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Insulated Concrete Form Walls Integrated With Mechanical Systems in a Cold Climate Test House

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Definitions

ACCA	Air Conditioning Contractors of America
ACH	Air Changes per Hour
ASHP	Air Source Heat Pump
BEopt™	Building Energy Optimization Program
CFL	Compact Fluorescent Lamp
CFM	Cubic Feet per Minute
CZ	Climate Zone
DOE	U.S. Department of Energy
DSHP	Ductless Split Heat Pump
EF	Energy Factor
EL	Equivalent Length
EPS	Expanded Polystyrene
ERV	Energy Recovery Ventilator
FPM	Feet per minute
FR	Friction Rate
GSHP	Ground Source Heat Pump
HPWH	Heat Pump Water Heater
HSPF	Heating Season Performance Factor
HVAC	Heating Ventilation and Air Conditioning
ICF	Insulated Concrete Form
IECC	International Energy Conservation Code
iwc	Inches Water Column
LCCTC	Lancaster County Career and Technology Center
LED	Light-Emitting Diode
NCTH	New Construction Test House
Pa	Pascal
PEX	Cross-Linked Polyethylene
SDHW	Solar Domestic Hot Water
SEER	Seasonal Energy Efficiency Ratio
SEF	Solar Energy Factor
SF	Solar Fraction
SRCC	Solar Rating and Certification Corporation
TEL	Total Equivalent Length

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Executive Summary

Transitioning from standard light frame to a thermal mass wall system in a high performance home will require a higher level of design integration with the mechanical systems. The much higher mass in the insulated concrete form (ICF) wall influences heat transfer through the wall and affects how the heating and cooling system responds to changing outdoor conditions. This is even more important for efficient, low-load homes with efficient heat pump systems in colder climates where the heating and cooling peak loads are significantly different.

With the support of the U.S. Department of Energy Building America Program, Home Innovation Research Labs partnered with Lancaster County Career and Technology Center (LCCTC) to build a new construction test house (NCTH) in the cold climate of south central Pennsylvania (International Energy Conservation Code climate zone 5A [CZ 5A]) using ICF high mass wall construction. This research compares ICF construction to the increasingly complex frame walls and foundation walls of high performance houses in cold climates and evaluates the integration of the mechanical systems for energy performance and air distribution.

The NCTH cost-effectively achieved 40% whole-house energy savings, U.S. Department of Energy Challenge Home certification, and National Green Building Standard gold level certification. All of the project goals support the educational efforts at LCCTC, a vocational high school where students gain practical experience building real houses that incorporate state-of-the-art energy efficiency and green technologies.

This report encompasses a range of design features and component performance estimates in an effort to select practical, cost-effective solutions for high performance homes in a cold climate. Of primary interest is the influence of the ICF walls on developing an effective air sealing strategy and selecting heating and cooling equipment type and capacity. The domestic water heating system is analyzed for costs and savings to investigate options for higher efficiency electric water heating. A method to ensure mechanical ventilation airflows is examined. The final solution package includes high-R mass walls, very low infiltration rates, multistage heat pump heating, solar thermal domestic hot water system, and energy recovery ventilation.

This solution package can be used for homes to meet or exceed 2012 International Energy Conservation Code requirements throughout all CZs. The high mass wall construction system can enhance green benefits such as durability and reduced construction waste.

Key findings from the design analysis show that:

- The ICF walls exceed building code wall performance requirements for all CZs and the R-value is similar to 2 × 6 light-frame wall systems with 1 in. of exterior insulation; the ICF walls cost more but were practical to build and deemed cost effective as a component of the overall energy solution package.
- Simulated hourly energy use of an ICF wall compared with a light-frame wall system of the same R-value during a very cold period in the heating season shows an average of 9% less annual energy use and as much as a 30% energy use reduction for a given hour period.

- Annual energy costs for the high efficiency air source heat pump nearly equal that of high efficiency natural gas heating and are 30% lower than those for high efficiency propane fuel heating.
- Carbon factor, a metric often used to compare various fuels, for the high efficiency air source heat pump is nearly the same as for a high efficiency propane fuel; both are approximately 7% higher than that for natural gas, which is not available at the site. A 100-year value is used per ASHRAE Standard 105-2013.
- Based on standard heating, ventilation, and air conditioning sizing methodologies and in this climate, there is no significant difference in peak sizing for high mass and light frame wall systems of similar R-value, but two-stage heating and cooling equipment was selected to effectively respond to the expected thermal mass effects that increase the low-stage operation.
- Domestic water heating energy, based on simulation estimates, shows that the difference in energy usage between a solar water heating system and a heat pump water heater is minimal, but there is about 5% additional household heating energy use and about a 1% household cooling energy savings with the heat pump water heater.
- The design analysis for the NCTH also evaluates the implementation and marketability of the solution package elements and uses construction cost estimates to find approximate return on investment. With current utility rates and an assumed 5% mortgage interest rate, the estimated cost premiums and utility savings are nearly equal to the increased mortgage costs before any interest savings or technology incentives are applied.

This report will support design efforts of builders and architects in evaluating options for wall systems, heating and cooling technology, and water heating systems applicable to the cold climate (CZ 5) and the mixed climate (CZ 4).

1 Introduction and Background

1.1 Problem Statement

Builders face increasingly complex decisions to meet energy efficiency demands. Recent energy codes and energy programs require higher levels of thermal insulation and air sealing. Tight and well-insulated buildings make effective mechanical systems more critical, but selecting more energy-efficient and complicated mechanical systems may be difficult to justify. Builders must evaluate and select systems that together meet energy savings goals and that are also durable and affordable.

Insulated concrete form (ICF) wall construction is energy efficient and durable, but is often perceived as not cost effective compared to standard wall construction. ICF construction, however, should be evaluated for energy performance and affordability with respect to the increasingly complex frame walls and foundation walls common in today's high performance houses.

Lower space conditioning loads require careful heating and cooling equipment selection and air distribution designs to ensure efficient operation and occupant comfort. Effective mechanical ventilation is important to help control humidity, air quality, and comfort, but tested airflows frequently do not meet design expectations. The relative energy use of domestic hot water is increased and presents an opportunity for additional energy savings.

This research focuses on the interrelated performance of the ICF walls, air sealing strategy, and mechanical systems for a test house in a cold climate. This report compares ICF walls with the builder's standard foundation and light frame walls, evaluates alternative heating fuels and equipment, examines a design method to ensure that mechanical ventilation system airflows meet design expectations, and analyzes alternative domestic water heating systems. Builders, particularly small builders, can benefit from this research when developing a final energy solution package.

1.2 Project Overview

With the support of the U.S. Department of Energy (DOE) Building America Program, Home Innovation Research Labs (Home Innovation) partnered with Lancaster County Career and Technology Center (LCCTC) to build a third new construction test house (NCTH) (Figure 1) in Apprentice Green (LCCTC 2013), a community next to the school in Mount Joy, Lancaster County, Pennsylvania (International Energy Conservation Code [IECC] climate zone [CZ] 5A). LCCTC is a vocational high school with a Construction Technology program that prepares students for careers in the construction trades. The students gain practical experience building real houses that incorporate state-of-the-art energy efficiency and green technologies. Two homes are complete and occupied (Figure 2 and Figure 3). For the NCTH, construction began in September 2011 and was completed in June 2013 (Figure 4 and Figure 5; see floor plan in Appendix A).

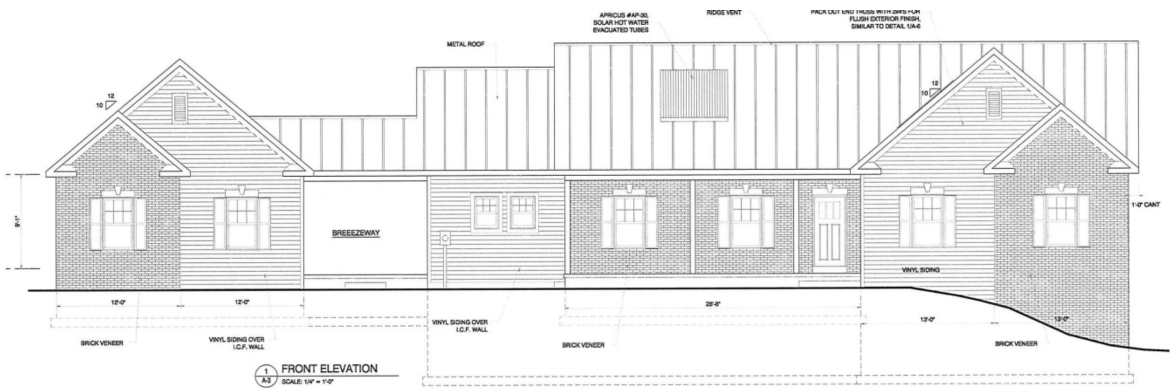

Figure 1. NCTH: LCCTC Green Home 3

Figure 2. LCCTC Green Home 1

Figure 3. LCCTC Green Home 2

The single-family 2,384-ft^2 (above grade) single-story house features ICF construction for the foundation and above-grade walls, a conditioned basement, vented attic, high levels of insulation and air sealing, and a detached garage (2-in. × 6-in., 24-in. on-center frame construction). Energy-efficient systems include a high efficiency air source heat pump (ASHP), ducts in conditioned space, energy recovery ventilator (ERV), thermal preheat solar domestic hot water (SDHW) system, cross-linked polyethylene (PEX) manifold plumbing distribution, and efficient lighting and appliances. Water efficiency is enhanced with a 3500-gallon rainwater collection and distribution system.

The overall program goals for the NCTH research project:

- Develop a design to achieve 40% whole-house energy savings over the Building America B10 benchmark (the B10 benchmark is equivalent to meeting the 2009 IECC).
- DOE Challenge Home certification (DOE 2013).
- Document and evaluate costs for efficiency measures.
- National Green Building Standard gold level green certification (NGBS 2009).

Additional goals for the thermal enclosure and mechanical systems were established:

- Compare the construction process of ICF walls with builder standard walls.
- Compare the energy performance of ICF walls with builder standard walls.
- Develop an air sealing strategy to achieve a house tightness of 2 ACH50.
- Analyze the design and selection of heating and cooling system options most appropriate for ICF construction and this climate.
- Integrate the ERV with the heating and cooling air distribution system.
- Develop and evaluate a method to ensure measured mechanical ventilation system airflows meet design expectations.

Figure 4. NCTH: LCCTC Green Home 3

Figure 5. Apprentice Green Community Mount Joy, Pennsylvania

1.3 Relevance to Building America

The goals for this project align well with the Building America goals to develop market ready solutions that improve energy efficiency (reduce home energy use by 30%–50% compared to 2009 energy codes), durability, quality, affordability, and comfort (DOE 2012).

ICF construction provides both structural and thermal components of the wall (Building America 2013). Previous Building America research indicates that ICF walls above grade provide an effective high performance air barrier, reliable thermal performance, very good durability, and simplified interior and exterior finish attachments due to the embedded fastening strips (Smegal and Straub 2009; Straub 2010). ICF foundation walls compare favorably to high performance alternatives in terms of thermal control, durability, and constructability (BSC 2009; Smegal and Straub 2010). Previous Building America research identifies recommended "high-R" wall performance targets in CZ-5: R-15 for foundation walls (R-20 in CZ-6, R-25 in CZ-7), and R30 for above-grade walls (R-25 in CZ-4, R-35 in CZ-6, and R-40 in CZ-7) (Straub 2010). Based on these recommendations and common ICF specifications (R-22 assembly for this project), ICF construction would be considered "high-R" for foundation walls through CZ-6, and for above-grade walls through CZ-3. Generally, ICF construction costs are noted as relatively high or high compared to standard construction, but did not include a cost analysis (Chasar et al. 2002; Desjarlais et al. 2002).

This project compares ICF walls to the builder standard high performance walls. The combined energy performance of foundation and above-grade walls is compared to combined "high-R" recommendations to determine the overall energy comparison. The conventional vented attic and heating, ventilation, and air conditioning (HVAC) system allow for an isolated evaluation of ICF walls. This comparison will provide builders a more current comparison of ICF performance and affordability with respect to current wall systems in cold climates.

The measured airflows of mechanical ventilation equipment are typically lower than design values due to an overly restrictive duct system. Anecdotal evidence suggests this issue persists simply due to ignoring best practices. Manufacturer instructions, industry standards, and publications recognize the importance of sufficient duct layouts and provide suggested methods (ASHRAE 2010; Rudd 2009). But prescriptive duct sizing tables often use different design parameters than manufacturer's performance data. The method presented in this report should be a relatively simple and effective tool for HVAC trade partners in all climates.

The approach to evaluate heating fuel and hot water systems should be useful for builders and mechanical trade partners for all climates and particularly for houses without natural gas.

2 Technical Approach

2.1 Research Questions

Based on research gaps and project goals, the research questions for this project are:

1. How does the ICF wall system compare with the builder's standard high performance foundation and framed wall systems in terms of estimated energy use?
2. How is the air sealing strategy different for ICF construction?
3. What are the heating and cooling design, selection, and performance issues and solutions that emerge based on the high performance ICF envelope design in CZ 5?
4. Are the proposed methods to ensure effective mechanical ventilation successful?
5. How do domestic hot water system design options compare in terms of energy savings and cost?
6. Are the elements of the energy efficiency package cost effective and market ready?

2.2 Design Phase Analysis

During the design phase, reviews were conducted between LCCTC, vendors, and Home Innovation. Home Innovation provided recommendations to improve air sealing, moisture management, and electrical installation specific to ICF construction. Home Innovation also provided heating and cooling load calculations (Air Conditioning Contractors of America [ACCA] Manual J), equipment selection, and duct design support. The major systems were evaluated for energy performance, durability, occupant comfort, and cost. LCCTC was committed to building the house with high performance features to exceed current energy code requirements (IECC 2009) and adhere to its green building philosophy. Notably, the educational component for students was consistently considered during this step. An iterative design process was used to evaluate the benefits and tradeoffs of alternative systems. For example, to select the best type of heating system, Home Innovation provided a detailed analysis of heating and cooling options for this low-load house.

As a result of the design reviews, the plans were updated with new construction details and specifications. Goals and expectations were mutually agreed upon, and site reviews, inspections, and tests were scheduled for quality assurance. The analysis and selection of the major systems are described below.

2.3 Wall Systems

LCCTC had previous success building ICF foundation walls and wanted to explore using ICF walls above grade to improve energy efficiency and sound attenuation. Sound attenuation was important because the NCTH is close to a gun club firing range.

