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Building America Residential System Research Results: Achieving 30% Whole House Energy Savings Level in Cold Climates

U.S. Department of Energy
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Building Technologies Program

Building America Residential System Research Results: Achieving 30% Whole House Energy Savings Level in Cold Climates

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Definitions

ACCA	Air Conditioning Contractors of America
ACH	air changes per hour
ACT2	Advanced Customer Technology Test for Maximum Energy Efficiency
AFUE	Annual Fuel Utilization Efficiency
AHU	air-handler unit
ALA	American Lung Association
ASHRAE	American Society of Heating
BECT	Building Energy Code Training
BEopt	Software for identifying optimal building design
BESTEST	A benchmark for building energy simulation: Building Energy Simulation Test and Diagnostic Method
BII	Building Industry Institute
BPI	Building Performance Institute
CAD	computer-aided design
CDCU	Community Development Corporation of Utah
CEC	California Energy Commission
CFL	compact fluorescent bulbs
CFM	cubic feet per minute
CRI	color-rendering index
CT	color temperature
DHW	domestic hot water
DOE	U.S. Department of Energy
DOE2	Building energy analysis program that can predict the energy use and cost for all types of buildings
ECM	electronically commutated motor
EDHA	Eastern Dakota Housing Alliance
EEBA	Energy and Environmental Building Association
EEM	Energy-efficient mortgages
EER	Energy Efficiency Rating
EF	energy factor

EFL	Environments for Living®
EGUSA	Energy-Gauge USA software (FSEC's residential front-end user interface for DOE2.1E simulation tool)
EPA	U.S. Environmental Protection Agency
EPS	expanded polystyrene
ERV	Energy recovery ventilation
FF	framing factor
FFA	finished floor area
FG	fiberglass
GenOpt	generic optimization program
HVAC	heating, ventilation, and air conditioning
HERS	Home Energy Rating System developed by RESNET
HPL	high-performance lighting
HRV	heat recovery ventilators
HSPF	Heating Seasonal Performance Factor
HUD	U.S. Department of Housing and Urban Development
IAQ	Indoor air quality
IDEC	Indirect-Direct Evaporative Cooler
IDP	Integrated Design Process
IECC	International Energy Conservation Code
IEQ	Indoor Environmental Quality
IOSEU	incremental overall source energy use
Mcf	million cubic feet
MEC	Model Energy Code
MEF	modified energy factor
MERV	Minimum Efficiency Reporting Value
NAECA	National Appliance Energy Conservation Act
NAHB	National Association of Home Builders
NASEO	National Association of State Energy Officials
NATE	North American Technician Excellence
NHQ	National Housing Quality
NZEH	net zero energy home
OA	outdoor air

OASys	an indirect/direct evaporative cooler
oc	on center
OSB	oriented strand board
PA	Pascal
PATH	Partnership for Advancing Technology in Housing
PEX	cross-linked Polyethylene tubing
PITI	principal, interest, tax, and insurance
PSC	permanent split-capacitor motors
PV	photovoltaics
R-Value	A measure of thermal resistance used to describe thermal insulation materials in buildings
R.A.P.	return-air pathway
RESNET	Residential Energy Service Network
RH	relative humidity
SA	supply air
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
SHW	solar hot water
SLA	specific leakage area
SIP	Structural insulated panels
TAB	testing, adjusting, and balancing
TMY2	Typical Meteorological Year weather data
TOU	time of use
UL	Underwriter's Laboratory
U-Value	The thermal transmittance of a material, incorporating the thermal conductance of the structure along with heat transfer resulting from convection and radiation.
UA	heat loss coefficient
VOC	volatile organic compounds
WUFI	Modeling program for simulating heat and moisture transfer
XPS	extruded polystyrene
ZEH	zero energy home
ZNE	zero net energy

Abstract

The Building America program conducts the system research required to reduce risks associated with the design and construction of homes that use an average of 30% to 90% less total energy for all residential energy uses than the Building America Research Benchmark, including research on homes that will use zero net energy on annual basis.

To measure the program's progress, annual research milestones have been established for five major climate regions in the United States (Table A). The system research activities required to reach each milestone take from 3 to 5 years to complete and include research in individual test houses, studies in pre-production prototypes, and research studies with lead builders that provide early examples that the specified energy savings level can be successfully achieved on a production basis. As additional homes are completed at each performance level, future studies will be conducted to confirm the average energy savings of large numbers of homes and the impacts of improved housing quality on builder warranty and callback costs.

Two criteria are used to evaluate progress toward annual Building America research goals:

1. At a minimum, system energy savings must be achievable at neutral cost relative to the Building America Research Benchmark.
2. System solutions must be "production-ready" and meet minimum constructability, reliability, durability, and availability requirements to be implemented successfully by lead builders.

This report summarizes research results for the 30% energy savings level and demonstrates that lead builders can successfully provide 30% homes in the Cold Climate Region on a cost-neutral basis. These research results represent the early starting point for the construction of increased numbers of high-performance homes. The broad diffusion of 30% homes in the Cold Climate Region will depend upon a number of other factors in addition to the research results presented in this report, including the level of technical support provided by federal, state, and local deployment programs, the consumer cost of energy, and the development of policy incentives that support implementation of whole-house residential energy efficiency strategies.

Table A. Target Energy Savings for Five Major Climate Regions in the United States

Target Energy Savings	Marine	Hot Humid	Hot-Dry / Mixed-Dry	Mixed Humid	Cold
30%	2006	2007	2005	2006	2005
40%	2008	2010	2007	2008	2009
50%	2011	2015	2012	2013	2014

Executive Summary

Background

Building America uses a team-based systems-research approach to identify cost and performance trade-offs that improve whole-building performance and value while minimizing increases in overall building cost when applied on a production basis. This systems-research approach is applied to the development of advanced energy-efficient residential buildings using system-performance studies in test houses, pre-production houses, and community-scale developments. Research includes analysis of system performance and cost tradeoffs as they relate to whole-building energy performance and cost optimization, including interactions between advanced enclosure designs, mechanical and electrical systems, lighting systems, space-conditioning systems, hot water systems, appliances, miscellaneous electric loads, energy control systems, and onsite power generation systems. Research results are documented in technical research reports that serve as references for students, educators, building scientists, architects, designers, and engineers.

The overall objective of Building America is to develop integrated energy efficiency and onsite/renewable power solutions that can be successfully used on a production basis to reduce whole-house energy use in new homes by an average of 50% by 2015 and 90% by 2025 relative to the Building America Research Benchmark, including homes that are capable of achieving zero net energy (ZNE) use on an annual basis. Building America's energy-saving goals form the core of the research effort and have been staged to complete an additional 10% of incremental savings every 3 to 5 years. To ensure meeting the interim targets along the path to Zero Energy Homes (ZEH), Building America has specified performance targets for each climate region, as shown in Table ES-1. The climate regions defined by Building America can be seen in Figure ES-1. Technical performance requirements to meet these targets are driven by regional differences in building energy loads and construction techniques. The purpose of this report is to provide an overview of three years of Building America systems research that led to the development of production-scale homes that can be built cost-effectively and can reduce whole-house energy use by 30% relative to the Benchmark in the Cold Climate Region.

Table ES-1. Building America Performance Targets by Climate Region

Target Energy Savings	Marine	Hot Humid	Hot-Dry / Mixed Dry	Mixed Humid	Cold
30%	2006	2007	2005	2006	2005
40%	2008	2010	2007	2008	2009
50%	2011	2015	2012	2013	2014

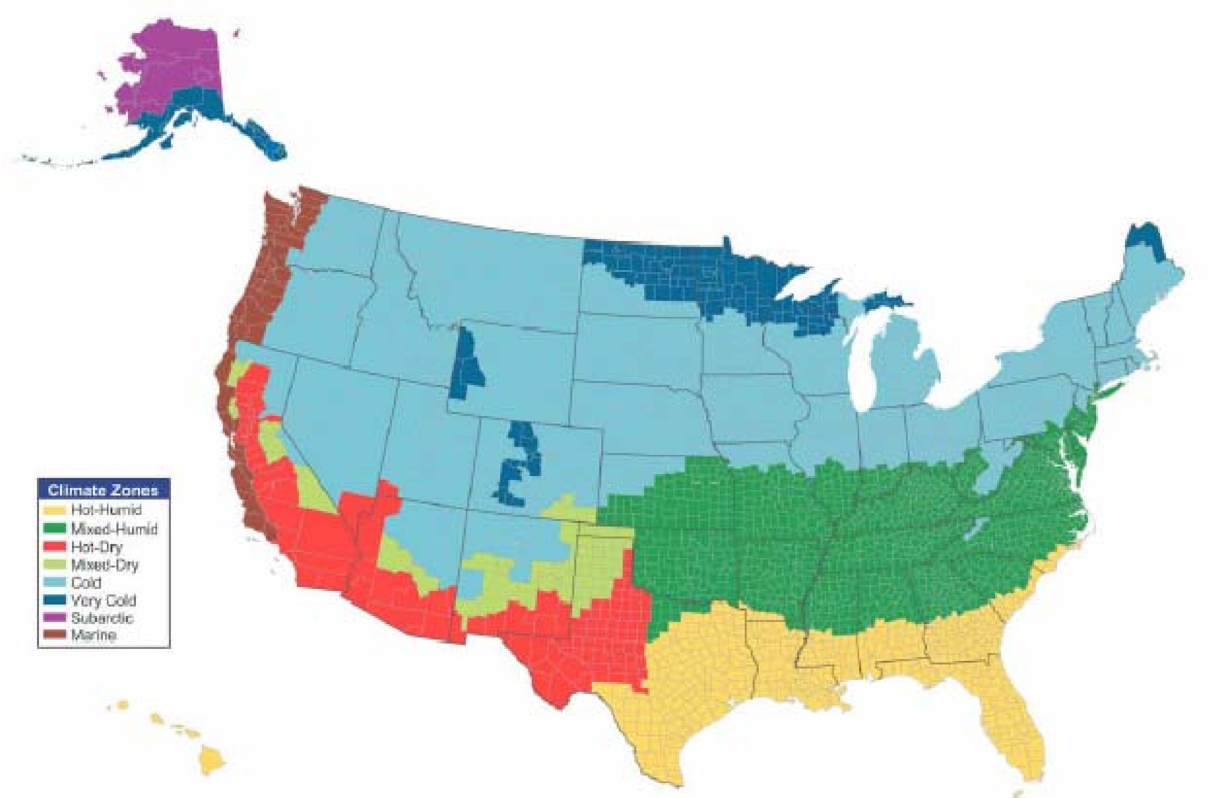

Figure ES-1. Building America climate regions

To ensure a well-defined reference for evaluation of energy savings and progress toward multi-year goals, a detailed Benchmark building definition has been developed for use by all participants in Building America research projects. The Benchmark is generally consistent with the 1999 Home Energy Rating System (HERS) Reference Home, with additions that allow the evaluation of all home energy uses. The Benchmark represents typical standard practice in the mid-1990s, when DOE initiated the Building America program. A standard reporting format for research results has also been developed to facilitate comparisons of performance between different research projects.

Design Strategies

This report is not intended to be an exhaustive design guide. Rather, the intent is to document the results of several years of research on houses that reduce whole-house energy use by 30% compared to the Benchmark in Cold climates. Specific design strategies are recommended once proven effective and reliable in production housing built by Building America partners. Other alternatives may be equally or even more cost-effective depending on the specific housing type, micro-climate, risk tolerance, market conditions, and builder cost structure, along with many other considerations.

To achieve the 30% level of energy savings, it is not necessary to orient homes in any particular direction. It is also not necessary to undertake any special passive solar-design strategies, though it should be recognized that proper orientation of the building and implementation of passive solar strategies can be a low or no-cost method to significantly improve the energy performance of a house.

An Integrated Design Process (IDP) ensures that all the key players and design consultants, including the architect, planner, mechanical engineer, landscape architect, energy consultant and the site engineer, work together starting with the conceptual design stage, even though the role of each may be limited for a particular design stage. The IDP is a key aspect in achieving the systems-design approach. By utilizing an IDP, builders are better able to incorporate the 30% improvement level strategies with less disruption of their normal construction process and to do so cost effectively. Creating specific high-performance goals early in the design process will also allow the design and construction team and their external vendors to have a clear understanding of the intent and performance metrics associated with the design.

A key component of high-performance system design and any high-performance construction process is quality project management. In the context of Building America high-performance homes, quality management is an ongoing effort to systematically and comprehensively improve customer-focused satisfaction with emphasis on methods and processes that yield an optimal combination of energy efficiency, comfort, durability, indoor air quality, and moisture management. This definition recognizes quality management as an integral part of achieving 30% whole house energy savings, and encompasses homebuyer expectations of performance with energy efficiency as just one of several performance attributes that any home should provide.

In high-performance home building, quality is only achieved with performance standards for design AND materials (specifications) AND installation (scopes). Building America takes this premise one step further by stating that many performance standards must be climate-specific; indeed even lot-specific when local terrain and environments bring with them additional challenges, such as extreme slopes, expansive soils, coastal high winds and flooding. Training is also an essential element of quality in the Building America program. Ongoing efforts within the industry are necessary to develop, deploy, and continually update training programs to disseminate accurate information. Also important are verification tools for both performance and quality, including performance testing and inspection checklists. In general, for production builders, Building America has recommended a testing strategy similar to the EPA ENERGY STAR® strategy of 1-in-7 random testing after a period of 100% testing to verify that key performance metrics are met on a consistent basis. Commissioning is also critical for ensuring that the house developed through the whole-building design process is successfully constructed and operates as intended.

In general, Building America houses at the 30% energy savings level in the Cold Climate Region include increased levels of thermal insulation, low-e windows, significant air sealing, a strategy that eliminates the possibility of introducing the by-products of combustion into the house, a mechanical ventilation system, a properly sized and engineered space-conditioning system, higher efficiency space-conditioning and water-heating appliances, and may also include improvements in the efficiency of the appliances and lighting. The extent to which any of these strategies must be implemented varies by the specific micro-climate within the Cold Climate Region, and the level of energy performance the builder is seeking to achieve.

In order to function as an environmental separator, the elements, components, assemblies, and sub-systems that comprise a house must control the flows of heat, air, rainwater, groundwater, and water vapor.

Exterior walls are usually wood-frame construction with 2x6 framing and cavities insulated with fiberglass batts, spray-applied cellulose, or low-density spray-applied foams. The 2x4 framing may also be acceptable in parts of the Cold Climate region when used with insulating sheathing. However, insulating sheathing of sufficient thickness moves the condensation temperature out of the framing and allows the removal of interior vapor barriers and increasing the permeability of vapor retarders, thereby enhancing the inward drying capability of the assembly and reducing the likelihood of moisture problems. An interior vapor diffusion retarder with permeability less than 1 perm is recommended if insulating sheathing is not used. Fenestration with a maximum U-value of 0.35 and with a SHGC value of 0.4 or lower is recommended, primarily for comfort reasons. An interior air barrier is necessary and is most cost effectively obtained using interior gypsum sheathing combined with framing elements, such as draft-stopping and fire-stopping components. Installing both interior and exterior air-barrier systems can address the weaknesses of each. The air leakage target should be less than 2.5 in.^{2} per 100 ft^2 of thermal envelope area. The approach to rainwater control is to shed water by layering wall materials in such a way that water is directed downward and outward from the building. This principle applies not only to walls, but to assemblies such as roofs and foundations, as well as to the components that can be found in walls, roofs, and foundations such as windows, doors, and skylights.

When using slab-on-grade construction in Cold Climates, it is recommended that the concrete slab be thermally isolated from the ground and outdoor air. Passive sub-slab ventilation is recommended to reduce atmospheric air pressure soil gas drivers. Crawlspaces may be conditioned by insulating the crawlspace walls and supplying conditioned air either via a dedicated duct or via transfer air from the house with a continuously operating exhaust fan in the crawlspace. Alternatively, crawlspaces may be vented and insulated above the crawlspace as long as any ducts located in the crawlspace are well-sealed and insulated. The recommended approach for basements includes insulating and conditioning the basement. Interior rigid foam insulation is the insulation system of choice for both basement and crawlspace walls because it is not water sensitive.

As long as there is no ductwork planned for the attic space, the optimum approach to roof insulation involves blowing insulation on the top surface of ceiling gypsum board. Roof trusses should be constructed in such a manner such that the full thickness of ceiling insulation is maintained completely to the top plates of the exterior wall framing. It is recommended that all ductwork be placed in conditioned space; however, if there is ductwork in the attic space, the ducts should be buried under the insulation to minimize air leakage and thermal losses from the ductwork.

To accomplish the target of 30% whole-house energy savings in the Cold Climate region, a sealed-combustion condensing furnace is recommended. Sealed-combustion furnaces use outdoor air for combustion and can be easily located within the conditioned space. In regions where natural gas is not available, a high efficiency electric heat pump is recommended.

30% performance goal is generally achievable by applying air conditioners that meet the minimum 2006 federal (NAECA) standard of 13 SEER. This is particularly true if efficient duct systems are employed and if cooling loads are reduced by incorporating high performance (Low-

E^2) windows and architectural window shading in the design. However, it should be noted that there is a wide range of cooling requirements in the Cold climate region, and the SEER rating should be evaluated based on annual hours of operation. In general, the greater the cooling need, the higher the SEER rating should be. Designers also need to check the mean coincident wet-bulb temperature at outdoor design conditions and select equipment based on this. This strategy helps to prevent oversizing of the equipment. All space heating and cooling systems should be sized according to the procedures described in ACCA Manuals J and S.

It is recommended that all ductwork to be located within the thermal envelope of the house. Methods for locating the duct system within the conditioned space include the use of open-web floor trusses, dropped ceilings and soffits, interior chase walls with duct risers (exterior walls should not be used as chase walls), modified roof trusses, or an unvented or “cathedralized” attic. The “best” method for locating ducts in conditioned space depends upon the house plan, the type of foundation, and the builder’s preferences. The ducts may also be buried in attic insulation. Central hard-ducted returns are recommended with passive return air paths such as jump ducts or transfer grilles from bedrooms. If ducts cannot be brought within conditioned space, supply ducts should be insulated to R-8 minimum and return ducts to R-4 minimum.

Furnaces or air handlers with “variable-speed” brushless permanent magnet (BPM) DC motors are recommended. These motors are more efficient at lower speeds than the more common permanent split-capacitor (PSC) type motors. Efficiency at lower speed operation is increasingly important for systems that feature multiple gas firing stages, enhanced dehumidification capability during cooling, air cleaning equipment, or integrated ventilation.

Providing good indoor air quality (IAQ) at the 30% improvement level is important to maintain occupant health and comfort and may minimize the possibility of high humidity levels and associated mold growth. Because 30% houses will have higher levels of insulation (which affects enclosure hygrothermal characteristics) and because they will be reasonably air tight (which will affect internal moisture gain and removal), good IAQ requires a more proactive approach. There are several approaches to good IAQ, including control of pollutant-generating sources, removal of the contaminants from the indoor air by ventilation, and air filtration or cleaning. A whole house mechanical ventilation system is recommended, such as an exhaust-only system rated for continuous duty, a supply-only system integrated with the central air-handling unit or a heat-recovery ventilator.

For high-performance, low-sensible-heat gain homes, there may be a need for supplemental dehumidification during the mild swing seasons and at night. However, houses in the Cold Climate are less likely to require supplemental dehumidification, Because the outdoor air dewpoint is almost always at or below a comfortable interior level. In this case, outdoor ventilation air can be used to dilute interior moisture without the need for separate dehumidification.

Tankless water heaters offer the best efficiency for domestic water heating within the Cold Climate region. If electricity is the energy source for water heating, additional improvements to other areas of the house will likely be needed to achieve the 30% savings levels, because there is very little room for improvement in electric water-heating efficiency compared to the possible efficiency gains using gas-fired technologies. .

Simple screw-in CFL substitution is a viable strategy at the 30% level; however, there are questions as to the persistence of energy savings because the homeowner is free to replace the

CFL with a traditional incandescent light bulb. A High-Performance Lighting (HPL) approach using a full complement of hard-wired, dedicated compact and linear fluorescent fixtures does not appear to be cost effective for a house at the 30% improvement level.

At the present time, the best practice recommendation for the 30% improvement house is to use ENERGY STAR-rated appliances. Within the ENERGY STAR-rated offerings, there are differences in performance levels, but these are probably not of significance at the 30% improvement level.

At the 30% energy savings level, it is not required to address the miscellaneous electric load (MEL) category.

On-site power systems such as photovoltaic systems and fuel cells are very costly and are not cost effective as a strategy to achieve the 30% energy savings level.

All of these systems must be properly designed and applied to realize both energy-related and non-energy performance benefits associated with occupant health, safety, comfort and long-term building durability and efficiency.

One of the key challenges in developing best practice recommendations is to develop an approach that quickly focuses on combinations of measures that represent the least-cost solutions for a given level of energy savings. To address this challenge, NREL has developed an iterative trade-off analysis method, which identifies packages of energy efficiency measures that provide energy savings at an annual cost that is less than or equal to the utility cost for a reference house when energy improvements are financed as part of a 30-year mortgage.

Use of this method of analysis for one- and two-story homes in Chicago helps to identify the trends that result in a home that saves 30%-39% whole-house energy relative to the Benchmark. The results suggest that several envelope, mechanical equipment duct and lighting improvements are necessary to meet the 3% savings level in Chicago. A tight envelope and R-19 walls, R-40 ceiling insulation, low-e windows, gas-tankless water heater, and a condensing furnace combined with ducts inside conditioned space, appear to be sufficient. At the 39% level higher SEER air conditioning systems, additional basement insulation and efficient appliance measures may be needed. Of course other considerations, such as durability, comfort, aesthetics, and health, are also important, but cannot be easily addressed in an automated optimization program.

Through the use of systems engineering and operations research, the Building America program has shown that homes that save 30% whole-house source energy in Cold Climates can be built on a cost-neutral basis by production builders while improving comfort, reliability, durability, and indoor air quality. A series of five case studies are presented in this report, documenting some of the important cost and performance trade-offs that were made by Building America builder partners in order to achieve the 30% energy-savings target in a production context. While the specific combinations of technologies described in this document may not represent cost-optimal solutions for all areas and housing types covered by the Cold Climate, the key features of the approaches demonstrated in each of these examples can be adapted as needed to provide homes that achieve at least 30% whole-house energy savings in a cost-neutral manner.

Building America Residential System Research Results: Achieving 30% Whole House Energy Savings Level in Cold Climates

Introduction

About Building America

Purpose

The objective of the Building America Program is to develop innovative system-engineering approaches to advanced housing that will enable the housing industry in the United States to deliver energy-efficient, affordable, and environmentally sensitive housing while maintaining profitability and competitiveness of homebuilders and product suppliers in domestic markets. For innovative building energy technologies to be viable candidates over conventional approaches, it must be demonstrated that they can cost-effectively increase overall product value and quality while significantly reducing energy use and use of raw materials when used in community-scale developments. To make this determination, an extensive, industry-driven, team-based, system-engineering research program is necessary to develop, test, and design advanced-building energy systems for all major climate regions of the United States in conjunction with material suppliers, equipment manufacturers, developers, builders, designers, and state and local stakeholders.

Building America research results are based on use of a team-based systems-research approach, including use of systems-research techniques[1] and cost and performance trade-offs that improve whole-building performance and value while minimizing increases in overall building cost. Figure 1 shows the Building America system-research approach in its most basic form. Building America is an analysis-focused research program that specifically targets technical barriers that limit residential system energy performance. Building America applies system research approaches to the development of advanced energy-efficient residential buildings using system-performance studies in test houses, pre-production houses, and community-scale developments. Research includes analysis of system performance and cost tradeoffs as they relate to whole-building energy performance and cost optimization, including interactions between advanced envelope designs, mechanical and electrical systems, lighting systems, space-conditioning systems, hot water systems, appliances, plug loads, energy-control systems, and onsite power generation systems. Use of a systems approach creates process innovations that improve efficiency and flexibility of housing production and increase control over component interactions that improve house efficiency and performance.

Use of a systems approach also accelerates adoption of new technologies by increasing integration between the design and construction process, increasing system performance, increasing system cost effectiveness, and increasing system reliability and durability. Community-scale evaluation of advanced system concepts in partnership with builders, contractors, and state and local governments provides opportunities for early adopters and

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[1] Systems Research is research focused on understanding cost, performance, and reliability interactions between different system components.

