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DOE Building America Technology and Energy Savings Analysis of Two 2,721 ft^2 Homes in a Mixed Humid Climate

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Energy and Transportation Science Division

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Abbreviations and Acronyms

ACH	Air Changes per hour
CFM	Cubic feet per minute
DOE	U.S. Department of Energy
DHW	Demand Hot Water
ECM	Electronically commuted motor
EF	Energy factor
EIFS	Exterior insulation finishing system
EPS	Expanded polystyrene
ERV	Energy Recovery Ventilator
HERS	Home Energy Rating System
HDP	High density polyethylene
HP	Heat pump
HPWH	Heat pump water heater
HSPF	Heating seasonal performance factor
IRR	Infrared reflective
LVL	Laminated veneer lumber
MELs	Miscellaneous electrical loads
MW	Megawatt
MWh	Megawatt hour
NFRC	National Fenestration Rating Council
ORNL	Oak Ridge National Laboratory
OSB	Oriented strand board
OVE	Optimum Value Engineering
SEER	Seasonal energy efficiency rating
SHGC	Solar heat gain coefficient
SIP	Structural insulated panel
SLA	Specific leakage area
TVA	Tennessee Valley Authority
XPS	Extruded polystyrene

1. Introduction

The ZEBRAlliance is an opportunity to accelerate progress toward DOE's goal of maximizing cost-effective energy efficiency by investing in a highly leveraged, focused effort to test new high-efficiency components emerging from Oak Ridge National Laboratory's (ORNL) Cooperative Research and Development Agreement (CRADA) partners and others. The Alliance integrated efficient components into the construction of four research houses that will be used as test markets to gauge the success of the components and houses. These four research houses are expected to be the first houses used to field-test several newly emerging products such as the ClimateMaster ground-source integrated heat pump. When these new components are proven, they will become available to serve regional and national homebuilding markets. Some of these products will impact existing housing retrofit markets as well as new construction. These four houses demonstrate different strategies for saving energy, but all are about 55-60% more efficient than traditional new construction (based on third party certified HERS evaluations). After the research period, the houses will be sold to interested home buyers. The outcome will contribute to efforts by TVA to defer 1,400 MW of new electricity generation and reduce growth in energy consumption by 4.3 million MWh per year by 2012, and in the longer term, to transform how homes are built and retrofitted for improved energy efficiency in the Tennessee Valley.

Two floor plans are used for the four research houses. Houses 1 and 2 have a total of 3713 ft^2 conditioned floor space consisting of 1518 ft^2 on the main floor, 677 ft^2 on the second floor, and an unfinished basement with 1518 ft^2. Houses 3 and 4 have a crawlspace foundation with first and second floor square footages of 1802 ft^2 and 919 ft^2, respectively.

Each house utilizes a different envelope strategy to test efficiency and durability. House 1's envelope is composed of structural insulated panels (SIPs). Each panel consists of an inner core of insulating foam sandwiched between two outer skins made of oriented strand board (OSB). With a typical wall thermal resistance of R_{US}-21, SIPs enable airtight construction and meet energy code requirements with minimal thermal short circuits from dimensional framing lumber. House 2's envelope utilizes optimum value engineering (OVE) advanced framing. By placing 2-by-6 studs at 24 inch centers with stacked structural framing, two stud corners, insulated headers, and ladder blocking to tie interior walls to exterior walls, the total amount of framing in the building is reduced by 5-10% (Lstiburek, 2010), while structural integrity is maintained. Additionally, the amount of thermal insulation can be increased, since the cavity is approximately 60% deeper. House 2's air tightness is improved by applying a spray applied liquid to the sheathing to create a weather resistant membrane. Insulation is a combination of spray-applied polyurethane foam and fiberglass batts that provide an insulating value of R_{US}-21. The house's cathedral roof is fitted with two layers of foil-faced, phenolic foam board between the rafters, and a third layer fastened to the underside of the rafters prior to drywall installation, thereby yielding an overall thermal resistance of about R_{US}-50.

House 3's envelope uses cellulose insulation with a paraffin material to enable thermal energy storage. Talc-like micro-capsules containing the paraffin (i.e. phase change materials [PCMs]) are mixed with the recycled newspaper, adhesives, and fire retardants of conventional cellulose. The PCM-enhanced cellulose, designed to absorb heat during the day and release it at night, is installed on the attic floor and in the exterior walls. A hybrid insulating approach of conventional cellulose on the indoor side of the walls and the PCM-enhanced insulation on the outside of the walls was used. Similarly in the attic, the conventional insulation was applied on the attic floor with the PCM-enhanced insulation on top. This novel approach to building envelopes earned ORNL and its industry partners, Advanced Fiber Technology and MicroTek Laboratories, a R&D 100 Award in 2009.

House 4's envelope utilizes an advanced exterior insulation finishing system (EIFS). Because the insulation is wrapped around the outside of the building frame, thermal short-circuiting through structural members is eliminated. This system is self-drying through the use of a layer integrated into the assembly that provides a path for buoyancy or wind-driven air movement in addition to a condensation and drip plane. The new self-drying design by Dryvit Systems, Inc., addresses moisture management while also including a flexible, polymer-based membrane applied as a liquid over the plywood sheathing to serve as a weather resistant membrane and improve air tightness.

High-efficiency, ground-source heat pumps provide space conditioning and hot water in Houses 1, 2, and 3. House 4 has a high-efficiency air-source heat pump and heat pump water heater (HPWH). Houses 1 and 2 utilize the foundation excavations for placement of the horizontal ground loops, in contrast to the more common vertical borehole ground loop in House 3. While four research houses have been built as a part of the ZEBRAlliance, this report will detail the energy efficient improvements over new construction made to House 3 and 4, hereafter described in this report as WC3 and WC4.

The description of the various technologies detailed in this report are similarly described in the publication by Miller et al. (2010) which is used as a basis for this document.

2. Energy Efficient Technologies and Systems

Roof Systems

An infrared reflective (IRR) painted metal shake is installed on WC3. Solar reflectance of the metal shake is 0.34 and its thermal emittance was measured at 0.85 (Miller et al., 2010). A tapered EPS insulation is inserted under the metal shakes to provide walking support and some resistance (ca. $R_{US} = 4$) to heat transfer across the deck (Figure 1).

Figure 1. Prototype assembly of WC3 roof.

WC4 has a conventional IRR asphalt shingle roof. Solar reflectance is 0.26 and the thermal emittance of the shingle is 0.88 W/m^2 (Miller et al., 2010). To mitigate the heat transfer effects of the darker, more heat absorbing shingles, a profiled and foil faced 1-in (0.0254-m) EPS insulation was placed over the roof rafters and covered by a foil[1]-faced OSB with the foil facing into the inclined air space (Figure 2). The assembly provides a radiant barrier facing into the attic plenum, two low-e surfaces facing into the inclined 1-in (0.0254-m) high air space, and passive ventilation from soffit to ridge. A slot is cut into the roof deck near the eave just above the soffit vent to provide make up air from the soffit vent and attic. As thermally induced airflows move up the inclined air space, cool make up air is pulled from the soffit and attic plenums to enhance thermal performance of the deck. The design puts the air intake of the inclined air space within the enclosure, just above the soffit. A perforated metal soffit vent acts as a fire block to prevent any burning embers from entering the air space.

Figure 2. Prototype assembly of WC4 roof

[1] Thermal emittance of the foils is 0.04 as measured using ASTM C-1371 (ASTM, 1997).

Attic Systems

WC3 and WC4 are built with conventional attics. WC3 has an OSB deck and the OSB is overlaid with a micro-perforated aluminum foil that faces into the attic. Solar powered gable ventilators are installed on the interior of the attic gables to enhance attic ventilation. At solar noon with clear sky, the fans are designed to induce about 10 air changes per hour from the perforated fiber cement soffit panels and the gable vents. Total soffit and gable-end vent area exceeds the 1:150-code.

Phase change materials (PCMs) were added to the blown fiber insulation on the attic floor of WC3 to absorb the remaining heat that escapes the reflective metal shake roof, the radiant barrier and the solar powered attic ventilation. The attic floor is insulated with 10-in (0.25-m) of regular cellulose insulation and an additional 4-in (0.10-m) of 20% by weight PCM-enhanced cellulose insulation.

A similar arrangement is setup for the attic floor of WC4. In addition to the foil faced EPS insulation serving as a radiant barrier (Figure 2), ceiling insulation of approximately R_{US}-50 is included. However, unlike WC3, no PCM is added to the cellulose insulation. The R-value is achieved via increased insulation thickness.

Cladding and Exterior Paint

Plain lap siding and vertical siding were used as the cladding for WC3. A stack stone covers the exposed wall sections from just below grade to the bottom of the 1st floor windows. According to the manufacturer, the siding is composed of a fiber cement material that is fireproof and water resistant; therefore, it will not crack or rot.

WC4 has an EIFS system covered with a textured acrylic stucco finish. Similar to WC3, a stack stone was placed around the masonry block of the home's crawlspace. However the stacked stone does not extend as high vertically. Images of the cladding and exterior painting can be seen in Figure 3.

Figure 3. Exterior painting and cladding for WC3 (left) and WC4 (right)

Cladding on the exterior wall of the WC3 used conventionally pigmented paints because of the expected high R-value resultant from the PCMs in the wall insulation. The solar reflectance (SR) and thermal emittance (ε) of the exterior paints for WC3 and WC4 are shown in Table 1.