ICF construction provides both structural and thermal components of the wall. These walls are well insulated, inherently tight, and durable. The foam provides consistent thermal performance and minimizes thermal bridging. The concrete makes the walls air tight. Additionally, ICF walls are highly resistant to fire and wind. The thermal mass properties attenuate sound well and help create a uniform and stable temperature inside the house.

ICF walls are usually built using rigid, insulating foam block forms that are stacked on site and remain in place after the concrete is poured. The concrete is reinforced with rebar that is installed as the blocks are stacked. The forms must be braced during concrete placement to prevent bulging and breakage. For this project, the forms consist of two 2 ½-in. thick expanded polystyrene (EPS) foam panels separated 6 in. using polypropylene ties. The ties are imbedded in the foam 6 in. on center and provide attachment points for siding and drywall. The foam blocks are 48 in. wide, 16 in. high, and 11 in. deep.

The decision to install ICF walls must take into account practical construction issues that are unique to ICF construction, and represent a change from most builders' standard practices:

- ICF walls are generally poured one level at a time, and must be braced during concrete placement to prevent bulging and breakage.
- Sleeves for penetrations (utilities, ventilation ducts) should be installed before concrete.
- Electrical wiring in exterior walls requires either conduit within the forms before concrete, or wiring chases cut into the foam after concrete.
- Waterproofing below grade is required.
- ICF walls are vapor retarders (the vapor permeance of EPS is 0.8–1.5 perms at 2 ½-in. thickness) and therefore the concrete requires an extended period of time to dry, so the interior and exterior wall coverings should allow drying to the interior and exterior (Smegal and Straub 2009).
- Pressure-treated wooden window and door bucks, if used, are installed before concrete.
- Deeper window and door jambs.
- Unfinished basements require a thermal barrier over the foam (e.g., drywall) for code prescribed fire resistance.
- Floor framing in multistory houses must be attached to the ICF assembly.
- The thermal mass properties may impact the sizing and operation of the heating and cooling system.

For this project the wall system had to meet, or preferably exceed, the prescriptive minimum insulation requirements of the 2012 IECC for CZ 5:

- Wood frame wall: R 20 cavity, or R-13 cavity + R-5 continuous (same as 2009 IECC)
- Mass wall: R-13, or R-17 if more than half of the insulation is to the interior of the mass (same as 2009 IECC)
- Basement wall: R-15 continuous or R-19 cavity. (R-10 or R13 in 2009 IECC).

The ICF foundation walls[1] are specified by the manufacturer at an R-22 based on 5 in. of EPS foam equally divided outside of a 6-in. concrete core (Figure 6).

Figure 6. ICF wall

A simple parallel path R-value calculation using the manufacturer's stated EPS foam R-value of 4.17/in. of foam thickness but without finishes or film factors calculates to R-21.5 for a clear wall section. This R-value for the foundation walls would satisfy 2012 IECC code requirements through all U.S. CZs and through CZ 6 based on recommendations for foundation walls (Straube 2011). The R-value of the ICF above-grade wall will satisfy the 2012 IECC prescriptive requirements in all CZs based on mass wall minimum requirements. (High mass walls in the IECC have a lower R-value requirement than do low-mass walls.) When comparing the ICF wall system with a frame wall system, a parallel path calculation shows that a 2×6 wall with R-21 cavity insulation, a framing factor of 20% and exterior insulation of R-5 has the same wall U-value as the ICF system, aside from any thermal mass benefit.

Given the ICF's capability to provide sound attenuation[2] and above-code thermal performance, ICFs were deemed valuable for this NCTH.

2.4 Air Sealing

There are few pathways through ICF walls for air leakage. This increases the relative importance of air sealing other critical areas. For this project, the ICF wall runs from the basement to the roofline; floor framing is connected to the concrete and within the thermal and air barrier of the building, eliminating this common leakage area found in standard frame construction. The critical areas for air sealing were window and door bucks, roof truss bearing plates, a framed attic knee-wall and exterior gable wall for the living room cathedral ceiling, the framed fireplace bump-out, a tray-ceiling in the dining room, and ceiling penetrations.

[1] The ICF manufacturer is Reward Wall Systems, the specific product is the 11-in. iForm.
[2] See for example www.structuremag.org/Archives/2007-8/C-BuildingBlocks-Doerr-August07.pdf for typical discussions of the sound attenuation benefits of ICF technology.

To achieve the house tightness goal of 2 ACH50, the team wanted to use readily available materials that can be installed by any trade contractor given a clear and concise list of air sealing details. Air sealing technologies were selected to achieve consistent and reliable results and simplify installation. A table was developed during the design phase to identify critical areas and specify air sealing products and methods (Table 1). This table was used in the field for quality assurance. Critical areas were sealed using one-part spray foam. Rigid foam boards were used as air barriers at knee walls.

Table 1. Air Sealing Critical Areas

Critical Area	Locations To Be Air Sealed (Implementation Details)	Sealant
ICF Walls[a]	Truss bearing plates (before drywall)	Spray foam[b]
	Rough openings of windows and doors	Low-expansion spray foam[c]
	Penetrations	Spray foam[b]
	Electrical rough-in cuts at forms, as needed	Spray foam[b]
Ceiling Plane	Top of ICF walls (after drywall, from attic)	Spray foam[b]
	Top plates of partition walls (after drywall, from attic)	Spray foam[b]
	Penetrations (electrical boxes, exhaust fans, attic access)	Spray foam[b]
	Attic access panel (gasket, insulate R-10 minimum)	Gasket
	Dining room tray ceiling (install drywall air barrier at the ceiling and sides of tray before framing the tray)	
	Top of the HVAC central duct chase (framed cavity)	Spray foam[b]
Framed Walls, Exterior	Fireplace bump-out (seal stud cavities at sheathing, top and bottom plates, and floor before insulation. Install and seal drywall air barriers behind and above fireplace after insulation)	Closed-cell spray polyurethane foam[d]
	Living room cathedral ceiling gable (seal stud cavities at sheathing and top and bottom plates before insulation)	Spray foam[b]
Knee-Wall Air Barrier	Living room cathedral ceiling gable (install rigid foam air barrier, then seal stud cavities before insulation and drywall	Spray foam1[b]
Framed Cavity Air Barriers	For this project, framed cavity air barriers have been addressed under Ceiling Plane above	

[a] All products in contact with the ICF must be compatible with EPS (i.e., no solvents)
[b] HILTI single-component polyurethane foam sealant, closed-cell, minimal expanding, fire-block, installed using application gun (or equivalent, such as Knauf EcoSeal spray applied elastomeric sealant, or such as DOW ENERFOAM Professional Foam Sealant)
[c] HILTI sealant for window and door applications (or equivalent)
[d] Spray polyurethane foam: two-component polyurethane foam insulation and sealant, closed-cell.

Although the air sealing process is understood by many contractors whose work scope includes air sealing details, builder associates and ultimately the customer must also understand air sealing as an important part of the house design. The benefits of reducing air infiltration to the builder and customer include:

- Provides excellent heating and cooling energy savings.
- Reduces potential for moisture migration.
- Optimizes insulation effectiveness.
- Helps improve comfort and indoor environmental quality.
- Reduces risk of ice dams.
- Conforms to increasing code requirements.

When discussing air sealing with builders, it is important that they understand air barriers and their function. Air barriers:

- Prevent movement of air and moisture through the building thermal envelope.
- Must be continuous to be effective.
- Must be sealed to resist airflow and air pressure.
- Must be air impermeable ($\leq$ 0.004 cfm/ft^2 (0.02 L/s/SM) @ 75 Pa).

2.5 HVAC Systems

2.5.1 Duct Design

Installing the HVAC system entirely in conditioned space is a key early-on decision that must be made before performing heating and cooling load calculations. Installing systems in conditioned space provides significant heating and cooling energy savings by minimizing duct conduction and leakage losses. House leakage is reduced without register and grille penetrations through the building enclosure, and without the pressure drivers of leaky exterior ducts. Additionally, ducts in conditioned space may improve air quality (minimizes pollutants from attics, crawl spaces, and garages) and may contribute to smaller capacity systems. A simplified, compact duct layout can improve performance (reduced duct pressure losses) and further reduce energy losses and installed costs.

For the NCTH, the entire heating and cooling system (air handler and ducts) was designed to be installed in conditioned space. The air handler was installed in a central location in the basement. The duct board (R-4) supply trunk was installed in the basement next to the steel beam (Figure 7), below and perpendicular to the floor joists. Metal (not insulated) supply branch ducts installed between the open-webbed floor joists serve perimeter floor registers upstairs and ceiling registers in the basement. Manual airflow balancing dampers were installed in each supply branch at the trunk. The simplified central return serving the upstairs was installed inside a framed duct chase that was suggested during the design phase and included in the revised plans (Figure 8). The duct system was designed in accordance with ACCA Manual D, after heating and cooling loads were calculated and equipment selected, including Table A1-1: Air Velocity for Noise Control (ACCA 2009). Bedroom transfer grilles, baffled to attenuate sound and light, provide return air pathways across closed doors in this compact return duct layout.

Figure 7. Duct system Installed in basement

Figure 8. Simplified central return inside framed duct chase

2.5.2 Load Calculations

With the ducts entirely in conditioned space, the heating and cooling load calculations were performed in accordance with ACCA Manual J (ACCA 2006). The results are summarized in Table 2.

Table 2. Heating and Cooling Load Calculations Summary

Calculated Heat Loss	Total Heat Loss	26,698 Btu/h
Calculated Heat Gain	Sensible heat gain	15,626 Btu/h
	Latent heat gain	3,356 Btu/h
	Total heat gain	**18,982 Btu/h**

The Manual J load calculations were developed for the high mass ICF wall system. Home Innovation substituted a light-frame 2 × 6 wall system with R-19 cavity insulation and R-4 exterior insulation (having a similar R-value to that of the ICF wall system) that showed very little calculated load differences between the wall systems. However, because the Manual J calculation produces peak load values, it may not account for lower heating and cooling requirements anticipated due to the thermal effects of the high mass wall, and may miss an opportunity to further reduce equipment capacity. Thermal mass, even in cold climates, is expected to even out the demand for heating (or cooling) since the mass helps to regulate the indoor temperature by causing a dampened response to large changes in outdoor temperatures. This dampening effect can cause multi-stage heat pump equipment to operate in a lower stage for a longer period of time rather than switching into high speed for peak heating or cooling.

2.5.3 Heating Fuel Selection

Selecting the type of fuel for heating was an important decision for this project. For the two previous projects, LCCTC installed ground source heat pump (GSHP) systems, which were acceptable, but the initial cost of a GSHP was deemed too expensive for this project. Instead, LCCTC initially considered propane gas because natural gas service is not available at the site and conventional ASHP technology has a negative perception locally as being costly to operate and uncomfortable. However, based on the following analysis, an ASHP system was ultimately selected.

Home Innovation conducted energy simulations (using the Building Energy Optimization Program [BEopt™] software version 1.4 and the EnergyPlus simulation engine, BEoptE+ v1.4) to compare heating operating costs of a high efficiency propane gas furnace, natural gas furnace, and two different ASHP systems. A summary of the simulation is shown in Figure 9. The summary, which includes all energy uses in the home with the heating system fuel differences, indicates that, at these efficiencies and current fuel prices, the propane gas furnace costs significantly more to heat the house than the natural gas furnace or heat pump systems. Furthermore, the heating cost for the natural gas furnace is nearly the same as the ASHP for the NCTH. Although not available for this house location, natural gas is an option for other houses in the area and is included for reference.

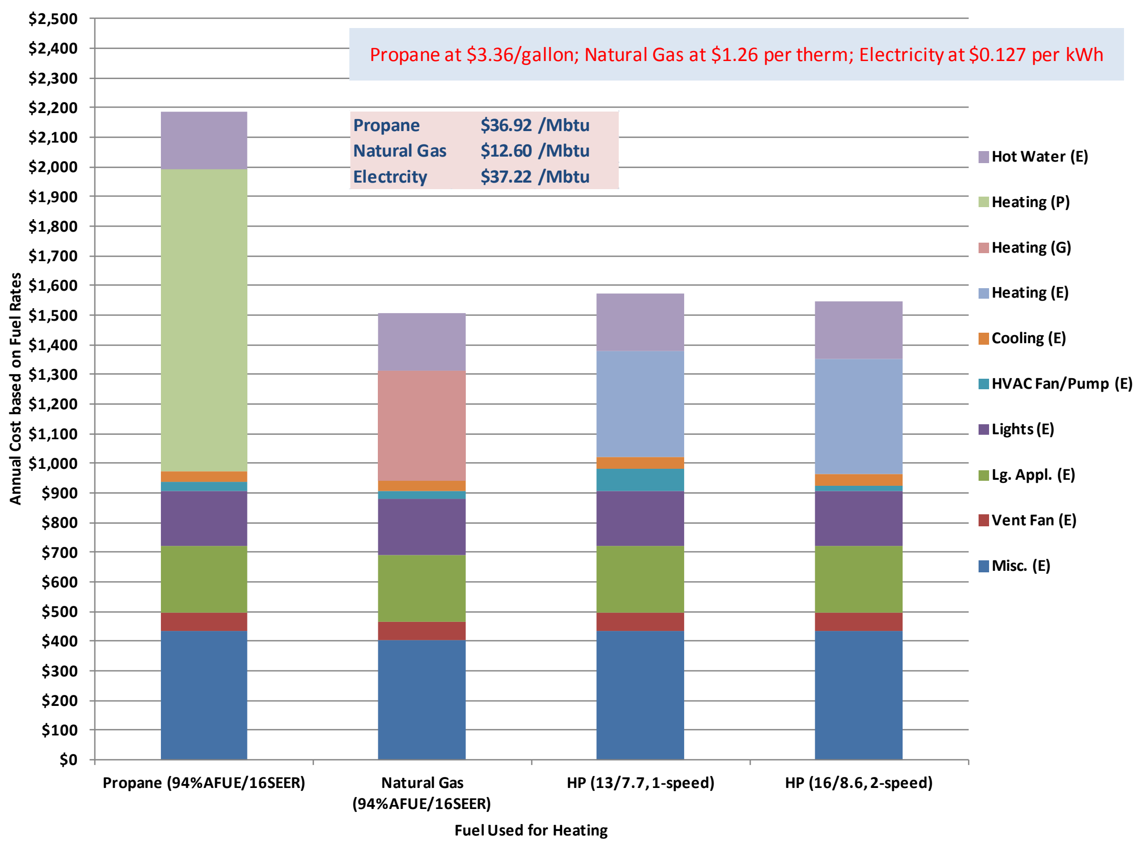

Figure 9. Cost comparison for heating fuel sources

A summary of the heating and cooling costs (energy only, no fixed costs) of the propane gas system and the 16 seasonal energy efficiency ratio (SEER) ASHP is shown in Table 3. The result is an annual operating cost savings of about $640 for the ASHP. This simulation was confirmed by an independent operating cost estimate by the HVAC vendor that showed an annual operating cost savings of $625 for a 16 SEER, 8.4 heating season performance factor (HSPF) heat pump compared to a 94% annual fuel utilization efficiency propane gas furnace with a 16 SEER cooling system.

