missing period, the usage appears to be high, but valid. An example is shown in the following table and equation.

Table E.3. Example usage calculation

Time	Meter Reading	Filled Meter	Time Step	Usage
8:00 AM	102	102	-	-
8:15 AM	110	110	0.25	8
8:30 AM		110	0.25	10
8:45 AM		110	0.5	10
9:00 AM	140	140	0.75	10
9:15 AM	145	145	0.25	5

Equation E.1 ***Usage calculation at 9:00 AM***

$$\frac{Current\ Meter\ Reading - Previous\ Known\ Meter\ Reading}{Total\ time\ spanned\ by\ two\ meter\ readings} * standard\ time\ step$$

$$\frac{140 - 1100.75}{} * 25 = \frac{30}{3} = 10$$

Step J: Systematic Evaluation of Unrealistic Consumption

Using the usage values that were calculated in step I, the macro identifies any points that exhibit consumption above 100 kWh / 15 minute. These values are removed from any further calculations and are labeled as "override" for future analysis.

Step K: Manual Evaluation of Data
At any point in the analysis process a set of data may be observed that is determined to be erroneous. These errors are generally discovered by examining usage patterns for outliers. As an example, a meter may continue to report a value, but it may not increment. When these points are plotted the error becomes obvious. During this step, these data points are identified and removed from future analysis steps, via the override category. All future processes must be repeated if any data are changed in this step. The inclusion of the step gives traceability for any data points that were removed from analysis.

Steps L/M/N: Conversion, Averaging, and Evaluation
Data are converted to kBtu at the most granular scale available, 15-minute data. These data are then used to generate an average consumption (AC) over a time period of interest (t). The total consumption during the period is defined as AC*t. Hourly, daily, and monthly time periods are presented. At the conclusion of these steps the data are reviewed for erroneous values. Some examples would include a long period of zero consumption in the heating or cooling season, or a consumption that is an order of magnitude (or more) than what is expected. Any data inconsistencies are then addressed by repeating step K.

Step O: Comparison of Degree Days and Consumption
At this point the consumption is evaluated versus the number of cooling or heating degree days in the month. The comparison created offers context for consumption and can show months that would be expected to have similar consumption. Any data inconsistencies are addressed by repeating step K.

Step P: Building Comparison
The water and electricity usage of the different buildings is evaluated in this step. It offers context to the presented numbers and can therefore highlight additional erroneous data. As with the previous steps, these data are corrected as needed by repeating step K.

Step Q: Additional Graphs
Additional graphs are created using Statsoft Statistica to observe weekly, seasonal and daily trends. Statistica was chosen for its robust graphing capability as well as the Lowess curve fit. This curve fit calculates a locally weighted least square curve fit around a subset of the graphed data. By adjusting this window, it is possible to more accurately interpolate data than with a simple average or a moving average. The graphs generated in this step are intended to evaluate the relationship between HVAC consumption and external environmental conditions. Any abnormalities discovered in this step are addressed in step K.

E.4 METER ACCURACY

As discussed Section 5, there were some data discrepancies between the various meters monitoring electricity use at the four housing units. The sum of the submeters did not always match the whole home energy meter, and the whole home energy meter did not always match the

utility meter (Minol data). No clear trends, such as the sum of the submeters were always a certain percentage above or below the whole home energy meter, could be identified. However, it is not unusual that different meters measuring the same energy end use may record different energy use data. Meters can read different types of power depending on their individual characteristics, and the submeter and whole home meters may not have been designed to read the same type of power as the utility meter. The submeters and the whole home meters were also consumer-grade current transformers that captured indirect power measurements, meaning they were not hard-wired into the home electrical system, while the utility meter was a direct power measurement. In addition, aggregating individual submeter readings will aggregate any individual meter variances, which can result in a larger overall variance. In this case, each home had over 35 different energy metering points; if each meter had a 1-2% accuracy, when added together, the overall accuracy range would be much larger than 1-2%.

Figure E.4 gives an example of a situation where meters recorded different energy uses (Fitzpatrick and Murray 2011).