Table 1. Cladding and exterior paint for WC3 and WC4

Description	WC3	WC4
Cladding	Fiber cement lap siding and stack stone	Acrylic stucco and stack stone
Exterior paints		
Gray	SR= 0.30 ε = 0.9 W/m^2	SR=0.23 ε = 0.9 W/m^2
Light Green	SR= 0.37 ε = 0.9 W/m^2	
Yellow	SR= 0.59 ε = 0.9 W/m^2	

Exterior Walls

WC3 has an exterior wall assembly made of two 2 by 4 walls. Wall studs are made of laminated strand lumber and are at 24-in (0.61-m) on-center. The studs from one wall are offset by 12-in (0.3-m) from the other wall's studs (Figure 4). The interior framing is supported by the floor truss while the exterior framing is installed on the sill plate and is fastened to the floor truss. A top plate was used to tie the two walls together for lateral strength. A fabric mesh is stapled between the two sets of 2-by-4 studs to separate and hold two different types of blown fiber insulation. Conventional blown fiber is contained in the interior cavity, while 20% by weight microencapsulated PCMs were added to blown fiber in the exterior framed cavity. Because of the dynamic nature of the PCM enhanced insulation, a conventional R-value cannot effectively describe the resistance to heat transfer through the wall. However, for reference, the R-value of only the cellulose insulation can be estimated as R_{US} – 26. Furthermore, in dynamic hot box testing, Kosny et al. (2010) found that PCM induced a 40% reduction in surface heat flow when blended with cellulose insulation. While this reduction was achieved during thermal ramp-up and cannot be interpreted as reduction in cooling load for all hours during cooling period, it does provide insight into the thermal storage potential of the PCM system. The exterior wall OSB sheathing (ZIP® Board) has a built-in protective weather resistive barrier (WRB) overlaid at the factory to eliminate the need for house wrap. All joints were taped to maintain the continuity of the sheathing air tightness. A high-density, polyethylene sheet with a ¼-in (6-mm) dimpled profile was also installed on the exterior of the sheathing to ventilate the exterior walls. It provides drainage of transient moisture migrating through the wall and creates two independent air flow streams to dry out both the cladding and the concealed wall cavities. This simultaneously reduces the impact of solar driven moisture problems and the impact of interior moisture loading. It is expected that the combination of phase change insulation, the polyethylene dimpled sheet, and the OSB sheathing will facilitate enhanced charging and discharging of the PCM, while also limiting air infiltration across the sheathing.

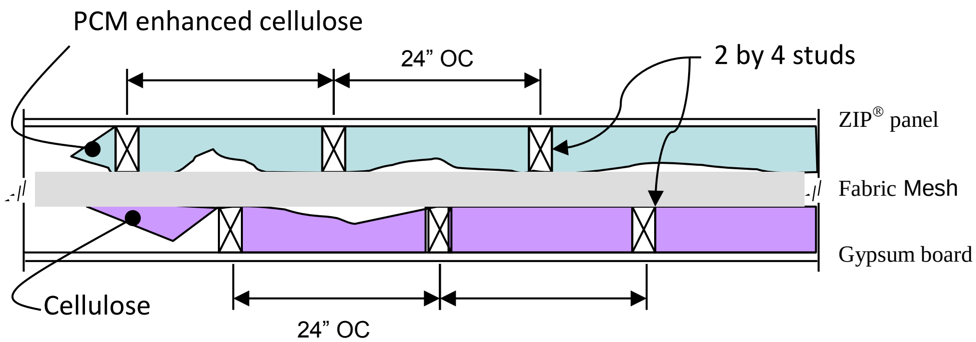

Figure 4. Double-stud wall assembly for WC3.

WC4 has an EIFS system, which is an insulated cladding made of 5-in (0.13-m) of EPS insulation on the outside of the exterior wall with studs installed 16-in (0.61-m) on center. The 5-in (0.13-m) of EPS insulation will reduce thermal bridging that contribute to energy losses in high performance wall systems. The system is lightweight, highly energy efficient and vapor permeable. The EPS insulation extends from about 1-ft (0.31-m) above the ground to the soffit of the roof. A flexible polymer-based membrane was manually applied as a liquid over all of the exterior sheathing. The membrane resists water penetration and decreases air infiltration. Afterwards, a fiber-reinforced cementitious adhesive was trowel applied to the weather resistive membrane to adhere the EPS insulation. The trowel application forms rows of the adhesive with each row approximately 0.25-in (6-mm) high. The rows provide a small drainage cavity between the WRB and the EPS insulation board through which incidental water can weep to the outdoor ambient. The exterior of WC4 is an acrylic-based coating finish over stucco. The interior has gypsum board fitted with a laminated low-e foil facing (permeated on site with a spike roller to increase the moisture permeability) to reduce radiation exchange across the wall cavity, which was left void of insulation. The thermal resistance of the wall is estimated as R_{US}-21

Windows

Both homes have triple pane windows with insulated glass unit (IGU) air spaces filled with argon gas. Argon gas is denser and less conductive than air. Therefore, in sealed glass units the argon reduces the convection within the air space, thereby, creating a better IGU. National Fenestration Rating Council (NFRC) ratings for the windows in WC3 consist of a U-factor of 0.22 Btu/h-ft^2-F and a SHGC of 0.17. Numbering the surfaces of the panes from 1 to 6 with 1 being the outside surface and 6 being the inside surface, the 2nd and the 4th surfaces are low-e surfaces. The two spacing's between the three panes of the IGU are the same thickness.

For WC4, selected window U-values and SHGC were based on the window's placement in the home. Southeast and southwest facing windows had U-values of 0.24 Btu/h-ft^2-F and a SHGC of 0.50. Northeast and northwest facing windows had a U-value of 0.18 Btu/h-ft^2-F and SHGC of 0.22.

Foundation

WC3 and WC4 are built on crawlspaces. The crawlspace in WC3 is ventilated with two R-19 batts installed in the floor chase cavities above the crawlspace, while the crawlspace for WC4 is sealed and insulated on the interior side of the block wall with rigid foam insulation. The masonry block forming the crawlspace on both homes was waterproofed using Tremco's emulsion based asphalt coating. Stack stones were installed on the exterior wall up to the termite barrier between the masonry wall and the base plate in both houses. A 20 mil liner covers the floor of both crawlspaces and is taped to a 10 mil wall liner in WC4 only. The wall liner was adhered to the masonry block using a low VOC polyurethane caulk. In WC4, the wall liner stops about 3-in below the sill plate to allow for termite inspections. DOW's Thermax™ rigid polyisocyanurate foam insulation (R_{US} -10) was glued to the wall liner using a polyurethane caulk adhesive. R_{US}-10 was a code requirement for the Tennessee Valley region in October 2010. Photographs of the sealed crawlspaces in WC3 and WC4 are shown in Figure 5.

Figure 5. Vented crawlspace in WC3 (left) and walls insulated and sealed in WC4 crawlspace (right)

Space Conditioning Equipment

A 310 ft deep vertical bore ground loop provides source energy for a high efficiency water-to-air heat pump (WAHP) in WC3. The WAHP is a ClimateMaster (model TTV026) two-stage (dual capacity) unit with an integral water/brine pump. The nominal low-stage cooling capacity rating ground source heat pump conditions is 21.3 kBtu/hr with a rated EER under these conditions of 26.0 kBtu/W. The rated high stage EER for the unit is 18.5 kBtu/W with a capacity of 26.6 kBtu/hr. The rated coefficients of performance for heating at high and low stages are 4.0 and 4.6, respectively (which does not include pumps and fans). The high stage heating capacity is 19.8 kBtu/hr, while the low stage capacity is 16.5 kBtu/hr. Electric heating elements are provided for emergency use if needed. A Duct Blaster test was conducted to measure the total air leakage of the duct system. The results from this test showed 102 CFM of leakage to the outside at 25 Pascal. Approximately 80% of the supply side ducts are located in the conditioned space while 100% of the return side ducts are in the conditioned space. The remaining 20% of supply side ducts are located in the attic, but were sealed with mastic and wrapped in R_{US}-5 insulation.

In WC4, a nominal 2 ton cooling, dual capacity air-source heat pump donated by Lennox is used for space condition (model XP19-024 with a CBX32MV-024/030 air handler unit). The AHRI-rated cooling performance of this unit (high stage operation) is 25 kBtu/h at 95°F with SEER of 18.4. Rated heating performance (high stage operation) is 22,600 Btu/h at 47°F and 13,100 Btu/h at 17°F with HSPF of 9.1.

Backup electric elements are provided to supplement the heat pump heating output during periods of low ambient temperature and for emergency heating. The CBX32MV air handler has a continuously variable speed blower with nominal air flow of 540-1320 CFM depending upon the selected speed setting. A Duct Blaster test was conducted to measure the total air leakage of the duct system. The results from this test showed 60 CFM of leakage to the outside of the building at 25 Pascal. Similar to WC3, approximately 80% of the supply side ducts are located in the conditioned space, while 100% of the return side ducts are in the conditioned space. The remaining 20% of supply side ducts are located in the attic, and were sealed in mastic and wrapped in R_{US}-5 insulation.

Mechanical ventilation is provided to WC3 and WC4 by running a 6 inch duct to the return plenum of the space conditioning heat pump, in line is a motorized damper and a manual damper. The heat pump variable speed indoor fan is used to bring in fresh air, based on the controls in the programmable ventilation system provided by an AirCycler. An average ventilation air flow of 30 CFM is maintained in both houses by seasonally adjusting the manual damper. During heavy heating and cooling periods, the air handler runs more hours on high speed than during the shoulder months. At higher fan speeds, larger volumes of air are drawn into the house when compared to lower fan speeds. Therefore, since the AirCycler controls do not monitor the amount of inlet fresh air induced by the variable fan speeds, the manual damper is adjusted to maintain average air flow.