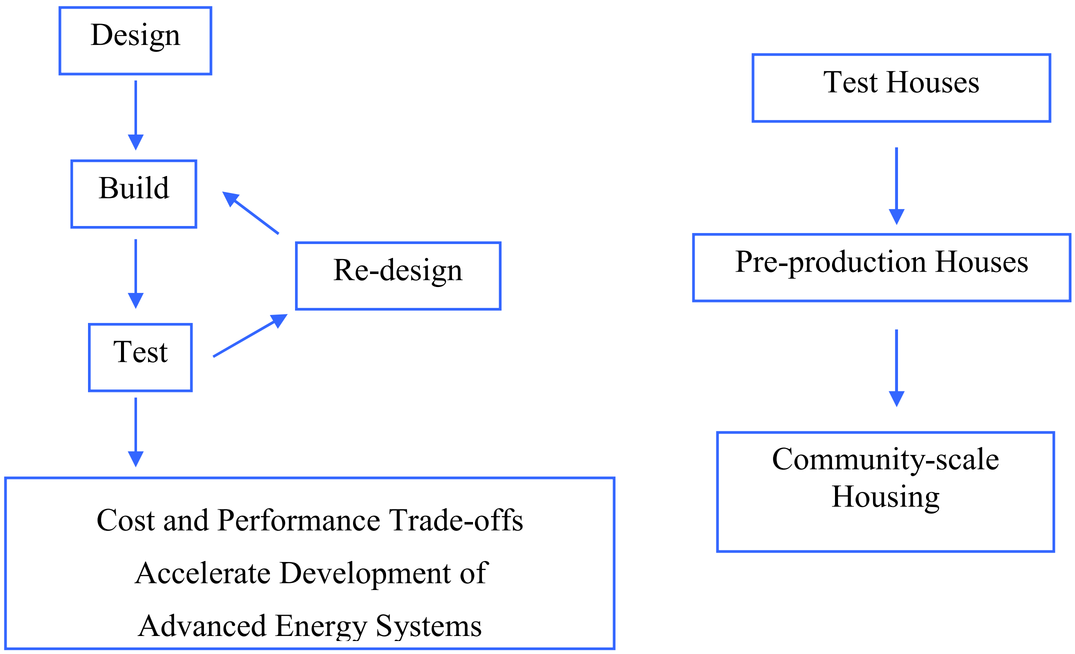

Figure 1. Overview of Building America's systems-engineering approach. The development of production-ready results covering the range from test houses to community-scale housing takes 3 to 5 years.

industry leaders to directly contribute to key results from the research program. A systems approach for development of advanced residential buildings is defined to be any approach that utilizes comprehensive examination and analysis of overall design, delivery, business practices, and construction processes, including financing, and that performs cost and performance tradeoffs between individual building components and construction steps that produce a net improvement in overall building value and performance. A systems approach requires integrated participation and team building among all interested parties in the building process including developers, architects, designers, engineers, builders, equipment manufacturers, material suppliers, community planners, mortgage lenders, state and local governments, utilities, and others.

The final products of each Building America research project include performance measurements and cost/performance evaluations in test houses, pre-production homes, and community-scale developments. These measurements and evaluations lead to development of innovative system concepts that can be applied on a production basis by the industry partners and stakeholders involved in the program. The range of innovative system concepts considered in projects include onsite power systems, innovative envelope systems, advanced mechanical and lighting systems, advanced space-conditioning systems, efficient water-heating systems, renewable energy systems, efficient appliances, energy-control systems, and design and construction strategies. Performance results from the evaluation of these systems are presented to a broad residential building science audience via development of technical papers, the Building America Web site, and presentations at major building-industry conferences.

Building America industry teams and team leads continuously evolve and increase the partners and stakeholders that participate in their projects so that the number of buildings and systems influenced by the program continues to grow over time.

The overall objective of the Building America research program is to develop integrated energy efficiency and onsite/renewable power solutions that can be successfully used on a production basis to reduce whole-house energy use in new homes by an average of 50% by 2015 and 90% by 2025, relative to the Building America Research Benchmark,[2] including homes that are capable of achieving zero net energy (ZNE) use on an annual basis.

The key system research questions addressed by Building America research teams include the following:

- Evaluation of overall system cost tradeoffs relative to current systems. What are the system's incremental costs and how will the system affect overall building costs?
- Evaluation of overall system benefits relative to current systems. What overall value is delivered by the system to builders? To contractors? To consumers? (Examples of system benefits include utility bill savings, contribution to whole-house energy-savings goals, increased durability, reduced warranty and callback costs, increased comfort, reduced construction waste, increased labor productivity, increased water efficiency, increased safety and health, reduced peak loads)
- Evaluation of the expected market impact of new residential energy systems. What fraction of the residential housing market will be directly affected by research results? What are barriers to broad market use? What research can be done to reduce barriers to broad use?
- Evaluation of the constructability of new residential energy systems. What are barriers and risks associated with the use of new systems? Can results be implemented on a production basis? What additional research is required to develop a clear description of whole-house system-performance requirements and key system-design details that minimize barriers and risks and maximize benefits?
- Evaluation of the potential community-scale benefits of advanced residential energy systems. What additional benefits will result when systems are implemented on a community scale?

Taken together, these research questions frame the overall difficulty of resolving the risks associated with use of advanced energy systems, help to define the systems research required to integrate new systems seamlessly into a production construction process, and emphasize the importance of documenting the performance benefits of advanced systems.

Construction of new homes requires the combined efforts of a large number of suppliers and contractors whose efforts are coordinated by a large number of builders. Because of the high

[2] Hereafter in this report referred to as the Benchmark. Hendron, R. 2005. Building America Research Benchmark Definition, Updated December 29, 2004. NREL/TP-550-37529. Golden, CO: National Renewable Energy Laboratory.

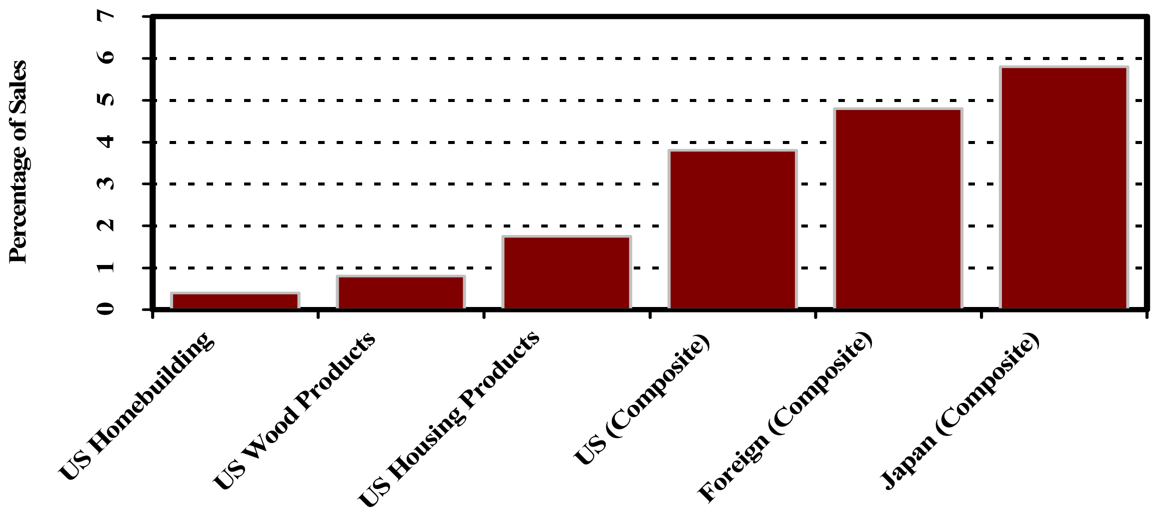

Figure 2. Research and Development expenditures[3]

cost of failure, the residential construction industry is highly risk-intolerant and first-cost sensitive. Development of new systems and corresponding changes in design and the relatively low level of R&D investment further complicate construction practices by the housing industry.

Figure 2 compares R&D expenditures for various residential markets. The key market barriers to development of advanced residential energy systems are the large number of market players, the relatively low level of investment in R&D relative to other sectors of the economy, and strict requirements for market acceptance based on achievement of low incremental costs and high reliability.

The key technical barriers to the development of advanced residential energy systems are the large number of technical performance requirements that must be met before a new system can be implemented on a production basis. These technical performance requirements are driven by regional differences in building energy loads and construction techniques. Systems that work well in Cold Climates may not be applicable in Hot Climates. Systems that work well in Hot-Dry Climates may not function well in Hot-Humid Climates.

A recent study by the RAND Corporation for HUD's Partnership for Advancing Technology in Housing (PATH), entitled *Building Better Homes: Government Strategies for Promoting Innovation in Housing*[4], concludes that,

> … the housing industry is large and complex, involving many public and private entities. The interests, roles, and capacities of each participant and the relationships they share have shaped the housing industry into what it is today…Instead of trying to identify barriers and asking the industry to change itself (or asking the government to change it), this study seeks to identify options to accelerate innovation within the housing industry as it exists today. It begins by

[3] The United States homebuilding industry invests 0.25% of sales in research compared to $3.8% for all market sectors (Business Week R&D Scoreboard, June 28, 1993).
[4] RAND, Building Better Homes: Government Strategies for Promoting Innovation in Housing, 2003.

> critically examining the concept of innovation and how it might be better understood within the context of the housing industry. What results is a departure from the linear model of innovation that assumes logical and unidirectional movement from research to development, demonstration, and deployment to one that recognizes much greater interactive dynamics in the innovation process. Research in this model is a base for knowledge, which contributes to invention, development, demonstration, and deployment. Moreover, all these activities or stages in the innovation process are affected by market forces."

Because of the strong interaction between technical and market barriers, a linear research approach that begins with basic R&D and ends with technology deployment is not likely to be successful when applied to residential systems. A market-driven, system-based research approach can provide valuable benefits to builders, consumers, and utilities while simultaneously resolving market and technical barriers to innovation.

Pulte Homes Southwest Division has used technical assistance from the U.S. Department of Energy's (DOE) Building America program to create what one residential expert calls "the best production house in the world," which won the 2001 National Association of Home Builders' Energy Value Housing Award. In Tucson, Phoenix, and Las Vegas, Pulte Homes has worked with the DOE to redesign the energy features of its basic models. Using advanced insulation techniques, highly efficient equipment and windows, and right-sized heating and cooling systems, the homes look the same, but perform so well that they use half the energy for heating and cooling at virtually no increase in construction costs. The whole-building/systems engineering approach used in the Building America program allows builders to add more insulation and more efficient windows while reducing the size of the heating and cooling equipment. The trade-off means no added cost to the builder, better value for the buyer, reduced electric load for the utility and improved affordability.

Background

Building America was started in 1995 to conduct the systems research required to develop residential energy efficiency solutions that achieve 30%-100% savings when used on a production basis by builders of new homes. The long-term 2025 research goal for the program is to develop cost-effective system designs that can result in Net Zero Energy Homes (NZEH).[5] In the past 10 years, Building America has made significant progress on the path to NZEH, including the completion of more than 30,000 homes.

Building America research participants have developed an in-depth systems research process by combining operations research[6] and systems engineering.[7] The first step of the systems-research process is to use operations research techniques to identify the technology pathways that will achieve the target energy savings in each region for the lowest potential installed cost. From these results, the optimal efficiency targets can be identified and technologies can be developed

[5] A net zero energy house is a house that produces as much energy as it uses on an annual basis through integration of energy efficiency solutions and onsite power systems.
[6] Operations Research is research aimed at understanding the best way to operate a system to maximize performance, based on system constraints.
[7] Systems Engineering is engineering based on knowledge from systems research aimed at maximizing the performance and durability of a system, subject to operating constraints.

that will meet the energy-savings needs cost effectively in all climate regions. The second step in the systems research is to implement the optimal technology pathways through systems engineering in homes. The systems-engineering step will identify challenges and barriers unanticipated by the optimization. The combination of operations research and systems engineering ensures that the solutions created meet the energy savings and cost goals and can be used on a production basis. Figure 3 shows a more detailed look at the Building America systems research approach (Table 1).

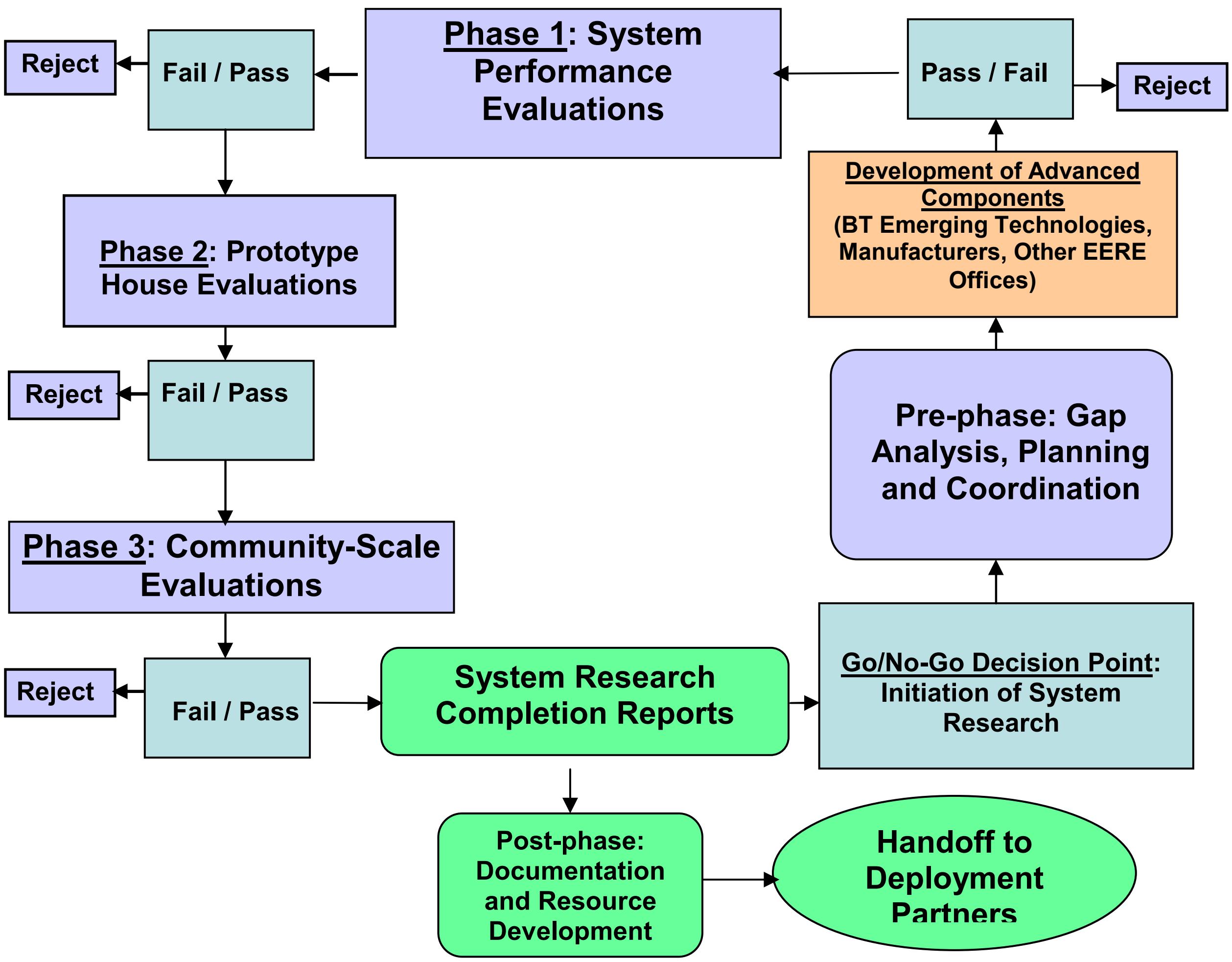

Figure 3. A more detailed look at the Building America system research strategy

Table 1. Building America Background

Start date	1995
Target market(s)	New, single-family residential buildings
Accomplishments to date	1. Developing the Benchmark Definition 2. Developing protocols for validating whole-house energy performance 3. Documenting research and publishing *Houses That Work*, *Builder Guides*, and *Best Practices* 4. Increasing the number of ENERGY STAR® homes
Current activities	Developing integrated cost-effective, whole-building strategies to enable new, single-family residential buildings to use 30% less total energy than the Building America Benchmark in the Cold and Hot-Dry/Mixed-Dry Climate regions.
Future directions	Continuing to develop the strategies for new, single-family residential buildings to use 40%-100% less energy than the Benchmark in the Marine, Hot-Humid, Hot-Dry/Mixed-Dry, Mixed-Humid, and Cold Climate regions
Projected end date(s)	2025

The systems research is applied in three phases for each climate zone. During the three phases, which are conducted in parallel to allow feedback between phases, Building America acts as a national residential energy systems test bed where homes with different system options are designed, built, and tested at three levels of system integration, including research houses, production prototype houses, and evaluations in community-scale housing to validate the reliability, cost effectiveness, and marketability of the energy systems when integrated in production housing. After completion of the community evaluations, a low level of technical support may be provided as needed to ensure successful implementation of system research results at each performance level targeted by the program. A detailed summary of the three phases of the system research process is captured in Table 2.

The three system-engineering stages overlap one another to allow issues to be quickly resolved as they are identified. The three system-research stages currently take about 3 to 4 years, but for more advanced energy efficiency levels at and above 40% whole-house savings, the systems-

Table 2. Residential Integration Systems Research Approach

Phase 1 – System Evaluations
In Phase 1, the Building America Consortia design, construct, and test subsystems for whole-house designs in research houses to evaluate how components perform. The focus of Phase 1 is to evaluate and field-test prototype subsystems to determine the most reliable and cost-effective solution for a given performance level and climate.
Phase 2 – Prototype Houses
In Phase 2, the successful Phase 1 subsystems are designed and constructed by production builders working with the Building America Consortia to evaluate the ability to implement the systems on a production basis. The focus of Phase 2 research is to move the research prototype house and building practices to the point that they are production-ready and capable of being integrated with production construction techniques practiced by today's builders.
Phase 3 – Community Evaluations
In Phase 3, the Building America Consortia provide technical support to builder partners to advance from the production prototypes to evaluation of production houses in a subdivision. The results are documented in a case-study report. Several of these reports are distilled into a final research report that describes the system design and construction practices needed to achieve a particular level of energy savings within each climate zone targeted by the program.

research process is expected to take additional iterations of whole-house testing before implementation in production ready homes. At the 50% whole-house level and above, the system research stages are expected to take 4 to 5 years to complete.

Electronic Reporting of System Research Results

Final research results from the program are reported electronically via the Building America Website (www.buildingamerica.gov). Research results include project data, research reports, case studies, research highlights, and background information on the research program and its participants. The website also includes a document database and reference materials on the performance analysis and measurement procedures.

Identification of Component Development Needs

The three-phase systems-engineering approach (Table 2) requires identification of future system needs to allow the lead time required to develop and evaluate options to meet those needs. Before initiation of Phase 1 studies in research houses, components must be developed and evaluated to determine their potential to fill gaps between the performance of current systems and future whole-house performance goals. The component research requires significant lead time in some cases and focuses on communication of system-integration needs and requirements to component developers. Building America's role is to provide inputs to component developers that help to identify residential system integration needs, requirements, and gaps based on annual residential cost/performance studies using the BEopt analysis method.[8] Components must be developed for Phase 1 and have to meet minimum requirements for energy performance, reliability, and cost effectiveness before they are included as part of the residential integration activities in Phases 2 and 3.

Documentation and Resource Development

At the completion of Phase 3, the research results are documented in technical research reports that serve as references for students, educators, building scientists, architects, designers, and engineers. For the research results to be successfully transferred to additional important participants in the housing industry, they must be translated into a format appropriate for dissemination to developers, builders, contractors, homeowners, realtors, insurance companies, and mortgage providers.

This post-Phase-3 activity of the DOE fosters movement of the research and building techniques of the Building America Program to the market and establishes voluntary collaborations with housing and financial industries to make the nation's houses more energy-efficient and affordable. This final stage of the process focuses on documentation of best practices and development and evaluation of resources to hand-off DOE building-research findings to private and public sector implementation programs. This work supports activities that improve the energy efficiency of public and privately owned single-family housing. The program coordinates presentations at technical conferences on peer-reviewed, validated, research results and facilitates validation, field-testing, and evaluation of the post-phase-3 documentation.

The Building America resource development effort creates "Best Practices" manuals from the Phase-3 research reports that are designed for builders, manufacturers, homeowners, realtors, educators, insurance companies, and mortgage providers. The Best Practices manuals summarize best-practice recommendations in illustrated text that is targeted to a specific audience to make it easily assimilated and that synthesize research findings into energy-efficient processes for the building industry. To facilitate construction of affordable homes designed for non-profit organizations and small builders, Building America plans to make floor plans and section details available through the web and other means.

Building America's Research Goals

Building America's energy-saving goals form the core of the research effort and have been staged to complete an additional 10% of incremental savings every 3 to 5 years (Table 3).

To ensure meeting the interim targets along the path to Zero Energy Homes (ZEH), Building America has also specified the interim performance targets for each climate region (Table 4).

[8] BEopt stands for "Building Energy Optimization Analysis Method," as defined in "*Analysis of System Strategies Targeting Near-Term Building America Energy-Performance Goals for New Single-Family Homes*," Anderson, Ren et al. November 2004, NREL/TP-550-36920.

Table 3. Building America Research Goals[9]

Characteristics	Units	Year				
		2007	2010	2015	2020	2025
Average Source Energy Savings	%	30	40	50	70	90
Cost	$	Zero or Less Net Cash Flow[10]				

Table 4. Building America Performance Targets by Climate Region

Target (Energy Savings)	Marine	Hot Humid	Hot-Dry / Mixed Dry	Mixed Humid	Cold
30%	2006	2007	2005	2006	2005
40%	2008	2010	2007	2008	2009
50%	2011	2015	2012	2013	2014

In addition to energy savings, Building America has additional system-performance goals that are critical to the success of the systems research process. These include the following:

- Accelerating the development and implementation of advanced-energy systems in new and existing residential construction through application of systems-engineering research projects by cross-cutting industry teams
- Reducing residential building construction site waste, increasing the use of recycled materials, reducing construction cycle time, increasing system durability and reliability, and reducing warranty and call-back costs
- Developing innovative technologies and strategies that enable the housing industry in the United States to deliver environmentally sensitive, quality housing on a community-scale while maintaining profitability and competitiveness of homebuilders and product suppliers
- Increasing housing value and affordability for homeowners in the United States.

[9] Year of completion of annual performance targets in six climate regions. Energy savings are measured relative to Benchmark. The targets in Table 4 are updated on an annual basis dependent on technical progress and funding.
[10] Life cycle cost, see TP-550-37529.

30% Whole-House Energy Savings

Building America's current research activities target 30% total energy savings in new single-family homes in six climate regions. Residential buildings include a limited number of different end uses with many similarities in a particular climate region. Therefore, a climate region approach is appropriate because residential system solutions can be easily replicated on a regional basis. The climate regions defined by Building America can be seen in Figure 4.

Because of limited resources, Building America is targeting six of the eight climate regions, including Marine, Hot-Humid, Hot/Mixed-Dry, Mixed-Humid, and Cold. The Hot-Dry and Mixed-Dry Climates have been combined into a single climate target for Building America planning purposes because of the similarities of the solutions for the two climates. The severe Cold and Subarctic Climate regions have been omitted because of limited resources and the lack of residential growth in those regions.