Table 3. Estimated Heating and Cooling Cost Summary

System	Annual Heating Energy Cost	Annual Cooling Energy Cost	Annual Blower Energy Cost	Total Annual Heating and Cooling Costs
ASHP[a]	$389	$39	$17	$444
Gas Furnace[b] (Propane)	$1,018	$38	$28	$1,084

[a] Nominal 16 SEER, 8.6 HSPF heat pump
[b] Nominal 94% annual fuel utilization efficiency furnace and 16 SEER air conditioner

Beyond operating cost savings, by choosing an ASHP, LCCTC would save on the initial cost of a propane tank and gas piping. The cost of buying a 1000-gallon propane tank was quoted at $2,750 plus installation with a propane rate of $2.63/gallon. If the builder opted to lease a tank, the propane cost jumped to $3.48/gallon. With the lease option, it would take nearly 11 years to pay off the tank if purchased outright. Additionally, 100-gallon tanks were available for lease but not for sale, so the cost of propane would have been at the higher rate.

2.5.4 Simulated Carbon Factor Emissions

The goal of using the carbon factor estimates is to standardize the measurement and characterization of building energy performance. Using conversion factors from site energy use to carbon factor emissions (Deru and Torcellini 2007), global warming emissions estimates were compared for three fuel types. Whole-house energy consumption emissions estimates are presented; simulations were conducted by varying the heating and cooling system only. The heating systems that were compared include standard and high efficiency heat pump technology, high efficiency natural gas, and high efficiency propane fuels for heating. Results of simulated carbon dioxide emissions are presented in Figure 10.

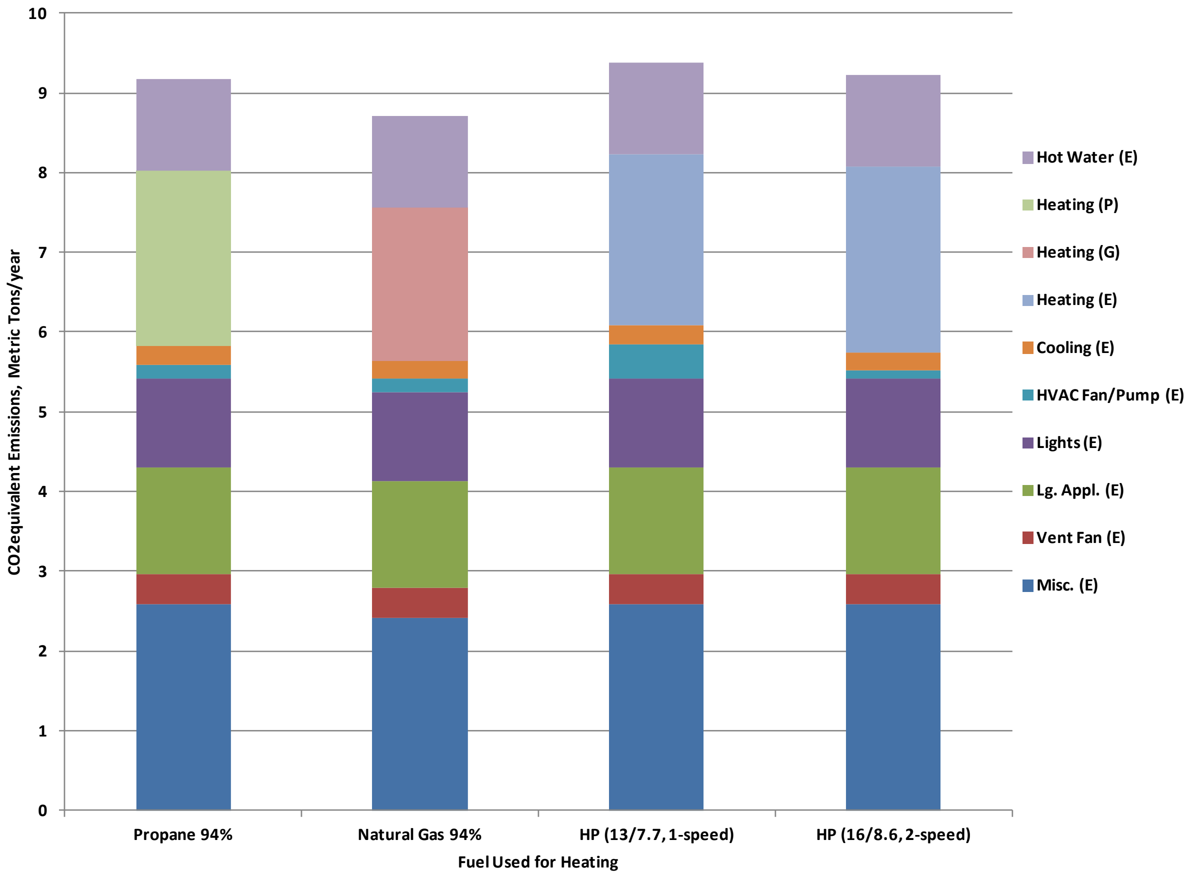

Figure 10. Carbon factor estimates for different heating fuel types

The carbon factor for all systems are within 10% of each other with natural gas showing the lowest overall emission production. The high efficiency heat pump system with electricity fuel is nearly equal to the propane fueled heating system indicating that the use of electricity for heating at the higher efficiencies is an equivalent option to using on-site fuel.[3]

2.5.5 Heating System Comfort Considerations

Based on the builder and local market perception that conventional heat pumps do not deliver sufficiently high air temperatures in a cold climate to be comfortable, the builder initially did not want to install an ASHP. The issue was of sufficient concern that further investigation was performed to evaluate ASHP delivery temperature from the duct system.

Although a propane furnace generally delivers a higher supply air temperature than a heat pump system, modern heat pumps, due to advanced technology, provide somewhat warmer air than older heat pumps. For example, a high efficiency air handler (fan coil) often includes an electronically commutated motor, which can reduce fan speed during the heating mode, increase time that the air is in contact with the heating coil, and increase supply air discharge temperature

[3] Due to transmission and distribution losses, electricity often results in a higher production of emissions (depending on the fuel used for generation) than burning fuel directly on-site for heating or other uses.

and improve comfort; the tradeoff is a marginal decrease in efficiency, because the heating and cooling capacity of direct expansion equipment is conditional on operating conditions and parameters including airflow. This comfort setting is similar to a dehumidification setting in the cooling mode.

Equipment capacity can also affect comfort. The heating capacity of a conventional ASHP decreases as the outdoor air temperature drops. Heat pumps are typically sized to meet the cooling load and rely on supplemental electric heat, as needed, to meet the heating load. Heat pump systems with two-stage compressors (that commonly operate at two thirds capacity in low-stage) are more energy efficient and can improve comfort. For two-stage systems, low-speed operation normally provides improved dehumidification and comfort in the cooling mode. For colder climates, a two-stage system can be selected so that low-stage operation satisfies the cooling demand and high-stage operation meets most or all heating requirements This selection approach produces greater heating capacity, and reserve cooling capacity, but the tradeoff is less capacity for dehumidification during cooling (because there is only one stage for cooling) and the need for a larger duct system to accommodate the increased high-stage airflow. Residential two-stage equipment is generally available in 2-, 3-, 4-, or 5-ton capacities only (1-ton increments, and not 2.5- or 3.5-ton capacities; 1 ton of cooling equals 12,000 Btu/h).

Similarly, heat pump systems with inverter-technology compressors (variable speed compressors that ramp down to about 20% capacity) can be sized to meet the heating load in a colder climate and provide a steady heat output down to about 0°F (producing a relatively flat heating curve similar to a GSHP). In such a system, supplemental heat is generally reserved for comfort during the defrost cycle. Inverter compressors ramp down to efficiently meet sensible and latent cooling requirements. This technology, common in ductless split heat pumps (DSHP), is particularly well-suited for cold climate applications.

2.5.6 Equipment Selection

After eliminating propane gas as cost prohibitive the team shifted its attention to selecting the most cost-effective ASHP technology. Inverter compressor technology applied to conventional ducted distribution systems was eliminated due to its initial cost and lack of availability through LCCTC's preferred distributor. Inverter technology common in DSHP systems was not considered because LCCTC considers installing a conventional duct system an important educational aspect. The team selected a two-stage compressor heat pump, 16 SEER, 9.8 HSPF for optimum efficiency and performance. A 19 SEER system was ruled out because its rated heating performance was nearly identical to that of the selected, lower cost unit.

The equipment capacity was selected in accordance with ACCA Manual S (ACCA 2004). Using manufacturer product data for the selected model, the capacity was selected to meet the cooling loads in low-stage in order to improve the heating performance in high-stage. A 2-ton system had a heating balance point of approximately 30°F, but the selected 3-ton system provided additional heating capacity at design temperatures and a considerably better heating balance point of approximately 17°F. The total cooling capacity of the 3-ton system in low-stage is within the 115% (any climate) and 125% (cold climate) over-sizing Manual S limits. The resulting HVAC equipment schedule is shown in Table 4.

Table 4. HVAC Equipment Schedule

Equipment	Equipment Data
Heat Pump	Amana ASZ160361, 3-ton, 2-stage, 16 SEER, 9.8 HSPF, American Heating and Refrigeration Institute # 4431376
Fan Coil	Amana AVPTC31714, variable speed
Supplemental Heat	Amana HKR-08C, 8 kW
Thermostat	Amana CTK02BB Comfortnet
Filtration	Minimum efficiency reporting value 13 media filter
Mechanical Ventilation	Honeywell VNT5150E1000 and W8150 control

2.5.7 HVAC and Wall System Performance

This analysis is performed not so much to quantify energy savings (overall performance of the wall systems in this climate are very similar) but is more important for sizing the heating and cooling system and for determining the anticipated operation of two-stage equipment.

The selection of a high mass wall system impacts how the heating and cooling system will operate. Given that lumber density is about 28 lb/ft^3 and concrete density is about 140 lb/ft^3, a 100-ft^2 advanced frame wall system with about 20% framing factor has about 250 lb of mass compared with about 7,000 lb of mass in a 100-ft^2 ICF wall. The much higher mass in the ICF wall influences the process of heat transfer across the wall system and affects how the HVAC system responds to changing outdoor conditions. The thermal mass will slow the heat loss from the house since the mass reacts much less quickly to changing outdoor conditions. This thermal mass effect will generally cause the HVAC system to run in lower speed (given a multistage unit) but for a longer period of time.

Hourly estimated heating energy consumption for a light-frame wall system and an ICF wall of similar R-value is shown in Figure 11.

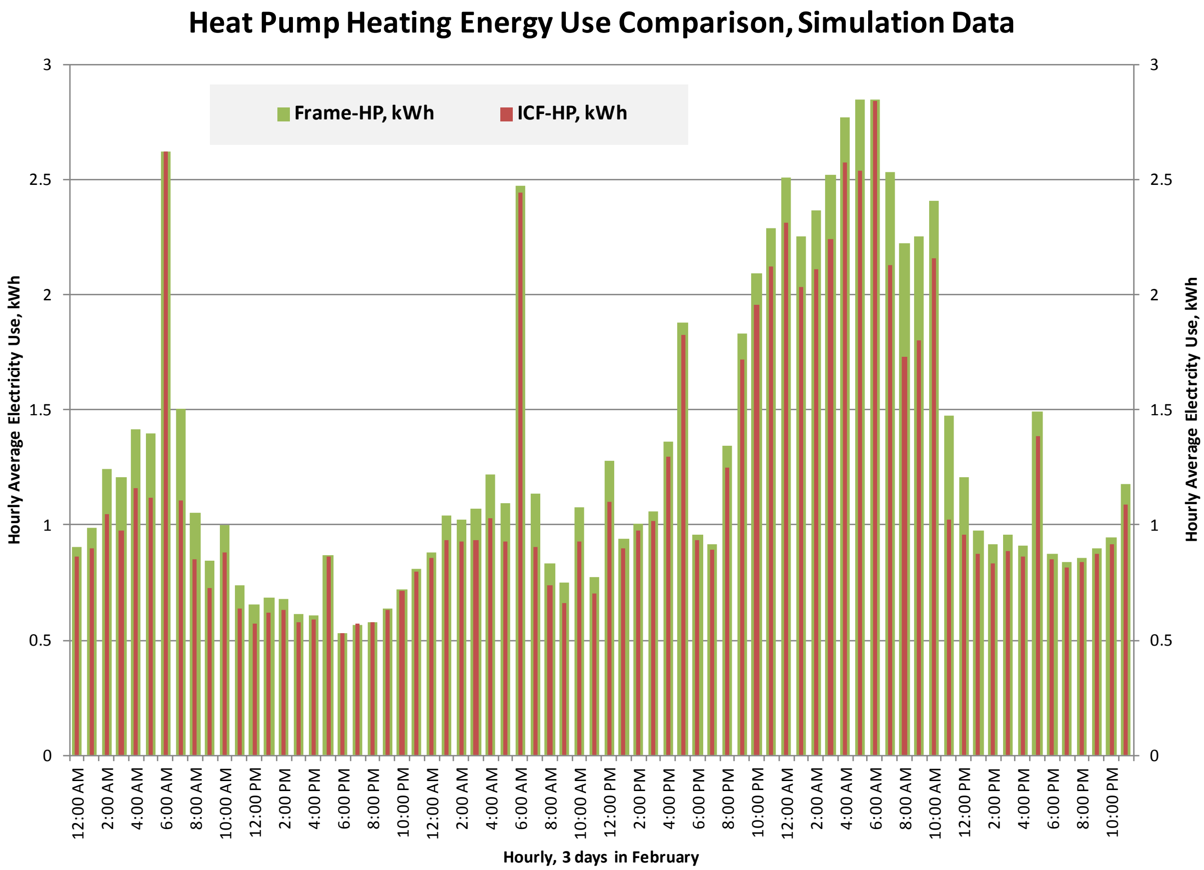

Figure 11. Energy use comparison of ICF to light-frame wall system

For most of the time during the select heating period, the simulation predicts less average hourly energy use for the ICF wall system than for the light-frame wall system. The thermal mass of the ICF walls is expected to mitigate larger shifts in energy use due to changing outdoor conditions due to the large heat storage capacity of the mass wall (compared with a light frame wall) The high heat capacity of the wall material dampens the heat flow across the wall system from indoor to outdoor (heating).The absolute difference, however, is not large for any hour during the 3-day analysis period.