Water Heating

Water heating is provided in WC3 by a specialty built water-to-water heat pump (WWHP) unit of ~1½-ton nominal capacity with integral pumps for both the source and load sides. The source energy is provided by the same ground source brine loop used by the WAHP. With a source entering water temperature of 68°F, the WWHP in WC3 has a COP of 3.7 for 120°F load water temperature. A back-up 82 gallon standard electric water heater with an EF of 0.92 is used for water storage. The storage water heater and the WWHP are both located in the utility room inside of the conditioned space.

In WC4 water heating is supplied by a donated GE GeoSpring®, 50 gallon hybrid electric heat pump water heater. The energy factor for this unit is approximately 2.35, and is located inside of the conditioned space in the utility room.

Lighting

WC3 is equipped with pin-based, ENERGY STAR®-rated, 100 percent fluorescent lighting. In contrast, WC4 has solid state LED lighting. The system efficacy of the LED lighting is approximately equivalent to CFL down lights (Willmorth, Zaderej, and Miller, 2010). The LED lighting solution did lead to more down light cans penetrating into the unconditioned attic space. This can lead to a risk of uncontrolled air leakage if not installed airtight to the ceiling plane under the insulated attic space.

Appliances

WC3 and WC4 have equivalent advanced appliances installed. Whirlpool Corporation donated all the appliances for all homes. The appliances are ENERGY STAR, or high-efficiency products for categories not yet ENERGY STAR certified. Salient appliance features are:

- *Refrigerator:* 36" wide by 25 cubic feet side-by-side unit. The refrigerator is ENERGY STAR certified; model number is GS6NVEXV. Manufacturer suggested retail price is $1,749.

- *Clothes Washer & Dryer*: Whirlpool donated their high-end horizontal axis washer and matching dryer because of their potential to reduce energy and water use and because of future enhancements using Whirlpool's load manager. The washer can steam wash and the dryer can steam dry.
- *Dishwasher*: The dishwasher is ENERGY STAR certified; model GU3600XTV. http://www.whirlpool.com/catalog/product.jsp?categoryId=108&productId=1329&successful_search=gu3600xtv
- *Range*: The appliance was just introduced onto the market by Whirlpool. It is a free-standing range with glass cook top featuring an energy saver mode; model GFE471LVQ. http://www.whirlpool.com/catalog/product.jsp?categoryId=76&productId=1293&successful_search=GFE471LVQ

Technology and Systems Summary

Table 2 below provides a summary of salient energy efficient technologies and systems in WC3 and WC4.

Table 2. Summary of technology and systems in WC3 and WC4

	WC3	WC4
Stories	2	2
Floor (ft2)	2721	2721
Foundation	Conventional vented crawlspace with two R-19 batts installed in the floor joist cavities	Sealed and insulated crawlspace with R_{US}-10 polyisocyanurate foil faced insulation on the walls
Exterior Walls	2 - 2x4 stud walls; 24-in O.C. with PCM enhanced cellulose	R-21 wall assembly 2x4 wood 16-in O.C. 5-in EPS exterior insulation
Attic	R-50 Conventional attic with PCM enhanced cellulose insulation Trusses at 24 -in O.C.	R-50 Conventional attic with floor filled blown-fiber insulation Trusses at 24 -in O.C.
Windows	Triple pane; U= 0.22 Btu/h-ft²-F, SGHC = 0.17	Triple pane; Southeast and Southwest facing windows: U = 0.24 Btu/h-ft²-F, SHGC = 0.50. Northeast and Northwest facing windows: U = 0.18 Btu/h-ft²-F, SHGC = 0.22.
Cladding	Fiber cement lap siding and stack stone	Acrylic stucco and stack stone
Exterior paints		
Light Green	SR= 0.37 ε = 0.9 W/m^2	SR=0.23 ε = 0.9 W/m^2
Yellow	SR= 0.59 ε = 0.9 W/m^2	

	WC3	WC4
Space Conditioning	Single vertical well ground source HP, dual-speed compressor, cooling capacity: 26.6 kBtu/hr (high stage), EER: 18.5 kBtu/W (high stage) heating capacity: 19.8 kBtu/hr (high stage), COP: 4.0 (high stage)	Single air-source HP, dual-speed compressor, cooling capacity = 25 kBtu/hr (high stage), SEER: 18.4 (high stage), heating capacity: 22.6 kBtu/hr (high stage), HSPF: 9.1 (high stage)
Mechanical ventilation	30 CFM	30 CFM
Duct location	Supply: 80% inside conditioned space, 20% attic Return: 100% inside conditioned space R-5 insulation, supply area = 551 ft^2 , return area = 306 ft^2, duct air leakage (to the outside) = 15%	Supply: 80% inside conditioned space, 20% attic Return: 100% inside conditioned space R-5 insulation, supply area = 551 ft^2 , return area = 306 ft^2, duct air leakage (to the outside) = 8%
Air handler location	Conditioned Space	Conditioned Space
Water heater	WWHP, COP = 3.7	Hybrid hot water heat pump, EF = 2.35
Lighting	100% fluorescent	LED lighting

3. Energy Use and Savings Analysis

Methodology

Per the methodology outlined in Hendron and Engebrecht (2010) for Building America (BA) research teams, an analysis of the energy use and potential savings of WC3 and WC4 was conducted using EnergyGauge software. As a first step in this approach, a BA Benchmark house (BAB) was defined to facilitate comparison. Once the specifications for the prototype house (i.e. WC3 or WC4) were defined, a BAB model was generated by the EnergyGauge software. Further details of the analysis methodology can be found in Hendron and Engebrecht (2010).

WC3

The simulated energy consumption from EnergyGauge models of WC3 and the BAB energy usage are shown in Table 3. Appliance and lighting schedules were set to the BA Prototype Reference in EnergyGauge for both simulations. Since miscellaneous electrical loads (MELs) were not the focus of the energy analysis conducted in this report, the MELs of WC3 were set at the same consumption level as simulated in BAB to facilitate a more straightforward evaluation of the energy saving measures included in WC3. The whole house energy consumption of WC3 was simulated to be approximately 60% less than the BAB. If the consumption loads attributed to MELs are not considered, WC3 would have energy savings of 68% in comparison to the BAB. The energy savings for heating, cooling, and domestic hot water loads range from 65% to 78%. EnergyGauge simulated HERS ratings of 111 and 45 for the BAB and WC3, respectively. The HERS rating of 45 thereby qualifies the builder for a federal tax credit of $2,000.

Table 3. BA Benchmark and WC3 site energy consumption

End Use	Annual Site Energy		
	BA Benchmark (2008) (kWh)	WC3 (kWh)	Savings over BA Benchmark
Space Cooling	5,039	1,089	78%
Space Heating	11,011	2,792	75%
DHW	3,590	1,271	65%
Washer	105	23	78%
Dishwasher	206	181	12%
Dryer	835	713	15%
Lighting	2,739	711	74%
MELs	3,443	3,443	0%
Range	605	447	26%
Refrigerator	669	583	13%
Total Usage	28,242	11,253	60%

Since the BAB is based on a house built using standard building practices of the mid-1990s, a model house consistent with current building practices of home builders in the East Tennessee region was also defined in EnergyGauge for comparison and is referenced hereafter as the Builder Standard house (BSH). Common building practices in the Oak Ridge, Tennessee, region are described in detail by Christian et. al. (2010) as the Builder House and was used as a reference in defining the BSH. Table 4 below describes the salient details of WC3, BAB, and BSH with respect to energy consumption. EnergyGauge was used to evaluate a HERS rating of 99 for the BSH.

Table 4. Salient details of the Building America Benchmark, Builder Standard house, and WC3 as modeled in EnergyGauge

	BA Benchmark	Builder Standard (BSH)	WC3
Stories	2	2	2
Floor Area	2,721 ft^2	2,721 ft^2	2,721 ft^2
Foundation	Conventional vented crawlspace, R-18.5 insulation above the crawlspace (U=0.05) Floor framing factor = 13%	Conventional vented crawlspace, R-19 insulation above the crawlspace (U=0.053) Floor framing factor = 13%	Conventional vented crawlspace, R-38 insulation above the crawlspace (U=0.035) Floor framing factor = 13%
Exterior Walls	R-19 wall cavity insulation (Total Wall U =0.061) Wall framing factor = 0.23 Solar absorptance = 0.5	R-13 wall cavity insulation (Total Wall U = 0.082) Wall framing factor = 0.20 Solar absorptance = 0.62, 0.41	R-26 wall cavity insulation (Total Wall U = 0.058) Wall framing factor = 0.20 (staggered double wall) Solar absorptance = 0.62, 0.41