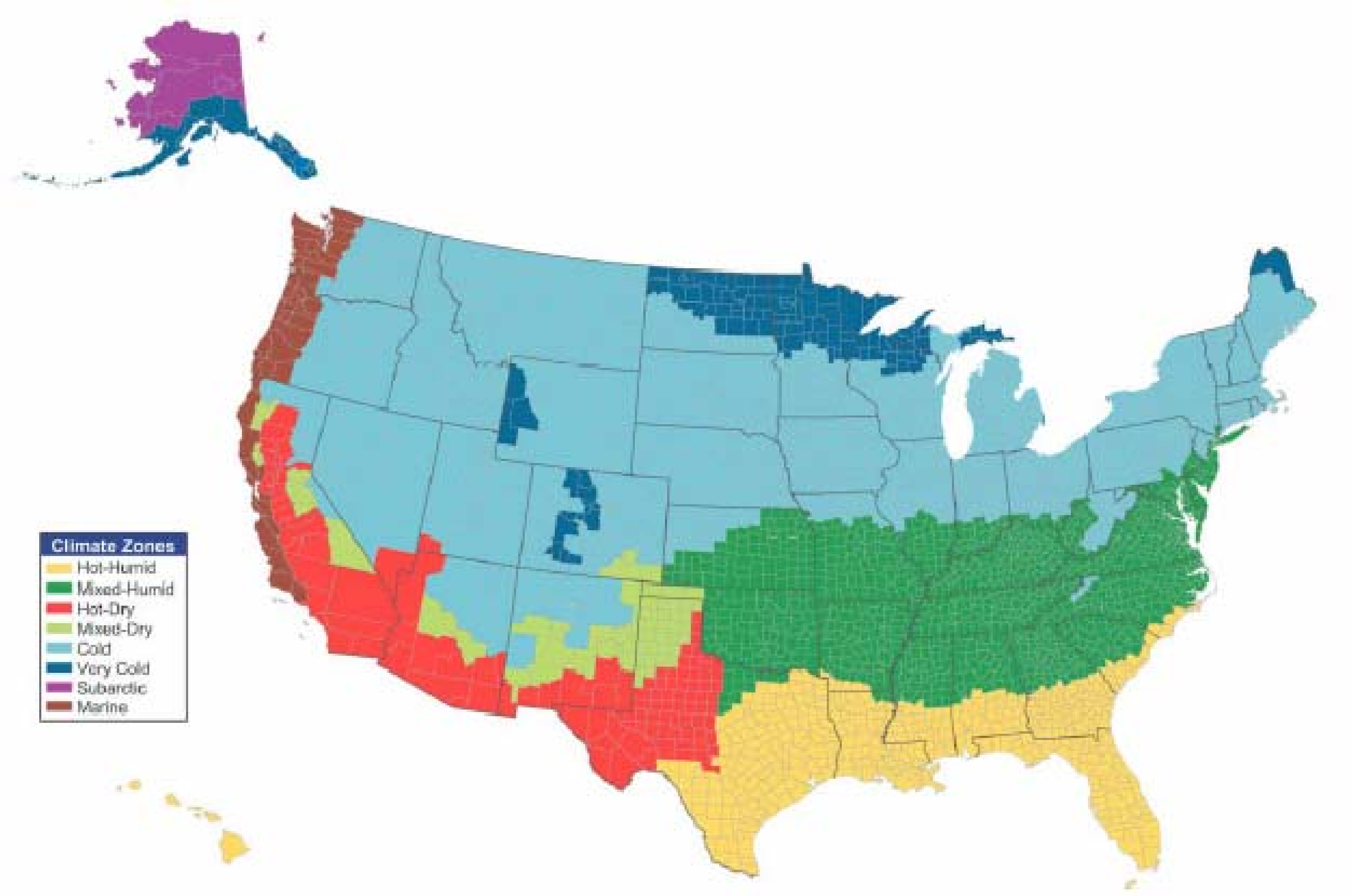

Figure 4. Building America climate regions

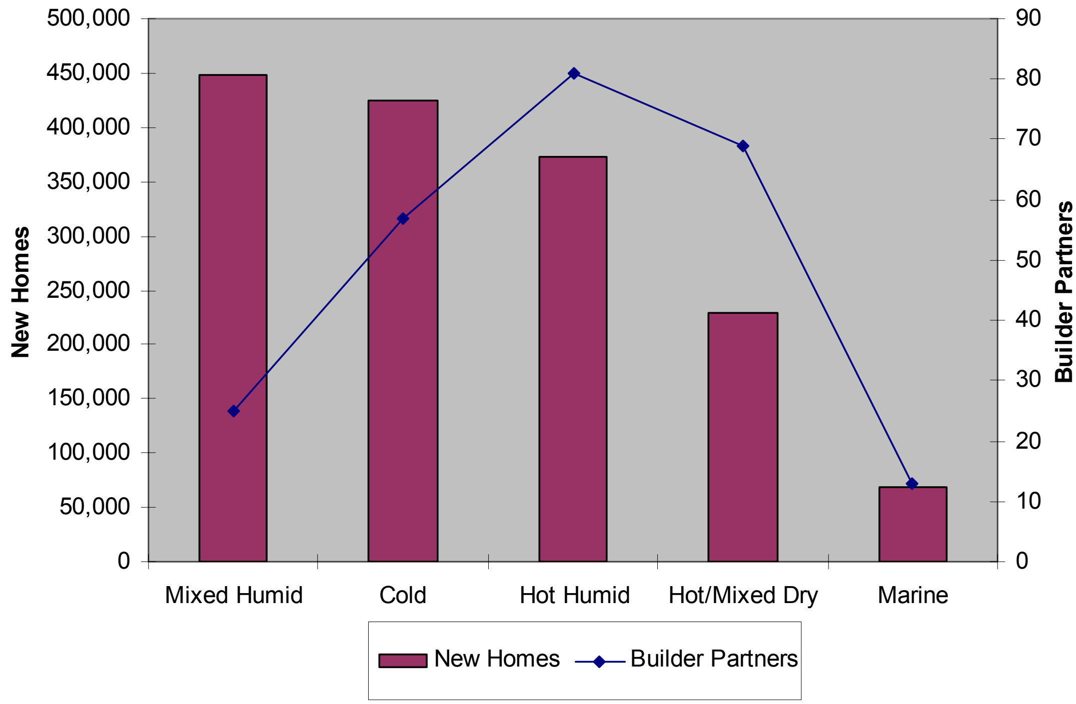

Figure 5. New homes [11] and builder partners[12] by climate region

From 2003 to 2005, Building America has developed the following solutions to use 30% less total energy than the Building America Benchmark for the Hot-Dry/Mixed-Dry and the Cold Climate regions. These climate regions present opportunities for research because of the number of new homes being built and the relationships established with builder partners. The number of new homes and builder partners for each climate region can be seen in Figure 5. Building America will focus on developing the 30% solutions for the Mixed-Humid and Marine regions in 2006.

Through 2025, Building America will continue to develop the strategies for new, single-family residential buildings to use 30%-100% less total energy in the Marine, Hot-Humid, Hot-dry/Mixed-Dry, Mixed-Humid, and Cold Climate regions over the full range of house sizes, styles, and price points.

The purpose of this report is to provide an overview of 3 years of Building America system research that led to the development of homes that save 30% relative to the Benchmark.[13] Based

[11] July 1, 2002, to July 1, 2003. U.S. Census Bureau Housing Unit Estimates (HU-EST2003-04), "Annual Estimates of Housing Units for Counties: April 1, 2000, to July 1, 2003," Last revised September 2, 2004.

[12] "House Counts by Climate Zone (detailed)", U.S. Department of Energy, Building America House Performance Database, January 5, 2005.

[13] The Research Benchmark provides a detailed description of all residential energy uses and serves as the reference point for the energy savings goals in Building America research project. More information about the Benchmark can be found on the Building America website: http://www.eere.energy.gov/buildings/building_america/pa_resources.html.

on the research results and case studies included in this report, the Building America Research teams have demonstrated that 30% homes can be reliably designed and constructed by production builders in Cold Climates. The actual rate of adoption of the research results contained in this report will depend upon a number of factors, including residential energy costs and national, state, and local incentives for the use of energy-efficient construction techniques.

System Approach to Least-Cost Energy Savings

Integrated Design Process

Building America's team-based systems-research approach, including use of systems-engineering and operations research techniques, provides opportunities for cost and performance trade-offs that improve whole-building performance and value, while minimizing increases in overall building cost. Systems engineering is conducted at multiple scales, including individual test houses, pre-production houses, and community-scale developments. Systems research includes analysis of system performance and cost tradeoffs as they relate to whole-building energy performance and cost optimization, including interactions between advanced envelope designs, mechanical and electrical systems, lighting systems, space-conditioning systems, hot water systems, major appliances, miscellaneous electric loads, energy control systems, renewable energy systems, and onsite power generation systems. Accordingly, the best practice recommendations in this report have been demonstrated to cost-effectively increase overall product value and quality compared to conventional approaches, while significantly reducing energy use and use of raw materials when used on a production basis.

The final products of each research project include performance measurements and cost/performance evaluations in prototype houses, pre-production homes, and community-scale developments, and climate-based system research design/technology packages, including system performance specifications. These measurements, evaluations, and system-performance packages are the basis of the recommendations provided in this report.

Analysis and Design Optimization

The research path to future residential energy savings extends from a base case (e.g., a current-practice building, a code-compliant building, or some other reference building) to a ZNE building with 100% energy savings. To ensure a well-defined reference for evaluation of energy savings and progress toward multi-year goals, a detailed Benchmark[14] building definition has been developed for use by all participants in Building America research projects. A standard reporting format for research results has also been developed to facilitate comparisons of performance between different research projects.

The Benchmark is generally consistent with the 1999 Home Energy Rating System (HERS) Reference Home, as defined by the National Association of State Energy Officials/Residential Energy Services Network (NASEO/RESNET), with additions that allow the evaluation of all home energy uses. The Benchmark represents typical standard practice in the mid-1990s, when DOE initiated the Building America program. Additional documentation to support the use of

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[14] Hendron, R. 2005. Building America Research Benchmark Definition, Updated December 29, 2004. NREL/TP-550-37529. Golden, CO: National Renewable Energy Laboratory.

the Benchmark, including spreadsheets with detailed hourly energy usage and load profiles, can be found on the Building America Web site.[15] As Building America teams develop innovative new technologies and systems approaches that move the program toward its research goals, the Benchmark will be re-evaluated and refined periodically to ensure that energy savings from these features are accurately credited. Many other valid techniques and definitions have been developed by other organizations, and they can be very useful to builders for specialized applications. For example, the HERS rating procedure (RESNET 2002) must be followed to obtain an ENERGY STAR® rating for building energy efficiency. Also, it might be necessary to determine whether or not a Prototype meets the International Energy Conservation Code (IECC)[16] or Model Energy Code (MEC),[17] which could apply if adopted by the state or local government.

Building America Research Benchmark

The Benchmark was developed to track and manage progress toward the Building America multi-year whole-building energy savings goals for new construction, using a fixed reference point. To provide a context for the potential impacts of research projects on local and regional markets at a given point in time, energy usage is also compared with current Regional Standard Practice and Builder Standard Practice. Standard occupant profiles for use in conjunction with these reference houses have also been developed based on review of the available literature; the intent is to represent typical occupant behavior. Additional analysis and end-use monitoring[18] are required to evaluate energy savings for specific occupants whose individual behavior could vary from the average profiles defined in the Benchmark. In general, relative savings for an individual user are expected to be approximately the same as those for an average user.

Energy savings can be defined in terms of site energy (used at the building site) or source energy (sometimes called primary energy). For electricity purchased from a utility, site energy can be converted to source energy to account for power plant generation efficiency and electrical transmission and distribution losses. The source-to-site energy ratio for electricity typically has a value of about 3, depending on the mix of electrical generation types (coal-fired, natural gas combined cycle, nuclear, hydropower, etc.). For the purpose of Building America analysis, national average site-to-source multipliers of 3.16 for electricity, 1.02 for natural gas, and 1.00 for all other fuels are used. From the view of all stakeholders in the building process, site and source energy are both important. Source energy has been chosen as the basis for tracking progress toward the Building America energy-saving targets and is also used as the basis of the cost/performance tradeoffs analyzed in this report. Site energy savings are also calculated as part of ongoing research projects and included in project evaluations because of their importance in determining specific utility bill savings.

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[15] www.eere.energy.gov/buildings/building_america/pa_resources.html.

[16] International Energy Conservation Code®: 2003 Edition with 2004 Supplement. Country Club Hills, IL: International Code Council, Inc. 2003, 2004.

[17] MEC 1995, Council of American Building Officials (CABO) 5203 Leesburg Pike, Falls Church, VA 22041.

[18] Norton, P.; Hancock, E.; Barker, G.; Reeves, P. et al. 2003. The Hathaway "Solar Patriot" House: A Case Study in Efficiency and Renewable Energy. NREL/TP-550-37731. Golden, CO: National Renewable Energy Laboratory.

Analysis Methods

A key issue in any building energy analysis is which tool or program to choose to estimate energy consumption. An hourly simulation is often necessary to fully evaluate the time-dependent energy impacts of advanced systems used in Building America houses. Thermal mass, solar heat gain, and wind-induced air infiltration are examples of time-dependent effects that can be accurately modeled only by using a model that calculates heat transfer and temperature in short time intervals. In addition, an hourly simulation program is also necessary to accurately estimate peak energy loads. Because of the large number of users, public availability, and level of technical support, DOE-2 is the most commonly used hourly simulation engine for systems analysis studies performed under the DOE Building America program.

EnergyGauge[19] is a frequently used interface for DOE-2; it has been tailored specifically to residential buildings. EnergyGauge can also automatically calculate HERS scores and evaluate compliance with the IECC performance path. Teams are also encouraged to use other simulation tools when appropriate for specialized building simulation analysis, provided the tool has met the requirements of BESTEST[20] in accordance with the software certification sections of the RESNET/HERS Guidelines.[21]

Building energy simulations are often used for trial-and-error evaluation of “what-if” options in building design (i.e., a limited search for an optimal solution). In some cases, a more extensive set of options is evaluated and a more methodical approach is used. For example, in the Pacific Gas and Electric ACT2 project,[22] energy-efficiency measures were evaluated using DOE2 simulations in a sequential-analysis method that explicitly accounted for interactions. With today’s computer power, the bottleneck is no longer simulation run time, but rather the human time to handle input/output. Computerized option analysis has the potential to automate the input/output, evaluate many options, and perform enough simulations to explicitly account for the effects of interactions among combinations of options. However, the number of simulations still needs to be kept reasonable, by using an efficient search technique rather than attempting exhaustive enumeration of all combinations of options. Even with simulations that run in a few seconds, run time for an exhaustive study of all possible combinations is prohibitive for the millions of combinations that can result from options in the ten or more categories needed to accurately describe a residential building. Several computer programs to automate building energy optimization have been recently developed. For example, EnergyGauge-Pro[23] uses successive, incremental optimization (similar to the ACT2 approach) with calculations based on the “energy code multiplier method” for Florida. GenOpt[24] is a generic optimization program

[19] This is available for purchase from the Florida Solar Energy Center (http://energygauge.com/).
[20] Judkoff, R., Neymark, J. 1995. International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method. 300 pp.; NREL Report No. TP-472-6231. See further information at this Web site: www.eere.energy.gov/buildings/tools_directory/software.cfm/ID=85/pagename=alpha_list.
[21] Residential Energy Services Network (RESNET). 2002. “Mortgage Industry National Home Energy Rating Systems Accreditation Standards.” Chapter 3, pp. 29-54. San Diego, CA: RESNET.
[22] Davis Energy Group. ACT2 Stanford Ranch Site, Final Design Report. Davis, CA: Davis Energy Group.
[23] Florida Solar Energy Center. EnergyGauge Pro. Cocoa, FL: Florida Solar Energy Center (http://energygauge.com/FlaRes/features/pro.htm).
[24] Wetter, M. “GenOpt®, "Generic Optimization Program,” Seventh International IBPSA Conference, Rio de Janeiro, Brazil. (www.ibpsa.org/bs_01.htm).

for use with various building energy simulation programs and user-selectable optimization methods.

To evaluate the cost required to reach a specific energy target, energy and cost results can be plotted in terms of annual costs (the sum of utility bills and mortgage payments for energy options) versus percent energy savings (Figure 6). The optimal least-cost path can then be determined by connecting the points for building designs that achieve various levels of energy savings at minimal cost (i.e., that establish the lower bound of results from all possible building designs). Alternatively, net present value or other economic figures of merit could be chosen. Inclusion of even a modest number of possible options for major system choices can lead to a very large number of possible building designs. One of the key challenges in developing a practical analysis method is to develop an approach that quickly focuses on the combinations that are nearest to the least-cost limit. To address these challenges, NREL is currently developing the BEopt Analysis Method.

Points of particular interest on the least-cost path are shown in Figure 6 and can be described as follows: from the Benchmark at point 1, energy use is reduced by employing building efficiency options (e.g., improvements in space-conditioning systems, hot water systems, lighting systems, thermal distribution systems, etc.) A minimum annual cost optimum occurs at point 2. Additional building efficiency options are employed until the marginal cost of saving energy for these options equals the cost of producing power onsite at point 3. In this study, residential PV systems are used as the system option for onsite power. As research on distributed energy systems continues, it is anticipated that other onsite power technologies will also become available for residential-scale projects. From point 3 on, the building design does not change and energy savings are solely a result of adding additional onsite power capacity, until ZNE is achieved at point 4.

The horizontal dashed line in Figure 6 defines solutions that provide energy savings at an annual cost that is less than or equal to the utility cost for the reference house when energy improvements are financed as part of a 30-year mortgage. All solutions in a vertical region below

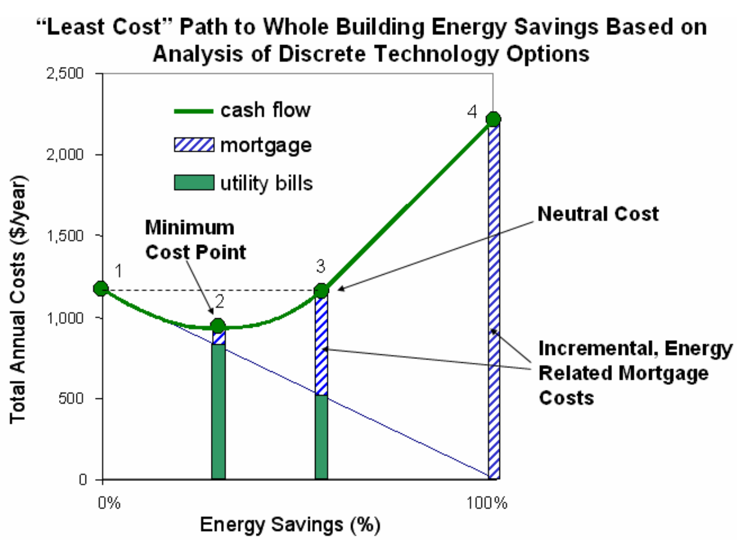


Figure 6. Least-cost curve calculated using the BE-opt analysis method

the neutral-cost line are essentially equivalent from an energy-savings perspective. The specific design package chosen by a builder to achieve a specific energy-savings level will depend on a number of factors, including material and equipment cost and availability, and overall homeowner preferences.

Performance Verification

Modeling provides the generalized energy calculations necessary to compare a prototype house to the Benchmark. Because weather, occupant behavior, and miscellaneous electric loads can dramatically affect actual energy use, it is essential that simulations be used to separate the objective performance of a prototype house from the effects of these uncontrolled variables. Modeling also allows the evaluation of "what-if" scenarios, where alternative design features are compared to those of the as-built prototype house.

However, short-term field evaluations of actual prototype building systems provide information that modeling alone cannot. Field testing increases confidence in building models by improving simulation accuracy in areas that are difficult to know without direct measurements, such as duct and envelope air leakage, solar collector efficiency for solar hot water (SHW), and even the whole-building heat loss coefficient (UA). Common measurement techniques include tracer-gas tests, blower-door and duct-blaster tests, infrared imaging, current-voltage traces for photovoltaic systems (PV), and co-heating tests. Other tests are often developed based on the specific design features and uncertain performance characteristics of the house.

The intent of short-term testing is to characterize the performance of unoccupied building and systems under controlled conditions, not under the idiosyncratic control of random occupants. Short-term tests may be repeated seasonally to characterize performance changes from winter to summer. These tests can also help identify equipment installation issues, operational problems, or malfunctions at an early stage before the occupants are inconvenienced.

HERS raters are a valuable resource for continuing the process of energy-efficient construction with builders. Many Building America teams have successfully partnered with local HERS raters to provide initial testing, construction monitoring, and performance-verification testing services during the construction of test homes. The relationship between the builder and rater may continue after the test home, with the rater providing services, including ongoing performance verification and, in some cases, design and engineering services, depending on the rater's skill set.

The current RESNET HERS scoring system, which has been undergoing substantial change over the past few years, is of questionable value to builders participating in the Building America program, because they are generally most interested in whether they meet the overall energy efficiency goals of the program and not necessarily just achieving a score. It is not clear in the long run how builders will embrace and promote numeric scores provided by a system where the basis of the scoring system is periodically adjusted to reflect changes in codes or adding other energy end uses that make up the score. In this respect, a prescriptive set of criteria may be more valuable to builders – criteria such as those being developed by the Building America Program and the 2006 version of the EPA ENERGY STAR Homes® program with certain performance criteria pertaining to building and space-conditioning distribution system tightness targets. Whole-house energy-performance analysis may be the best approach for the industry instead of a scoring system that periodically changes; is not comprehensive of all energy uses, which can cause confusion with homeowners; and is not easily marketed by the builder.

Long-term field measurements provide valuable insights into the actual performance of the home under realistic conditions, including interactions between occupants and technology. Ultimately, it is essential for Building America to demonstrate that houses can meet the target levels of energy efficiency in reality and not just on paper. However, individual long-term tests under occupied conditions must always be put in the context of the specific occupants. Number of occupants, thermostat settings, operation of windows and interior shades, hot water and appliance-use patterns, and lifestyle are all important drivers of energy consumption. The recommended approach is, therefore, to compare measurements with simulated energy use based on actual occupant behavior and weather conditions and to make adjustments to the simulation based on the results of this comparison if justified. An adjusted energy savings analysis can then be performed based on actual instead of theoretical operating conditions.

Long-term monitoring activities are still ongoing for the houses designed to meet the 30% savings target discussed in this report. The results will be reported in future technical publications, and the lessons learned will be used to inform future projects at the same or higher energy-savings target. Building America is committed to long-term energy savings, health and comfort, durability, and reliability of its system design recommendations at each performance level, and we will continue to track the performance of our prototype houses for several years to come.

System Design and Construction Process

Climate Analysis

Key Climate Elements that Affect Building Design

Houses should be designed and constructed in a manner that is suited to their environment, both exterior and interior. Rain, temperature, humidity, sunlight, and wind are examples of environmental loads that act on houses.

The recommendations in this research report are applicable to houses constructed in the Cold Climate region. A Cold Climate (Figure 4) is defined as a region with approximately 5,400 heating degree days (65°F basis) (3,000 heating degree days @ 18°C basis) or greater and less than approximately 9,000 heating degree days (65°F basis) (5,000 heating degree days @ 18°C basis).

Individual locations within the broad general regions and zones described above can vary significantly. For a specific location, designers and builders should consider local weather records, local experience, and the microclimate around a building. Elevation, incident solar radiation, wind, nearby water and wetlands, vegetation, and undergrowth can all affect the microclimate.

Design Strategy Modification for Variances within a Climate Zone

In general, the approach to rain control (Figure 7) is far more dependent on individual location within this climate zone, than the approach to energy efficiency. For example, levels of thermal insulation do not vary significantly across this region; however, approaches to rain control do.