A different view of the hourly simulation results indicate that, based on the simulation of heat transfer through the wall system, mass delays the response of heating energy usage to decreasing and increasing outdoor temperatures. The cumulative effect of this delay is shown in Figure 12, which shows whole-house hourly energy difference between light-frame walls and ICF walls.

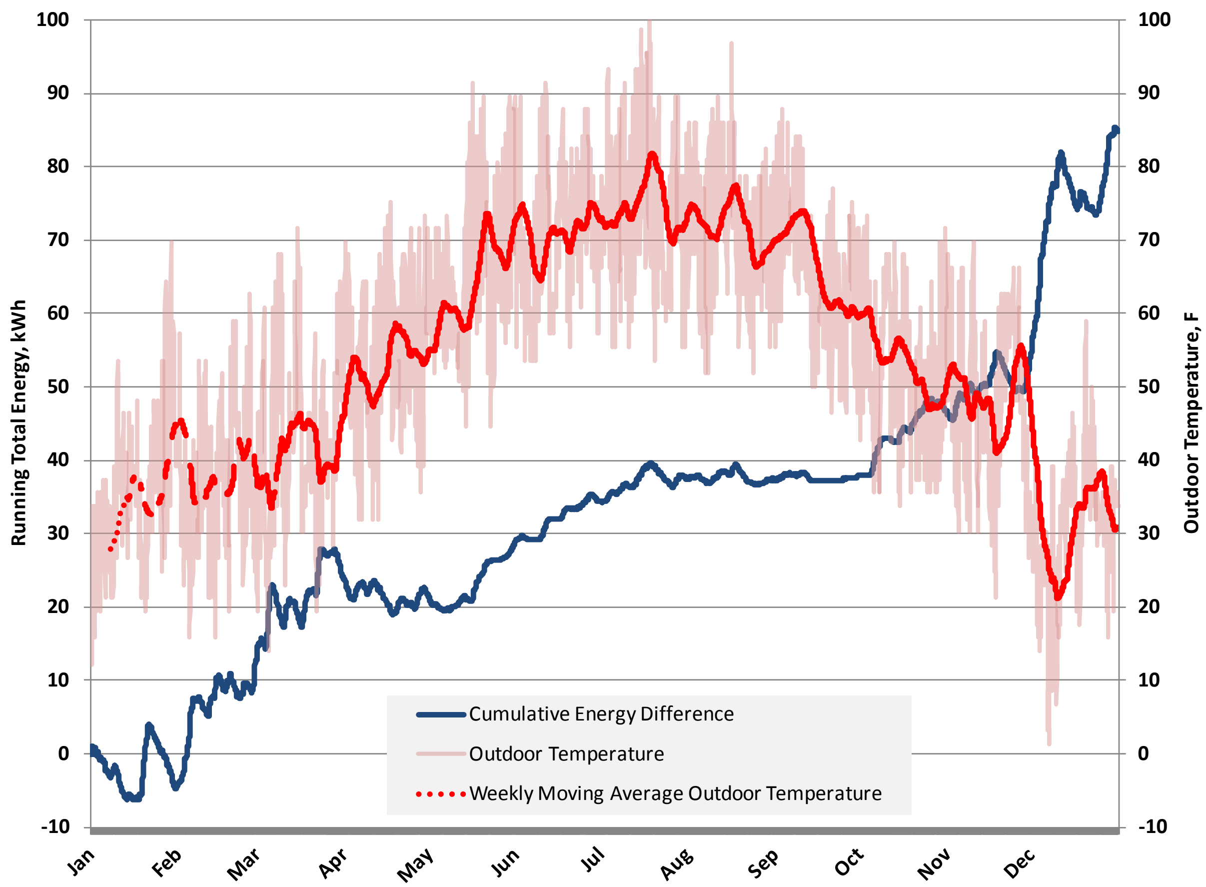

Figure 12. Hourly HVAC energy for light frame and ICF wall systems

The blue line plotted on the left axis in Figure 4 represents the cumulative difference in energy usage between the light-frame and ICF walls ($E_{frame} - E_{ICF}$). When the curve increases, the energy use of the ICF wall system is less than the frame wall system and opposite when the curve is decreasing. The rise of the cumulative energy difference is indicative of the ICF response to decreasing outdoor temperature (for which the stored thermal energy helps offset heating demand) and the decreasing cumulative energy difference indicates the response of the ICF walls to increasing outdoor temperature, in which the thermal mass is at a lower temperature than the outdoor air, and the heating system needs to continue to operate to provide heating to raise the thermal mass temperature.

Even though the thermal mass at times may cause the heating or cooling system to operate longer than for a system in a light-frame house, the net result is that, based on simulations, the ICF wall system uses less energy than the frame wall system (both of similar R-values).

2.5.8 Mechanical Ventilation

There are two types of mechanical ventilation. Source-exhaust mechanical ventilation, also known as local-exhaust and spot-exhaust, uses kitchen and bath exhaust fans ducted outdoors as the primary method to control moisture and odors. Whole-house mechanical ventilation, also known as fresh-air ventilation, is the intentional exchange of “stale” indoor air with “fresh” outdoor air, at a controlled rate using fans. The purpose of whole-house mechanical ventilation is to improve indoor air quality, by diluting indoor contaminants (such as formaldehyde, cleaning agents, odors, allergens, and radon), which now take longer to dissipate in tighter houses, and helping to control relative humidity and moisture accumulation. The most recent building codes and above-code programs generally require whole-house mechanical ventilation.

Measured airflows of installed mechanical ventilation products are frequently different than design values. Under-ventilation could jeopardize moisture control, occupant comfort, and building code or energy program compliance. Over-ventilation may lead to excessive energy use, occupant discomfort, and during some periods excessive indoor moisture levels.

Based on numerous test sites, measured airflows are commonly lower than design values due to an overly restrictive duct system. An efficient duct layout will reduce airflow resistance and help ensure expected performance:

- Locate termination hoods to minimize duct lengths and number of elbows.
- Account for pressure drop of all components including termination hoods.
- Use manufacturer’s airflow and static pressure data; prescriptive duct sizing tables may use different static pressures.
- Increase duct diameter if necessary.
- Install rigid duct in place of flexible or corrugated duct as required.
- Install in accordance with manufacturer’s instructions.

A method to account for duct pressure drop is to apply the basic duct sizing principles described in ACCA Manual D commonly used for sizing heating and cooling air distribution ducts. The HVAC designer can simply apply these same principles to ventilation duct designs. This method is detailed below by way of example for the NCTH.

Interestingly, such a duct design is already technically required by code. The 2009 IRC, Section M1506.1, mandates that exhaust duct construction not specified in this chapter (bath exhaust fans and whole-house mechanical ventilation ducts are not) shall comply with Chapter 16. Section M1601.1 states that “duct systems serving heating, cooling and ventilation equipment shall be fabricated in accordance with the provisions of this section and ACCA Manual D or other approved methods.” Section M1601.4 mandates duct sealing.

For the NCTH, source-exhaust mechanical ventilation is provided by conventional kitchen range and bath exhaust fans (energy factor [EF]). Bath fans were specified for quiet performance and with timer controls to ensure adequate moisture removal. Whole-house mechanical ventilation is provided by an ERV. The ERV provides balanced ventilation and transfers a portion of the heat and moisture between the incoming fresh air and outgoing stale air streams. Installing an ERV is standard practice for LCCTC to ensure adequate indoor air quality. The team selected a two-speed ERV to provide continuous ventilation in accordance with ASHRAE 62.2-2010 recommendations (ASHRAE 2010).

An important goal for this project was to specify a design that effectively integrated the ERV with the heating and cooling duct distribution system. Incoming fresh air was ducted to the return plenum, so outdoor air is filtered and conditioned when the air handler is operating. The outgoing stale air was ducted from a dedicated grille in the living room; this approach avoids the "short-circuiting" of fresh air that occurs when both indoor and outdoor air ducts are installed in the return plenum and the air handler is not running. This partially integrated duct approach provides better fresh air distribution when the air handler is not running, and additionally provides a convenient grille to measure airflow using a standard flow hood. The ERV design criteria are shown in Table 5.

Table 5. Whole-House Mechanical (Fresh Air) Ventilation Design Data

Criteria	NCTH
Conditioned Floor Area (ft^2)	4,768 (2,384 above grade; 2,384 basement below grade)
Volume (ft^3)	45,980 (including joist area and cathedral ceiling sections)
Bedrooms (Quantity)	3
Airflow Rate* (CFM)	78
1. Type	Balanced ERV Partially integrated (fresh air to return trunk, stale air from single source (low-wall grille in living room; air handler has an electronically commutated motor). Duct to be rigid metal, short flexible sections at ERV, insulated ERV to outdoors.
2. Location	Installed in mechanical area of basement and ducted to the exterior
3. Design Rate (CFM)	78
4. Frequency and Duration of Each Ventilation Cycle	The ERV has a 3-position switch: OFF; CONT (continuous): operates at low-speed (half the flow of high-speed); INTER (intermittent) operates at high-speed. The ERV is rated at a nominal 150 CFM. The ERV was balanced and adjusted to run at 80 CFM continuously low-speed, 160 CFM intermittently high speed. The 3-position switch on the side of the ERV is easily accessible. The original design specified a control to optimize the air delivery schedule to make efficient use of normal HVAC run times to ensure adequate ventilation each hour. That control was not compatible with the heat pump system's 2-wire communicating control wiring.

* Minimum continuous rate in accordance with ASHRAE Standard 62.2-2010, Equation 4.1a: rate = 0.01*CFA + 7.5*(Nbr+1), or Table 4.1a (see also 2012 IRC Table M1507.3.3 (1)).

The equipment and duct layout design criteria for all mechanical ventilation systems are shown in Table 6. The duct layout details illustrate a method to design an effective duct layout; the systems will be field verified and tested to evaluate the design approach.

Table 6. Mechanical Ventilation Design Data

Step	Design Data	Half Bath	Hall Bath	Master Bath	Kitchen	ERV
1	Design airflow (CFM)	50	50	80	100 min.	150 high 75 low
2	Manufacturer	Broan	Broan	Broan	Broan	Honeywell
	Model	QTXE050	QTXE050	QTXE080	QDE30SS	VNT5150E1000
	ENERGY STAR® rated	Yes	Yes	Yes	Yes	Yes
	CFM @ 0.1 iwc	50	50	80	0-280	150 @ 0.4 iwc
	CFM @ 0.25 iwc	39	39	55		
	Sone @0.1 iwc	0.3	0.3	0.3	0.8-5.5	
	Watts @ 0.1 iwc	19.7	19.7	23.3		
	Duct fitting (in)	6	6 / 4	6	3.25*10	
	Specify control	Timer	Timer	Timer	Variable	Honeywell 8150
3	Termination hood location	N soffit/ S soffit	N soffit/ E gable	N soffit	Roof/ W gable	E wall
4	Duct construction	Metal	Metal	Metal	Metal	Metal/flex
	Duct sealing	Mastic	Mastic	Mastic	Mastic	Mastic
	Duct insulation	R-8	R-8	R-8	None	R-8 as required
	Duct length (ft)	30/3	20/3	15/7	12/12	32 in; 44 out
	Duct elbows (qty)	3/1 at soffit	2 / 1	2/1 at soffit	2/2	2 in; 4 out
5	Total equivalent length (TEL)	120/53	90/53	85 / 57	82	256
6	Friction rate (FR)	0.08/.19	0.11/0.19	0.12 / 0.18	0.13	0.16
7	Minimum duct (in)	5/4	5/4	6/5	3.25*10 (100 CFM)	6
8	Design duct (in.)	6/6	6/4	6/6	3.25*10	6

Note: values shown using #/# indicate the as-designed/as-built values.

Step 1: Determine the design airflow based on code requirements and industry best practices (e.g., ASHRAE Standard 62.2-2010; Home Ventilating Institute recommendations: www.hvi.org/)

Step 2: Select the fan and control

Step 3: Determine the termination hood location to minimize linear feet of duct and number of elbows

Step 4: Specify the duct construction details. Estimate the layout based on plans. Air sealing is required. Insulation is recommended to minimize condensation. Insulation is generally required for fresh air and stale air ducts that terminate outdoors for balanced (e.g., ERV or heat recovery ventilator) and supply-type whole-house ventilation.

Step 5: Calculate the TEL, in feet. Example: 30 linear ft of metal duct + 2 elbows at 20 equivalent length (EL, in feet) + 1 termination hood at 30 EL = 100 TEL

Step 6: Calculate the design FR, in iwc. FR = ASP*100/TEL, where ASP is the available static pressure (iwc) of the fan at the rated airflow (from the manufacturer's product data). Example: A bath exhaust fan rated 80 CFM @ 0.1 iwc, and a duct layout of 100 TEL: FR = 0.1*100/100 = 0.10

Step 7: Determine the minimum duct size: using a duct calculator set fan airflow to friction rate and read the required duct diameter, rounding up to the next nominal size diameter or rectangular dimensions.

Note: Fitting equivalent length (EL is conditional upon pressure drip and friction rate (FR), and pressure drop depends on, among other factors, velocity. EL is commonly rated at 900 feet per minute (FPM); all else the same, a lower velocity reduces the effective length and increases the calculated FR. At 600 FPM, EL is reduced by approximately 50%, and by about 2/3 at 500 FPM (Figure A3-2, ACCA Manual D, Third Edition). The FR may be recalculated using this iterative approach as needed.

Step 8: Specify the design duct size – may be increased to match the fan fitting, but if the duct size is larger than the than the fan fitting install a reducer fitting as close to the fan as practical.

2.6 Plumbing

The domestic hot water system design includes solar thermal collectors to preheat water for storage. In Green Home 1 and Green Home 2, the solar hot water storage tank fed into an electric on-demand auxiliary water heater. An alternative system was sought for Green Home 3, because of the cost of the electric demand backup system, which requires four 30-Amp circuits and a demand heater unit for a heater that is sufficiently large to supply all of the hot water under worst-case scenarios.

To reduce first cost and ensure acceptable performance for the owner, the team selected a more conventional, indirect solar preheat system with evacuated tube collectors heating an antifreeze solution that, in turn, heats water in a storage tank. Backup water heating is accomplished by an electric resistance element in the storage tank.

The energy savings for the SDHW system were estimated by software simulations (BEoptE+ v1.4) and through the solar rating analysis provided by the Solar Rating and Certification Corporation (SRCC).[4] When rated as a system[5] by SRCC, the solar thermal system uses a standard set of assumptions for the equipment including pumps, solar radiation, hot water use, hot water delivery temperature, and backup energy (either gas or electric). The system is rated by two metrics, solar energy factor (SEF)[6] and solar fraction (SF).