	BA Benchmark	Builder Standard (BSH)	WC3
Attic	Conventional attic, R-26 ceiling insulation (U=0.035), ventilation ratio = 1 to 300	Conventional attic, R-25 ceiling insulation (U=0.037), ventilation ratio = 1 to 150	Conventional attic, R-50 ceiling insulation (U=0.019), ventilation ratio = 1 to 150
Roofing Material	Composition shingles, solar absorptance = 0.75, Roof Deck R-0	Composition shingles, solar absorptance = 0.85, Roof Deck R-0	Metal, solar absorptance = 0.66, Roof Deck R-4
Windows	Double pane clear windows; U= 0.58, SGHC = 0.58	Double pane clear windows; U= 0.47, SGHC = 0.58	Triple pane; U= 0.22, SGHC = 0.17
Space Conditioning	SEER = 10, SHR= 0.75, cooling capacity = 43.6 kBtu/hr HSPF = 6.8, heating capacity = 66.4 kBtu/hr	SEER = 13, SHR= 0.75, cooling capacity = 48 kBtu/hr HSPF = 7.7, heating capacity = 48.3 kBtu/hr	Single ground source (vertical well) HP, SHR = 0.72, cooling capacity: 23 kBtu/hr, EER: 16 kBtu/W heating capacity: 15 kBtu/hr, COP: 3.85
Infiltration	ACH(50) = 9.75, SLA = 0.00057 in^2/in^2	ACH(50) = 8.5, SLA = 0.00050 in^2/in^2	ACH(50) = 3.49, SLA = 0.00020 in^2/in^2
Mechanical ventilation	6 CFM	30 CFM	30 CFM
Duct location	Supply: crawlspace Return: crawlspace R-5 insulation, supply area = 353.7 ft^2 , return area = 326.5 ft^2, duct air leakage = 12%	Supply: crawlspace Return: crawlspace R-5 insulation, supply area = 544 ft^2 , return area = 136 ft^2, duct air leakage = 12%	Supply: interior Return: interior R-5 insulation, supply area = 544 ft^2 , return area = 136 ft^2, duct air leakage = 15%
Air handler location	Crawlspace	Crawlspace	Interior
Water heater	Electric 50 gal capacity, EF = 0.86, usage = 63.5 gal/day, set temp = 120ºF	Electric 50 gal capacity, EF = 0.86, usage = 60 gal/day, set temp = 120ºF	Electric 50 gal capacity, EF = 0.92, usage = 60 gal/day, set temp = 120ºF, Add-on Heat pump COP = 3.0
Lighting	14% fluorescent, 86% incandescent	10.1% fluorescent, 89.9% incandescent	100% fluorescent

In order to evaluate the incremental energy savings of each energy efficient measure, a stepwise progression from the BSH to WC3 was modeled. As each energy efficient measure was added to the BSH model, an EnergyGauge simulation of household energy consumption was run. The order in which the technologies were added to the BSH model was based on tradeoffs between the ease of retrofitting and cost-effectiveness. For example, changing the household lighting to CFL's was given a higher priority than increasing wall insulation. The step-by-step addition of technologies and energy saving measures is shown in Figure 6 for the total, heating, cooling, and hot water heating loads. The energy savings from these measures are shown in Table 5. In total, WC3 is modeled to consume approximately 60% and 53% less energy than the BA Benchmark and the BSH model, respectively. The annual energy cost savings of each measure was determined by multiplying the decrement in energy consumption by the cost of electricity. With all of the features and equipment used, WC3 saves a total of $1,200 per year, based on local utility rates of $0.093/kWh).

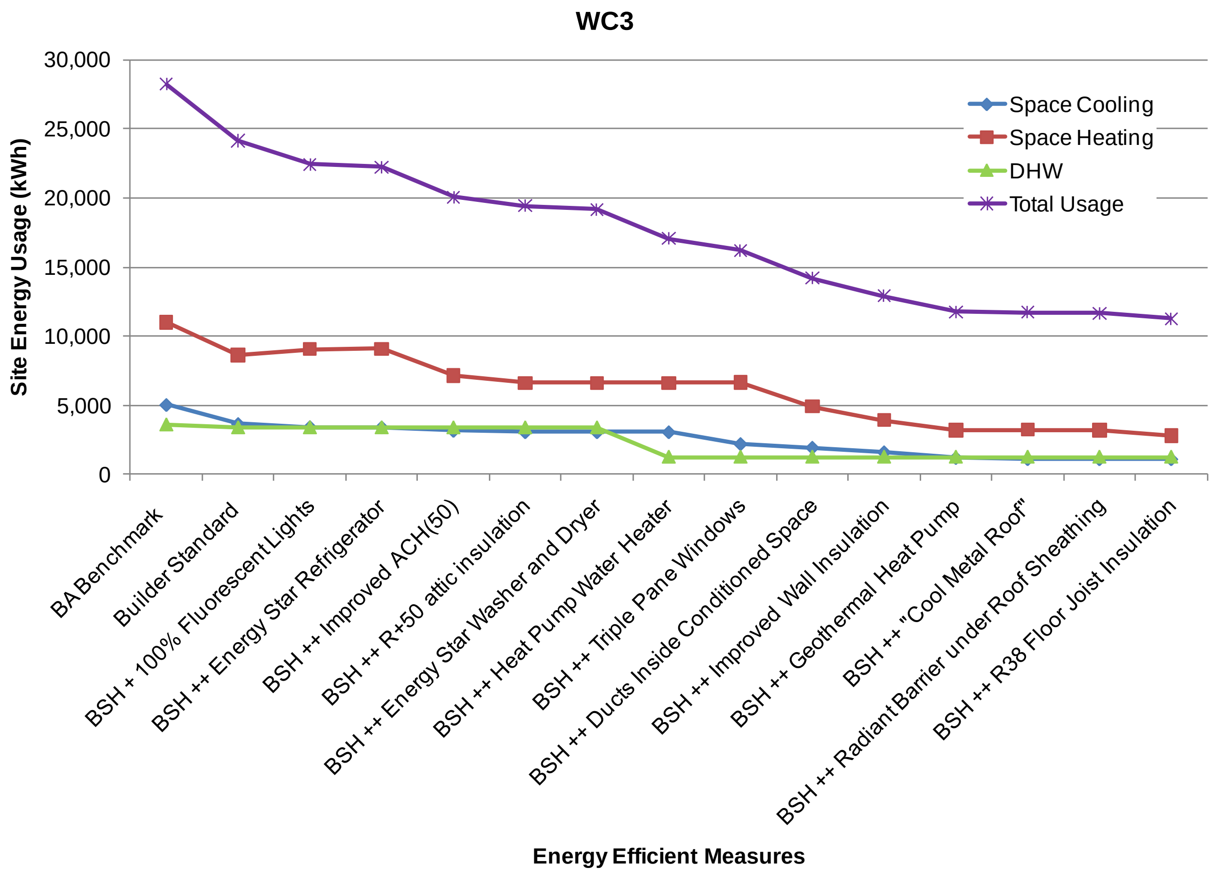

Figure 6. Simulated energy consumption after the addition of individual technologies

Since EnergyGauge does not have the ability to simulate the impact of dynamic insulation materials, an additional modification was needed to evaluate the energy savings of the PCM. The R_{US}-26 wall insulation modeled in EnergyGauge was determined by assuming no impact from the PCM. As an estimate of the PCM impact, we then reduced the simulated cooling loads by 7.85%. This was determined by assuming a 40% reduction in heat flux through the walls, which comprise 19.6% of the whole-house cooling load.

Table 5. WC3 energy consumption and savings after the addition of individual technologies

	Est. site energy (kWh)	Est. source energy (MBtu)	Energy Costs[2] ($/yr)	Energy Costs[3] ($/yr)	Cost Savings[3]	Measure Value[3] ($/yr)	Package Savings[3] ($/yr)
Increment							
BA Benchmark	28,242	324	$3,321	$2,627			
Builder Standard (BSH)	24,154	277	$2,841	$2,246	14%		
BSH + 100% Fluorescent Lights	22,415	257	$2,636	$2,085	21%	$162	$162
BSH ++ ENERGY STAR Refrigerator	22,236	255	$2,615	$2,068	21%	$17	$178
BSH ++ Improved ACH(50)	20,062	230	$2,359	$1,866	29%	$202	$381
BSH ++ R-50 attic insulation	19,434	223	$2,285	$1,807	31%	$58	$439
BSH ++ ENERGY STAR Washer and Dryer	19,174	220	$2,255	$1,783	32%	$24	$463
BSH ++ Heat Pump Water Heater	17,063	196	$2,007	$1,587	40%	$196	$659
BSH ++ Triple Pane Windows	16,223	186	$1,908	$1,509	43%	$78	$738
BSH ++ Ducts Inside Conditioned Space	14,202	163	$1,670	$1,321	50%	$188	$926
BSH ++ Improved Wall Insulation	12,902	148	$1,517	$1,200	54%	$121	$1,046
BSH ++ Geothermal Heat Pump	11,761	135	$1,383	$1,094	58%	$106	$1,153
BSH ++ "Cool Metal Roof"	11,713	134	$1,377	$1,089	59%	$4	$1,157

[2] Energy costs determined using an average national utility rate of $0.118/kWh
[3] Energy costs determined using an average local utility rate of $0.093/kWh

	Est. site energy (kWh)	Est. source energy (MBtu)	Energy Costs[2] ($/yr)	Energy Costs[3] ($/yr)	Cost Savings[3]	Measure Value[3] ($/yr)	Package Savings[3] ($/yr)
BSH ++ Radiant Barrier under Roof Sheathing	11,670	134	$1,372	$1,085	59%	$4	$1,161
BSH ++ R38 Floor Joist Insulation	11,253	129	$1,323	$1,047	60%	$39	$1,200

First Costs

A detailed breakdown of the cost to construct WC3 is shown in Table 6. The totals costs include construction costs incurred by Schaad Companies and the market value of all donated items by the ZEBRA partners. The construction costs incurred by Schaad were determined from invoices and spreadsheets that Schaad Companies provided. The market value of donated items was estimated by the relevant ZEBRA partners. Certain elements of the General Requirements cost section in Table 6 were estimated by Schaad to reflect more accurately the standard costs of building similar homes rather than the actual costs. Table 7 gives a comparative look at the actual versus the standard cost for the costs items in the General Requirements section that Schaad estimated. Finally, Table 8 shows a summary of the total and the per square footage cost of WC3.