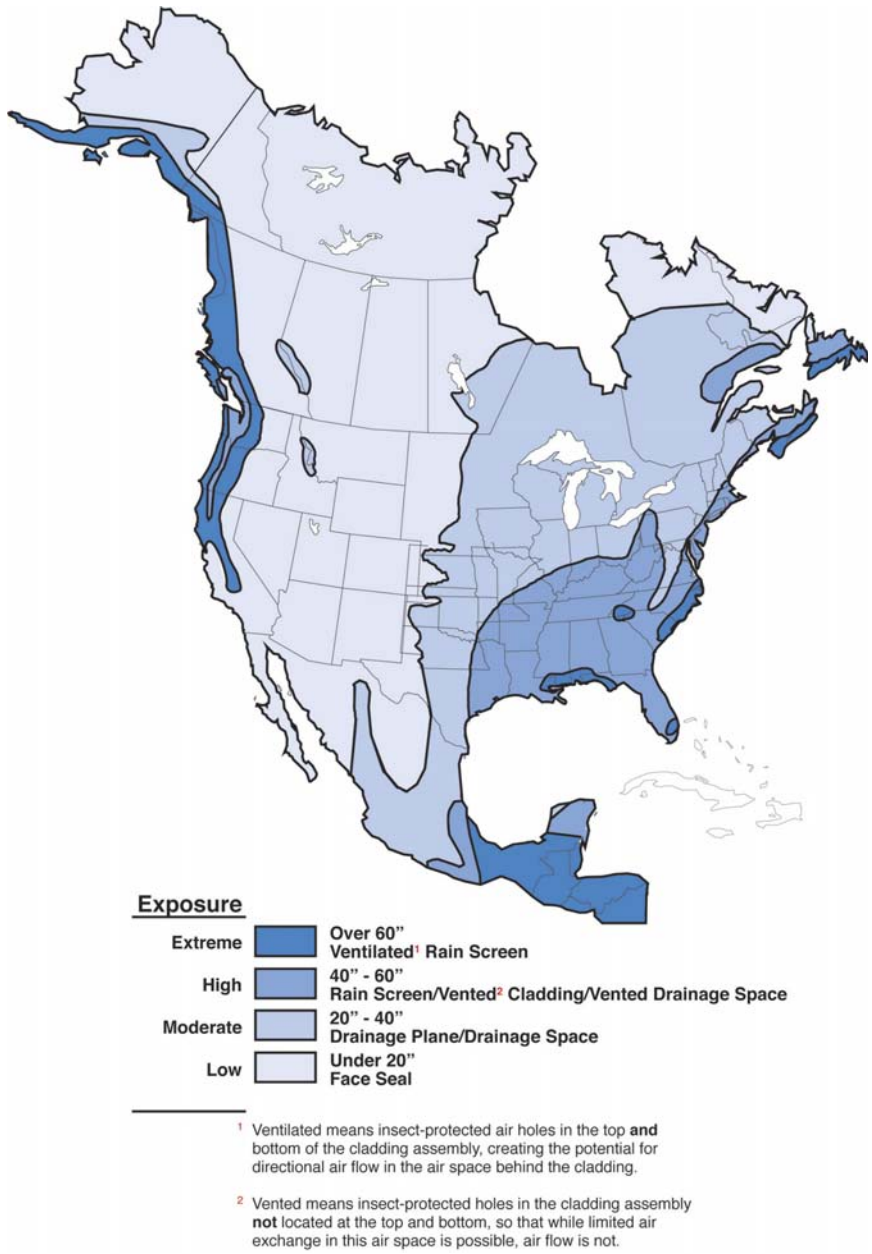


Figure 7. Rain exposure zones. Rainfall throughout the Cold Climate region varies dramatically from a low rain exposure zone to an extreme rain exposure zone.

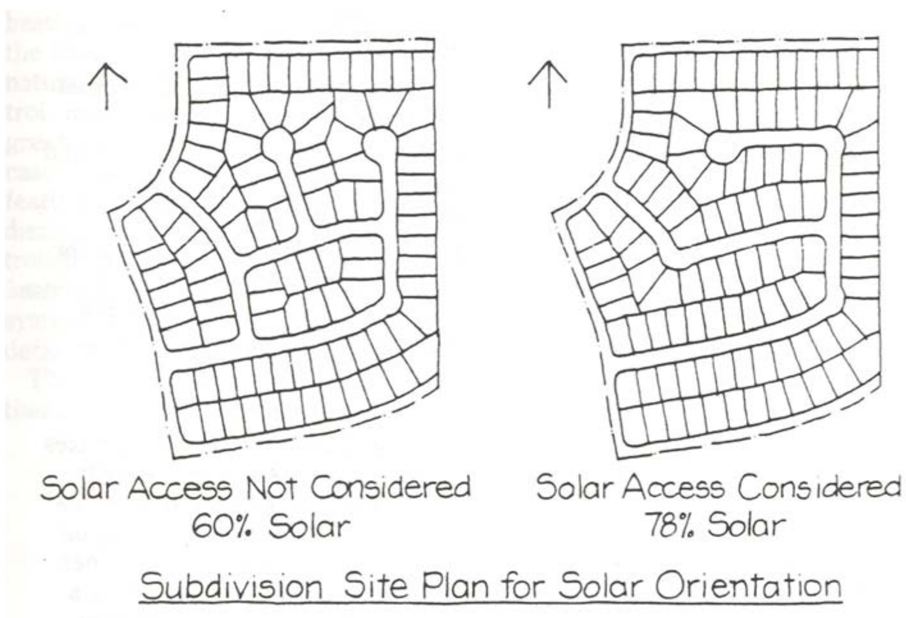


Figure 8. Subdivision site plan for solar orientation[25]

Site Development

Orientation Impacts

To achieve the 30% level of energy savings, it is not necessary to orient homes in any particular direction. In many instances, the builder does not have any influence over lot orientation, and the house will face the street as laid out by the developer. The predominant window placement will typically be to the street and the back of the house. If it is possible to consider orientation at the site development level of the homebuilding process, one virtually no-cost option for improving energy performance is to subdivide for solar orientation. Alternately, on larger lots that do not have to "respect the street," site planning can be undertaken to optimize the orientation of the house for passive solar benefit. An example of land planning and lot layout to allow for passive solar orientation is shown in Figure 8.

[25] Shelley Dean and Fuller, Energy Principles in Architectural Design Architects California Energy Commission 1981.

Landscaping

While not a required strategy for achieving 30% whole-house savings, evaluating the vegetation on a lot and retaining trees that provide beneficial shading can be a low- or no-cost way to improve energy performance, predominantly by providing shade in the cooling season and helping to buffer or direct beneficial prevailing winds. Shade trees block summer sunlight before it strikes windows, walls, and roofs, dissipating absorbed heat to the air where it can be carried away by the breeze. It is most effective when located next to windows, walls, and air conditioners and when located on the side of the home receiving the most solar exposure in summer. Shade to the southwest and west is especially important for blocking peak solar gain in the summer in late afternoon. Trees more than 35 feet from the structure are probably too far away for shade. Trees to the north of a house in a Cold Climate can help block cold north winds, reducing one driving force for air infiltration. Trees, shrubs, and vines not only blocks sunlight, but also can cool the nearby air beneath the canopy or behind the plant by as much as 15°F because of natural evaporation from the plant's leaves.

Water Management

In natural settings, most precipitation infiltrates into the ground while a small portion runs off on the surface and into receiving waters. This surface runoff water is classified as storm-water run-off. As areas are constructed and urbanized, surface permeability is reduced, resulting in increased storm-water run-off volumes that are transported via urban infrastructure (e.g., gutters, pipes, and sewers) to receiving waters. These storm-water volumes contain sediment and other contaminants that have negative impact on water quality, navigation, and recreation. Furthermore, conveyance and treatment of storm-water volumes require significant municipal infrastructure and maintenance.

Reduction and treatment of run-off volumes decrease or eliminate contaminants that pollute receiving water bodies. Minimizing the need for storm-water infrastructure also reduces construction impacts and the overall ecological footprint of the building. Finally, infiltration of storm water on site can recharge local aquifers, mimicking the natural water cycle.

Strategies. Storm-water management strategies that prevent or reduce the pollution of water include the following:

- Reduce impervious surface: The most effective method to minimize storm-water run-off volume is to reduce the amount of impervious area. By reducing impervious area, storm-water infrastructure can be minimized or deleted from the project. To minimize the impervious surface and to encourage the natural process of evaporation and infiltration, consider such methods as designing a smaller building footprint; clustering or concentrating developments to reduce the amount of paved surfaces, such as roads, parking lots, and sidewalks; and paving with pervious materials, such as poured asphalt or concrete with incorporated air spaces or concrete unit paving systems with large voids that allow grass or other vegetation to grow between the voids.
- Storm-water harvesting: This method captures storm water from impervious areas to reuse within the building. Storm-water harvesting from roofs and hardscapes can be used for non-potable uses such as sewage conveyance, fire suppression, and industrial applications.

- For storm-water volumes that must be conveyed from the site to a receiving water body, design treatment practices to match the needs of the location and the specific drainage area. Design storm-water facilities to remove contaminants and release the volumes to local water bodies. Utilize biologically based and innovative storm-water management features for pollutant load reduction, such as constructed wetlands, storm-water filtering systems, bioswales, bioretention basins, and vegetated filter strips.
- Use vegetated buffers around parking lots to remove runoff pollutants, such as oil and grit.
- Specify and install water-quality structures for pretreatment of runoff from surface parking areas. Do not disturb existing wetlands or riparian buffers when constructing ponds at the lowest elevations of a site.
- Design storm-water runoff to flow into vegetated swales rather than into structured pipes for conveyance to water-quality ponds. Swales provide filtration for storm-water volumes and require less maintenance than constructed storm-water features.

System Design Approach

Integrated Design Process

Typically a house goes through the following design process:

- **Conceptual Design Development.** Planning Stage where the price range, square footage, number of stories, lot sizes, general features, and styles are determined.
- **Preliminary Design Development.** Develop floor plan sketches, number of bedrooms, major options, basic circulation and function locations, as well as some elevation concepts.
- **Design Development.** Preliminary structural, mechanical, electrical, plumbing, and Compliance.
- **Construction Documents Development**. Final working drawings ready for bidding, submittal. Back-checking and coordination by consultants.
- **Construction and Commissioning.**

An Integrated Design Process (IDP) ensures that all the key players and design consultants - including the architect, planner, mechanical engineer, landscape architect, energy consultant, and the site engineer, work together starting with the conceptual design stage, even though the role of each may be limited for a particular design stage. The IDP is a key aspect in achieving the systems-design approach.

An IDP approach may seem to be an expensive approach, but in the long run the overall costs and advantages significantly outweigh the traditional approach. For example, the mechanical engineer may be involved in the project much later and be asked to design the mechanical system with the already defined constraints of attic/plenum space–resulting in an inefficient HVAC distribution system.

By developing a better IDP, builders are able to incorporate the 30% improvement level strategies more effectively with less disruption of their normal construction process and do so more cost effectively. While use of an IDP at the 30% improvement level for builders is quite desirable, it will be even more important at higher energy-performance levels, 40%, 50%, and 70% reduction.

Approaches to an IDP will vary with different builders, as their relationships with design professionals, suppliers, and the trades are often different. For example, a builder with an in-house architectural staff, that prepares all new house designs, may have a different level of control and continuity of design as compared to a builder that works with an independent architectural firm. Approaches to the IDP are evolving in Building America's programs, and a single, clearly defined process has not been established.

An example of this is the HVAC system because HVAC designers need to provide input as early as possible. They need to tell the architect which architectural features cause comfort issues and are difficult or impossible to overcome with typical HVAC practices. They also need to make sure the architect allows adequate space to run ducts. Many architects have had to re-design plans enough times as a result of HVAC issues that they know fairly well how to accommodate HVAC items. Still many problems commonly arise that could be avoided through earlier input and better coordination.

To continue with our example, Table 5 shows the main trades and consultants who are affected by the HVAC system. The first column lists the item or issue and each subsequent column how each trade is affected by it.

As shown from the matrix, all trades are intertwined in the design and building process. This matrix could be easily applied to the builder, electrician, plumber, etc. As homes become more efficient, it will be critical that all involved in the system will need to coordinate their efforts to ensure quality control and to employ quality assurance tools and processes through the IDP.

One model of the information flows and actions associated with an integrated design process are shown in Figure 9. Some of the key activities of the integrated design process is setting a performance standard, identifying and integrating all systems in the house from the predesign stage through construction documentation, and having feedback loops in the design process from key participants in organization and trade base.

Setting Performance Standards. In order to implement an IDP process, the team needs to have a set of standards to which the building will be expected to achieve. The first step in setting a performance standard is to understand the customer base and what level of performance they are receptive to. Targeted customer and market-area surveys help to give as clear a picture as possible of the factors that motivate home sales in general and home-purchasing patterns for the target market. This data is used to direct the design of new products and respond to market pressures. The ability to survey, synthesize, and extract meaning from customers and the market can provide a significant advantage to builders, in that they have a better understanding of market and can apply this knowledge to fulfill unmet needs. If the market is indicating a need for greater energy efficiency, durability, improved indoor air quality, or comfort, then the adoption of Building America performance packages may be appropriate as the standard.

Similarly, the builder must determine what level of quality and performance their housing will achieve. This may have to do with moisture performance, comfort, increased durability, and reduced risk. All of these issues are typically addressed by following the recommendations included in this report.

Table 5. Matrix of Trades

Item	Architect	Builder/Framer /Structural Engineer	HVAC Installer	Energy Consultant	Electrical	Plumber	Drywall or insulation
FAU location	Roof pitch, furnace closets, clearance in garage	Truss design, platform, clearance, closets, bollards, attic access framing	Type of FAU (upflow, horizontal), clearance, timing of installation	Modeling correct location of ducts for computer model	Power, service light, control wiring, etc.	Condensate lines, gas piping	Insulation under platform may be different
Equipment size, load calculations	Clearances, # of systems, building features	Structural impacts (weight)	Materials, labor, costs	Energy features impact sizing	Electrical loads		
Supply register locations	Aesthetics, clearances	Register boot support	Materials, labor				Sealing around registers
Return grille locations	Aesthetics, noise issues	Framed openings	Materials, labor				Sealing around grilles
Condenser locations and line set	Aesthetics, noise issues	Clearance, accessibility to yard (set-back issues), 2x6 walls, chases	Materials, labor, serviceability		Power, service disconnect		
Attic access	Aesthetics	Framed opening, truss issues	Access, serviceability				
Routing B-vent	Chases, clearances, aesthetics (on roof)	Framed chases, roof cap	Materials, labor, installation			No conflicts with vent	
Chases, soffits, and drops	Aesthetics, feasibility	Framing, clearances for ducts, conflicts	Materials, labor, installation			No conflicts with ducts	
Thermostat location	Aesthetics		Materials, labor, installation		Wiring		Seal hole for wires
Equipment efficiency			Materials	Efficiency determined by energy consultant			
Combustion air	Attic vent calcs, routing for CA ducts	Adequate attic vents (roofer)	Ducting, if any				

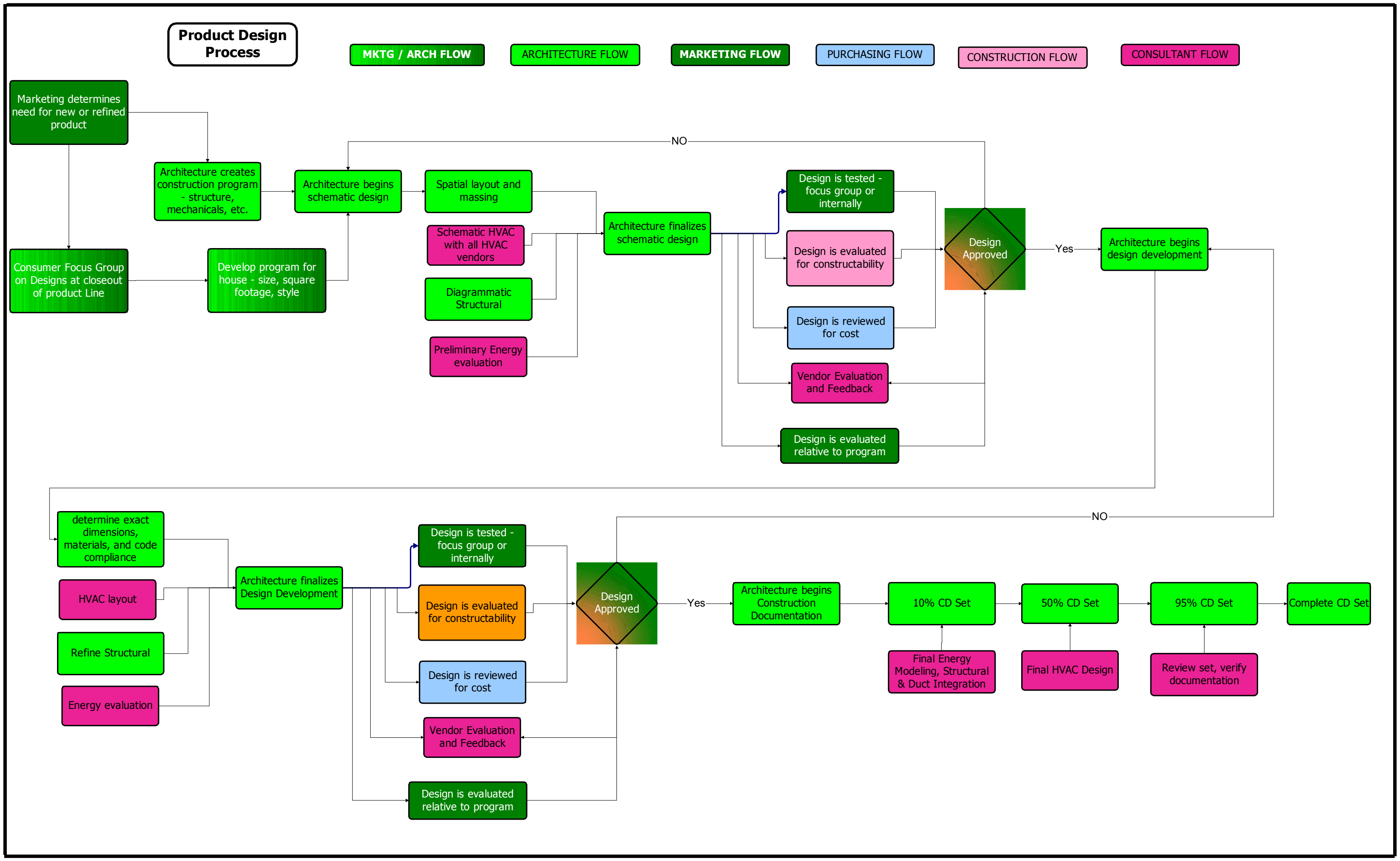


Figure 9.[26] Model of the information flows and actions associated with an integrated design process

[26] IBACOS, Inc. KAAX-3-33410-06 B.2, Community-Scale Process Research Results. Pittsburgh: IBACOS. November 2004

Set Goals Early in the Design Stage. By creating specific high-performance goals early in the design process, the design and construction team and their external vendors all have a clear understanding of the intent and performance metrics associated with a product line. As designs are being developed, all systems and strategies are considered, and feedback is solicited. This allows for early identification of potential conflicts or opportunities for alternate solutions before designs are finalized.

The goal setting also demonstrates to vendors that the builder has committed to a level of performance, and all parties will need to play their role in seeing that it is achieved. A recognized best practice found by many of the Building America teams is a commitment to vendors to participate in long-term relationships, as opposed to simply forming relationships based on the lowest bid. This allows for mutual trust and respect to be built, and the opportunity to improve and innovate is increased.

Gain Team-Based Feedback during Design. When asked about the most important design issue in its success in achieving higher performance levels, one participating builder identified framing as the area that they spend the most time on. The location of every stud, floor truss, and roof truss must be specifically located and coordinated with all other trades in order to make installation of other systems go smoothly and efficiently. This has been true throughout the Building America program. Builders may want to consider use of advanced CAD and panelization programs for generating a specific set of architectural and framing plans for each house type. It is important to work with the framing and HVAC contractors to identify conflicts and develop solutions before houses go into production.

This process is continually being refined, and a best practice by some builders is to create a single system design that would be approved, installed, and warranted by any installing contractor. This can apply for many systems in the house including, but not limited to, framing, electrical, plumbing, and HVAC. For example this level of up-front design with the HVAC system helps control consistency and allows for better performance through proper sizing and design. It is important to have proper load calculations, equipment selection, and duct layouts with documentation that is somewhat transparent, so that HVAC vendors can evaluate system design options and agree upon a final solution. At this point, design changes can also be made to floor plan and framing layouts that can facilitate duct installation. While there is never a perfect solution for all parties, this level of discussion between the vendors, design, and construction greatly enhances the opportunity to "get it right." This process can be applied for virtually any system in the house.

Energy Analysis

From purely an energy perspective, the section of this report on Analysis and Design Optimization describes the process involved with optimizing Building America houses. It must be noted that energy cannot be evaluated in a vacuum, and other issues have to be considered in the design process. In order for higher levels of efficiency to be accepted by builders and consumers, other key attributes of the house must be addressed. The systems-design approach is a process by which all the various subsystems in the house are evaluated and their interrelationships are understood, planned, and optimized. All of these systems must be designed and applied to realize both energy-related and non-energy-performance benefits associated with occupant health, safety, comfort, and long-term building durability and efficiency. To only achieve energy efficiency without meeting these other criteria could cause consumer dissatisfaction and ultimately rejection of higher levels of energy efficiency, because the occupant's other expectations of a new house are not being met.

In a general sense, Building America houses include increased levels of thermal insulation, higher performance windows, significant air sealing, a strategy that eliminates the possibility of introducing the by-products of combustion into the house, a mechanical ventilation system, a properly sized and engineered space-conditioning system, higher efficiency space-conditioning and water-heating appliances, and may also include improvements in the efficiency of the appliances and lighting. The extent to which any of these strategies must be implemented varies by climate zone and the level of energy performance the builder seeks to achieve. A systems-design approach helps to assure that the energy-related aspects of the project are being satisfied in conjunction with the non-energy benefits and done so in a way that optimizes the synergies of the various systems in the house.

Analysis results have shown that the most practical energy reductions to achieve at least 30% whole-house energy savings are in the end-use categories of space heating, space cooling, and domestic hot water. In general, energy reductions are not necessary in the other categories as long as energy savings averaging more than 50% are achieved in each of these three categories. As an alternative, a house design could include energy reductions in lighting or appliances to offset efficiency improvements of mechanical equipment. Energy reductions resulting from the use of solar thermal and photovoltaic systems are not necessary to achieve 30% savings.

Passive Design Strategies for Minimizing Cooling and Optimizing Heating

To achieve a 30% whole-house energy savings, it is not necessary to undertake any specific passive solar-design strategies. It should be recognized that proper orientation of the building and implementation of passive solar strategies can be a low- or no-cost method to significantly improve the energy performance of a house (see Appendix A for addition details on passive design).

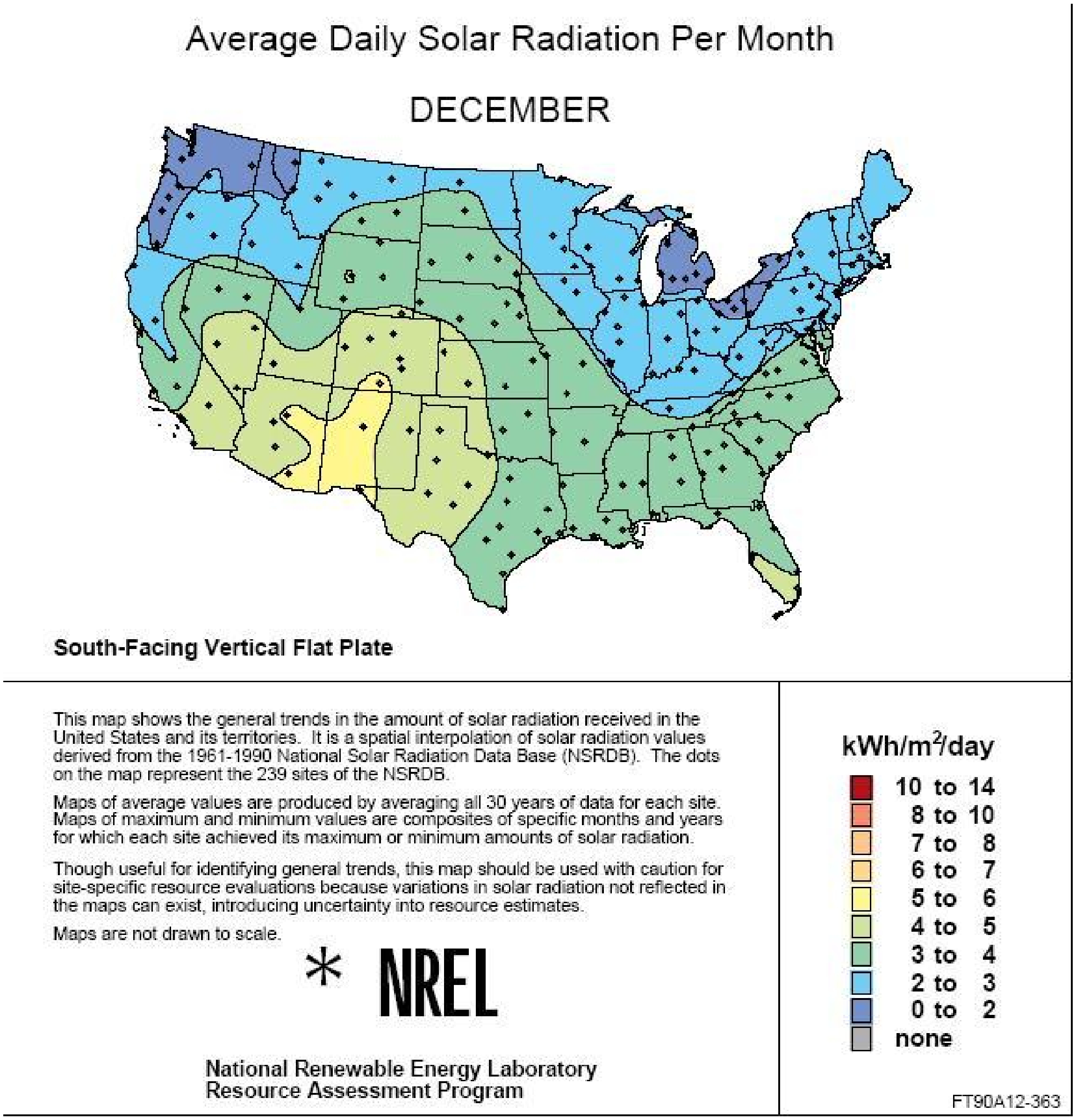
An almost invisible way of incorporating a "passive" strategy that is beneficial in all climate zones is the use of low-Solar Heat Gain Coefficient (SHGC) glazing in all fenestration units. This product generally has little impact on the visual characteristics of the window, and incorporating it does not require aesthetic redesign of the house. The 2004 Supplement to the 2003 International Residential Code[27] requires a SHGC of 0.4 in the Hot-Dry, Mixed-Dry, Marine, Hot-Humid, and southern parts of the Mixed-Humid Climate zones. Relatively low (0.30) SHGC glazing has been used successfully in 30% improvement homes in all climate zones. While a low-SHGC unit reduces beneficial heating season solar gain, Building America teams have found that where no attention is paid to passive solar design, low-SHGC windows generally provide a cost-effective option for builders, when all the systems interactions benefits are considered. The following are the reasons for this:

- Traditional production-builder house models are oriented in any direction. Using lower-SHGC glazing in all windows assures an overall reduction of the heat gain during the cooling

[27] International Residential Code®: 2003 Edition with 2004 Supplement. Country Club Hills, IL: International Code Council, Inc. 2003, 2004.

season, regardless of how the house is placed with respect to the sun. This reduction in heat gain avoids some of the need for air conditioner operation, which is a net energy savings.