Using SRCC methodology, SEF is calculated using equation 1.

$$SEF = \frac{Q_{del}}{Q_{aux} + Q_{par}} \text{ (1); where:}$$

> Q_{del} = Energy delivered to the hot water load. Using the SRCC rating conditions, this value is 41,045 Btu/d.
>
> Q_{aux} = Daily amount of energy used by the auxiliary water heater or backup element with the solar system operating.
>
> Q_{par} = Parasitic energy used to power pumps, controllers, shutters, trackers, or any other equipment needed to operate the SDHW system.

SEF generally represents the comparison of the SDHW system to a standard water heater. Where a standard water heater would be rated with an energy factor (EF) that includes the efficiency of the water heater and storage tank losses, similarly the SEF represents these same parameters as well as the contribution of the solar. An alternative representation of the contribution of the solar hot water supply to the domestic water heating energy is the solar fraction (SF) which generally represents the portion of the water heating energy expected to be supplied, on an annual average, by the solar system. The SF is related to the SEF as shown in equation 2.

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[4] Refer to www.solar-rating.org for information on collector and system ratings for solar hot water systems.

[5] SDHW systems can be rated to the SRCC Standard OG300, Minimum Standards for Certifying Solar Water Heating Systems, June 2012, SRCC, Cocoa, Fl.

[6] Refer to http://www.solar-rating.org/facts/system_ratings.html#RATING for a general discussion of the use of the SEF and SF in solar hot water system efficiency ratings.

$$SF = 1 - \frac{EF}{SEF} \text{ (2); where:}$$

EF is a standard unit of backup tank energy efficiency, 0.9 for electric tanks, and 0.6 for gas tanks. Both the SEF and the SF are reported through the SRCC for specific system designs. Certification reports are issued on the system performance for selected climates (by city). Appendix B shows the report for two different system configurations.

Energy use estimates, however, from the simulation software used for whole-house energy analysis are somewhat limited. The simulation software uses a standard protocol to estimate hot water use, incoming cold water temperature by climate, and demand profile for hot water use. The simulation software assumes a standard flat plate solar collector with a standard electric tank element for backup. The simulation software allows the orientation of the solar collectors to be matched to actual installation conditions; solar radiation estimates are based on 30-year average weather data for any given location. A summary of the simulation results for the estimated hot water energy supply and use and the ratings for the collector system from the SRCC are shown in Table 7.

Table 7. Summary of Annual Hot Water System Energy Supply and Use

Parameter	Value	Unit
Delivered Hot Water Energy[a]	8,992,976	Btu
Electric Input[b]	5,163,840	Btu
Solar Heating Input	4,003,665	Btu
Total Input Hot Water Energy	9,167,506	Btu
SEF (calculated)	1.74	
SF (calculated)	0.48	
SEF (SRCC)[c]	1.70/2.10	
SF (SRCC)[c]	0.46/0.57	
Hot Water Energy Use, Standard 80-gal Tank[d]	3,028	kWh
Hot Water Energy Savings (Simulation)	1,515	kWh
Estimated Hot Water Savings Based on Actual System	1,773	kWh

[a] Delivered energy is the domestic hot water supply from the tank for all uses in the home, based on simulations.
[b] Assumed to include all electrical inputs to the SDHW system.
[c] The first value is for a standard system similar to the simulation model, the second value is for the installed system
[d] Without solar preheat system

The whole-house energy simulation software provides only limited solar hot water components and was not able to simulate the exact components installed at the NCTH. Based on the simulations, a calculated SEF was close to SRCC-rated SEF for the system components which were simulated. However, the actual installed system components had a rated SEF of 2.1. There was not a way to compare simulation results with SRCC rating for the specific system installed at the NCTH. A correction factor, based on the ratio of the simulated results to the SRCC rating, was used to raise the simulated performance of the solar system to more closely match the actual installed solar water heating components.

Because the domestic hot water system operates mostly independently from other building components, a cost analysis can be performed for this system independent of the whole house. Energy cost savings for the solar preheat system is approximately $225 annually. The contractor estimate for the installed system was about $8,300 net of a standard 80-gallon water heater. At this cost, the simple payback is more than 35 years and the financed cost is about twice that of the savings. Without some incentive program to offset the installed costs, or an alternative system offering lower costs, there is little financial benefit to the solar water heating investment. Furthermore, this simplified cost analysis does not include any maintenance costs for the solar system.

One potential alternative to solar water heating at the NCTH is a heat pump water heater (HPWH). Simulation results of an HPWH are summarized in Table 8.

Table 8. Annual Estimates for Water Heating System Options

Parameter	Standard Electric Resistance Tank	SDHW	HPWH
Hot Water Energy Use, kWh	3028	1513	1503
Heating and Cooling Energy Use, kWh	3518	3497	3700
Total Heating, Cooling, Water Heating, kWh	6546	5010	5203
Net Energy Savings Over Standard	–	23%	21%
Heating and Cooling Energy Savings (Increase)	–	1%	(5%)*

Standard – 80-gal electric tank

* An HPWH draws its energy from the surrounding air. During cooling, it improves cooling efficiency. During heating, it increases the heating load. In a cold climate the net effect is typically an increased annual space conditioned energy use.

In this analysis, an HPWH uses approximately the same amount of energy as does the solar preheat system. Because an HPHW draws its energy from the surrounding air and the system is located in conditioned space, the energy penalty in this climate is an increase in heating energy. There is a very slight decrease in cooling costs in the summer months. Results are design estimates.

Based on an estimate of the installed cost for the HPWH of $2,781 and an annual energy savings of $171 (electricity at $0.127/kWh), the simple payback is almost 18 years, longer than the warranty and normal life expectancy for the appliance. As with the solar thermal system, state, utility, and/or federal incentives may reduce the installed cost by as much as 50% and, hence, could make this option cost effective to the owner.

2.7 Electric

For ICF construction, selecting the method to rough-in the electric is an important early-on decision. Different methods to install the electric wiring in ICF walls were debated during the design phase. One option was to have a final electrical design layout and install conduit for the wiring within the walls prior to pouring concrete. A second option was to pour the walls first, then cut the insulation on the interior to run the wires (commonly using a hot-knife), and foam over the wires. While the second method eliminates a minimal amount of insulation, it allows for more flexibility during installation and does not require a complete electrical plan and electrical work before concrete. The team decided on the second option as the most practical approach.

2.8 Lighting and Appliances

The team specified high efficiency lighting and appliances to maximize end-use energy efficiency for which the occupants are mostly in control. High efficiency lighting was increased to 100% using compact fluorescent lamps (CFLs) or fixtures or light-emitting diode (LED) products. Controls (e.g., dimming) and appropriate lighting efficacy (e.g., light levels on surfaces or use of lamps) throughout the house will maximize efficiency and allow multiple lighting options. Additionally, some lighting fixtures commonly installed on the ceiling (e.g., hall light) were specified to be installed on the walls to minimize ceiling penetrations. Builder supplied appliances were specified to be ENERGY STAR.

3 Final Energy Solution Package Analysis

3.1 Energy Simulation Estimates

Using BEoptE+ v2.1 software,[7] an energy use optimization was performed to determine the least cost approach to achieve the greatest energy savings. Options for use in the simulations included various wood frame wall systems, exterior insulation options, infiltration levels, heat pump system efficiencies, and water heating system options, including solar hot water heating. The options were selected to demonstrate primarily the building envelope and mechanical system opportunities to achieve energy savings at the least cost. Cost estimates were all based on the NREL National Residential Efficiency Measures Database.[8] Figure 13 shows the graphical results of the optimization.

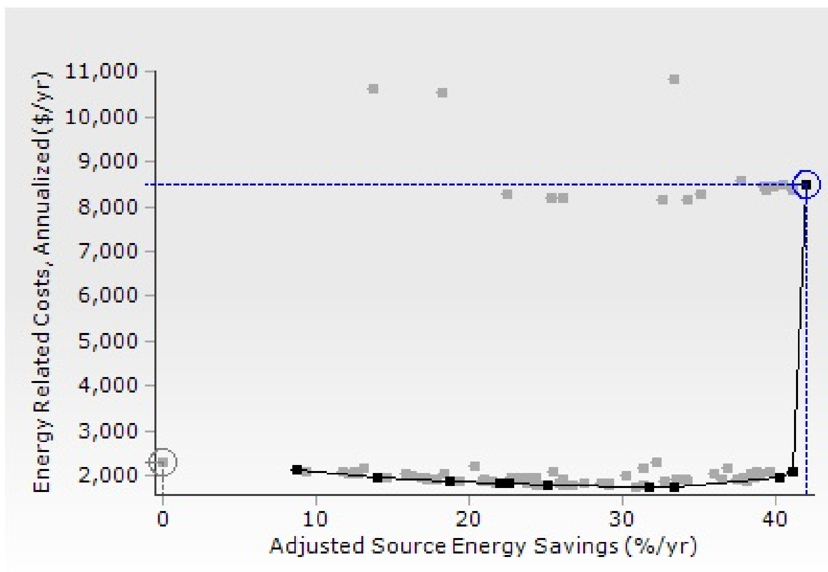

Figure 13. Energy cost optimization simulation results

The optimization results differ from the maximum savings to the highest energy savings that still show an annualized savings (approximately 46% over the Building America benchmark with high performance) by the use of foam insulation in the wall cavity and an addition of a solar water heating system. These results compare well with the selected 44% savings features used in the NCTH.

The final energy efficiency solution package represented months of development by Home Innovation, LCCTC staff, trade contractor professionals, manufacturers, and product suppliers. The design process involved technical input, energy modeling, and optimization by Home Innovation and input on costs and other practical factors by team members. The set of features selected based on the design analysis included:

[7] A newer version of BEopt software was used to perform final simulation results than was available at the time of the initial analysis.
[8] www.nrel.gov/ap/retrofits/

- Walls: ICF below-grade and above-grade, R-22 rated assembly
- Attic: vented, R-49 blown cellulose ceiling insulation, standard truss roof framing
- Windows: wood clad low-e, U-0.30, SHGC-0.28
- Air sealing: target and modeled 1.5 ACH50
- Heating and cooling: ducts in conditioned space, ASHP, 2-stage, 16 SEER, 9.8HSPF
- Mechanical ventilation: ERV
- Appliances and Lighting: ENERGY STAR; 100% high efficacy CFL or LED
- Hot water: SDHW (SEF of 2.0)

The energy simulations, originally using BEopt v1.1, were updated using BEoptE+ v1.4, and most recently using BEoptE+v2.1 (Figure 14), which charts annual source energy savings[9] of the house as designed versus the Building America Benchmark, shows a 44% reduction in the estimated energy use of the NCTH.[10] Table 9 provides the numerical results and percentage change from the Building America Benchmark.

Table 9. Simulation Source Energy Summary

End Use	Source Energy, MBtu		NCTH Percent Savings	End Use Percent of Total	
	Benchmark	NCTH		Benchmark	NCTH
Miscellaneous	39.89	28.54	28%	19%	24%
Ventilation Fan	1.94	3.02	–56%	1%	3%
Large Appliance	25.98	20.16	22%	12%	17%
Lighting	23.43	15.19	35%	11%	13%
HVAC Blower	11.86	1.41	88%	6%	1%
Cooling	5.42	3.55	35%	3%	3%
Heating	60.93	33.48	45%	29%	28%
Hot Water	40.61	12.61	69%	19%	11%
Total	**210.06**	**117.96**	**44%**	**100%**	**100%**

[9] Source energy represents the energy at the point of generation rather than at the house meter.
[10] The Building America Benchmark analysis using the House Simulation Protocols has gone through a series of revisions. The latest revision (released December 2013) allows for the reference house to use an electric heat pump when natural gas is not available at the site and has been implemented in this analysis.

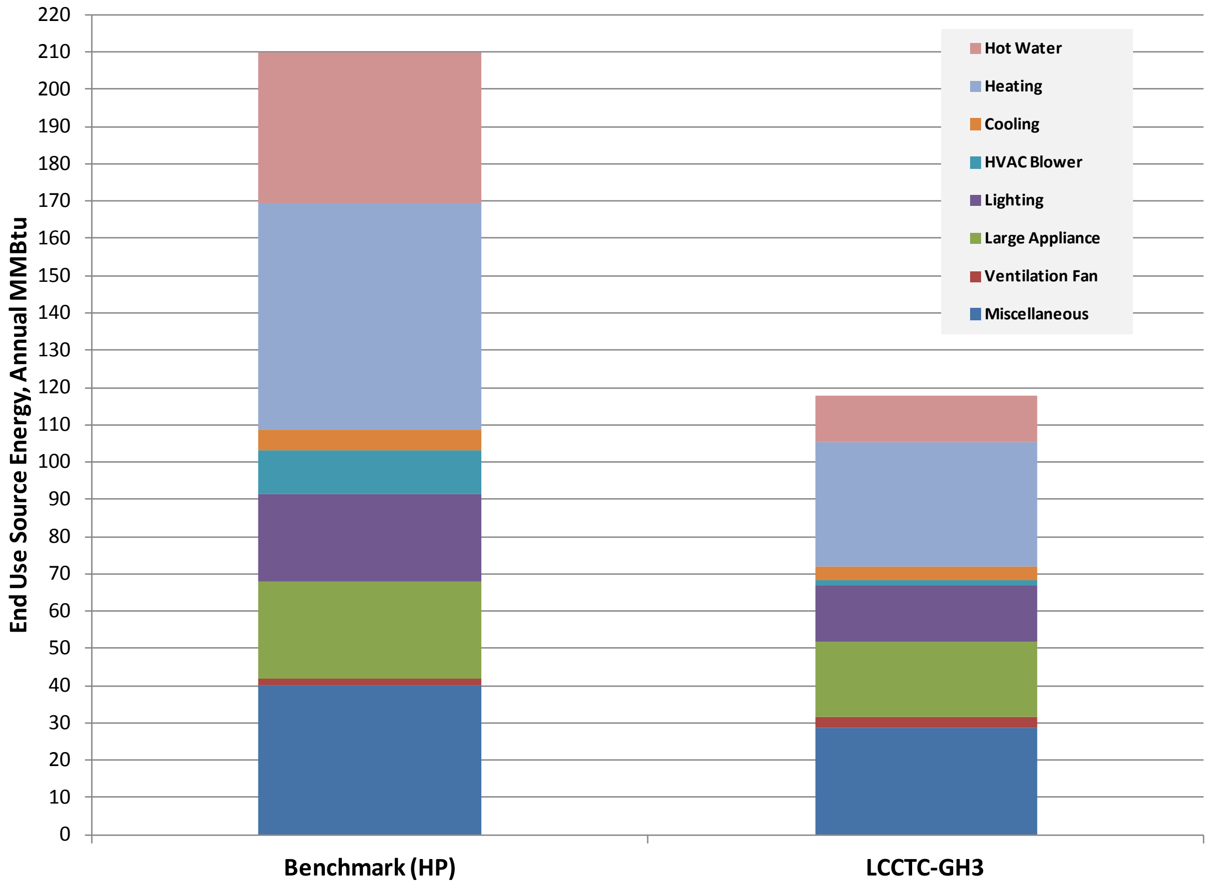

Figure 14. Simulation source energy results

3.2 Energy Efficiency Cost Analysis

The Research Center completed an in house cost analysis during the design process which provided the team with information for system selection (e.g., wall type). This analysis considered energy savings, occupant comfort, and synergistic cost containment benefits such as reduced material and labor costs. Original cost assumptions were refined and updated during the process, and are summarized in Table 10.