Table 6. Detailed construction estimates for WC3

Category	WC3 PCM House ($)
Envelope	
Framing	58,290
Roof	30,907
Cladding	25,708
Foundation	28,699
Site Development	5,565
Windows	10,026
Paint (exterior)	10,494
Doors (exterior)	2,140
Garage	4,798
Exterior Décor	1,476
HVAC	
Duct	5,100
Insulation	46,071
Heat Pump/Zone Control	8,400
Geothermal Loop	7,075
Water	
Water Heater	6,200

Category	WC3 PCM House ($)
Plumbing	14,856
Interior Finish	
Appliances	7,590
Floor Covering	19,204
Millwork	15,885
Paint	5,900
Drywall	10,750
Other Interior Décor	25,403
Electrical	
Electrical Systems	9,304
Security	1,000
Lighting	6,530
Utility Services	2,086
Landscaping	
Ornamental	4,000
Yard	6,260
General Requirements	
Labor~	6,750
Supervision/Administration~	27,000
Architectural*	21,227
Engineering°	2,945
Permits/Insurance	5,303
Utilities/Taxes/Dues	1,592
Other General	1,229
Total	**445,800**

Table 7 shows the actual versus standard cost estimated by Schaad for the specific costs items in addition to the total actual and standard costs. Below is a list of the cost items that Schaad estimated would be the standard costs for similar homes.

- **~**: Labor and Supervision/Administration are estimated by Schaad Companies. Actual costs were overstated and not equally allocated between the four houses. Schaad Companies estimated the standard amount that would be spent on Labor and Supervision/Administration for the completion of similar houses in business as usual conditions.
- *****: Architectural costs are estimated by Schaad Companies. Architectural costs are estimated to be 5% of total costs.
- **°:** Similar to Labor and Supervision, the standard Engineering costs were estimated by Schaad Companies. Actual costs were understated mostly due to the strong involvement from ORNL research and development engineers.

Table 7. Actual and Standard costs for WC3

	WC3 PCM House	
Costs Items	Actual Costs ($)	Standard Costs ($)
Labor~	7,376	6,750
Supervision/ Administration~	46,639	27,000
Architectural*	260	21,227
Engineering°	2,686	2,945
Total Costs	**444,800**	**445,800**

Table 8. Cost summary for WC3

	WC3 PCM House
Total Costs ($)	**$445,800**
Total Square Footage	2,721
Total Cost Per Square Foot ($)	**$163**

The first cost of WC3 is considerably more than would be expected based on recent low-energy homes (Christian and Blazer, 2010). However, a system performance evaluation approach is taken in WC3, in contrast to other low energy homes that utilize a whole-house methodology to select and install energy savings measures. Many of the technologies and systems employed in WC3 are "first wave" technologies that have yet to progress down the cost curve from higher initial prices to lower affordable prices through large scale deployment. For example, the cellulose enhanced with microencapsulated phase change materials employed in the attic and exterior wall insulation have yet to be employed at a scale beyond custom applications. Through our ongoing collaborations with industry partners such as MicroTek, we plan to facilitate integration of higher performing products such as these through validation of the whole-house energy savings that can be achieved.

Neutral-Cash-Flow analysis

Table 9 shows the neutral-cash-flow analysis for WC3 using the BA Benchmark Definition (Hendron and Engebrecht, 2009). The analysis was conducted by evaluating the incremental investment costs and energy savings of each energy efficient measure against the BSH. The amortized annual costs are based on a 30 year loan with an interest rate of 7%. All energy costs and savings were estimated based on local utility rates of $0.093/kWh. The net cost of each measure shown in the table was determined by subtracting the amortized investment costs from the energy savings.

Table 9. Neutral cash flow analysis for WC3

Increment	Site Energy (kWh/yr)	Site Energy Costs ($/yr)	Energy Savings (kWh/yr)	Energy Savings ($/yr)	Cumulative Energy Savings ($/yr)	Incremental Investment Costs ($)	Amortized Investment Costs ($/yr)	Net Cost ($/yr)	Cash-flow neutral
BA Benchmark	28,242	$2,627							
Builder Standard (BSH)	24,154	$2,246	4,088						
BSH + 100% Fluorescent Lights	22,415	$2,085	1,739	$162	$162	$3,330	$266	$104	No
BSH ++ ENERGY STAR Refrigerator	22,236	$2,068	179	$17	$178	$1,127	$90	$73	No
BSH ++ Improved ACH(50)	20,062	$1,866	2,174	$202	$381	$2,079	$166	($36)	Yes
BSH ++ R+50 attic insulation	19,434	$1,807	628	$58	$439	$17,704	$1,413	$1,355	No
BSH ++ ENERGY STAR Washer and Dryer	19,174	$1,783	260	$24	$463	$1,598	$128	$103	No
BSH ++ Heat Pump Water Heater	17,063	$1,587	2,111	$196	$659	$3,735	$298	$102	No
BSH ++ Triple Pane Windows	16,223	$1,509	840	$78	$738	$3,753	$300	$221	No
BSH ++ Ducts Inside Conditioned Space	14,202	$1,321	2,021	$188	$926	$2,095	$167	($21)	Yes
BSH ++ Improved Wall Insulation	12,902	$1,200	1,300	$121	$1,046	$18,955	$1,513	$1,392	No
BSH ++ Geothermal Heat Pump	11,761	$1,094	1,141	$106	$1,153	$5,990	$478	$372	No

	Site Energy (kWh/yr)	Site Energy Costs ($/yr)	Energy Savings (kWh/yr)	Energy Savings ($/yr)	Cumulative Energy Savings ($/yr)	Incremental Investment Costs ($)	Amortized Investment Costs ($/yr)	Net Cost ($/yr)	Cash-flow neutral
BSH ++ "Cool Metal Roof"	11,713	$1,089	48	$4	$1,157	$13,157	$1,050	$1,046	No
BSH ++ Radiant Barrier under Roof Sheathing	11,670	$1,085	43	$4	$1,161	$314	$25	$21	No
BSH ++ R38 Floor Joist Insulation	11,253	$1,047	417	$39	$1,200	$904	$72	$33	No
Total Energy Efficiency Investment					$1,200	$74,741	$5,967	$4,767	No
Rebates/Incentives									
Federal Energy Efficient House Tax Credit						$2,000			
TVA high efficiency water heater						$50			
State of TN ENERGY STAR Heat Pump						$250			
Federal Residential Geothermal Energy Tax Credit						$5,495			
Total Incremental Cost to Buyer Including Incentives					$1,200	$67,195	$5,365	$4,165	No

The simulated whole-house annual energy cost for BSH was $2,246. The total incremental investment for all energy efficient investments in WC3 is $74,741, with an annualized cost of $5,967. Neutral cash flow is not achieved in WC3, because when the annual energy costs savings and currently available incentives are considered, the annual cost of the efficiency measures is $4,165.

Table 10 shows a list of the energy efficient technologies in WC3 prioritized from the least annualized cost to the highest. No incentives for specific technologies are included in the table. Placing the ducts inside the conditioned space and air sealing to improve the ACH@50 from 8.5 to 3.49 are the only measures that are cash flow neutral. The incremental cost of improving air infiltration was estimated using BEOpt software.

Table 10. WC3 Prioritized list of energy efficiency technologies by annualized cost

	Incremental cost ($)	Annual Net Cost	Cash-flow neutral?
BSH ++ Improved ACH(50)	$2,079	($36)	Yes
BSH ++ Ducts Inside Conditioned Space	$2,095	($21)	Yes
BSH ++ Radiant Barrier under Roof Sheathing	$314	$21	No
BSH ++ R38 Floor Joist Insulation	$904	$33	No
BSH ++ ENERGY STAR Refrigerator	$1,127	$73	No
BSH ++ Heat Pump Water Heater	$3,735	$102	No
BSH ++ ENERGY STAR Washer and Dryer	$1,598	$103	No
BSH + 100% Fluorescent Lights	$3,330	$104	No
BSH ++ Triple Pane Windows	$3,753	$221	No
BSH ++ Geothermal Heat Pump	$5,990	$372	No
BSH ++ "Cool Metal Roof"	$13,157	$1,046	No
BSH ++ R+50 attic insulation	$17,704	$1,355	No
BSH ++ Improved Wall Insulation	$18,955	$1,392	No

The heat pump water heater has a high annualized cost. This is due to the large incremental cost of $3,753 associated with the unit. Because the heat pump water heater uses the same ground source as the geothermal heat pump, the excavation costs for the ground loop were split between both units. The proportion of the $6,000 ground loop costs allocated to each unit was based on their estimated retail value. Approximately $2,053 of the ground loop cost was appropriated to the heat pump water heater while the remaining $3,947 was added to the geothermal costs. In both cases, the cost of the ground loop was a significant contributor to why annualized costs were greater than zero. A 310 ft deep vertical bore was drilled for this application. However, if novel and more cost-effective drilling techniques could be employed, ground heat exchanger applications could be more appealing from a cost perspective. Such high, cost-prohibitive drilling costs are unfortunate, given that the heat pump water heater achieved the highest energy savings of 2,151 kWh/yr.