- Air-conditioning equipment is sized based on peak load. Using lower-SHGC glazing reduces peak load and, in turn, reduces air-conditioning unit sizes. Smaller air-conditioning systems have lower airflows rates and, therefore, require smaller ducts. Lower airflow rates also require smaller fans, which use less electricity to operate. Reducing the size of the AC system also means cost savings to the builder, which can be reinvested in other energy upgrades.
- The heating-season heat-gain penalty from the use of lower-SHGC glazing only occurs on cold sunny days. As seen in the map of Average Daily Solar Radiation for the Month of December (next page), there is comparably little solar resource across much of the northern United States in the winter months; thus, there is little opportunity for beneficial solar gain. In those areas of the Cold Climate zone where there is a good winter solar resource, high-SHGC windows may be considered, but need to be carefully designed to avoid overheating south-facing rooms on sunny winter days and need to be properly shaded to reduce solar heat gain in the summer months
- Use of low-SHGC glazing, by cutting the solar gain that varies in direction throughout the day, helps maintain more uniform room temperatures throughout the house. Even with zoned systems, it is not possible to control all room temperatures individually, and solar gain is one of the largest factors causing overheating and room-to-room imbalances.



Average south-facing vertical flat-plate radiation in December for the United States

Indoor Air Quality Strategies

The Environmental Protection Agency ranks poor indoor air quality (IAQ) among the top five environmental risks to public health. Levels of air pollution inside the home can be 2 to 5 times higher (and occasionally 100 times higher) than outdoor levels. If too little outdoor air enters a home, pollutants can accumulate to levels that can pose health and comfort problems. Unless they are built with special mechanical means of ventilation, homes that are designed and constructed to minimize the amount of outdoor air entering the home may have a higher pollutant levels.

Providing good IAQ at the 30% improvement level is important to maintain customer health and comfort and may minimize the possibility of high humidity levels and associated mold growth. Because 30% houses will have higher levels of insulation (which affects envelope hygrothermal characteristics) and will be reasonably air tight (which will affect internal moisture gain and removal), good IAQ requires a more proactive approach. Good IAQ requires control of indoor moisture, CO_2, CO, NO_2, SO_2, ozone, particulates, dust mite dropping, odors, and other hazardous airborne contaminants. There are several approaches to good IAQ: (1) control the generating source, (2) remove the contaminant from the indoor air by ventilation or air filtration and/or, (3) physical cleaning (vacuuming, dusting, etc.)

Source Control. Source control is the most positive approach in the 30% improved homes. A number of means of source control have been employed:

- Control of moisture to remove one of the key support elements for mold growth. This is a broad subject and includes application of all of the following principles:
  - Proper flashing details for windows, doors, wall/roof junctions, penetrations of all sorts (pipes, ducts, skylights, etc.), attachments (such as porches and decks), offsets, and projections (such as bay windows) to control the entry of bulk water.
  - Control of envelope condensation potential through appropriate insulation and vapor permeability of layers. Appropriate designs must be applied for all components of the building envelope including walls, roof, and foundations. The section of this report on Cost Analysis discusses climate-specific assemblies. In addition, a builder may utilize other regionally specific guidelines such as the EEBA Builders Guides.[28] At a more detailed level, static analysis techniques or dynamic models such as WUFI[29] can be used. It should be noted that currently WUFI analysis will handle many wall and roof configurations, but it is not capable of foundation analysis. While ongoing research projects are adding to our knowledge of the hygrothermal performances of different forms of foundation insulation, following the practices outlined in the section on Cost Analysis should result in good moisture performance.
  - One wood-frame wall-construction detail that has proven quite effective for condensation control is to use an exterior insulating sheathing in addition to the traditional cavity

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[28] Lstiburek, Joseph. 2004. Energy and Environmental Building Association. Builder's Guide to Cold Climates: A Systems Approach to Designing and Building Homes that are Healthy, Comfortable, Durable, Energy Efficient and Environmentally Responsible. Westford, MA: Building Science Press.

[29] WUFI 2D, Version 2.1. Simulation of heat and moisture transfer. September 2000.

insulation. During the heating season, this helps to raise the temperature of the interior surface of the sheathing (the first condensing surface) above the indoor-air dew point. During periods of hot, humid weather, it acts as a vapor retarder and helps prevent moist outdoor air from entering the wall, which reduces the potential for condensation on the backside of the interior gypsum board in air-conditioned homes. For specific design considerations of this wall assembly, see further detail in the section of this report entitled Building Enclosure Integration Strategies, Walls Section.

- o Foundation waterproofing, damp-proofing, and capillary moisture control are important moisture management actions taken at the 30% improvement level. Failure to properly control moisture in crawl-space and full-basement constructions can result in high relative humidity in these spaces, which can lead to mold and mildew growth. Recommendations include the following:
  - – Exterior foundation waterproofing/damp-proofing with a drainage layer and footing drain, to intercept and drain off exterior water. The drainage layer is often an impervious plastic mat, fiberglass or foam insulation board, or uniformly graded gravel. The insulation board offers the advantage of combining exterior foundation insulation (the most beneficial location for foundation insulation) with a good drainage material.
  - – After a heavy rainfall or after water has been applied for irrigating grass or plantings near the house, moisture can accumulate below and next to a footing. Moisture movement, by capillary action, can occur from this location through to the concrete footing and, from there, the moisture can be transferred into the slab or concrete or block foundation wall. Water stains on the perimeter of the slab or at the interior of the foundation wall can result and are not only unsightly, but they also offer an environment for mold growth to occur. This moisture pathway may be controlled by forming a continuous capillary break between the ground and the concrete foundation system. With monolithic slab-on-grade construction, polyethylene sheeting should be placed under the entire slab and footing up to grade. With footings poured independent of slabs or with foundation walls, a bituminous damp-proofing coating, masonry capillary break paint, or a layer of poly can be used to isolate the footing form the remainder of the assembly.

- Air leakage control is another key method of reducing IAQ pollution sources. Air leaking in from the outdoors may carry outdoor air pollutants (including vehicle exhaust and plant pollens) into the house, but outdoor air is typically (though not always) considered a fresh-air source. What outdoor air does bring, in hot humid weather, is moisture that can condense on internal building components that may then support mold growth. In winter, air leakage outward through the building envelope can bring relatively moist indoor air into contact with cold surfaces. Building envelope air sealing (in addition to reducing energy consumption) is valuable to reduce moist-air migration that could lead to mold growth under both summer or winter conditions and reduce occupant exposure to outdoor pollutants.
- Sealing against air leakage is primarily for thermal reasons, but when coupled with appropriate mechanical ventilation it also assists in providing good IAQ for the occupants. Extensive air sealing is one of the primary 30% improvement strategies. It includes a range of recommendations to builders including the following:

- Developing a continuous air barrier with interior gypsum board on walls and ceilings giving attention to sealing at edges and joints, around penetrations and electrical boxes (including ceiling recessed downlights). Particularly important is to get sheathing continuity behind bathtubs and showers, at fireplaces, soffits, stairways, and at the band joist.
  - Developing an air barrier with exterior sheathing using taped and caulked joints.
  - Foam sealing (non-expansive) around window and doorframes.
  - Construction of well-sealed attic access hatches.
  - Taking particular care to seal all contact surfaces between attached garages and the occupied house. This must include sealing at all penetrations and the provision of gasketed, self-closing doors between garage and house.

- **Seal forced-air distribution systems.** Leaky duct systems contribute to poor IAQ in several ways. Leaky ducts can cause pressure imbalances, which can draw air from the outdoors, building cavities, or attached garage spaces. In addition, pressure imbalances can move moisture-laden air into building cavities where the water vapor can condense, causing a habitat for mold and mildew. Specific strategies and techniques associated with the proper design and construction of air distribution systems can be found elsewhere in this report.

- **Control of radon and other soil gasses.** The principal method of controlling the entry of these gases into a house is through the use of under-slab ventilation. House pressurization can be effective for this purpose as well, but is difficult to implement and control with current HVAC technologies. Under-slab ventilation typically takes the form of modest depth of uniformly graded crushed stone (i.e., with good void spaces) 4 in. to 8 in. deep in which is embedded an array of perforated-plastic drainpipe and covered with a poly air/vapor barrier. The piping is linked by a header to which is connected a vertical vent pipe leading up through the house and out at the roof. This system is often installed as a precaution even when no evidence of radon has been shown because it is far easier to do this than to come back later and retrofit an under-slab venting system. Usually the vent goes through the roof and functions as a passive vent. It is designed, however, for the subsequent installation of an exhaust fan should the need for a more positive ventilating action be demonstrated. An electrical outlet for a possible future fan installation is located in the attic or basement adjacent to the vent pipe. Further information on sub-slab ventilation systems can be found in the EPA's *Model Standards And Techniques For Control of Radon in New Residential Buildings*[30]

- **Combustion Safety.** To avoid the possibility of the introduction of the by-products of combustion being brought into the house, several components associated with combustion safety must be addressed in the 30% improved house. Because these houses are generally quite air tight, natural draft appliances are not recommended. The basic recommendations are as follows:
  - **Furnaces.** Use sealed-combustion units or draft-induced units with dedicated make-up air so that the combustion process is atmospherically decoupled from the house itself.

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[30] Environmental Protection Agency. Model Standards and Techniques for Control of Radon in New Residential Buildings. Environmental Protection Agency Website. www.epa.gov/radon/pubs/newconst.html

- **Tank or tankless domestic hot water heaters.** Use sealed-combustion, direct-vent, or power-vented types that are atmospherically decoupled from the house.
- **Fireplaces.** If fireplaces are installed (gas-fired or solid-fuel-burning), use units that directly vent the by-products of combustion to the outdoors, are equipped with tight-fitting glass doors, and preferably use outside air for combustion.
- **Gas Appliances.** Eliminate unvented gas appliances except cooking appliance, which should be vented to the outdoors by a ducted range hood.

- **Finishes.** Finishes such as paints, sealers, adhesives, fabrics, and surface-covering roll goods (e.g., vinyl wall coverings) are all potential sources of indoor air pollutants, including various volatile organic compounds (VOCs). Most of the liquid-applied materials dissipate rather rapidly as they dry; leaving windows open as they are applied and dry removes the high initial concentrations. After this initial "dry out" period, a properly designed ventilation system will continue to bring in fresh air and remove further off gassing of pollutants. Thus, for any but highly sensitive occupants, the selection of special, low-VOC, materials and finishes is not seen as necessary to achieve the 30% whole-house energy-savings level. Should a homeowner have IAQ sensitivity needs, then the application of the American Lung Association (ALA) Health House Specifications[31] or specifications to meet the EPA's Indoor Air Quality (IAQ) Label[32] would be appropriate.
- **Relative Humidity Control.** The control of indoor relative humidity (RH) is another key strategy to maintain good IAQ. The desirable range of indoor RH is from 20% in winter to 65% in summer, with a preferable range of 30% to 50%. Ventilation strategies play a key role in maintaining these ranges and are discussed more fully in the ventilation section of this report. However, a variety of ventilation forms including heat recovery ventilators (HRVs) or energy recovery ventilation (ERVs) are used to remove excess humidity in the winter and ERVs, dehumidifying ventilators, dedicated dehumidifiers, and advanced HVAC control systems are used to control excess humidity in the summer. The importance of winter or summer humidity control, of course, varies with climate region.
- **Pollutant Removal and/or Dilution.** Ventilation and air cleaning are the principle methods of airborne pollutant removal or dilution. Ventilation system design and strategies are treated more fully in the section of this report on Building America System Research Results, but key features relative to good IAQ in 30% improvement houses will be noted here.
  - Whole-house mechanical ventilation in accordance with ASHRAE Standard 62.2[33] is recommended. Any of a number of system configurations can meet this requirement and include the following:
    - Passive inlet direct to the return air duct with appropriate dampers and controls
    - Dedicated supply fans designed for continuous operation
    - HRVs or ERVs

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[31] American Lung Association. Builder Guidelines. American Lung Association® (ALA) Health House®. www.healthhouse.org/build/Guidelines.asp October 1, 2004.

[32] Environmental Protection Agency. Indoor Air Quality Label. Environmental Protection Agency Website. www.epa.gov/iaq/energystar/label_specifications.html. 2004.

[33] ANSI/ASHRAE 62.2-2004, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*

– Dedicated central dehumidifier with ventilation.

- Whole-house ventilation air should be distributed to all the primary occupied spaces in the house, particularly bedroom and living areas. This is typically accomplished by ducting ventilation air into the heating/cooling duct system. For this distribution to be continually effective, however, the HVAC system must be periodically cycled, even at times when no heating or cooling is required. Dedicated ventilation distribution ductwork is occasionally used, particularly if no forced-air systems exits, but it is a more costly option. Fresh-air intakes should be provided with nominal filtration to prevent the entry of insects and large particulates.
- For good IAQ, the HVAC return-air stream should be filtered with a 4-in. standard filter or a new Minimum Efficiency Reporting Values (MERV)[34] 6 or 8 normal-thickness filters. Ventilation air should also pass through this filter, if possible. Filters should be easily accessible for cleaning or replacement, and the filter slot should be designed so that there is no air bypass around the filter when the HVAC system is operating.
- It is important to provide local exhaust fans for bathrooms, range hoods in the kitchen, and exhaust fans in other areas where pollutants may be generated (utility, hobby rooms, etc.) All of these fans must be ducted to outdoors via the most direct path.
- Ventilation technology has developed significantly in recent years, but a few areas remain problematic:
  - It is difficult to find low airflow ventilation units, particularly HRVs and ERVs.
  - Design of distribution systems is a challenge. Using HVAC ductwork requires cycling the central fan, which increases the electric consumption. Dedicated ventilation ductwork is quite small and must be well designed to function properly. The ventilation air from a dedicated ventilation fan (i.e., ERV, HRV) may not be fully distributed to all rooms when only the ventilation airflow is being moved through the larger ducts of the central space-conditioning system.
  - Builders do not like the additional cost of installing a ventilation system and often have a difficult time explaining to the consumer why it is needed.
  - Ventilation controls are often difficult to integrate with the HVAC system because the products are not usually designed for integration. A newer generation of integrated ventilation and space-conditioning controls are beginning to be introduced by major manufacturers, and it is anticipated that this trend will continue in the future with more options becoming available to builders.
  - Ventilation should be accomplished in the most energy-efficient manner, balancing fan energy consumption with the cost of conditioning the ventilation air.

- **Physical Cleaning**. Builders have very little control over occupant behavior and, as such, there are limited strategies a builder can incorporate in this area. One primary opportunity is in the installation of a whole-house vacuum system that exhausts to the outdoor, which limits the reintroduction of dust in the house. Another is the inclusion of a discussion of

[34] See www.filters-for-home.com/merv.htm for MERV definitions.

maintaining good indoor air quality in an owners' manual for the house, including cleaning practices as they relate to indoor air quality.

Heating and Cooling Equipment and Distribution Strategies – Creating Conditioned Space for HVAC Systems

For the 30% improvement house and all new home construction, it is highly recommended that the heating and cooling system be designed according to industry standard methodologies, most notably ACCA Manual J,[35] S,[36] D,[37] and T.[38] With the use of low-SHGC glass, it is practical to design each house model of a builder's line for the worst orientation without significant penalty in other orientation. The use of low-SHGC glazing reduces the solar component of the cooling load and helps to level the cooling load and minimize variations resulting from orientation. Whenever practical, the design should be specific to an individual house and its orientation. System implications based on variations in orientation are the result of the different solar loads and, for system design purposes, do not affect heating loads. The impact is primarily on the cooling system design because of solar load through windows.

Heating and Cooling Equipment. The preference is for a single heating/cooling unit to serve the entire house, frequently utilizing a zoning system with multiple fan speeds and variable output. This is an efficient approach and allows the closest tailoring of unit size to peak and part load conditions. In some cases, especially homes more than 2,500 ft^2, two or more units may be needed in order to meet the load or to serve distinct zones in the house. With the better thermal envelope of the 30% improved house, a single HVAC unit may often be feasible where two were used before. A single HVAC unit with zoning dampers and controls is also better able to adapt to major load differences. It is strongly recommended that the air-handler unit be located within the conditioned space of the house. When located in unconditioned space, as in vented attic or garage locations, the units are exposed to full winter and summer temperature conditions and experience major thermal losses, because HVAC units are poorly insulated and have significant air leakage.

More detailed discussion of heating and cooling equipment selections are given in the section of this report on Space Conditioning and Ventilation. In the 30% improvement house, the recommendation is to use a sealed-combustion furnace or draft-induced unit with dedicated make-up air so that the combustion process is atmospherically decoupled from the house itself, located in conditioned space, for efficiency and combustion safety reasons.

A high-efficiency electric heat pump may also be an effective choice for heating, although because of the source energy conversion a Heating Season Performance Factor (HSPF) of approximately 9.7 is necessary to match the source energy efficiency of a 92% AFUE furnace. Where the thermal envelope of the house has been significantly improved, the heating load may be dramatically reduced and the cost effectiveness of a gas furnace and all the associated piping

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[35] ACCA. Manual J: Residential Load Calculation 8th Edition. Air Conditioning Contractors of America, Arlington, VA 2003.

[36] ACCA, Manual S: Residential Heating and Cooling Equipment Selection, Air Conditioning Contractors of America, Washington, D.C., 1995.

[37] ACCA, Manual D: Residential Duct Systems, Air Conditioning Contractors of America, Washington, D.C., 1995.

[38] ACCA, Manual T: Air Distribution Basics, Air Conditioning Contractors of America, Washington, D.C., 1993.

and utility infrastructure costs need to be weighed against the potential increase in source energy consumption associated with using a heat pump with a HSPF lower than 9.7.

Air conditioners in Cold Climates should have SEER ratings of 13 or greater, which will be code minimum starting in 2006. It should also be noted that there is a wide range of cooling requirements in the Cold Climate zone, and SEER rating should be evaluated based on annual hours of operation. In general, the greater the cooling need, the higher the SEER rating should be. From a design standpoint, if the architecture of the home incorporates passive strategies for cooling-load reduction (such as shaded south, west, and east glass; minimized unshaded west glass; or a design that incorporates low-SHGC glazing and a small number of windows), cooling system run hours can be reduced and smaller-capacity equipment will be appropriate. In some parts of the Cold Climate zone, designers should also recognize that because of the minimal latent loads, some of the latent capacity in the equipment can be used for sensible load. In general, the sensible capacity equals the total capacity when the design wet-bulb temperature of the return air is less than 59°F. Designers need to check the mean coincident wet-bulb temperature at outdoor design conditions and select equipment based on this. This strategy helps to prevent oversizing of the equipment.

Air Distribution Systems. To achieve a 30% whole-house energy reduction, a number of requirements apply to design of the duct system:

- Design should be in accordance with ACCA Manual D
- Ductwork should be located within the thermal envelope of the house or in some locations in the Cold Climate zone they may be buried in attic insulation
- Ducts should not be located in exterior walls
- Ducts must be air-sealed using UL 181-approved mastic or equivalent for the particular duct type
- “Panning” between joists and the use of stud cavities for supply or return air is not recommended
- Ducts may be of galvanized sheet metal, duct board, or flex duct
- There must be continuity of the vapor barrier on insulated ducts not running inside conditioned spaces.

Sometimes duct systems need to run in unconditioned spaces. For a discussion of the treatment of these ducts, see the section entitled Space Conditioning and Ventilation Systems.

To accommodate heating and cooling units and duct systems within the thermal envelope of the house, a number of techniques may be employed. This typically impacts the architectural design of the house and should be considered at the early schematic phase of design. Keeping ducts inside the conditioned space may also involve framing systems that allow ducts to be run through it, such as an open-web floor-truss system. Alternately, dropped soffits, tray ceilings, and lower ceiling heights in “service” function rooms like baths, hallways, and closets can accommodate ducts inside the envelope. Strategies include the following:

- Locate ducts within an insulated, non-vented, conditioned crawl space or basement
- Locate ducts within an insulated “cathedralized” attic

- Locate ducts in open-web floor trusses
- Develop chase walls to accommodate duct risers
- Design closets inside the conditioned space for locating the air handler in houses using slab on grade construction.

More specific discussion of many of these recommendations is found in the section of this report on Space Conditioning and Ventilation Systems.

Where a boiler or water heater is used for space heating, a hydronic distribution system is necessary. These are particularly suited to Cold Climate applications where there may not be a need for air conditioning and the associated duct distribution system. Their most common configuration is a radiant floor or baseboard convection units. If a radiant floor system is selected in a slab-on-grade installation, it is required than the slab be insulated from the ground and at the slab edge with at least R-10 (2 in.) of rigid insulation. Slab edges need to be insulated because it is exposed to cold exterior conditions. If a boiler or water heater serves a fan coil and ducted system, all recommendations for ducts noted above apply. Hydronic systems are described in more detail in the section on Space Conditioning and Verification Systems.

First Costs, Cost Tradeoffs, and Owner Annualized PITI + Energy

Useful and representative costs information for 30% improvements has not been easy to determine. In many cases these are pilot homes and are the first of this level of energy performance that have been done by a builder. Thus, the energy-use-reduction construction strategies are new to the builder, and costs do not represent a mature purchasing structure or experienced installation practices. Furthermore, there are often compensating or beneficial attributes of the improvement strategies that are not realized until multiple houses are built. An example is the ease of air sealing that is inherent with spray-foam insulation systems that replace tedious hand caulk and foam-gun sealing done by laborers. Until a builder experiences the change, it is usually not valued.

Some of the common cost tradeoffs that builders in the Building America program have used include the following:

- Reduced costs associated with advanced framing
- Reduced costs associated with downsizing space-conditioning equipment and simplifying air-distribution systems
- Increased costs for higher performance windows and insulation and air-sealing packages, that enable the reduction in HVAC system size
- Substituting insulating sheathing for structural panel sheathing increases wall insulation levels at low or no incremental cost
- Increased cost of installing mechanical ventilation
- More usable floor space in slab on grade construction through the use of tankless water heaters instead of tank type water

Builders who commit to evolving their organizations to the consistent production of quality high-performance homes face a transition period. Figure 10 illustrates how the organization will typically change through phases and the corresponding change in first costs.

The transition strategy outlined here provides a logical progression to higher performance housing, but builders need to be prepared to make an investment in other costs associated with implementing a high-performance package, including staff and vendor training, product redesign, collateral development, and testing. Each of these issues will be discussed and suggestions made as to best practices in order to minimize costs.

If the steps taken to transform a company are followed, a builder will have a transitional period where higher costs will be incurred. It is only at the last step, where integrated designs are developed, that a builder can realize immediate construction cost savings. If the total operational costs of running a homebuilding business are considered, potential cost savings should begin to accrue from the first step.