Home Innovation worked with LCCTC to understand incremental costs and finalize the cost analysis. Based on the estimated cost for the upgrades and the stated financing parameters, there will be on average an annual cost penalty of about $164 with the investment in the energy upgrades. Simple payback is about 18 years and the simple return on investment is about 6%. The high cost of the SDHW is one feature that may be optimized in lieu of other efficient water heating technologies.

Table 10. LCCTC Green Home 3 Revised Cost Analysis

Design Feature	Construction Category	NCTH Design Specification	Standard Feature	Cost Premium[a]
Foundation	Construction	ICF system	Poured concrete	$2,528
	Insulation, total value	R-22	R-13, frame	
	Slab insulation	Integrated with wall	none	
Above-Grade Walls	Construction	ICF, 6-in. concrete core	2×4, R-13, R-5 ext.	$3,305
			2×6, R-19, R-5 ext.[b]	$2,158
	Structural sheathing	None	Wood structural	none
	Insulation, nominal	R-22	R-18/R-24	none
	Exterior air barrier	House wrap	House wrap	none
	Exterior finish	Vinyl/brick	Vinyl/brick	none
Attic	Insulation	R-49 cellulose	R-38 fiberglass	$746
Windows	U-value/SHGC	0.30/0.28	0.35/0.35	$124
Air Sealing	Infiltration ACH50	1.5 ACH50 (target)	< 7ACH50	$380
Heating and Cooling Equipment	Heating	ASHP 2-stage 16 SEER/9.8 HSPF	1-stage ASHP 13 SEER/7.7 HSPF[b]	$1,625
			80% furnace/ 13 SEER AC	$1,025
HVAC Duct	In conditioned space	100%	100%	none
	Return duct	Simplified, central	Standard, central	–$300
	Return air pathway	BR transfer grilles	Door undercut	
Spot Ventilation	Bath exhaust fan (no.)	ENERGY STAR	Standard	$120
	Kitchen exhaust fan	Vented outdoors	Vented outdoors	$0
Whole-House Ventilation	Mechanical control	ERV with control	Bath fan/timer	$1,560
			Return air duct/damper auto. controller[b]	$1,355
Domestic Water Heating	Water heater	SDHW	Standard electric	$8,309
	Capacity	80 gal	80 gal	
	Fuel	Electric element	Electric element	
	Tank EF	0.95	0.91	
Plumbing	Fixtures	Low flow	Standard	$40
Lighting	CFL lamps/fixtures	100%	50%	$41
ENERGY STAR Appliances	Dishwasher, refrigerator, clothes washer	Dishwasher, refrigerator, clothes washer	Standard	$470
Total Cost Premium Over Standard[c]				$18,348
Annual Mortgage Premium at 5% Interest and 30 Years				$1,182
Annual Utility Cost Savings				$1,018

[a] Cost premium over standard construction feature (local standard or LCCTC standard)

[b] Used for comparison purposes only, not used in the cost analysis

[c] Premium over standard construction elements and gas furnace

4 Test Results

The test plan for this NCTH outlined the technical approach for this project. Test results are summarized below (Table 11).

Table 11. Home Innovation Test Results

Test	Measurement	Result
House Leakage, Intermediate[a]	1220 CFM50	1.59 ACH50
House Leakage, Final[a]	843 CFM50	1.10 ACH50
Duct Leakage, Intermediate[b]	Not measured	
Duct Leakage, Total[b]	239 CFM25	5 CFM25/100 ft^2 cfa
Duct Leakage, Outdoors[c]	0	0
EF: Powder Room[d]	67 CFM	Exceeds 50 CFM rating
EF: Hall Bath[d]	127 CFM	Exceeds 50 CFM rating
EF: Master Bath[d]	91 CFM	Exceeds 80 CFM rating
EF: Kitchen Range	Not measured	
ERV[d]	90 CFM low-speed	Exceeds 75 CFM rating

[a] Depressurization test to 50 Pa using Minneapolis Model 3 blower door and DG700 manometer
[b] Pressurization test to 25 Pa using Minneapolis Series B duct blaster and DG700 manometer
[c] Pressurize house to 25 Pa, then pressurize duct system until the difference between the house and duct system is zero, using above equipment.
[d] Measured using Alnor 6200 flow hood

The intermediate blower door test was performed after drywall and extensive air sealing from the attic, but before attic insulation. The only noticeable leakage was through the top plate at the laundry room plumbing and through the master bath exhaust fan. These areas were sealed again before insulation. The final blower door test was a notable 1.10 ACH50.

Due to the students' schedules, the duct system in the basement was not completed until after drywall. This unusual sequence precluded a planned intermediate duct test. During final testing, total duct leakage was higher than expected, but duct leakage to outdoors was zero as expected. Air balance testing, described below, indicates that the majority of leakage is in the air handler cabinet and return ducts.

All mechanical ventilation ducts were inspected before attic insulation to confirm duct sealing, insulation, and geometry. The measured bath EF airflow rates exceed the nominal ratings and fall along the manufacturer's fan curve for lower static pressure (except the hall bath), indicating a properly designed duct layout. The measured airflow of the hall bath far exceeds design and fan curve data, and indicates a larger capacity fan was installed. The kitchen EF could not be measured at the range hood or termination hood using a standard flow hood, and that duct was not easily accessible in the attic to use a hot-wire anemometer.

The ERV low-speed operation was originally measured at 90 CFM, but reduced to 80 CFM (this ERV has a built-in procedure to adjust motor speeds for airflow and balance). The method to install the stale air exhaust in the living area low on a wall using a standard return duct boot and grille made measuring the airflow using a flow hood a simple matter. The team decided that the

ERV should run continuously at low speed, and the ERV was balanced, to provide a slight positive house pressure, with the air handler off because this condition represents the majority of hours per year. When the air handler operates, the fresh airflow rate will be somewhat higher due to the air handler fan (the stale exhaust airflow rate is more of a constant because that is ducted independently of the distribution duct system). The team considered this the best compromise, because balancing with the air handler operating would have led to a somewhat lower fresh air rate the majority of the time.

The heating and cooling air distribution system was balanced and tested. The dip-switches in the air handler were selected so that the electronically commutated motor drive would provide a nominal 1040/700 (high-stage/low-stage) CFM. Actual high-stage airflow was measured at 1100 CFM using a flow-grid. The supply branch ducts required balancing to be within the 25 CFM/20% ENERGY STAR limit. Measured airflows at all supply registers and return grilles indicated that the majority of duct leakage was due to the air handler cabinet or return ducts or a combination of both. The bedroom transfer grilles provided pressure balance for these rooms within the 3 Pa ENERGY STAR limit. The accuracy of the airflow measurements at the basement registers and grilles is somewhat questionable; the registers and grilles located at the ceiling height of the unfinished basement did not have drywall to place the flow hood against. However, testing was conducted in the cooling mode and supply registers were closed, and the measurements appeared reasonable.

There are no combustion appliances with the potential to back-draft, but the effect of exhaust fan operation on house depressurization was measured for research purposes. The adjusted house depressurization was 8 Pa with the three bath exhaust fans operating, 12 Pa with all bath fans and the kitchen exhaust on low, and 17 Pa with all bath fans and kitchen fan on high.

HVAC commissioning was considered an important component of final testing. A factory technical representative was on site to verify that all equipment was installed and operating within manufacturer specifications. This step was helpful to complete all startup forms and served as a valuable educational component.

The domestic hot water pipe volumes were measured. The volume of the PEX manifold and pipe from the water heater was estimated at 28 ounces. The farthest fixture, by volume, the ½-in. branch run to the hall bath, added approximately 55 ounces, for a total of 83 ounces. Actual flow was measured using a calibrated bucket and thermometer to measure the water temperature rise. Even with a “hot” manifold, this test method required more than 64 ounces of water to produce a 10°F temperature rise. This result may be due in part to the rotary shower valve that allowed a relatively large volume of cold water when initiated; sinks with standard faucets appeared to provide results more in line with expectations.

5 Discussion

5.1 U.S. Department of Energy Challenge Home Certification

The NCTH earned certification by the DOE Challenge Home Program. The mandatory requirements (DOE 2013) are summarized below (Table 12).

Table 12. DOE Challenge Home Mandatory Requirements

Area of Improvement	Mandatory Requirements (summarized)	NCTH
1. ENERGY STAR	Certified under ENERGY STAR Qualified Homes Version 3	Met
2. Envelope	Fenestration shall meet ENERGY STAR requirements. Ceiling, wall, floor, and slab insulation shall meet 2012 IECC levels	Met
3. Duct System	Within the thermal and air barrier boundary	Met
4. Water Efficiency	Hot water delivery systems shall meet efficient design requirements	Exempt
5. Lighting and Appliances	Installed refrigerators, dishwashers, clothes washers are ENERGY STAR qualified 80% of lighting fixtures are ENERGY STAR qualified Bath ventilation fans are ENERGY STAR qualified	Met
6. Indoor Air Quality	U.S. Environmental Protection Agency Indoor airPLUS checklist	Met
7. Renewable Ready	Solar electric checklist Solar thermal checklist	Met

The NCTH meets all other DOE Challenge Home certification requirements except for hot water delivery. The PEX manifold distribution was carefully designed to minimize tubing diameter and length, but the two largest volume runs, both ½-in. serving tubs, exceed the 64-ounce limit by approximately 20 ounces. As of this writing, DOE is reviewing the hot water delivery requirement for the time-temperature profile for hot water fixtures, and is not enforcing the original requirement at this time. The NCTH Home Energy Rating System Index is 45 (ENERGY STAR Target Index is 60; DOE Challenge Home Target Index is 52).

5.2 Insulated Concrete Form Wall Implementation

The footer was formed using a product that integrates the form and perimeter drainage on the interior and exterior and left in place after the concrete is poured (Form-a-drain). A self-adhesive capillary break was installed over the footer. The ICF walls were formed and poured one level at a time. The upstairs walls were constructed directly on the foundation walls, creating a monolithic wall, without framed rim areas, from the footer to the top of the first floor ceiling. A peel and stick water proofing membrane was installed over the footing and 3 ft up the foundation wall, and dimpled water proofing membrane was installed from footer to grade and flashed, to protect the foundation from groundwater. A metal termite shield was let into the EPS, but the continuous exterior foam could be a termite issue in specific mixed-humid climates.

Pressure-treated wood bucks for windows and doors were installed before concrete. At the top of the ICF wall, a treated wood top plate supports high-heel trusses installed 24 in. on center. The 2-in. × 12-in. bucks and top plates were rip-cut to 11 in. to cover the entire width of the ICF wall without interfering with interior or exterior finishes. Laminated veneer lumber ledger boards were anchored to imbedded steel connectors to support hangars for the 14-in. open web floor truss joists 24-in. on center (Figure 15).

Figure 15. Floor framing

House wrap, not required by the ICF manufacturer, was installed above grade to help control water entry. Water does not generally affect the foam or concrete but could adversely affect interior finishes. The house wrap also protected the EPS foam from ultraviolet radiation during the summer construction break between academic years (the schedule allowed roof and window installation but not siding before summer break) (Figure 16). Windows and doors were installed after house wrap and flashed using ice and water barriers and butyl flashing tape (Figure 17). Doors were ordered with full depth exterior casings, but arrived with short door-steps that had to be modified in the field (Figure 18). The windows were flanged. Their standard depth casing required finish casings on the interior. After summer break, vinyl siding and a limited amount of brick veneer were installed.

Figure 16. House wrap installed before summer break

Figure 17. Window flashing

Figure 18. Door step details

The ICF manufacturer provided training to install the electric within exterior walls. Interior foam was cut using a hot-knife to rough-in the electrical boxes and wiring. The majority of wiring was installed horizontally within the floor framing and then vertically as required to minimize horizontal wiring runs through the foam. Installing the wire behind the ledger board was tricky at first but proceeded smoothly after the first few. Cutouts in the foam were sealed using spray foam (Figure 19).

Drywall was installed directly on the ICF walls. The basement was not finished, but drywall provided a thermal barrier over the EPS foam (Figure 20).

Figure 19. Foam over rough wiring at ICF

Figure 20. Basement drywall

5.3 Air Sealing and Insulation

The framed portion of exterior walls represented a relatively small area, but required a relatively large effort to air seal and insulate compared to the ICF walls. For the fireplace bump-out, the 2 × 6 wall cavity was sealed at the sheathing, and the bottom plate was sealed at the deck. Next, the wall cavity and ceiling area behind the fireplace were netted and blown with cellulose insulation (Figure 21). Drywall was installed before the direct vent fireplace unit. The cantilevered floor was sealed and insulated from below. The living room cathedral ceiling exterior gable was sealed at the sheathing, and then netted and blown with cellulose the full 11-in. depth of the ICF (Figure 22 and Figure 23). Similarly, the opposing knee wall gable at the vented attic was sealed and installed in this same fashion after a rigid foam air barrier was installed (Figure 24 and Figure 25).

Figure 21. Fireplace bump-out

Figure 22. Framed gable before air sealing and insulation

Figure 23. Framed gable after air sealing and insulation

Figure 24. Knee wall air barrier

Figure 25. Knee wall insulation

Penetrations, rough openings for windows and doors, and the truss bearing plates at the top of the ICF walls were sealed in a conventional manner using canned spray foam. One student sealed the ceiling plane at all top plates (Figure 26), penetrations, and air barrier at the top of the HVAC duct chase (Figure 27) using canned spray foam. This approach to seal the ceiling plane from the attic allowed for inspection, testing, and remediation before attic insulation. For the tray ceiling in the dining room, drywall was installed at the ceiling, and sides, and sealed before the tray framing, so no additional air sealing was required from the attic for this detail. An insulation dam was built at the attic access to prevent the blown R-49 attic insulation from spilling (Figure 28).