With simulated annual energy savings of 1,141 kWh, the performance of the geothermal heat pump is less than expected. The EER and heating COP modeled in EnergyGauge for this heat pump were 16 kBtu/W and 3.85, respectively, in contrast to manufacturer ratings of 18.5 kBtu/W and 4. Since the same geothermal heat pump model has been in use in two other ZEBRAlliance homes for approximately nine months, the average heating and cooling performance metrics that have been measured in these units were used as inputs to EnergyGauge.

The radiant barrier located on the underside of the roof sheathing had the lowest incremental cost of all technologies ($314), therefore, the total annualized costs are also relatively low. However, the EnergyGauge model only predicts an annual energy savings of $4 over the BSH. This converts to a simple payback of over 78 years. The impact of the radiant barrier is mitigated by the ventilated attic with R-50 insulation over the ceiling joists, in addition to the location of the HVAC equipment in the conditioned space. Similarly, the annualized cost of the additional floor joist insulation is lower than most other technologies due to its lower overall incremental costs.

In contrast to expectation, the ENERGY STAR refrigerator has a positive annual cost. This can be attributed to the fact that the refrigerator donated by Whirlpool is a premium model with amenities superior to a standard refrigerator modeled in the BSH. Therefore, the incremental cost captured in the analysis includes amenity costs in addition to increased energy efficiency. If an “apples to apples” comparison of refrigerators with similar amenities was done, the refrigerator would likely be cost neutral.

The requirement of 100% fluorescent lights was not cost neutral. The incremental cost of the lights was determined by taking the cost of the lighting package in WC3 and comparing it with the lighting package cost of a similar size house recently built by Schaad Companies. The resulting high incremental cost is mostly attributable to the use of ENERGY STAR rated pin base CFL bulbs in contrast to CFL bulbs with an Edison screw base. Pin based CFL bulbs and fixtures are significantly more expensive than the latter.

The “cool metal roof” has significant annualized costs. This is due in large part to the research nature of the technology employed. The IRR painted metal shakes have tapered EPS insulation inserted underneath to provide support when one walks across the roof and to increase the resistance to heat transfer across the deck. The added cost of the total assembly and installation makes the roof application cost-prohibitive in WC3. Additionally, because the cooling loads are already significantly reduced by triple pane windows, R-50 insulation, and the placement of the ducts inside the conditioned space, the performance of the cool roof application is mitigated as well.

The addition of triple pane windows reduces the cooling load by approximately 28%. However, Oak Ridge, Tennessee, is a heating dominated climate with cooling loads comprising only 44% of the required heating loads in standard residential construction. Therefore, the total annual energy savings are only $78, which are not enough to offset the incremental cost of $3,753 over clear, double pane windows.

The technology measures of R-50 attic insulation and increased exterior wall insulation both employ technology applications on the cutting edge of building construction. The retail value of the PCM material was approximately $35,450. These costs are at least three to four times higher than what should be expected for a larger scale production. The primary cost components are the cost of running the encapsulation reactor and the cost of drying of the PCM. It is expected that it will take application in at least 1,000 to 5,000 houses a year to make a reasonable business case for PCM residential building integration. However, WC3 does provide an opportunity to verify the whole house performance of this material to help inform manufacturers and building contractors.

WC4

The simulated energy consumption from EnergyGauge models of WC4 and the BAB energy usage are shown in Table 11. Appliance and lighting schedules were set to the BA Prototype Reference in EnergyGauge for both simulations. Since MELs were not the focus of the energy analysis conducted in this report, the MELs of WC4 were set at the same consumption level as simulated in BAB to facilitate a more straightforward evaluation of the energy saving measures included in WC4. The whole house energy consumption of WC4 was simulated to be approximately 55% less than the BAB. If the consumption loads attributed to MELs are not considered, WC4 would have energy savings of 63% in comparison to the BAB. The energy savings for heating, cooling, and domestic hot water loads range from 61 to 71%. EnergyGauge simulated HERS ratings of 111 and 55 for the BAB and WC4, respectively. The HERS rating of 55 thereby qualifies the builder for a federal tax credit of $2000.

Table 11. BA Benchmark and WC3 site energy consumption

End Use	Annual Site Energy		
	BA Benchmark (2008) (kWh)	WC4 (kWh)	Savings over BA Benchmark
Space Cooling	5,039	1,969	61%
Space Heating	11,011	3,167	71%
DHW	3,590	1,373	62%
Washer	105	23	78%
Dishwasher	206	181	12%
Dryer	835	713	15%
Lighting	2,739	712	74%
MELs	3,443	3,443	0%
Range	605	447	26%
Refrigerator	669	583	13%
Total Usage	28,242	12,611	55%

Since the BAB is based on a house built using standard building practices of the mid-1990s, a model house consistent with current building practices of home builders in the East Tennessee region was also defined in EnergyGauge for comparison and is referenced hereafter as the Builder Standard House (BSH). Common building practices in the Oak Ridge, Tennessee, region are described in detail by Christian et. al. (2010) as the Builder House which was used as a reference in defining the BSH. Table 10 below describes the salient details of how WC4, BAB, and BSH were modeled in EnergyGauge. EnergyGauge was used to evaluate a HERS rating of 99 for the BSH. In some of the newer technologies applied in

WC4, it was not possible to explicitly model them in EnergyGauge. In these cases, technologies available in EnergyGauge and corresponding performance specifications were modeled as a surrogate. For example, instead of modeling LED lighting technology, WC4 was modeled in EnergyGauge with all fluorescent lighting. Because the lighting efficacy of the LED downlight modules in WC4 of 30 lumens/watt was comparable to similar CFL downlights (Willmorth, Zaderej, and Miller, 2010), the authors deemed this as an appropriate technology substitute. EnergyGauge also does not have the option of selecting a heat pump water heater. In this case, a standard electric water heater with an energy factor of one was selected. However, an add-on heat pump with a COP of 2.35 was modeled as an equivalent to the GeoSpring® heat pump water heater that is in operation in WC4.

Table 12. Sample EnergyGauge model details of the Building America Benchmark, Builder Standard house, and WC4

	BA Benchmark	Builder Standard (BSH)	WC4
Stories	2	2	2
Floor Area	2,721 ft^2	2,721 ft^2	2,721 ft^2
Foundation	Conventional vented crawlspace, R-18.5 insulation above the crawlspace (U=0.05) Floor framing factor = 13%	Conventional vented crawlspace, R-19 insulation above the crawlspace (U=0.053) Floor framing factor = 13%	Sealed crawlspace, No insulation above the crawlspace, R-10 wall insulation Floor framing factor = 13%
Exterior Walls	R-19 wall cavity insulation (Total Wall U =0.061) Wall framing factor = 23% Solar absorptance = 0.5	R-13 wall cavity insulation (Total Wall U = 0.82) Wall framing factor = 23% Solar absorptance = 0.77	R-21 whole wall value (Total Wall U = 0.048) Wall framing factor = 23% Solar absorptance = 0.77
Attic	Conventional attic, R-26 ceiling insulation (U=0.035), ventilation ratio = 1 to 300	Conventional attic, R-25 ceiling insulation (U=0.037), ventilation ratio = 1 to 150	Conventional attic, R-50 ceiling insulation (U=0.019), ventilation ratio = 1 to 150
Roofing Material	Composition shingles, solar absorptance = 0.75, Roof Deck R-0	Composition shingles, solar absorptance = 0.85, Roof Deck R-0	Composition shingles, solar absorptance = 0.74, Roof Deck R-4
Windows	Double pane, clear; U= 0.58, SGHC = 0.58	Double pane, clear; U= 0.47, SGHC = 0.58	Triple pane; Southeast and Southwest facing windows: U = 0.24, SHGC = 0.50. Northeast and Northwest facing windows: U = 0.18 SHGC = 0.22.
Space Conditioning	SEER = 10, SHR= 0.75, cooling capacity = 43.6 kBtu/hr HSPF = 6.8, heating capacity = 66.4 kBtu/hr	SEER = 13, SHR= 0.75, cooling capacity = 48 kBtu/hr HSPF = 7.7, heating capacity = 48.3 kBtu/hr	Single air-source HP, cooling capacity = 25 kBtu/hr SEER: 18.4, heating capacity: 22.6 kBtu/hr, HSPF: 9.1
Infiltration	ACH(50) = 9.75, SLA = 0.00057 in^2/in^2	ACH(50) = 8.5, SLA = 0.00050 in^2/in^2	ACH(50) = 2.3, SLA = 0.00017 in^2/in^2

	BA Benchmark	Builder Standard (BSH)	WC4
Mechanical ventilation	6 CFM	30 CFM	30 CFM
Duct location	Supply: crawlspace Return: crawlspace R-5 insulation, supply area = 353.7 ft^2 , return area = 326.5 ft^2, duct air leakage (to the outside)= 12%	Supply: crawlspace Return: crawlspace R-5 insulation, supply area = 551 ft^2 , return area = 102 ft^2, duct air leakage (to the outside) = 12%	Supply: interior Return: interior R-5 insulation, supply area = 551 ft^2 , return area = 102 ft^2, duct air leakage (to the outside)= 8%
Air handler location	Crawlspace	Crawlspace	Interior
Water heater	Electric 50 gal capacity, EF = 0.86, usage = 63.5 gal/day, set temp = 120ºF	Electric 50 gal capacity, EF = 0.86, usage = 60 gal/day, set temp = 120ºF	Electric 50 gal capacity, EF = 1, usage = 60 gal/day, set temp = 120ºF, Add-on Heat pump COP = 2.35
Lighting	14% fluorescent, 86% incandescent	10.1% fluorescent, 89.9% incandescent	100% fluorescent

In order to evaluate the incremental energy savings of each energy efficient measure, a stepwise progression from the BSH to WC4 was modeled. As each energy efficient measure was added to the BSH model, an EnergyGauge simulation of household energy consumption was run. The order in which the technologies were added to the BSH model was based on tradeoffs between the ease of retrofitting and cost-effectiveness. For example, changing the household lighting to CFL's was given a higher priority than increasing wall insulation. The step-by-step addition of technologies and energy saving measures is shown in Figure 7 for the total, heating, cooling, and hot water heating loads. The energy savings from these measures are shown in Table 11. The annual energy costs savings of each measure was determined by multiplying the decrement in energy consumption by the cost of electricity. With all of the features and equipment used, WC4 is modeled to save a total of $1,049 per year, based on local utility rates of $0.093/kWh).