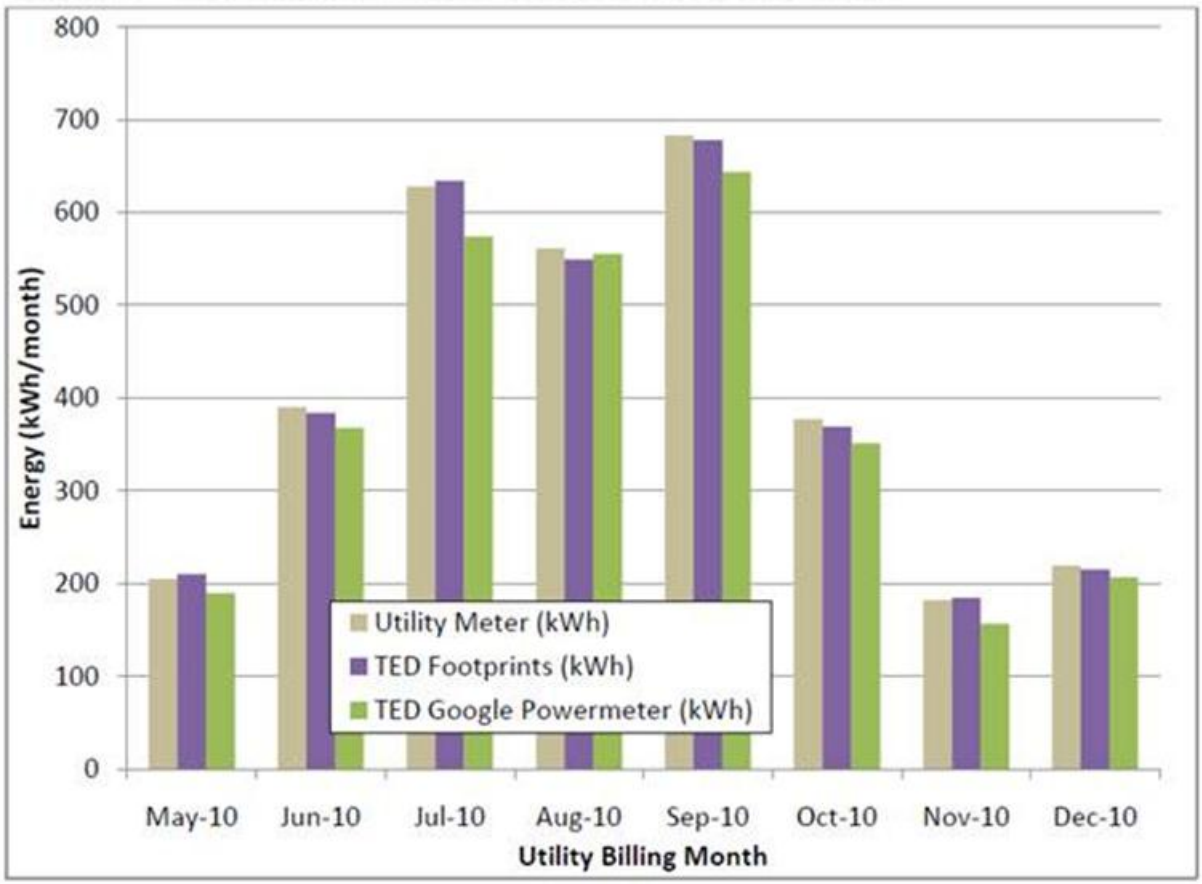


Figure E.4. Comparisons of Metered Energy (TED compared to Utility Meter) (Fitzpatrick and Murray 2011)

APPENDIX F: FINAL OCCUPANT SURVEY QUESTIONS

Campbell Crossing Zero Energy Home Project

End-of-Project Resident Questionnaire

Thank you for your participation in the Net Zero Home project this past year! We have enjoyed getting to work with you during the course of this project. As we finish the research, we have some questions regarding your experience in the homes. Your responses will be kept anonymous.

General Questions

1. Rank the following elements of this study with 1 being the most impactful or useful, and 8 being the least.

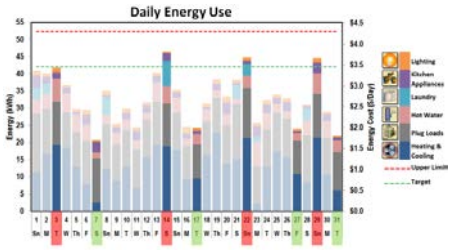
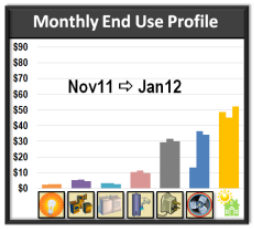
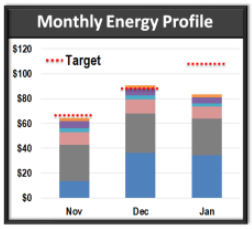
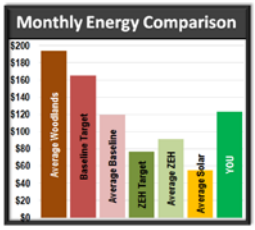
Item	Rank
Orientation before move-in	
Home Energy Manual	
TED – The Energy Detective	
ShowerMinder	
Monthly energy reports	
Monthly call with PNNL	
Publicity surrounding the project	
Awareness of project goals and energy monitoring	
Other (please specify):	

2. Has your family made any changes in the way you use energy or water as a result of this project and the above items? If so, what were the changes you consider significant?

3. Did you share information about the research project or your home energy reports with others? If so, what did they find interesting?

Energy Reports

Please rate the Energy Reports by selecting the word that best describes how useful the information was, and indicating why you did or did not find it useful

Monthly energy use calendar		**Daily energy use**	
			
☐Very Useful ☐Somewhat Useful ☐Not Useful	Why?	☐Very Useful ☐Somewhat Useful ☐Not Useful	Why?
Month-to-month energy comparison		**Comparison to other homes in the neighborhood**	
 			
☐Very Useful ☐Somewhat Useful ☐Not Useful	Why?	☐Very Useful ☐Somewhat Useful ☐Not Useful	Why?
Was the frequency of the monthly reports (check one): ☐Too frequent ☐Just right ☐Not frequent enough			

Any Other Comments?

Please use the space below to add any additional comments on your experience, including areas for improvement.

APPENDIX G: LIFE CYCLE COST ANALYSIS MODEL

CostModelFinalSept14 2012.xlsx

APPENDIX H: HOME ENERGY MANUAL

ZEHtipsSubmittal.pdf