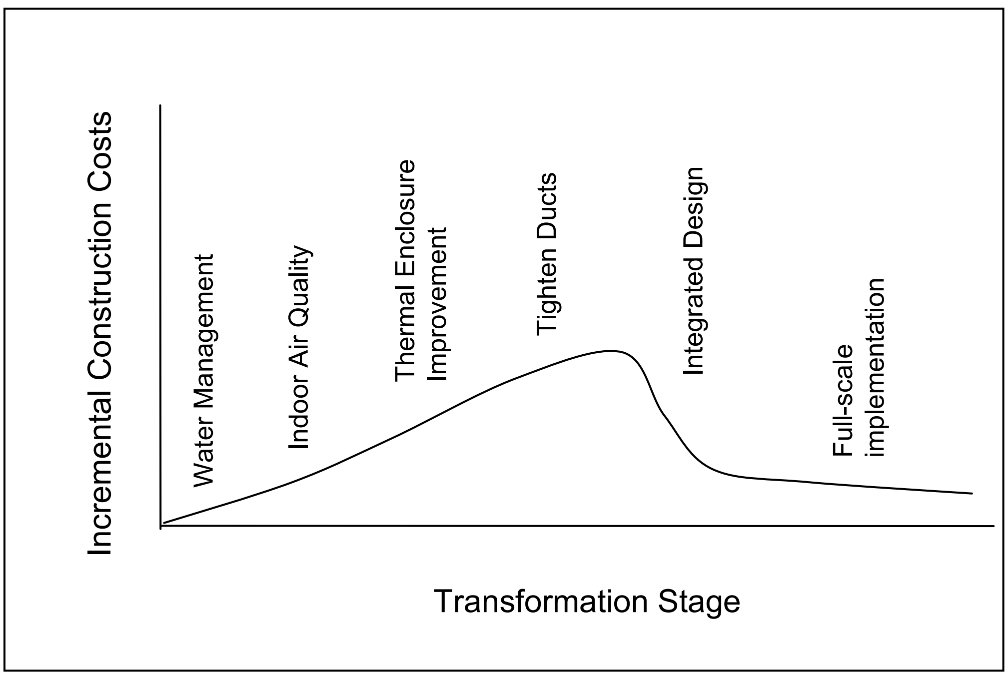

Figure 10. Incremental Cost versus Transformation Stage Curve

Water Management

Because many warrantee issues are associated with water intrusion, a solid water management plan can reduce future costs, limiting the reserves builders need to put aside for future claims. Analysis of past history of water-damage issues, both short-term and long-term, can help quantify the per-house costs associated with the "status quo" versus an improved water-management strategy.

The improvements to the Indoor Air Quality, Thermal Enclosure, and Duct Sealing will all require additional expense. It is, therefore, important to successfully integrate these strategies as quickly as possible. This is where relationships with vendors are critical. Builders must be willing to support the trades during the transition; however, trades must take some level of responsibility for adapting and developing cost-effective solutions for delivering improved performance. Examples of this include rethinking duct installations to allow for prefabrication and sealing of major components or panelization of structural systems to speed erection, cut cycle time, and reduce costs. In addition, vendors must have continuing education costs built into their overhead structure.

A diagrammatic Incremental Construction Cost versus Transformation Stage curve on a per house basis for a builder might be as seen in Figure 10. It should be noted that this curve is diagrammatic by nature and will vary from builder to builder and by region. For example, if a builder has already addressed water management, then there is no expected incremental cost associated with this practice. Also note that the tail end of the curve still shows some increase in costs. This represents the most conservative scenario, where a builder has already optimized many aspects of their houses (i.e., integrated advanced framing or does not significantly oversize HVAC equipment). For the consumer this added cost is offset by reduction in utility bills and, as discussed in the section on System Approach to Least-Cost Energy Savings, should prove to be net cost neutral or even put the consumer at a net positive monthly cash flow.

In order to achieve the goals of a high-performance home transformation, builders and vendors must embark on a training program that engages all levels of the companies. Training must be provided for different levels of employees within the company and for the different departments within the company.

The integrated design process comes with some inherent additional costs, especially if the builder takes responsibility for HVAC system design, as opposed to having the vendors do a "design build" system. The advantages of the builder doing the design are that a greater level of consistency can be achieved and documentation exists for site supervisors to readily check work. It does involve additional costs, either through contracting with outside designers or by training and utilizing internal resources to cover systems integration, including HVAC, framing integration, and detailing. In addition, the cost of re-bidding work involves time and expense on the part of the builder's purchasing department, the trades, and their suppliers. For this reason, it is best that as a builder transitions to a high-performance approach, they do it as part of their ongoing product redesign process, where many of these activities are already budgeted for. Unfortunately, this can lead to a disparity in the builder's marketing approach because some product may meet the new standards and others may not during the transition period. Builders must evaluate the volume they are building, the number of plan types, the current redesign cycle, and the uniformity of marketing message they wish to project when doing this cost benefit analysis.

During the transformation, builders will need to be measuring how well they are doing compared to the performance goals they set. This measuring requires undertaking some level of performance testing. Typically this performance testing will be 100% during the initial steps in order to gain insight into the effectiveness of various practices and techniques being used in the field. As vendors become adept at achieving performance targets, some builders have chosen to ramp down testing activities, while others have chosen to maintain 100% testing as a quality-control measure. In either case, performance testing is a cost that needs to be budgeted for.

Some cost data has been developed from recent Building America projects at the 30% improvement level. The extent of improvement work varies considerably depending on the thermal performance quality of a builder's basic model. These costs are also generally not representative of mature costs and, in some instances, are reduced because materials have been donated by manufacturers.

Table 6 is one example of the incremental costs associated with achieving 39% energy savings in a house in one community in Pittsburgh, Pennsylvania. The case study for this project, Kacin Homes, is included later in this report.

It should be noted that this house included an extensive use of hard-wired fluorescent fixtures, which substantially increased the cost of the project. Similar lighting savings could have been achieved at significantly lower costs with screw-in replacement CFLs; however, this house was part of a more comprehensive research study on strategies for hard-wired energy-efficient lighting solutions. While the builder was already familiar with achieving well above ENERGY STAR Homes® levels of performance, the incremental costs for water heating reflect a "first-time" incremental cost and should be reduced if the builder implemented this throughout all of their houses and negotiated volume pricing.

Table 6. Illustrative Incremental Costs of a High-Performance Home[39]

	Energy Features IECC 2003 Code Compliant		Energy Features Kacin Homes Specifications	Incremental Cost Estimate
ENVELOPE: (Insulation U-Values or R-Values)				
Roof (attic)	U-value = 0.030		**38 (U-value = 0.025)**	
Wall (Exterior)	U-value = 0.060		**R-15+1 inch XPS (U-value = 0.067)**	$400
Floor (above garage)	U-value = 0.033		N/A	
Floor (cantilever)	U-value = 0.033		N/A	
Crawl Space Wall	U-value = 0.065			
Low Air Infiltration	No		**3.8 ACH at 50 Pa**	$200
GLAZING:				
U-Factor			**Wood-framed, double-glazed, argon-filled units**	Builder upgraded windows standard before this project, so no incremental costs
Double Hung	Uvalue =0.35		**U=0.33,**	
SHGC				
Double Hung	SHGC = .55		**SHGC = 0.31**	
HVAC SYSTEM:				
Furnace: AFUE	0.78		**0.91**	$500
A/C: SEER	10 SEER		**13 SEER**	$500
Duct Insulation / Location	5.00		**13.0 (buried in insulation)**	
Duct Testing	No		**Yes**	
ACCA Manual D	No		**Yes**	
Veetilation	No		**Energy Recovery Ventilator**	$1,500
WATER HEATING:				
Water Heater Size	40 gal		**Tankless System**	$1,500
Energy Factor	0.54		**0.82**	
Distribution Type	Standard		**Standard**	
External Wrap	None		**None**	
Solar Credit	None		None	
3rd Party Inspections and Testing			**1 in 7 tested**	Paid for by Community Develop
Fluorescent lighting			**Extensive hard wired flourescent lighting package**	$8,000
Appliances	NAECA Minimum		Al Energy Star	$800
			Total Estimated upgrade cost	**$13,400**
			Total Estimated cost excluding lightng	**$5,400**
CASH FLOW	**Total Incremental Cost**	**$13,400.00**		
	Total Incremental Cost Excluding Lighting	**$5,400.00**		
	Estimated Monthly Energy	**$28**		
	Monthly Amortized Cost	**$36.26**	At a 7% interest rate For 30 years	
	Net Monthly additional cost	**$7.93**		

[39] 1815-ft^2 home in Pittsburgh, Pennsylvania

Reducing Construction Waste

Research conducted by the National Association of Home Builders (NAHB) and the NAHB Research Center shows that 87.7% of the 1.7 million homes built in the United States in 1999 were stick-framed, that a “typical” home consumes just over 13,100 board feet of framing lumber (about three-quarters of an acre of forest), and that the wood scrap pile for the construction of this “typical” home is approximately 2 tons.

A combination of factors has worked to increase the consumption of wood in home building.

Single-family detached units. A single-family detached home uses more wood per household than multi-family housing. According to NAHB, single-family detached units went from about 71% of overall housing starts to nearly 80% just between 1978 and 2001.

Home size. In the past 40 years, the median new home size in the United States has increased from 1,365 ft^2 to well over 2,000 ft^2, this despite the fact that household size has actually decreased by 20%.

Complexity. Not many of today’s homes are simple in form. Jogs, dormers, vaulted ceilings, convoluted roof lines, and elaborate staircases are common in new homes.

Safety standards. We require more of our structures today, particularly in regions with seismic and wind considerations. Re-engineering for these loads has resulted in some increase in wood use, but has also spawned site practices that simply “throw more wood” at the problem.

Lumber versus labor. Just as the relative value of materials versus labor seems to have reversed (today, materials are “cheap”—it’s the labor that is “dear”), the typical skills set of both designers and framers has diminished, leading to waste at the front and tail ends of wood construction.

The nature and structure of the industry. Home building is like no other production process in the 21st century. Nearly all of the 1.7 million homes built each year are site-built, making home building one of the most fragmented of industries in the United States. It is journeymen framers—not architects, engineers or even general contractors—who control what and how much wood goes where on the job site. And most training occurs informally, by word-of-mouth, during production.

Two-foot Module Design

Starting with foundation layout, the house footprint should be based on 2-ft increments, often with significant savings in framing members and sheathing and always with a lot less waste. Sheet goods come in 4-ft. by 8-ft. dimensions. Layouts should be based on the fundamental unit dimensions of the materials used. Work by the NAHB Research Center found that the wood savings are dependent on the starting dimension.

Value-Engineered or “Advanced” Framing

There are a number of substantial advantages to optimized framing: it saves time and money up front, it improves homebuyer satisfaction, its saves money and energy over the long term, and it improves builder image.

More than 7,000 homes built by Building Science Consortium production builders have used advanced framing. The resultant savings in waste are the products of "systems-thinking" and a breakdown of age-old myths about how wood framing works.

The following sections are descriptions of the major optimized framing techniques, with appropriate references from the *International Residential Code,*®[40] cited in brackets.

Frame 24 in. on center. The prevailing practice is to frame walls, floors, and often roofs at 16-in. centers. However, 24-in. centers are structurally adequate for most residential applications. Even when the stud size must be increased from 2x4 to 2x6, changing spacing from 16 to 24 in. can reduce framing lumber needs significantly. See Figure 11 for an example.

Align framing members and use a single top plate. Double top plates are used principally to distribute loads from framing members that are not aligned above studs and joists. By aligning framing members vertically throughout the structure, the second plate can be eliminated. Plate sections are cleated together using flat-plate connectors. For multistory homes that are framed with 2x4s, this may increase the stud size on lower floors to 2x6; however, there is still typically a net decrease in lumber used [Section R602.3.2 of the Code. A single top plate is listed as an acceptable option for in-line framing and with properly tied joints]. Figure 12 illustrates the alignment of framing and use of single top plates.

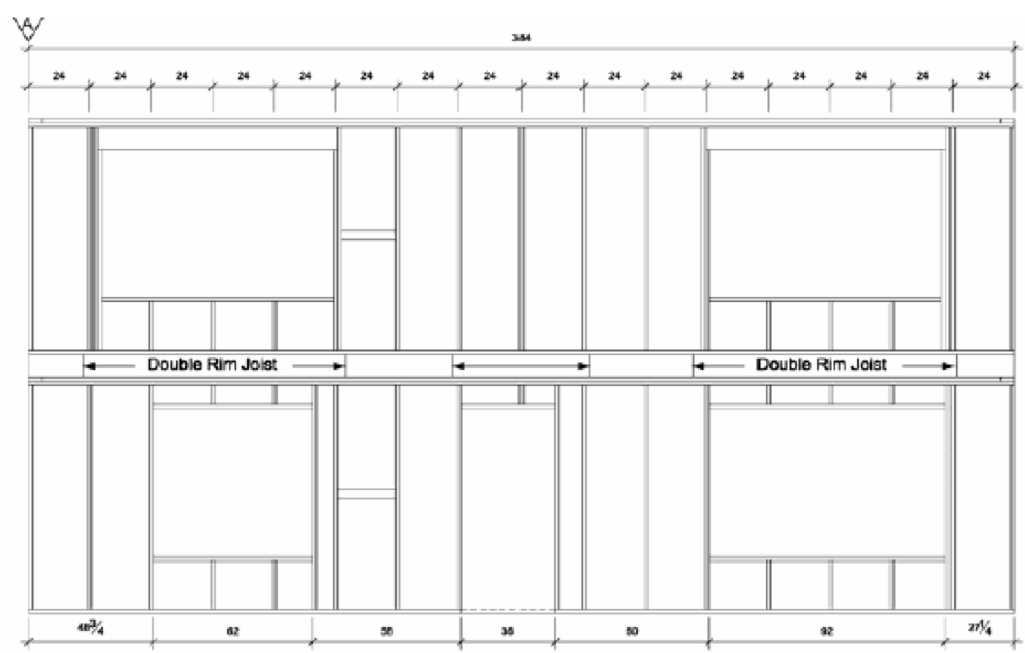

Figure 11. Advanced framing layout showing 24-in. stud centering

[40] International Residential Code®. 2003 Edition. Country Club Hills, IL: International Code Council, Inc. 2003.

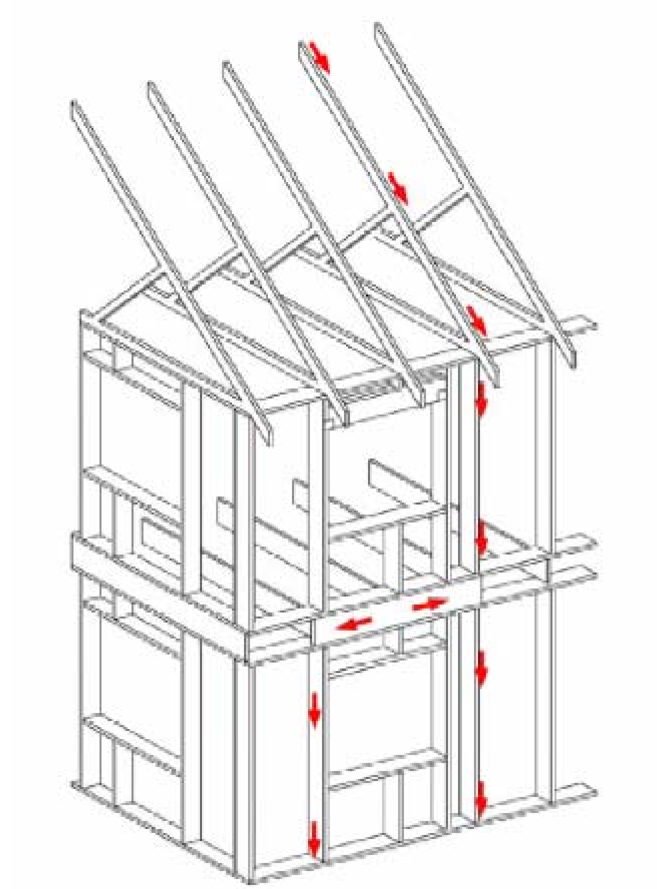

Figure 12. Advanced framing showing truss alignment with stud framing and single top plates

Size headers for actual loading conditions. Headers are often oversized for the structural work that they do. Doubled-up 2x6 (or 4x6) headers end up in non-load-bearing walls. Doubled-up 2x12 (or 4x12) headers end up in all load-bearing walls, regardless of specific loading conditions. “Load-tuned” headers should be in the vocabulary and practice of all engineers, architects, builders, and framers [Section R602.7.2. This section states that non-bearing walls do not need structural headers].

Ladder-block exterior wall intersections. Where interior partitions intersect exterior walls, three-stud “partition post” or stud-block-stud configurations are typically inserted. Except where expressly engineered, these are unnecessary. Partitions can be nailed either directly to a single exterior wall stud or to flat blocks inserted between studs. This technique is called “ladder blocking” or “ladder framing.” This also creates room for more insulation. Figure 13 shows a ladder block configuration.

Use two-stud instead of three-stud corners. Exterior wall corners are typically framed with three studs. The third stud generally only provides a nailing edge for interior gypsum board and can be eliminated. Drywall clips, a 1x nailer strip or a recycled plastic nailing strip can be used instead. Using drywall clips also reduces opportunities for drywall cracking and nail popping, frequent causes of builder callbacks. Figure 14 shows various stud corner arrangements.

Eliminate redundant floor joists. Double floor joists are often installed unnecessarily below non-load-bearing partitions. Nailing directly to the sub-floor provides adequate attachment and support. Partitions parallel to overhead floor or roof framing can be attached to 2x3 or 2x4 flat blocking.

Use 2x3s for partitions. Interior, non-load-bearing partition walls can be framed with 2x3s at 24 in. on-center or 2x4 "flat studs" at 16 in. on-center [Section R602.5].

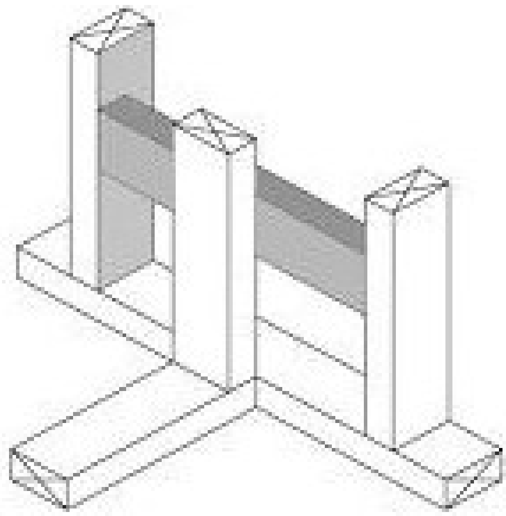

Figure 13. Example of ladder block exterior wall intersections

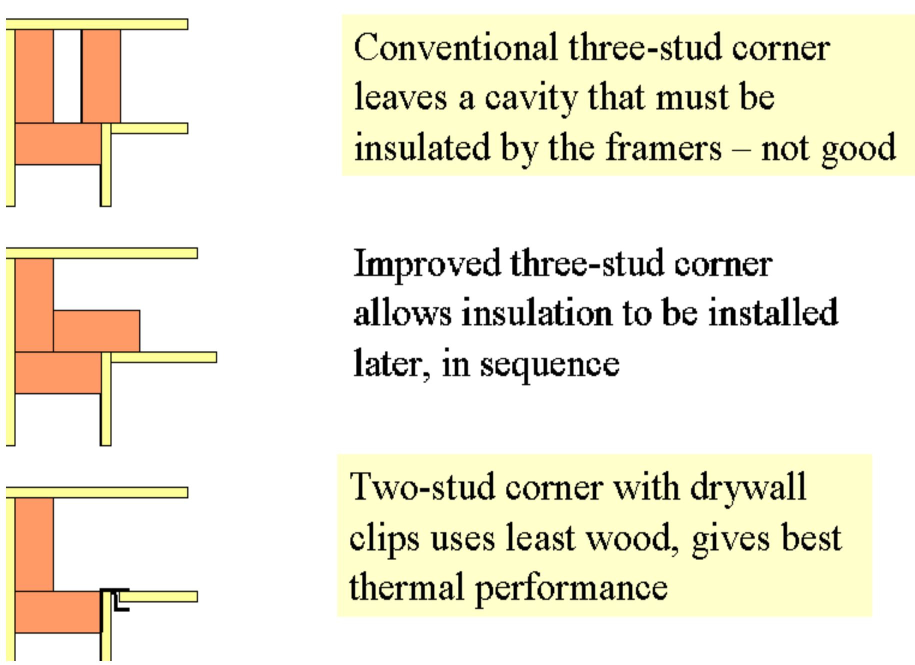

Figure 14. Wall stud corner configurations

Compact Duct Systems

A framing plan can do more than just lay out floor joists. There are opportunities to value-engineer the floor system and obtain a proper joist count, to ensure that all plumbing is coordinated with the floor framing, to ensure that all HVAC is coordinated with the floor framing, and to ensure that the "stack framing" concept is followed on the job site. Most importantly, all these issues are resolved on paper before casting the foundation. Figure 15 and Figure 16 show compact duct system layouts.

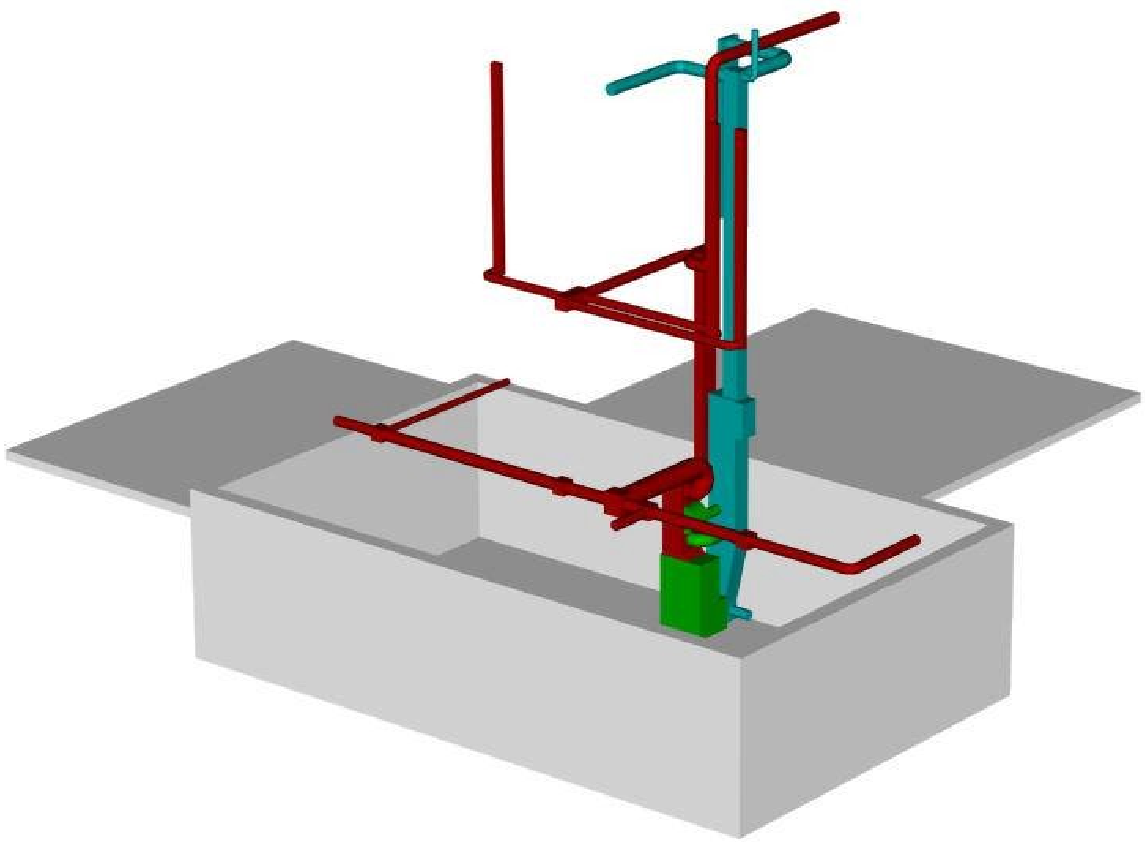

Figure 15. Three-dimensional example of compact duct system[41]

[41] Heating and cooling equipment shown in green, return duct shown in blue and supply ducts shown in brown.