Figure 26. Sealed top plate

Figure 27. Sealed air barrier at the HVAC duct chase

Figure 28. Insulation dam at attic access

5.4 Hot Water

The hot water system components are shown in Figure 29. The solar hot water tank has an integral heating element for backup heating to the solar supply. The PEX manifold water distribution system includes potable water delivery as well as filtered rain water delivery to the outdoor spigots, toilets, and clothes washer.

Figure 29. Solar hot water storage tank and PEX piping manifold

5.5 Lighting

The students designed and installed an impressive combination of LED ambient, task, and accent lighting in the kitchen (Figure 30). Wall sconces in the hall in lieu of standard ceiling fixtures helped to minimize ceiling penetrations. All lighting was LED or CFL fixtures or bulbs.

Figure 30. High efficacy lighting in the kitchen

5.6 Heating and Cooling Design

The heating and cooling duct distribution design operates very quietly during high-speed air handler operation, and provides good air mixing and even temperatures throughout the house based on a number of measurements during four visits during the cooling season. During one visit, relative humidity in the basement was 60%. This measurement was made (during a humid period when the doors were mostly open due to ongoing construction), and a dehumidifier was installed temporarily to control humidity. As mentioned, the 3-ton, 2-stage heat pump was sized to satisfy cooling in low-stage; a 2-ton, 2-stage system would dehumidify better, but the tradeoff was improved heating capacity for this climate. Potentially, higher humidity could be the result of concrete curing within the walls or the recently poured basement floor.

5.7 Mechanical Ventilation Design

The measured airflows of the bath exhaust fans exceeded nominal ratings because all had a low resistance duct layout (even fewer linear feet and elbows than designed for) (Figure 31). Ventilation ducts were rigid metal, larger diameter than standard, sealed with mastic, and insulated to prevent condensation. Two of the fans terminated at a low pressure drop soffit hood (Figure 32). The third, and the kitchen range exhaust, terminated at a gable wall.

Figure 31. Short and direct bath exhaust fan duct

Figure 32. Bath exhaust duct termination at soffit

The original plan was to regulate the ERV, operating intermittently on high speed, using a control to take advantage of air handler run times when possible. The heat pump system including the thermostat used a proprietary two-wire communication system that was not compatible with that control, so instead the ERV provides adequate ventilation rates running continuously on low-speed. This appears to be a better solution based on air handler run time, particularly during the moderate swing-season. The dedicated 7-in. oval stale-air duct from the living room (Figure 33) was initially somewhat noisy, objectionable because the air handler could not be heard at all. The duct between the grille boot and the ERV was reworked to minimize turbulence, and this eliminated all ERV system noise. This partially integrated duct layout allows for simple airflow measurement using a flow hood.

Figure 33. Dedicated "stale" air duct in living room

6 Conclusions

6.1 Research Questions

The high performance features of the NCTH were evaluated for energy savings, performance, and cost effectiveness. The design evaluation was used to develop a more cost effective approach to develop solution packages that could apply to CZs 4 and 5. The answers to the research questions from Section 1.4 are presented below.

1. How does the ICF wall system compare with the builder's standard high performance foundation and framed wall systems in terms of estimated energy use?

The design analysis demonstrated that an ICF wall system is a cost-effective option for the climate. When compared with walls of similar insulation, ICF construction is predicted to use less energy. Additionally:

- The ICF foundation wall is predicted to use less energy and estimated to cost at least neutral to a similarly insulated foundation wall. This is considered a "high-R" foundation wall.
- The ICF above-grade wall is predicted to use about the same energy and estimated to cost more to install. This is not considered a "high-R" above-grade wall in this climate.
- Installing additional rigid foam on the ICF walls would be a simple method to increase wall R-value as needed or desired.
- The high level of thermal mass is expected to reduce temperature swings within the rooms and cause the ASHP to operate in low-stage for longer periods, resulting in more even temperatures throughout the house and improved occupant comfort.
- Air sealing is simplified with ICF wall construction, and allows air sealing efforts to be focused on other critical areas such as the ceiling plane (see research question 2).

2. How is the air sealing strategy different for ICF construction?

The ICF wall system resulted in a notably low whole-house infiltration rate at a cost that is no more than air sealing a standard home to modest infiltration levels. The air sealing strategy for ICF construction is somewhat simplified because of the inherently tight wall assembly. This feature increases the relative importance of air sealing at windows and doors, the interface between the roof trusses and the top plate of the wall, and at the ceiling plane. The limited framed exterior walls in the NCTH (fireplace bump-out and living room cathedral ceiling gable) required a relatively large air sealing effort with respect to the small area of wall, reinforcing the air sealing advantages of ICF construction. Use of conventional air sealing techniques that do not require specialized equipment was appropriate to obtain the very low infiltration rate.

3. What are the heating and cooling design, selection, and performance issues and solutions that emerge based on the high performance envelope design in CZ 5?

The heating and cooling system design issues centered on the selection of the fuel type for the heating system and the sizing of the equipment. Fuel selection was of particular interest because the builder did not wish to use a GSHP system due to cost and complexity, and natural gas was not available. Analysis showed that the high efficiency ASHP was much less expensive to operate than a propane gas furnace. A two-stage ASHP was selected to provide sufficient heating capacity, cooling effectiveness, and system response to the ICF walls (the much higher mass in the ICF wall influences heat transfer through the wall and affects how the heating and cooling system responds to changing outdoor conditions). DSHP systems were not considered because LCCTC considers installing a conventional duct distribution system an important educational aspect; DSHP systems offer higher efficiency ratings but hardware costs tend to be higher as well. This project will not be monitored, so the performance of the selected high efficiency, two-stage heat pump system during the heating season will be evaluated based on feedback from LCCTC and the future home owner. An energy efficient ASHP can be the best heating and cooling solution for high performance, low-load homes in a cold climate, even where natural gas is available.

4. Are the proposed methods to ensure effective mechanical ventilation successful?

Yes, the measured airflows for the ERV and bath exhaust fans were well above the nominal capacities and therefore successfully met design expectations. The design approach identifies the duct design friction rate and minimum duct size, so rounding up to the next standard size duct should, and did, result in better than nominal rated performance. For this project, the as-built duct layouts for the bath exhaust fans were shorter than designed for (reduced total-effective-length) and this contributed to the good results. The ERV as-built duct layout was the same as the design, and the measured airflow verified the design method. This approach would benefit from additional termination hood pressure drop or equivalent length data from manufacturers or other industry organizations.

The partially integrated duct layout for the ERV was also successful because it allowed for a simple, single-point airflow measurement using the flow hood, and did not require the air handler to operate to distribute fresh air (although distribution will be better when the air handler is operating). The best solution would be a dedicated duct layout for the ERV to operate independently, but this approach would add cost.

A better method to measure kitchen range hood exhaust airflow is still needed. Using a flow hood to measure airflow at the termination hood from outdoors is not accurate (due to siding irregularities and wind) and may also require a ladder. Using a flow hood indoors would require a custom sleeve. A hot-wire anemometer could work in some situations but not others with limited access. For this project, the fan was rated at 300 CFM on high speed, so achieving the 100 CFM minimum required airflow was not a concern.

5. How do the theoretical domestic hot water system designs compare in terms of performance and cost?

The SDHW system provided the lowest estimated operating cost, but the installed cost was very high. LCCTC elected to use a SDHW system because a portion of the system was donated, continuity with the first two houses in the community, and for educational purposes, but based on analysis SDHW is not considered cost-effective, even with federal or state subsidies. Similarly, the HPWH provided a low estimated operating cost but a relatively high installed cost compared to a conventional electric tank water heater. The HPWH is also not considered cost effective unless subsidies are available. Propane gas alternatives were also not found to be cost effective given the high cost of propane in this market.

6. Are the elements of the energy efficiency package cost effective and market ready?

All selected components of the energy solution package for the NCTH are existing technologies that are market ready.

Building with ICF walls requires some different skill sets, but these skills would be relatively straightforward to acquire and could be worthwhile for a builder interested in making this technology standard practice. ICF construction is deemed cost effective for foundation walls and when used for both foundation walls and above-grade walls. ICF construction may or may not be cost effective if used only for above-grade walls with respect to energy use, but may still be a good choice if other criteria such as sound attenuation and resistance to wind and fire are priorities.

As mentioned above, the solar hot water system is not considered cost effective, and the ASHP is considered cost effective for heating and cooling.

6.2 Key Findings and Lessons Learned

This research addresses the primary Building America goals to develop market-ready solutions that improve energy efficiency, durability, affordability, and comfort. Small and large builders can benefit from the analysis methods used in this report to evaluate and select energy solution components.

ICF wall construction merits consideration as a practical, cost-effective, and energy-efficient alternative to conventional foundation walls and above grade walls for high performance homes in cold climates. For additional thermal insulation, select ICF blocks with thicker foam, or install additional rigid foam on the ICF walls. The sound attenuation and fire resistance properties may be particularly attractive in cities or other noisy environments (e.g., near an airport or train tracks) in all climates.

Attention to air sealing details, in conjunction with ICF construction, resulted in a very tight building envelope at a low incremental cost. An intermediate house leakage test was performed before attic insulation and other interior finishes. This additional test allowed for a few leakage areas to be sealed again, a relatively simple and inexpensive process at this stage, and resulted in a significant improvement of the house leakage rate.

An energy efficient ASHP can be a cost-effective solution to heat and cool low-load homes in a cold climate. Annual energy costs for the high efficiency ASHP nearly equals that of high efficiency natural gas heating and is 30% less than that for high efficiency propane fuel heating, and at a lower installed cost. The two-stage heat pump for this project provides higher heating capacity in high-stage, and sufficient dehumidification and cooling in low-stage. Additionally, the two-stage system is well suited to respond to the expected thermal mass effects of the ICF walls. The ICF walls slow the heat loss from the house because the thermal mass reacts more slowly to changing outdoor conditions (thermal lag), and this effect will generally cause the heat pump system to run in lower speed but for a longer period of time.

The importance of effective mechanical ventilation merits a careful duct layout, similar to those used for heating and cooling systems, to ensure measured ventilation airflows meet design expectations. The approach presented in this report could help HVAC designers and trade partners deliver the benefits of effective ventilation to builders and future occupants in any climate.

Without incentives, SDHW systems may not be as cost effective as other water heating technologies.

The thermal enclosure, heating fuel, and domestic hot water analyses reinforce the concept that for optimum energy performance in a cold climate, investing more in the building enclosure can result in less investment required in the mechanical systems.

Locally, this research project successfully demonstrated a higher energy performance level that is not common in this market. Students and faculty gained practical educational experience building with high performance methods and materials, so a knowledgeable workforce is accelerated into the market. The garage serves as a sales and educational showcase for this and previous Building America projects for prospective buyers and other interested parties in the community (Figure 34). Manufacturers and vendors are eager to participate in these high visibility projects.

Figure 34. ICF display in the garage (sales/education office) of the NCTH

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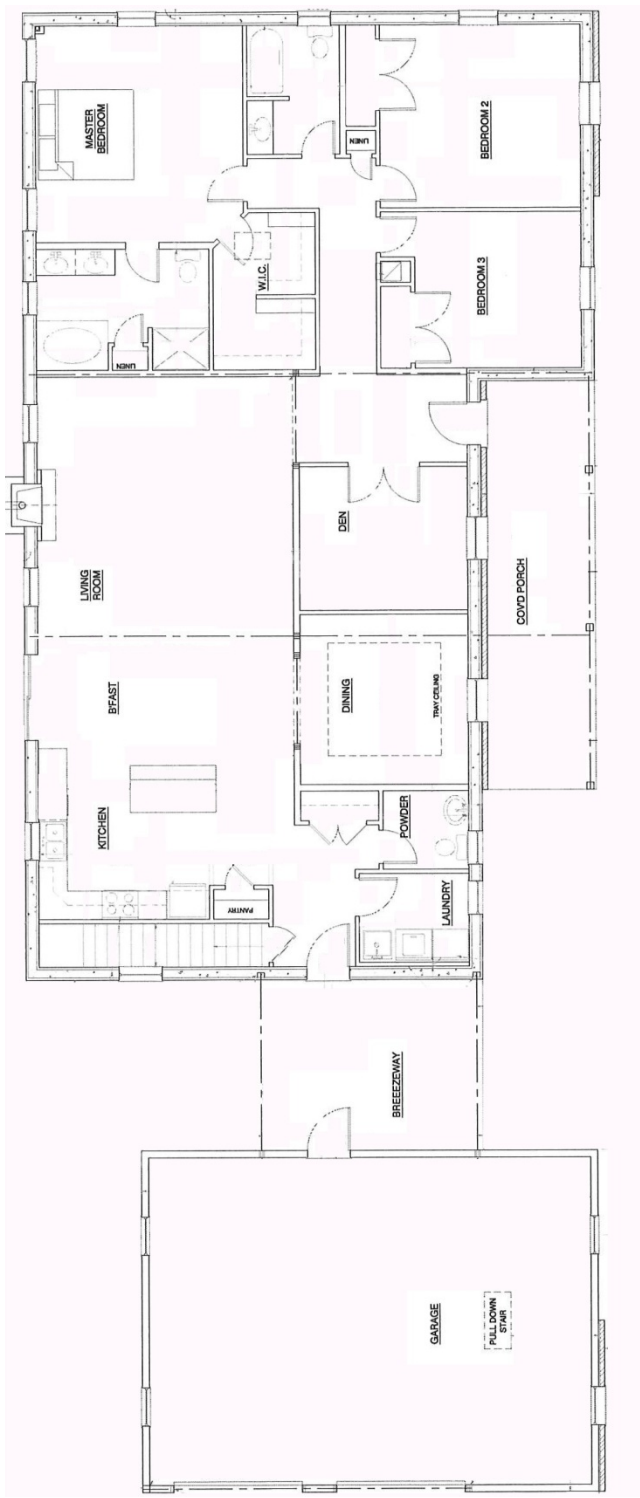
Smegal, J.; Straub, J. (2010). Building America Special Research Project: High-R Foundations Case Study Analysis. BA-1003. Somerville, MA: Building Science Corporation.