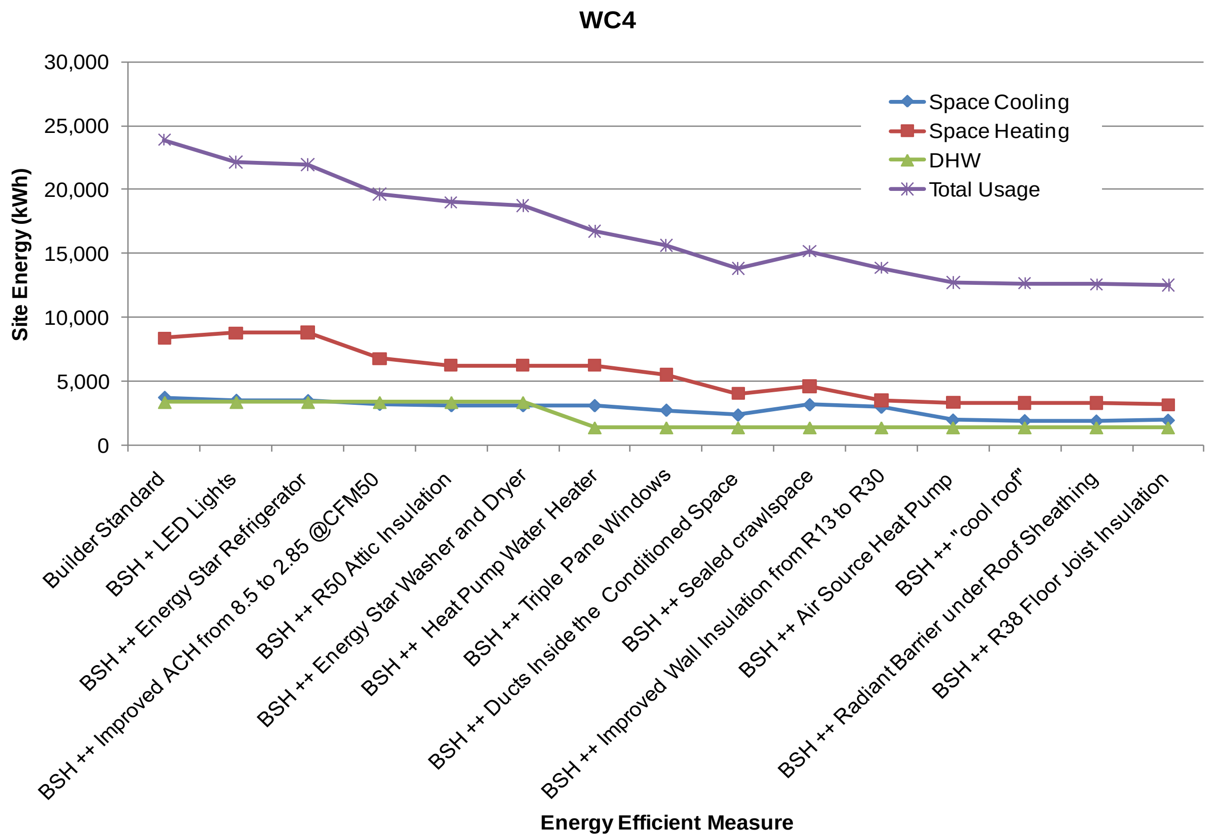

Figure 7. Simulated WC4 energy consumption after the addition of individual technologies

Table 13. WC4 energy consumption and savings after the addition of individual technologies

	Est. site energy (kWh)	Est. source energy (MBtu)	Energy Costs[4] ($/yr)	Energy Costs[5] ($/yr)	Cost Savings[3]	Measure Value[3] ($/yr)	Package Savings[3] ($/yr)
Increment							
BA Benchmark	28,242	324	$3,321	$2,627			
Builder Standard (BSH)	24,041	276	$2,827	$2,236	15%		
BS + LED Lights	22,292	256	$2,622	$2,073	21%	$163	$163
BS ++ ENERGY STAR Refrigerator	22,111	254	$2,600	$2,056	22%	$17	$179
BS ++ Improved ACH from 8.5 to 2.85 @CFM50	19,792	227	$2,328	$1,841	30%	$216	$395
BS ++ R50 Attic Insulation	19,151	220	$2,252	$1,781	32%	$60	$455

[4] Energy costs determined using an average national utility rate of $0.118/kWh
[5] Energy costs determined using an average local utility rate of $0.093/kWh

	Est. site energy (kWh)	Est. source energy (MBtu)	Energy Costs[4] ($/yr)	Energy Costs[5] ($/yr)	Cost Savings[3]	Measure Value[3] ($/yr)	Package Savings[3] ($/yr)
BS ++ ENERGY STAR Washer and Dryer	18,891	217	$2,222	$1,757	33%	$24	$479
BS ++ Heat Pump Water Heater	16,885	194	$1,986	$1,570	40%	$187	$666
BS ++ Triple Pane Windows	15,881	182	$1,868	$1,477	44%	$93	$759
BS ++ Ducts Inside the Conditioned Space	14,018	161	$1,649	$1,304	50%	$173	$932
BS ++ Sealed crawlspace	15,375	177	$1,808	$1,430	46%	($126)	$806
BS ++ Improved Wall Insulation from R13 to R30	13,871	159	$1,631	$1,290	51%	$140	$946
BS ++ Air Source Heat Pump	12,889	148	$1,516	$1,199	54%	$91	$1,037
BS ++ "cool roof"	12,813	147	$1,507	$1,192	55%	$7	$1,044
BS ++ Radiant Barrier under Roof Sheathing	12,760	147	$1,501	$1,187	55%	$5	$1,049

First Cost

A detailed breakdown of the cost to construct WC4 is shown in Table 14. The total costs include construction costs incurred by Schaad Companies and the market value of all donated items by the ZEBRA partners. The construction costs incurred by Schaad were determined from invoices and spreadsheets that Schaad Companies provided. The market value of donated items was estimated by the relevant ZEBRA partners. Certain elements of the General Requirements cost section in Table 14 were estimated by Schaad to reflect more accurately the standard costs of building similar homes rather than the actual costs.

Table 14. Detailed construction estimates for WC4

Category	WC4 EIFS House ($)
Envelope	
Framing	34,730
Roof	23,859
Cladding	16,976
Foundation	32,591
Site Development	9,260
Windows	10,202
Paint (exterior)	5,100
Doors (exterior)	2,627
Garage	5,054
Exterior Décor	1,811
HVAC	
Duct	9,240
Insulation	44,063
Heat Pump/Zone Control	12,654
Water	
Water Heater	1,500
Plumbing	15,165
Interior Finish	
Appliances	7,590
Floor Covering	20,214
Millwork	17,209
Paint	10,494
Drywall	12,423
Other Interior Décor	24,006
Electrical	
Electrical Systems	11,435
Security	1,000
Lighting	12,000
Utility Services	2,564
Landscaping	
Ornamental	1,600
Yard	11,005
General Requirements	
Labor~	6,750
Supervision/Administration~	27,000
Architectural*	20,094

Category	WC4 EIFS House ($)
Engineering°	3,052
Permits/Insurance	5,661
Utilities/Taxes/Dues	1,988
Other General	1,061
Total	**422,000**

Table 15 gives a comparative look at the actual versus the standard cost for the costs items in the General Requirements section that Schaad estimated. Finally, Table 16 shows a summary of the total and the per square footage cost of WC4.

The cost items that Schaad Companies estimated would be the standard costs for similar homes are described below.

- ~: Labor and Supervision/Administration are estimated by Schaad Companies. Actual costs were overstated and not equally allocated between the four houses. Schaad Companies estimated the standard amount that would be spent on Labor and Supervision/Administration for the completion of similar houses in business as usual conditions.
- *****: Architectural costs are estimated by Schaad Companies. Architectural costs are estimated to be 5% of total costs.
- **°:** Similar to Labor and Supervision, the standard Engineering costs were estimated by Schaad Companies. Actual costs were understated mostly due to the strong involvement from ORNL research and development engineers.