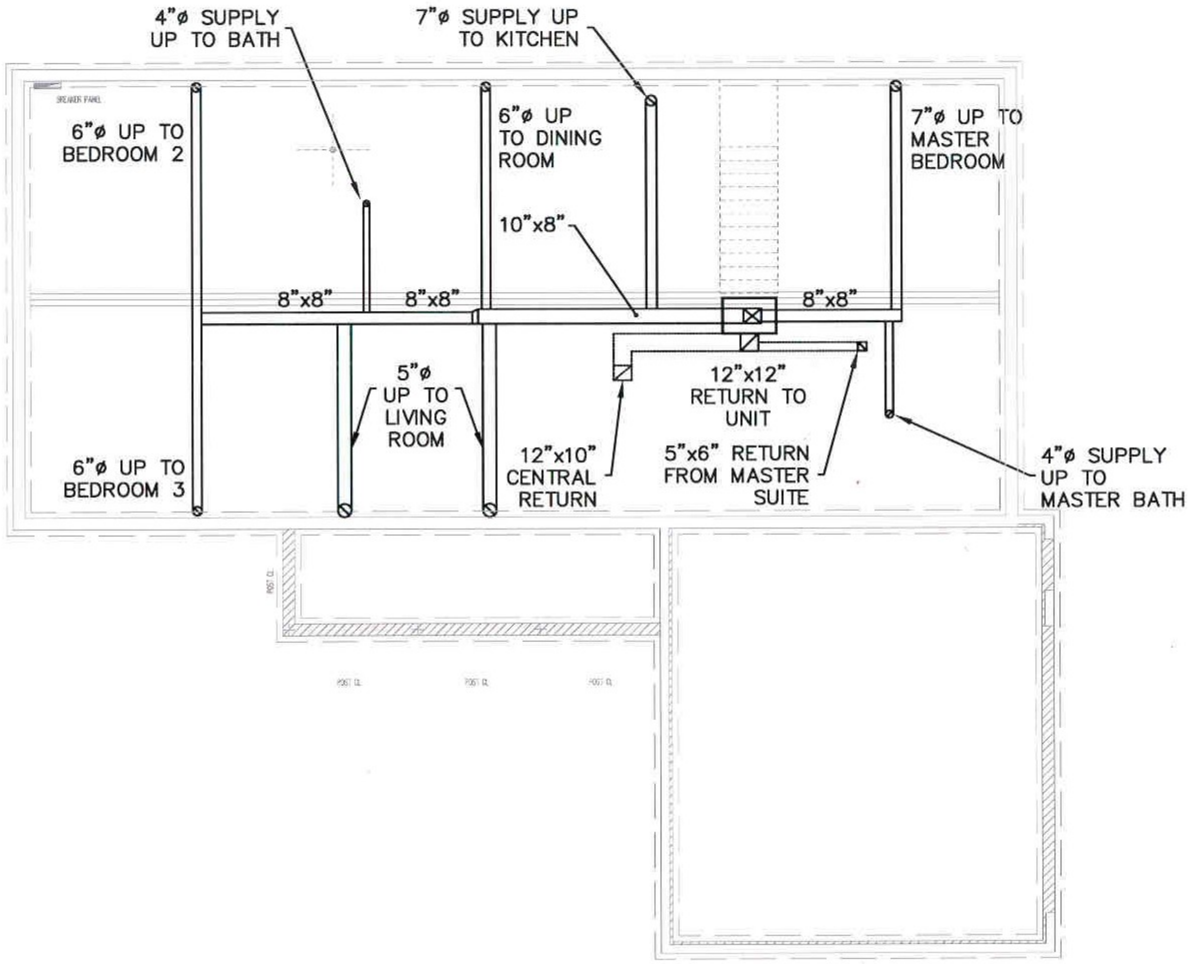

Figure 16. Example of a compact duct layout

Recycling of Construction Materials

No matter how efficient our use of wood, there will be some waste—cut-offs from both solid-sawn lumber and sheathing. Even for the most efficiently framed buildings, wood waste will be one of the largest components of the new construction waste stream.

Reduced wood purchase and disposal costs. Actual field counts for a production builder in California have found a 40% reduction in the cost of a wall-framing package after implementing optimized framing methods; a purchase savings for the builder of more than $1,100 on each house. Another builder in Maryland reduces total wood waste disposal by 15% using efficient framing. Neither of these examples takes into account the labor savings from handling less wood and wood waste.

Reduced environmental impact. The annual toll for residential construction in the United States is 2 billion board feet of framing lumber and nearly 2.5 million tons of wood waste. That translates into 1.1 million acres of clear-cut forest and 30-yard dumpsters lined up end-to-end from Phoenix to Chicago! Clearly, builders can achieve and claim significantly reduced global and local environmental impact with optimized framing.

On-site grinding. Waste that is grinded into wood chips makes a great soil-erosion-control mat at job site entrances or bermed at the base of silt fences.

Quality Project Management Approach

A key component of high-performance system design and any high-performance construction process is quality project management. Quality management is a well-traveled term, but its definition can be elusive. In terms of Building America high-performance homes, the following definition is useful:

> Quality management is an ongoing effort to systematically and comprehensively improve methods and processes that yield an optimal combination of energy efficiency, comfort, durability, indoor air quality, and moisture management.

This definition recognizes quality management as an integral part of achieving 30% whole house energy savings. It emphasizes that improvements in energy efficiency must be accompanied by commensurate improvements, or at least maintenance, of other key performance attributes of the home to reflect a true systems-thinking approach. This definition also reflects the built-in cost effectiveness of high-performance quality management as a risk-reduction strategy (comfort, durability, indoor air quality, and moisture management) for the builder. And finally, the definition encompasses homebuyer expectations of performance—with energy efficiency as just one of five performance attributes that any home should provide.

This definition also establishes the inherent relationship between quality and high performance, which is this: Whereas a quality home need not necessarily be a high-performance home, any high-performance home MUST be a quality home. For any Building America high-performance homebuilder to truly incorporate a systems approach, he or she must also incorporate a quality management approach.

The quality management approach is an essential element of the Building America approach to homebuilding because it is *the* main vehicle for moving from science and concepts of high performance to implementation.

The package of tools within the Building America quality management approach includes the following:

- Training/Education
  - For builders
  - For individual trades
  - Certifications
- Operational Evaluation (Modified NHQ[42])
  - Paper Review

[42] The NHQ is the NAHB Research Center's National Housing Quality Program, discussed in detail below. Building America team leader, IBACOS, modified the NHQ system to include criteria specific to housing performance.

    - Key Player Interviews
- Performance-Based Standards
    - Design
    - Specifications
    - Scopes
- Verification Tools
    - Performance Testing
    - Inspections (Checklists)
- Feedback Loops.

Although this package has not been developed from a single source or as a comprehensive system, it certainly could be used as a comprehensive quality project management approach. Each of these is discussed in detail below.

Training/Education

Builder and Subcontractor Training

Training has been found to be needed throughout the Building America program. Ongoing efforts within the industry will be necessary to develop, deploy, and continually update training programs to disseminate information from the Building America program if widespread implementation is to take place. While Building America has not been specifically charged with the development and deployment of training programs, this section discusses some of the opportunities, activities, and issues involved with training at the residential construction industry level.

Builders. The starting point for the quality management approach has always been builder training. These have included pre-construction training meetings and site training of trade contractors. Each Building America team has conducted such trainings, and their work in the context of Building America has led to any number of building-science based training programs in the industry:

- **The Energy & Environmental Building Association's Houses That Work training program.** This public-private training partnership has trained hundreds of builders all across the country in the principles of climate-based high-performance building science. Several of the Building America teams have certified Houses That Work trainers. Although not explicitly portrayed as such, the Houses That Work trainings have many of the elements of quality management as listed above.
- **The Environments for Living®[43] (EFL) Diamond Class Training.** Long-time Building America partner, Masco Contractor Services, has developed a new 3-day builder training

[43] Environments for Living is a building-science-based, high-performance homebuilding program of Masco Contractor Services. The program was developed approximately 5 years ago in a public-private partnership with Building America.

program, which focuses on the principles of building science and their application in production homebuilding.

- **Colorado Built Green® 2005 training.** The new three-tier version of this program has criteria based specifically on the Building America program and best practices, as well as Tier II and III training patterned after Houses That Work.
- **Build IQ Best Practices.** An online training company, Build IQ, has been incorporating best practices from the Building America program for inclusion in their free and for-fee coursework. Build IQ delivers online training to top 100 homebuilders throughout the United States, including Pulte Homes, John Laing Homes, Beazer, Morrison, and others.
- **BECT (Building Energy Code Training).** Since 1995, BECT has helped the building industry keep up with changes in energy codes. The Building Industry Institute (BII) and their subcontractor, ConSol, under contract to the California Energy Commission (CEC), began a training program for large production builders in California and Nevada. The program has improved compliance with energy standards by improving builders' understanding and implementation of the energy codes.

  The BECT program has trained more than 3,000 contractors and subcontractors in the California and Nevada area since its beginnings in the mid 1990s. Through the BECT program, California is able to train builders in the following:

  - Current codes and issues
  - Upcoming code changes
  - Construction techniques that improve quality of construction
  - Common enforcement issues.

California's energy code has always been at the forefront of implementing energy-efficient standards in home building. The energy code's goal in the beginning was to increase energy efficiency of a home being built in California every 3 years by approximately 5%. But since the energy crisis, the percentage has been increased to 12% in 2001 and 15% in 2005. Having an infrastructure in place like the BECT program has greatly facilitated this dramatic change to the building industry.

Training – Trade Contractors. Each Building America team has conducted trade contractor training on climate-specific building science and systems thinking. Targeted trades have included framing, insulation, and HVAC. The EFL program conducts trade contractor building science training for framing and insulation contractors and is developing an HVAC training module. The BECT program in California also provides training to subcontractors.

Training – Certifications. The Building America program has led at least one of its builders to develop its own certification related to high performance. Artistic Homes of Albuquerque, New Mexico, certifies its entire sales staff under a high-performance training program. The program is called the High Performance Homes Sales Specialist.

It is not clear at this time if certification of high-performance homebuilding skills from a third-party group such as the North American Technician Excellence (NATE) or the Building Performance Institute (BPI) would be used in the industry. There is time and expense on the part of the trade contractor and the individual technician to receive the certification, and this must then be built into the price of doing business, which ultimately gets transferred to the builder. There may be a correlation with better-trained technicians and reduced callbacks; however, this direct link has not been thoroughly researched or documented.

Feedback from builders who have participated in the Building America program reveals that one of the most difficult aspects of sustaining the delivery of high-performance housing is the continuous need for trade training and re-emphasizing the performance targets each trade must meet. This, in part, can be attributed to the high turnover in the building industry; however, it may be that a certification program for high-performance delivery of various key trade activities will be necessary for true transformation of the housing industry. A list of key trade-based certifications associated with delivery of high-performance housing can be found in Appendix C.

Operational Evaluation

Modified from the National Association of Homebuilders Research Center's National Housing Quality program, the Building America operational evaluation is a two-step process to help builders evaluate their own operations. The first is a paper review of all the documentation a builder has that is associated with its operations and the actual housing being built. The second is an interview with key individuals in the company. A reasonable list of the builders' primary source information for the first part of this evaluation includes the following:

- **Annual operating plan.** This includes company mission, vision, organizational values, goals for each department, strategic objectives, and reporting and other operational guidelines. The annual operating plan supports the long-range strategic plan, by documenting specific actions and goals that will help the company achieve the strategic plan.
- **Long-range strategic plan**. This includes the direction the company is headed, what types of barriers might exist, and how these barriers might be overcome. This document is a roadmap, which is made more specific in each year's annual operating plan.
- **Process maps.** These include any diagrammatic or written representation of the workflows operationally within the company.
- **Design documentation.** This category includes construction drawings, scopes of work, written specifications, contracts, field guides, etc., that communicate what should be built by the vendors.
- **Operational tools.** These include any sort of departmental tools used to facilitate business processes. For example, construction schedules or other field tools used by site supervisors to assist in the day-to-day management of construction or template letters and reports to assist in the standardization of company processes.
- **Training programs.** This includes any internally developed or externally developed program for continuing education of staff within the builder's operations. The intent here is not to specifically review the content of all training programs, but to evaluate the general attitude, approach, depth, and breadth of training activities in the builder's organization.
- **Human resource manual.** This includes company policy, safety programs, benefits, and items documenting company culture.

- **Marketing materials.** This includes any type of material used to communicate the builder's message about their product to consumers.
- **Survey mechanisms and results.** These include any surveys done by the company or outside consultants, which can be for employees, customers, or vendors, or can collect regional or local information on competitive information, such as sales prices or volume of construction.

A reasonable list of key builder staff to interview as part of the second step in an operational evaluation includes the following:

- Operations
- Marketing
- Sales
- Purchasing
- Construction
- Customer Service
- Human Resources
- Land Development.

This two-step process gives a comprehensive understanding of the builder's current operations. This evaluation process could be adopted internally by a builder or externally through the use of a consultant in order to identify what areas may need to be addressed if the builder is considering transforming their product line to achieve Building America high-performance home technology packages. The process is comprehensive, but not overly detailed—it takes approximately 20-30 hours for one person to work through, once all the data has been assembled. It can identify best practices and opportunities without dwelling on minutia. Appendix D contains the latest version of the modified NHQ two-step process as developed by IBACOS.

Performance Standards—Design, Specifications, Scopes

Quality is often compared to the three-legged stool (the stool is of little use without all three legs). In high-performance home-building, quality is only achieved with performance standards for design AND materials (specifications) AND installation (scopes). Building America takes this premise one step further by stating that many performance standards must be climate-specific; indeed, even lot-specific when local terrain and environments bring with them additional challenges, such as extreme slopes, expansive soils, coastal high winds and flooding, etc.

Design and Design Review. An effective means of assuring these goals are implemented during the planning stages of a project is through a design review of the project, this can be a key instrument in making sure the whole energy system is incorporated in the design. It is highly unlikely that a home will be designed singularly around the HVAC system or window orientation or its ability to resist heat. However, these are all factors that go into a home and are crucial in getting a house to achieve 30% whole-house energy savings. For this purpose, value-engineering techniques must be employed to ensure that all the systems in the home can not only be designed to perform at optimum levels but also be coordinated with those involved with actual construction of the project to make sure that the homes are built practically and as intended when designed on paper.

Each of the Building America teams has conducted dozens of detailed design reviews, resulting in resources such as the Building America Houses That Work climate-specific Best Practices, the Houses That Work building profiles, the Noisette Home Performance Standards, the draft Risk Assessment Protocol, etc. The common ground among these design standards is that they respond to climate-specific protection of the energy efficiency, the comfort, the indoor air quality, the durability, and the moisture management of each high performance home. Thus, they make up the first leg of the "quality stool"—high performance design.

Specifications. Specifiers, and subsequently purchasers, rarely take into account the overall performance of the home and its systems when making crucial material/component/subsystem choices. Standard specifications don't take into account individual component performance variations, much less the impact of single-component choices on assemblies or systems. Various Building America projects have addressed this issue. High-performance specifications were developed for the EcoVillage Townhome project in Cleveland. Ohio.[44] These specifications could and should be modified and applied to other high-performance home projects.

Scopes of Work. Even with intelligent design and the right materials, quality can fall short of intended performance without the right installation. Production builders generally rely upon their scopes of work to achieve the installation required. But as a rule, these scopes do not reflect systems thinking or climate-specific building science. More than one Building America team leader has developed project-specific mock-ups (for walls and window installation, for example [BSC—EcoVillage, IBACOS - Summerset at Frick Park]) or detailed installation procedures that could and should be used by high-performance builders in their scopes. BIRA, in conjunction with the Comfortwise program, has developed and posted high-performance specifications for several keytrades, including HVAC and insulation. It would not be difficult, for example, to take a well-known industry scopes resource, such as the NAHB BuilderBooks "The Scopes of Work Program,"[45] and develop a customized Building America set of scopes as a comprehensive resource that integrates performance and quality.

Verification

Verification tools for performance and quality include performance testing and inspection checklists. Clearly the first choice is almost always a quantitative test, such as any of the following:

- Using a blower door for measuring air tightness
- Using a calibrated fan system for measuring for duct tightness
- Using a flow hood for measuring supply and return airflows at registers and grilles

[44] Building Science Corporation. EcoVillage Sample Spec Language. www.buildingscience.com/buildingamerica/casestudies/ecovillage_specs.pdf. 2002.

[45] Haas Davenport, Linda. 2000. The Scopes of Work Program: Procedures and Standard to Increase Quality. Washington, D.C., BuilderBooks.com.

- Using a manometer for room-to-room pressurization
- Using a digital thermometer to measure room-to-room temperature variation
- Using a low-e detector to verify glazing properties.

The beauty of these tests is that quantitative metrics can be established that summarize the quality of design, materials, and installation for one or more performance attribute. Most performance tests for the residential building industry deal with energy efficiency directly and then may be indirectly reflective of other performance attributes, such as indoor air quality and comfort. But quantitative tests for other performance attributes, such as moisture management and durability, are generally not available, at least not in a cost-effective application. For verification of these performance attributes, a detailed inspection checklist and visual inspections act as a proxy determination of both quality and performance.

An important consideration in any quality management approach is the cost of verification. The primary determinants of at least the initial costs are the number of homes tested—ranging from one initial model home to 100% testing of every home built—and what entity does the testing—either in-house testing, third-party testing, or some combination of the two. In general, for production builders, Building America has recommended a testing strategy similar to the EPA ENERGY STAR strategy of 1-in-7 random testing after a period of 100% testing to verify that key performance metrics are met on a consistent basis. But more than one Building America production builder has determined that either the pace at which they build or their reputation for quality (or both) make 100% in-house testing and random 1-in-7 third-party testing the most cost-effective strategy in the long run, based on looking at the total costs and total benefits of a much more rigorous quality protocol. The Building America Best Practices Guides[46] produced by Pacific Northwest National Laboratory contain recommendations for testing protocols for each climate. In addition, a "SNAPSHOT" performance testing protocol and report process has been documented by Building Science Corporation and is included as Appendix E of this report.

Each Building America team has made up prescriptive checklists to handle non-quantitative performance assessment, particularly for performance attributes, such as durability and moisture management. While it is difficult to address ALL of the variables that lead to customization of these lists—climate, lot, aspect, surrounding local features, building type, etc.—these checklists can be referenced as examples of how quality management of high-performance attributes are assessed and verified for builders seeking to achieve the Building America "standard." One of the difficulties that builders face with non-quantitative metrics and verification are the questions, "How do I know when enough is enough? When is our practice a best practice, substandard, or overkill?" Builders MUST use their local conditions and past product history (in terms of callbacks, legal claims, 1- and 2-year warranty trends) to intelligently manage durability and moisture. Proxy, qualitative tools can be applied—such as infra-red imaging of assemblies, water testing, and moisture meter readings—but these approaches have not been documented as part of the Building America body of research.

[46] Building America Best Practices Series: Volume 3; Builders and Buyers Handbook for Improving New Home Efficiency, Comfort, and Durability in Cold and Very Cold Climates. 2005. 140 pp.; NREL Report No. TP-550-38309.

Commissioning

Building commissioning is a systematic process of ensuring that a building performs in accordance with the design intent, contract documents, and the owner's operational needs. As a result of the sophistication of building designs and the complexity of building systems constructed today, commissioning is necessary, but not automatically included as part of the typical design and construction process. Commissioning is critical for ensuring that the design developed through the whole-building design process is successfully constructed and operated.

Building commissioning includes the following:

- Systematically evaluating all pieces of equipment to ensure that they are working according to specifications. This includes measuring temperatures and flow rates from all HVAC devices and calibrating all sensors to a known standard.
- Reviewing the sequence of operations to verify that the controls are providing the correct interaction between equipment.

In particular, building commissioning activities include the following:

- Engaging a commissioning authority and team
- Documentation
- Verification procedures, functional performance tests, and validation
- Training.

Building commissioning is not one of the following:

- Construction observation (punch list)
- Start-up
- Testing, adjusting, and balancing (TAB)
- Final punch-out.

These activities are individual steps in the systematic process of commissioning, but by themselves these activities cannot meet the goals of building commissioning.

Commissioning HVAC systems is even more important in energy-efficient buildings because equipment is less likely to be oversized and must, therefore, run as intended to maintain comfort. Also, HVAC equipment in better performing buildings may require advanced control strategies. Commissioning goes beyond the traditional HVAC elements. More and more buildings rely on parts of the envelope to ensure comfort.

Commissioning includes evaluating the building elements to ensure that shade management devices are in place, glazing was installed as specified, air-leakage standards have been met—these are the static elements of the building. Commissioning can also evaluate other claims about the construction materials, such as VOC emission content and durability. It is important that the products that were specified for the building meet the manufacturer's claims (and are appropriate for the project.)

Continuous commissioning ensures that the building operates as efficiently as possible while meeting the occupants' comfort and functional needs throughout the life of the building. Continuous commissioning differs from building operation and maintenance.

Benefits of building commissioning include the following:

- Energy savings and persistence of savings
- Improved thermal comfort with proper environmental control
- Improved indoor air quality
- Improved operation and maintenance with documentation
- Improved system function that eases building turn-over from contractor to owner.

Feedback Loops

Quality is a process ideally supported by feedback within the corporate structure and across the full range of product. Every department—design, construction, purchasing, warranty, sales, and marketing—should report performance successes and failures to every department for each and every product type, taking full advantage of feedback loops. In reality, many production builders set up little incentive for quality of product, erring in favor of quantity of product. But some builders are beginning to understand that it is not just how much profit a company can make, but how much profit a company RETAINS, once the set-asides for warranty and claims are factored in. More than one builder is asking its managers a question like this:

> If we are currently setting aside about $5,000 for each home we build to cover warranty and claims, how much quality management can we afford?

Production builders in today's hot housing market are generally not having trouble making profits, just keeping them. If financial incentives can be created for quality of product, the reduction in warranty and claims can be used to finance the quality incentive structure. Feedback loops are a key element of any such quality-management approach.

Quality-Management Summary

In order to achieve whole-house energy savings of 30% or more, we are managing energy flows on, in, and through the structure to such a degree that we must manage the flow of air and moisture with equal attention. The links among energy efficiency, comfort, IAQ, durability, and moisture are not optional, they are built into the physics that builders face and the expectations buyers bring. Likewise, quality management is not an option when building high-performance homes. It is a process inherent to systems thinking and systems engineering. Without the quality-management tools to implement the principles of physics and building science, higher performance in housing is simply an technical exercise, not a business proposition.

Building Component Design Details

Building Enclosure Integrity

A house is an environmental separator with the function of separating the inside from the outside, as required by the local environment and the wishes of its occupants. A house creates an interior environment that is different from the exterior environment. This interior environment should be controllable by the occupants in a manner that meets their needs.

In order to function as an environmental separator, the elements, components, assemblies, and sub-systems that comprise a house must meet specific objectives, including the following:

- Control of heat flow
- Control of airflow
- Control of rainwater
- Control of groundwater
- Control of water vapor flow.

Control of Heat Flow

The key strategy in the control of heat flow is the use of thermal insulation in a manner that continuously encloses the conditioned space. If a conditioned space is considered a cube, then all six surfaces enclosing the cube are encased by thermal insulation. In the typical home, this means both the above- and below-grade walls are insulated, as wells as the attic ceiling/roof assembly and the foundation slab.

Fully insulating a basement slab is also not necessary to meet the 30% savings goal. However, it is a recommended approach for all new houses from a moisture-control perspective if basements are to be intended for occupancy. Installing carpets and other floor finishes over uninsulated concrete basement floor slabs often leads to problems with dust mites and mold in floor coverings.

With wood-frame construction, this means that exterior walls have 2x6 framing where cavities are insulated with fiberglass batts, spray-applied cellulose, or low-density spray-applied foams. In addition, the exterior 2x6 framing is sheathed with rigid-foam insulating sheathing.

In general, insulating sheathing is not necessary to meet the 30% savings goal. However, insulating sheathing has other significant benefits particularly in the areas of moisture control. Inwardly driven moisture from reservoir claddings, such as brick and stucco, can be controlled by insulating sheathing. Additionally, the use of insulating sheathing of sufficient thickness allows the removal of interior vapor barriers and vapor retarders, thereby enhancing the inward drying of the assembly. In other words “double vapor barriers” can be avoided.

Insulating sheathing also has cost advantages over oriented-strand board (OSB) and plywood sheathings when coupled with innovative framing techniques for wind and seismic loadings.