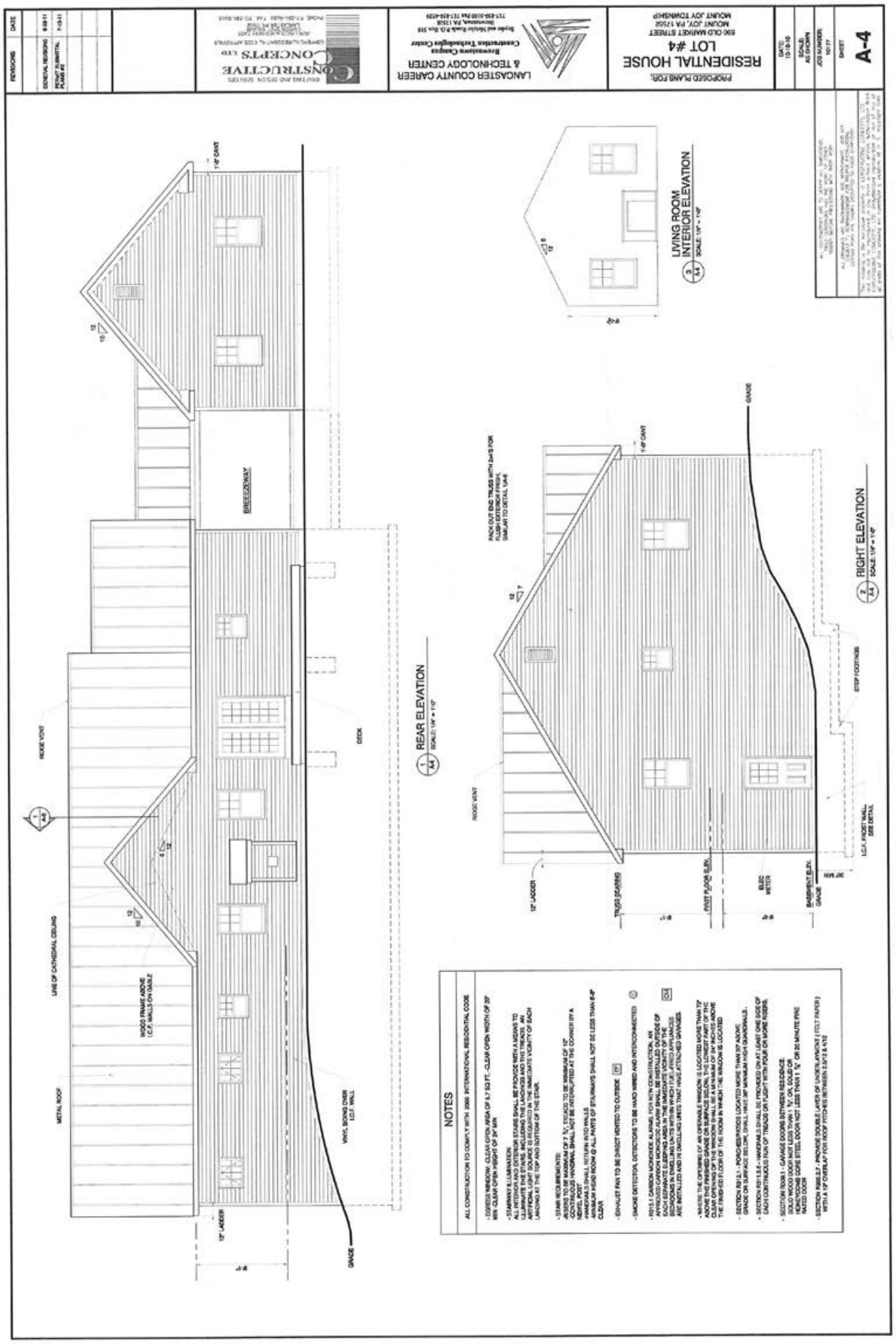
Straube, J. (2010). Building America Special Research Project: High R-Value Enclosures for High Performance Residential Buildings in All Climate Zones. BA-1005 (Rev. 2011). Somerville, MA: Building Science Corporation.

Appendix A: House Plans

LCCTC
Apprentice Green Community, Mount Joy, Pennsylvania




PROPOSED PLANS FOR:
RESIDENTIAL HOUSE
LOT #4
580 OLD MARKET STREET
MOUNT JOY, PA 17552
MOUNT JOY TOWNSHIP
LANCASTER COUNTY CAREER & TECHNOLOGY CENTER
A-3
FRONT ELEVATION
LEFT ELEVATION WITHOUT GARAGE
LEFT ELEVATION WITH GARAGE
BREEZEWAY
METAL ROOF
RIDGE VENT
VINYL SIDING
BRICK VENEER
GRADE



PROPOSED PLANS FOR:
RESIDENTIAL HOUSE
LOT #4
LANCASTER COUNTY CAREER & TECHNOLOGY CENTER
CONSTRUCTIVE CONCEPTS LTD
A-4
BREEZEWAY
REAR ELEVATION
RIGHT ELEVATION
LIVING ROOM INTERIOR ELEVATION
NOTES

Appendix B: Solar Thermal System Rating

CERTIFIED SOLAR SYSTEM

SUPPLIER:
Alternate Energy Technologies
1345 Energy Cove Court
Green Cove Springs, FL 32043 USA
www.aetsolar.com

BRAND:	EAGLESUN INDIRECT SOLAR WATER HEATING SYSTEM
MODEL:	I-80-40
SYSTEM TYPE:	Pumped, Indirect
CERTIFICATION #:	2010082I
Original Certification:	June 10, 2011
Expiration Date:	October 29, 2014

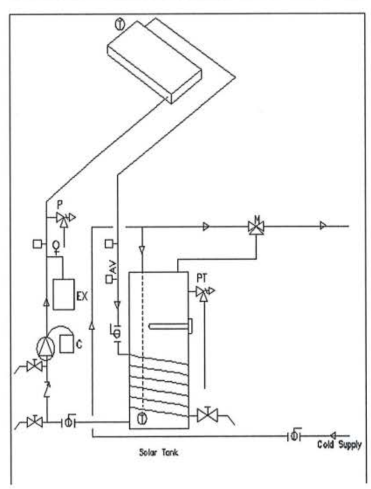
The solar system listed below has been evaluated by the Solar Rating & Certification Corporation™ (SRCC™) in accordance with SRCC OG-300, Operating Guidelines for Certifying Solar Water Heating Systems, and has been certified by the SRCC. This award of certification is subject to all terms and conditions of the Program Agreement and the documents incorporated therein by reference.

Description: Glazed Flat Plate, Differential, 2 °C 35 °F, Non-GRAS, UL listed electric tank, Drainback & Fluid, Tank high limit

Single-day Rating	
Solar Energy Factor (SEF_D)	Solar Fraction (SF_D)
1.80	0.51

Single-day Rating Conditions:
SEF_D = Solar Energy Factor (info link)
SF_D = Solar Fraction (info link)

SINGLE DAY RATING CONDITIONS	SI Units	Inch-Pound Units
System Set Temperature	57.2 °C	135 °F
Environmental Temperature	19.7 °C	67.5 °F
Ambient Temperature Profile Average	14.4 °C	58 °F
Water Mains Temperature	14.4 °C	58 °F
Delivered Load	43.3 MJ/day	41,045 Btu/day
Solar Irradiance	4,733 Wh/m^2-day	1,500 Btu/ft^2-day



Storage Tank(s)	
Solar Tank Vol (l)	Solar Tank Vol (gal)
303	80
Approximate Collector Area: 3.7 m², 39.8 ft²	

The solar water system listed here has been certified by the SRCC as meeting the minimum standards for testing, installation, operation, maintenance, performance, reliability and safety as specified in SRCC Document OG-300. Thermal performance ratings are based on the successful durability and performance testing of a sample collector, where said tests have been conducted by an independent laboratory approved and listed by the SRCC. The system has been modeled using the computer simulation program TRNSYS to calculate the ratings.

Before the Supplier can make any change in design, materials, specifications, parts, or construction, the change(s) must be reported to the SRCC for evaluation of continued certification.

REMARKS:

Jim Huggins
Technical Director

Print Date: November, 2012

www.solar-rating.org ♦ 400 High Point Drive, Suite 400 ♦ Cocoa, Florida 32926 ♦ (321) 213-6037 ♦ Fax (321) 821-0910

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CERTIFIED SOLAR SYSTEM

SUPPLIER:
Alternate Energy Technologies
1345 Energy Cove Court
Green Cove Springs, FL 32043 USA
www.aetsolar.com

BRAND:	EAGLESUN INDIRECT SOLAR WATER HEATING SYSTEM
MODEL:	I-80-40
SYSTEM TYPE:	Pumped, Indirect
CERTIFICATION #:	20100821
Original Certification:	June 10, 2011
Expiration Date:	October 29, 2014

The solar system listed below has been evaluated by the Solar Rating & Certification Corporation™ (SRCC™) in accordance with SRCC OG-300, Operating Guidelines for Certifying Solar Water Heating Systems, and has been certified by the SRCC. This award of certification is subject to all terms and conditions of the Program Agreement and the documents incorporated therein by reference.

Annual Ratings in PA-HARRISBURG		
Solar Energy Factor (SEF_A)	Solar Fraction (SF_A)	Energy Savings (kWh)
1.70	0.46	2040

Annual Rating using hourly weather data for the chosen city:
SEF_A = Solar Energy Factor (info link)
SF_A = Solar Fraction (info link)
Energy Savings = Estimated annual energy saved compared to a conventional water heater using the same type of backup

Only the following options for the collector array are approved:

Option	Collector Panel Manufacturer	Collector Panel Request Number	Collector Panel Model Number	Collector Panel Name	Quantity	Total Panel area(m²)	Total Panel area(ft²)
1	Alternate Energy Technologies	2002001F	AE-40	Alternate Energy	1	3.70	39.79

Option	Collector Panel Manufacturer	Collector Panel Request Number	Collector Panel Model Number	Collector Panel Name	Quantity	Total Panel area(m²)	Total Panel area(ft²)
2	Alternate Energy Technologies	2002002F	MSC-40	Morning Star	1	3.92	42.15

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CERTIFIED SOLAR SYSTEM

SUPPLIER:
Apricus Inc.
P.O. Box 167
6 Sycamore Way. Branford
Branford, CT 06405 USA
http://www.apricus-solar.com

BRAND:	APSS_CLOSED_AP30_FTB-E-1
MODEL:	APSS_CLOSED_AP30_FTB-E-1
SYSTEM TYPE:	Pumped, Indirect
CERTIFICATION #:	2011074A
Original Certification:	June 21, 2011
Expiration Date:	October 17, 2020

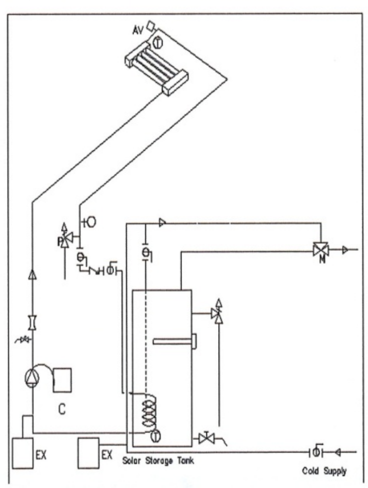
The solar system listed below has been evaluated by the Solar Rating & Certification Corporation™ (SRCC™) in accordance with SRCC OG-300, Operating Guidelines for Certifying Solar Water Heating Systems, and has been certified by the SRCC. This award of certification is subject to all terms and conditions of the Program Agreement and the documents incorporated therein by reference.

Description: Tubular, Differential, -46 °C -50 °F, GRAS, UL listed electric tank, Fluid, Recirculation

Single-day Rating	
Solar Energy Factor (SEF_D)	Solar Fraction (SF_D)
2	0.55

Single-day Rating Conditions:
SEF_D = Solar Energy Factor (info link)
SF_D = Solar Fraction (info link)

SINGLE DAY RATING CONDITIONS	SI Units	Inch-Pound Units
System Set Temperature	57.2 °C	135 °F
Environmental Temperature	19.7 °C	67.5 °F
Ambient Temperature Profile Average	14.4 °C	58 °F
Water Mains Temperature	14.4 °C	58 °F
Delivered Load	43.3 MJ/day	41,045 Btu/day
Solar Irradiance	4,733 Wh/m^2-day	1,500 Btu/ft^2-day



Storage Tank(s)	
Solar Tank Vol (l)	Solar Tank Vol (gal)
303	80
Approximate Collector Area: 4.2 m², 44.8 ft²	

The solar water system listed here has been certified by the SRCC as meeting the minimum standards for testing, installation, operation, maintenance, performance, reliability and safety as specified in SRCC Document OG-300. Thermal performance ratings are based on the successful durability and performance testing of a sample collector, where said tests have been conducted by an independent laboratory approved and listed by the SRCC. The system has been modeled using the computer simulation program TRNSYS to calculate the ratings.

Before the Supplier can make any change in design, materials, specifications, parts, or construction, the change(s) must be reported to the SRCC for evaluation of continued certification.

REMARKS:

Jim Huggins
Technical Director

Print Date: November, 2012

www.solar-rating.org ♦ 400 High Point Drive, Suite 400 ♦ Cocoa, Florida 32926 ♦ (321) 213-6037 ♦ Fax (321) 821-0910

CERTIFIED SOLAR SYSTEM

SUPPLIER:
Apricus Inc.
P.O. Box 167
6 Sycamore Way. Branford
Branford, CT 06405 USA
http://www.apricus-solar.com

BRAND:	APSS_CLOSED_AP30_FTB-E-1
MODEL:	APSS_CLOSED_AP30_FTB-E-1
SYSTEM TYPE:	Pumped, Indirect
CERTIFICATION #:	2011074A
Original Certification:	June 21, 2011
Expiration Date:	October 17, 2020

The solar system listed below has been evaluated by the Solar Rating & Certification Corporation™ (SRCC™) in accordance with SRCC OG-300, Operating Guidelines for Certifying Solar Water Heating Systems, and has been certified by the SRCC. This award of certification is subject to all terms and conditions of the Program Agreement and the documents incorporated therein by reference.

Annual Ratings in PA-HARRISBURG		
Solar Energy Factor (SEF_A)	Solar Fraction (SF_A)	Energy Savings (kWh)
2.10	0.57	2540

Annual Rating using hourly weather data for the chosen city:
SEF_A = Solar Energy Factor (info link)
SF_A = Solar Fraction (info link)
Energy Savings = Estimated annual energy saved compared to a conventional water heater using the same type of backup

Only the following options for the collector array are approved:

Option	Collector Panel Manufacturer	Collector Panel Request Number	Collector Panel Model Number	Collector Panel Name	Quantity	Total Panel area(m^2)	Total Panel area(ft^2)
1	Apricus Inc.	2007033A	AP-30	Apricus	1	4.16	44.76

buildingamerica.gov

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE/GO-102014-4485 ▪ September 2014