Table 15. Actual and standard costs for WC4

	WC4 EIFS House	
Costs Items	Actual Costs ($)	Standard Costs ($)
Labor~	5,455	6,750
Supervision/ Administration~	39,181	27,000
Architectural*	158	20,094
Engineering°	2,894	3,052
Total Costs	**412,800**	**422,000**

Table 15. Cost summary for WC4

	WC4 EIFS House
Total Costs ($)	**$422,000**
Total Square Footage	2,721
Total Cost Per Square Foot ($)	**$155**

Similar to WC3, with at total costs per ft^2 of $155, the first cost of WC4 is considerably more than would be expected based on recent low-energy homes (Christian et al., 2010). However, a systems performance evaluation approach was taken in WC4, in contrast to other low energy homes which utilize a whole-house methodology to selecting and installing energy savings measures. Many of the technologies and systems employed in WC4 are "first wave" technologies that have yet to progress down the cost curve from higher initial prices to lower affordable prices through large scale deployment. An example can be seen in the use of LED lighting throughout WC4.

Neutral-cash-flow analysis

Table 17 shows the neutral-cash-flow analysis for WC4 using the BA Benchmark Definition (Hendron and Engebrecht, 2010). The analysis was conducted by evaluating the incremental investment costs and energy savings of each energy efficient measure against the BSH. The amortized annual costs are based on a 30 year loan with an interest rate of 7%. All energy costs and savings were estimated based on local utility rates of $0.093/kWh. The net cost of each measure shown in the table was determined by subtracting the amortized investment costs from the energy savings.

Table 16. Neutral cash flow analysis for WC4

	Site Energy (kWh/yr)	Site Energy Costs ($/yr)	Energy Savings (kWh/yr)	Energy Savings ($/yr)	Cumulative Energy Savings ($/yr)	Incremental Investment Costs ($)	Amortized Investment Costs ($/yr)	Net Cost ($/yr)	Cash-flow neutral
Increment									
BA Benchmark	28,242	$2,627							
Builder Standard (BSH)	24,041	$2,236	4,201						
BSH + LED Lights	22,292	$2,073	1,749	$163	$163	$8,800	$703	$540	No
BSH ++ ENERGY STAR Refrigerator	22,111	$2,056	181	$17	$179	$1,127	$90	$73	No
BSH ++ Improved ACH from 8.5 to 2.85 @CFM50	19,792	$1,841	2,319	$216	$395	$2,588	$207	$(9)	Yes
BSH ++ R50 Attic Insulation	19,151	$1,781	641	$60	$455	$790	$63	$3	No

	Site Energy (kWh/yr)	Site Energy Costs ($/yr)	Energy Savings (kWh/yr)	Energy Savings ($/yr)	Cumulative Energy Savings ($/yr)	Incremental Investment Costs ($)	Amortized Investment Costs ($/yr)	Net Cost ($/yr)	Cash-flow neutral
BSH ++ ENERGY STAR Washer and Dryer	18,891	$1,757	260	$24	$479	$1,598	$128	$103	No
BSH ++ Heat Pump Water Heater	16,885	$1,570	2,006	$187	$666	$1,282	$102	$(84)	Yes
BSH ++ Triple Pane Windows	15,881	$1,477	1,004	$93	$759	$3,929	$314	$220	No
BSH ++ Ducts Inside the Conditioned Space	14,018	$1,304	1,863	$173	$932	$1,955	$156	$(17)	Yes
BSH ++ Sealed crawlspace	15,375	$1,430	-1,357	($126)	$806	$5,393	$431	$557	No
BSH ++ Improved Wall Insulation from R13 to R30	13,871	$1,290	1,504	$140	$946	$44,897	$3,584	$3,445	No
BSH ++ Air Source Heat Pump	12,889	$1,199	982	$91	$1,037	$4,039	$322	$231	No
BSH ++ "cool roof"	12,813	$1,192	76	$7	$1,044	$1,303	$104	$97	No
BSH ++ Radiant Barrier under Roof Sheathing	12,760	$1,187	53	$5	$1,049	$2,191	$175	$170	No
Total Energy Efficiency Investment					$1,049	$79,892	$6,378	$5,329	No
Rebates/Incentives									
Federal energy efficient builder house						$2,000			
TVA high efficiency water heater						$50			
Total Incremental Cost to Buyer Including Incentives					$1,049	$77,842	$6,215	$5,166	No

The simulated whole-house annual energy cost for BSH was $2,236. The total incremental investment for all energy efficient investments in WC4 is $79,892, with an annualized cost of $6,378. Neutral cash flow is not achieved in WC4, because when the annual energy costs savings are considered, the annual cost of the efficiency measures is $5,329. Even when incentives are added, the total cost to the buyer would be $5,166.

Table 17 shows a list of the energy efficient technologies in WC4 prioritized from the least annualized cost to the highest. No incentives for specific technologies are included in the table. The GeoSpring® hybrid heat pump water heater, the placement of the ducts inside the conditioned space, and air sealing to improve the ACH (50) to 2.85 are the only measures that are cost neutral. The costs of improving ACH were estimated using BEOpt software. BEOpt was also used to estimate the cost of placing the ducts inside the conditioned space. Not only are these three measures cost neutral, they are the three largest energy saving measures included in WC4. Out of a total energy savings of 11,281 kWh, these measures comprised 55% of the savings.

In contrast to WC3, increasing the attic insulation to R-50 is almost cost neutral. Conventional cellulose insulation was used to achieve R-50 insulation in this case. With simulated annual energy cost savings of $60 per year, the simple payback of the insulation is slightly more than 13 years.

The ENERGY STAR refrigerator, clothes washer, and dryer have similar annual costs. These donated models are all premium models and thus include the incremental cost of amenities not included in the builder standard refrigerator. If an "apples to apples" comparison of refrigerators with similar amenities was done, it is expected that the refrigerator would likely be cost neutral, while the washer and dryer would be closer to achieving cost neutrality.

Table 17. WC4 Prioritized list of energy efficiency technologies by annualized cost

	Incremental cost ($)	Annual cost	Cash-flow neutral
BSH ++ Heat Pump Water Heater	$1,282	($84)	Yes
BSH ++ Ducts Inside the Conditioned Space	$1,955	($17)	Yes
BSH ++ Improved ACH from 8.5 to 2.85 @CFM50	$2,588	($9)	Yes
BSH ++ R50 Attic Insulation	$790	$3	No
BSH ++ ENERGY STAR Refrigerator	$1,127	$73	No
BSH ++ "cool roof"	$1,303	$97	No
BSH ++ ENERGY STAR Washer and Dryer	$1,598	$103	No
BSH ++ Radiant Barrier under Roof Sheathing	$2,191	$170	No
BSH ++ Triple Pane Windows	$3,929	$220	No
BSH ++ Air Source Heat Pump	$4,039	$231	No

	Incremental cost ($)	Annual cost	Cash-flow neutral
BSH + LED Lights	$8,800	$540	No
BSH ++ Sealed crawlspace	$5,393	$557	No
BSH ++ Improved Wall Insulation from R13 to R30	$44,897	$3,445	No

The cool roof application applied in WC4 is less costly than the metal shakes used in WC3. However, because the cooling loads are already significantly reduced by triple pane windows, R-50 insulation, and the placement of the ducts inside the conditioned space, the performance of the cool roof application is mitigated.

The radiant barrier installed in WC4 is an assembly that provides a radiant barrier facing into the attic plenum, two low-e surfaces facing into the inclined 1-in high air space, and passive ventilation from soffit to ridge. A slot is cut into the roof deck near the eave just above the soffit vent to provide make up air from the soffit vent and attic. As thermally induced airflows move up the inclined air space, cool make up air is pulled from the soffit and attic plenums to enhance thermal performance of the deck. The incremental cost of this system is $2,191. EnergyGuage does not provide an input option for this type of radiant barrier assembly. Therefore the energy performance is very likely underestimated. After data has been collected on this assembly in WC4, a better understanding and verification of the energy saving contribution of this assembly will be known and manipulated in the EnergyGauge software. However, it is known that the impact of the radiant barrier will be mitigated by the ventilated attic with R-50 insulation over the ceiling joists, in addition to the location of the HVAC equipment in the conditioned space.

The addition of triple pane windows reduces the cooling load by approximately 19% and the heating loads by 7%. However, Oak Ridge, Tennessee, is a heating dominated climate with cooling loads comprising on 44% of the required heating loads in standard residential construction (BSH). Therefore, the total annual energy savings are only $93, which are not enough to offset the incremental $3,929 over clear, double pane windows.

According to the EnergyGauge simulation, sealing the crawlspace and providing conditioned air increases the cooling and heating loads by 16% and 23% respectively. When the model was simulated, no insulation was included in the floor above the crawlspace, only R-10 on the crawlspace walls. The energy penalty attributed to sealing the crawlspace could be attributed to factors such as reduced ground coupling benefits in the summer, additional volumetric space to heat and cool, as well as software/model inaccuracies. As tests are run at WC3 and WC4, more information regarding the energy penalty/benefit of sealing crawlspaces can be determined. However, in humid climates such as Oak Ridge, Tennessee, sealed crawlspaces are primarily utilized to address moisture management issues.

4. Summary

This report describes the technology, energy, and cost savings analysis of two 2721 ft^2 homes in Oak Ridge, Tennessee, a mixed humid climate. In comparison to the Building America Benchmark, WC3 is simulated to achieve energy savings of $1,200 per year, while WC4 is simulated to achieve energy savings of $1,049. The HERS ratings of WC3 and WC4 are 44 and 55, respectively. The cost to construct WC3, including all market-valued donations and labor was $445,800, or 163/$ft^2$, while the cost for WC4 was $422,000, or $155/$ft^2$.

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