Reducing heat-flow wood-,frame construction can be accomplished by minimizing the amount of framing materials through which conductive heat transfer can occur, increasing the cavity thickness to accommodate more thermal insulation and utilizing sheathing materials that provide thermal resistance.

Materials can be reduced at corners and where interior partition walls intersect exterior walls. Thermal bridging can be reduced at door and window openings through the use of insulated headers and using hangers to eliminate king studs and cripple studs. Stud spacing can also be increased to 24-in. spacing and point loading trusses.

Increasing cavity thickness to accommodate more thermal insulation can be facilitated in wall framing by utilizing thicker framing materials and at the intersection of roof trusses and exterior walls through the use of specialized trusses. In all truss and roof assemblies, baffles should be installed to prevent the wind washing of thermal insulation and to prevent insulation from blocking ventilation in vented-roof assemblies.

Fenestration has minimum U-values of 0.3 and SHGC values of 0.4 or lower.

Control of Airflow

One of the key strategies in the control of airflow is the use of air barriers. Air barriers are systems of materials designed and constructed to control airflow between a conditioned space and an unconditioned space. The air-barrier system is the primary air-enclosure boundary that separates indoor (conditioned) air and outdoor (unconditioned) air. In multi-unit/townhouse/apartment construction the air-barrier system also separates the conditioned air from any given unit and adjacent units. Air-barrier systems also typically define the location of the pressure boundary of the building enclosure.

The air-barrier system also separates garages from conditioned spaces. In this regard, the air-barrier system is also the "gas barrier" and provides the gas-tight separation between a garage and the remainder of the house or building.

Air-barrier systems keep outside air out of the building enclosure or inside air out of the building enclosure depending on climate or configuration. Sometimes, air-barrier systems do both.

Air-barrier systems can be located anywhere in the building enclosure: at the exterior surface, the interior surface, or at any location in between. In Cold Climates, interior air-barrier systems control the exfiltration of interior, often moisture-laden, air. On the other hand, exterior air-barrier systems control the infiltration of exterior air and prevent wind washing through cavity insulation systems.

Numerous approaches can be used to provide air-barrier systems in buildings. Rigid materials such as gypsum board, exterior sheathing materials like plywood or OSB, and supported flexible barriers are typically effective air-barrier systems if joints and seams are sealed.

Spray-applied foam insulations can be used as interstitial (cavity) air-barrier systems. Damp-spray-applied cellulose does not meet the performance requirements of air-barrier materials or assemblies — it is an air retarder.

The significant advantage of exterior air-barrier systems is the ease of installation and the lack of detailing issues related to intersecting partition walls and service penetrations.

An additional advantage of exterior air-barrier systems is the control of wind washing that an exterior air seal provides with insulated-cavity frame assemblies.

The significant disadvantage of exterior air-barrier systems is their inability to control the entry of air-transported moisture into insulated cavities from the interior. As a result, most exterior air-barrier systems are insulated on their exterior side with rigid or semi-rigid insulations that are not sensitive to wind washing.

An advantage of interior air-barrier systems over exterior systems is that they control the entry of interior moisture-laden air into insulated assembly cavities during heating periods. The significant disadvantage of interior air-barrier systems is their inability to control wind washing through cavity insulation and their inability to address the entry of exterior hot-humid air into insulated cavities in Hot-Humid Climates.

Installing both interior and exterior air-barrier systems can address the weakness of each.

Utilizing framing elements in conjunction with the interior gypsum sheathing can meet the requirements of a building-envelope air-barrier system. In this approach, primary reduction of air-leakage openings is shared by both the framer and the gypsum-board installer.

Air leakage at the platform frame floor assembly can be reduced by sealing the rim joist to the frame wall or plate below and the sub-floor sheathing above. This is typically accomplished by using a continuous bead of sub-floor adhesive to seal the sub-floor sheathing to the rim joist and caulking to seal the bottom of the rim joist assembly to the plate below. Gaskets and other seals can also be utilized. Where floor trusses or other manufactured wood-product floor system components are used (wood I beams), solid rim-joist material installed in a continuous manner should be provided to prevent air leakage at the rim-joist assembly.

Air leakage between the bottom plates of exterior walls and the sub-floor sheathing is controlled by sealing the bottom plate to the sub floor. This is typically accomplished by installing a continuous bead of sealant or caulk under wall plates.

Air leakage at floor assemblies where cantilevers occur is also controlled at rim-joist locations. Blocking utilizing wood or rigid insulation can be used with both exterior and interior cantilever floor assemblies. Where floor-framing members are installed parallel to exterior walls (or garage walls), solid rim-joist material can be installed directly over wall plates to provide for air-barrier continuity.

Air leakage through sub-floor sheathing installed over unconditioned spaces, such as vented crawl spaces, unconditioned garages, or cantilevered floors over exterior walls, can be controlled by sealing all panel joints.

Tubs, shower stalls, and one-piece manufactured tub/shower enclosures installed on exterior walls can provide the single largest source of air-leakage areas when uncontrolled. Rigid sheathing material should be installed on the interior surfaces of exterior walls and sealed to framing and sub-floor sheathing before the installation of tubs and shower enclosures. Thin, non-insulating sheathings can be installed in a manner that allows the installation of interior gypsum-board sheathing over sheathing edges without noticeably altering wall thickness. With one-piece manufactured tub/shower enclosures, the entire height of the interior surface of exterior walls should be sheathed. This usually requires the installation of cavity insulation before the installation of the interior sheathing.

Where fireplaces are installed on exterior walls, air leakage can be as significant as air leakage at tubs and shower stalls. Fireplace enclosure framing should be lined on the interior with rigid sheathing material. Such enclosures should be considered as small rooms that are conditioned. Accordingly, they require a sealed top, bottom, and three sides. Gypsum board, plywood, wafer board, and foil-covered pressed paper can provide satisfactory performance when sealed. This will also greatly reduce callbacks from cold drafts coming from fireplaces.

Interior soffit assemblies above cabinetry on exterior walls or adjacent insulated ceilings and attics also require air sealing. Where the ends of soffit assemblies or framing boxing in mechanicals intersects exterior walls, the "footprint" of the soffit or framing against the exterior wall should be enclosed with sheathing.

Window and door openings can be sealed by the framer sealing the window or door unit to the rough framing with foam, caulk, or other sealant. Alternatively, the drywaller can return the gypsum-board interior finish to the window or door unit and seal the joint with caulk.

Interior utility chases or dead spaces between two closely spaced walls, dropped ceilings, and split levels require special attention. Sealing responsibilities are shared between framers and drywallers at dropped ceilings and split-levels. Blocking is installed and sealed by the framers; gypsum board is installed and sealed by the drywallers.

Attic access openings located within conditioned spaces should also be sealed, as well as flue pipe penetrations.

Whole-house fans require a cover that can be installed during the heating season in an airtight manner. Some whole-house fan units come equipped with airtight covers. Those units that do not can have removable covers site manufactured in a similar manner to removable attic access covers.

Control of Moisture

Control of Rainwater. The fundamental principle of rainwater control is to shed water by layering materials in such a way that water is directed downward and outward from the building or away from the building. It applies to assemblies such as walls, roofs, and foundations, as well as to the components that can be found in walls, roofs, and foundations, such as windows, doors, and skylights. It also applies to assemblies that connect to walls, roofs, and foundations, such as balconies, decks, railings, and dormers.

Layering materials to shed water applies to the building as a whole. Overhangs can be used to keep water away from walls. Canopies can be used to keep water away from windows, and site grading can be used to keep water away from foundation perimeters.

All exterior claddings pass some rainwater. Siding leaks, brick leaks, stucco leaks, stone leaks, etc. As such, some control of this penetrating rainwater is required. In most walls, this penetrating rainwater is controlled by a drainage plane that directs the penetrating rainwater downward and outward.

Drainage planes are water-repellant materials (building paper, house wrap, foam insulation, etc.) that are located behind the cladding and are designed and constructed to drain water that passes through the cladding. They are interconnected with flashings, windows, door openings, and other penetrations of the building enclosure to provide drainage of water to the exterior of the building. The materials that form the drainage plane overlap each other shingle fashion or are sealed so that water flow is down and out of the wall.

Materials that absorb and store rainwater when it rains and that are located on the outside of buildings can create problems. They can act like reservoirs or sponges absorbing and holding water when exposed to rain. Stored water can migrate elsewhere and cause problems. Common reservoirs are brick veneers, stuccos, wood siding, wood trim, and fiber-cement cladding.

The best approach to dealing with reservoirs is to eliminate them or disconnect them from the building. Back priming (painting all surfaces, back, front, edges, and ends of wood siding, cement siding, and all wood trim) gets rid of the moisture storage issue with these materials.

Back-venting brick veneers and installing them over foam sheathings disconnects the brick-veneer moisture reservoir from the building. Installing stucco over two layers of building paper or over an appropriate capillary break, such foam sheathing, similarly addresses stucco reservoirs.

Control of Groundwater. The fundamental principles of groundwater control are to keep rainwater away from the foundation wall perimeter and to drain groundwater with sub-grade perimeter drains before it gets to the foundation wall. This applies to slabs, crawl spaces, and basements.

Concrete and masonry are sponges – they can wick water through capillarity. This is the main reason that damp-proofing (the black tar-like coating) is applied to exterior basement walls. The damp-proofing fills in the pores in the concrete and masonry to reduce ground water absorption. The damp-proofing is a capillary break. Under concrete-floor slabs, the stone layer combined with polyethylene serves a similar function (they act as capillary breaks). Unfortunately, the capillary rise through footings is typically ignored. This can be a major problem if foundation perimeter wall are finished or insulated.

In new construction, a capillary break should be installed on the top of the footing between the footing and the perimeter foundation wall. This can be done by damp-proofing the top of the footing or by installing a membrane at this location.

The interior insulation and finishing approach must take into account the moisture migrating up through the footing. This is best accomplished by installing rigid foam insulation on the interior of the assembly to protect the interior finishes.

The best foams to use have a perm rating of greater than 1 perm for the thickness used. This means limiting extruded polystyrene insulation to less than 1-in. thickness for walls (if more than 1 in. thick, they do not breathe sufficiently) and making sure that the rigid insulation is not faced with polypropylene skins or foil facings. Additionally, because foams need to be protected from fire, and this is often done with gypsum board, only latex paint should be used on interior gypsum finishes (because it breathes).

Capillary control also applies to slab-on-grade construction and crawl spaces. Monolithic slabs need plastic ground covers that extend under the perimeter grade beam and upward to grade. Additionally, the exposed portion of slabs must be painted with latex paint to reduce water absorption and a capillary break must be installed under perimeter wall framing.

Control of Water Vapor Flow. The fundamental principle of control of water in the vapor form is to keep it out and to let it out if it gets in. The following things are discouraged:

- The installation of vapor barriers on both sides of assemblies (i.e., “double vapor barriers”)
- The installation of vapor barriers, such as polyethylene vapor barriers, foil-faced batt insulation, and reflective radiant barrier-foil insulation on the interior of air-conditioned assemblies
- The installation of vinyl wall coverings on the inside of air-conditioned assemblies

- The installation of polyethylene vapor barriers on the interior of internally insulated basements.

The following things are encouraged:

- The construction of assemblies that are able to dry by diffusion to at least one side and, in many cases, to both sides
- The ability to use insulating sheathings in Cold Climates without the creation of "double vapor barriers"
- The ability to use of damp-spray insulations in Cold Climates with insulating sheathings without the creation of "double vapor barriers."

Specific Recommendations

- Soil surfaces shall be graded away from below-grade envelope surfaces.
- Materials next to below-grade envelope surfaces shall be free-draining and shall connect to a sub-grade drainage system through a filter media that will prevent fines build-up in the drainage system.
- A clay cap or other water-flow-resistant surface layer shall be installed to prevent surface water from draining into the free-draining material next to below-grade envelope surfaces.
- Below-grade surfaces shall be provided with a damp-proofing layer or coating that will be effective as a capillary break.
- All surfaces subject to wind-driven rain or snow shall be provided with a drainage plane or layer that will prevent rain wetting of internal materials.
- Indoor relative humidity shall be maintained at the center of the room or as low as necessary to keep the room air next to cool/cold surfaces at less than 70% relative humidity.
- All building envelope assemblies should include at least one air barrier and one vapor-retarder surface.
- All crawl-space assemblies should have a continuous impermeable ground cover that functions as both an air barrier and vapor retarder.
- Provide air-barrier systems that control air movement from the interior.
- Locate vapor diffusion retarders toward the interior of building assemblies and avoid vapor diffusion retarders toward the exterior of building assemblies. Where low permeance exterior sheathings are utilized, temperature of condensing surfaces under heating conditions should be controlled (use of insulating sheathings, external insulation), as well as interior vapor pressures.
- Provide secondary air barriers that control wind washing from the exterior.
- Control interior relative humidities during the coldest portion of the heating season (maintain below 35%).
- Allow wet or moist materials used in construction to dry toward the exterior.

Envelope Systems

Foundation Systems

The function of a foundation system is to hold up the building. This involves facilitating the transfer of loads from above grade to the ground. Foundation systems, depending on their configuration and location, may also have to control other factors, such as heat flow, airflow, rainwater, groundwater, and water-vapor flow.

Slab on Grade

Structure. In Cold Climates the primary slab-on-grade approach involves stem wall and footing construction because of the historic necessity of locating the bottom portion of the foundation below the frost depth. Shallow frost-protected foundation approaches have proven to be incompatible with typical tract construction practices; horizontal insulation projections are prone to damage during the construction process.

Insulation and Air Infiltration. The perimeter of the concrete slab must be thermally isolated from both the stem wall and the ground below. In Cold Climates, additional insulation is also necessary to provide thermal comfort and this necessitates full-height thermal insulation installed internally on the stem wall. This thermal insulation extends from the top of the footing to the underside of the slab. A sill gasket also provides an air seal between the foundation and the frame structure on top, as well as a soil gas seal between the slab and the stem wall.

Water Management: Drainage, Vapor Diffusion. As in all foundation systems the perimeter grade must slope away from the foundation to reduce the saturation of ground adjacent the structure. With stem-wall slab construction footings, stem walls do not need to be damp-proofed if the slab is isolated with both a capillary break and vapor barrier from both the ground and the stem wall. The sill gasket functions as the primary capillary break between the stem wall and the frame structure. A polyethylene-sheet membrane vapor barrier should be installed in direct contract with the concrete slab — above any thermal insulation under the slab.

Interaction with Mechanical Systems. Excessive long-duration interior negative pressures should be avoided. A depressurization limit of 5 Pascals is recommended for continuously operating exhaust appliances. A depressurization limit of 20 Pascals is recommended for intermittent-operating exhaust appliances. Only sealed-combustion appliances should be installed within the pressure boundary of the building enclosure. Passive sub-slab ventilation is recommended to reduce atmospheric air-pressure soil-gas drivers.

Crawl Space

Structure. In Cold Climates, the primary crawl space approach involves conditioned crawl-space construction. Vented crawl spaces are energy inefficient compared to conditioned crawl spaces and lead to comfort problems (cold-floor complaints) and freezing pipes.

Insulation and Air Infiltration. The perimeter of crawl spaces must be insulated typically to the same level of thermal resistance of the frame wall above. Interior rigid insulation is the insulation system of choice because it is not water sensitive. The interior location is preferred from both a constructability perspective and insect-resistance perspective.

This thermal insulation extends from the top of the footing to the underside of the floor framing. A sill gasket provides an air seal between the foundation and the frame structure.

Water Management: Drainage, Vapor Diffusion. As in all foundation systems the perimeter grade must slope away from the foundation to reduce the saturation of ground adjacent the structure. All below-grade surfaces in ground contact should be damp-proofed. A continuous sealed air barrier and vapor-barrier ground cover should be installed. If the interior crawl space grade is below the exterior grade, a perimeter drain system is required. This perimeter drain works best when located on the exterior of the foundation assembly.

Interaction with Mechanical Systems. Excessive long-duration interior negative pressures should be avoided. A depressurization limit of 5 Pascals is recommended for continuously operating exhaust appliances. A depressurization limit of 20 Pascals is recommended for intermittent-operating exhaust appliances. Only sealed-combustion appliances should be installed within the pressure boundary of the building enclosure. Passive sub-ground cover ventilation is recommended to reduce atmospheric air pressure soil gas drivers.

Conditioning of the crawl space should be accomplished by supplying conditioned air to the crawl space either via a dedicated duct or via transfer air from the house where a continuously operating exhaust fan is used as the pressure driver.

Basement

Structure. In Cold Climates, the primary basement construction approach involves perimeter cast-in-place concrete foundation walls over strip footings. The footings are located below the frost depth. Shallow frost-protected foundation approaches have proven to be incompatible with typical tract construction practices; horizontal insulation projections are prone to damage during the construction process.

Insulation and Air Infiltration. The perimeter of the basement assembly must be insulated full height from the top of the footing to the top of the foundation wall. Interior rigid insulation is the insulation system of choice because it is not water sensitive. The interior location is preferred from both a constructability perspective and insect-resistance perspective. Additionally, thermal comfort issues require insulation below the basement slab over the entire surface area of the basement floor.

A sill gasket provides an air seal between the foundation and the frame structure.

The interior surface of the rigid insulation must be protected from fire.

Water Management: Drainage, Vapor Diffusion. As in all foundation systems the perimeter grade must slope away from the foundation to reduce the saturation of ground adjacent the structure. All below-grade surfaces in ground contact should be damp-proofed. A capillary break should also be installed over the top of the strip footings, isolating the perimeter concrete foundation wall from the ground. A polyethylene-sheet membrane vapor barrier should be installed in direct contract with the concrete slab — above any thermal insulation under the slab.

Interaction with Mechanical Systems. Excessive long-duration interior negative pressures should be avoided. A depressurization limit of 5 Pascals is recommended for continuously operating exhaust appliances. A depressurization limit of 20 Pascals is recommended for intermittent-operating exhaust appliances. Only sealed-combustion appliances should be installed within the pressure boundary of the building enclosure. Passive sub-slab ventilation is recommended to reduce atmospheric air pressure soil gas drivers.

Building Enclosure Integration Strategies

Walls

The function of wall systems is to provide environmental separation between the interior and exterior, as well as to transfer wind and seismic loads to the foundation. And, similarly, walls transfer loads from the roof to the foundation. As part of the provision for environmental separation, wall systems have to control heat flow, airflow, rainwater, and water vapor flow.

Structure. In Cold Climates, the primary structural approach is site-built wood frame utilizing engineered elements, such as prefabricated lintels, headers, and sheet goods, such as OSB, plywood, and gypsum wallboard.

Resistance to shear loads as a result of wind and seismic events must be provided. The choice of construction or framing approaches addressing shear loads should reflect the local conditions. For example, houses constructed in low-wind zones can be constructed with wood frame assemblies with non-structural sheathings and metal cross braces or wood "let-in" braces. A similar home built in a higher wind zone, such as in a coastal wind zone or built in a more severe seismic zone, may have to be constructed with structural sheathing or inset shear panels.

The principle means of controlling lateral loads are as follows:

- metal cross braces
- wood "let-in" braces
- structural sheathing such as plywood or OSB
- proprietary shear panels.

Insulation and Air Infiltration. The optimum approach to insulation involves 2 x 6 advanced-frame walls with insulating sheathing replacing OSB or plywood sheathing. Cavity insulation is either unfaced fiberglass-batt insulation or damp-sprayed cellulose.

Air infiltration control is provided by an air barrier. An interior air barrier is used, specifically interior gypsum sheathing combined with framing elements, such as draft-stopping and fire-stopping components.

Water Management: Drainage, Vapor Diffusion. Rainwater management is provided by using the insulating sheathing as a drainage plane and integrating window and doors with the insulating sheathing to provide drainage-plane continuity.

Vapor diffusion is addressed on a location by location basis via the thermal resistance of the insulating sheathing. No interior vapor barrier is installed; however, the temperature of the condensing surface is controlled by increasing the thermal resistance of the insulating sheathing. As the average outdoor temperature of the three coldest months decreases, the thermal resistance of the insulating sheathing increases. For example, in Chicago, R-5 (or 1-in.) insulating sheathing is used, whereas in Minneapolis, R-10 (or 2-in.) insulating sheathing is used (Figure 17 and Figure 19).

Interaction with Mechanical Systems. The tighter the building enclosure, the greater the pressure differential created with exhaust appliances. The use of an air barrier results in a tighter building enclosure.

Excessive long-duration interior negative pressures should be avoided. A depressurization limit of 5 Pascals is recommended for continuously operating exhaust appliances. A depressurization limit of 20 Pascals is recommended for intermittent-operating exhaust appliances. Only sealed-combustion appliances should be installed within the pressure boundary of the building enclosure.

Floors

The function of floor systems is to provide environmental separation between the interior and exterior where they intersect the exterior enclosure, as well as to transfer wind and seismic loads to the foundation by functioning as a diaphragm and similarly to transfer loads from the roof to the foundation. As part of the provision for environmental separation, floor systems have to control heat flow, airflow, rainwater, and water-vapor flow.

Structure. In Cold Climates, the primary structural approach is site-built wood framing utilizing engineered elements, such as prefabricated I-joists and sheet goods, such as OSB.

Insulation and Air Infiltration. The optimum approach to insulation involves using spray-foam insulation on the interior of the rim-joist assembly. An alternative approach in severe Cold Climates is to use a prefabricated insulated rim joist.

Air-infiltration control is provided by an air barrier. The air barrier is the rim-joist assembly itself sealed to the framing elements above and below using sealant or spray-foam insulation.

Water Management: Drainage, Vapor Diffusion. Rainwater management is provided by using insulating sheathing installed exterior to the rim joist as a drainage plane and integrating this with the insulating sheathing of the frame assembly, either above or below the floor system to provide drainage-plane continuity.

Vapor diffusion is addressed on a location-by-location basis via the thermal resistance of the insulating sheathing installed exterior to the rim joist. No interior vapor barrier is installed; however, the temperature of the condensing surface is controlled by increasing the thermal resistance of the insulating sheathing. As the average outdoor temperature of the three coldest months decreases, the thermal resistance of the insulating sheathing increases. For example, in Chicago, R-5 (or 1-in.) insulating sheathing is used, whereas in Minneapolis, R-10 (or 2-in.) insulating sheathing is used (Figure 17 and Figure 19).

Interaction with Mechanical Systems. The tighter the building enclosure, the greater the pressure differential created with exhaust appliances. The use of an air barrier results in a tighter building enclosure.

Excessive long-duration interior negative pressures should be avoided. A depressurization limit of 5 Pascals is recommended for continuously operating exhaust appliances. A depressurization limit of 20 Pascals is recommended for intermittent-operating exhaust appliances. Only sealed-combustion appliances should be installed within the pressure boundary of the building enclosure.

Roof / Ceiling / Attic

The function of roof/attic systems is to provide environmental separation between the interior and exterior, as well as to transfer wind and seismic loads to the foundation by functioning as a diaphragm. As part of the provision for environmental separation, floor systems have to control heat flow, airflow, rainwater, and water-vapor flow.

Structure. In Cold Climates, the primary structural approach is site-built wood framing utilizing engineered elements, such as prefabricated roof trusses and sheet goods, such as OSB and plywood.

Insulation and Air Infiltration. The optimum approach to insulation involves blowing insulation on the top surface of ceiling gypsum board. This ceiling insulation level is maintained throughout the entire plane of the ceiling extending to the perimeter walls. Roof trusses are constructed in such a manner as to maintain the thickness of ceiling insulation directly above the top plates of the exterior wall framing. Baffles are installed to control wind washing.

Air-infiltration control is provided by an air barrier. The ceiling gypsum board is installed to function as an air barrier. Dropped ceiling areas are draft-stopped, ceiling light fixtures are selected to be airtight, and all penetrations through plates are air sealed.

Water Management: Drainage, Vapor Diffusion. Traditional roofing materials such as shingles are used to provide rainwater management at the roof deck.

Vapor diffusion is handled by providing roof/attic ventilation.

Interaction with Mechanical Systems. The tighter the building enclosure, the greater the pressure differential created with exhaust appliances. The use of an air-barrier ceiling assembly results in a tighter building enclosure.

Excessively long-duration interior negative pressures should be avoided. A depressurization limit of 5 Pascals is recommended for continuously operating exhaust appliances. A depressurization limit of 20 Pascals is recommended for intermittent operating exhaust appliances. Only sealed combustion appliances should installed within the pressure boundary of the building enclosure. Passive sub-slab ventilation is recommended to reduce atmospheric air pressure soil gas drivers.

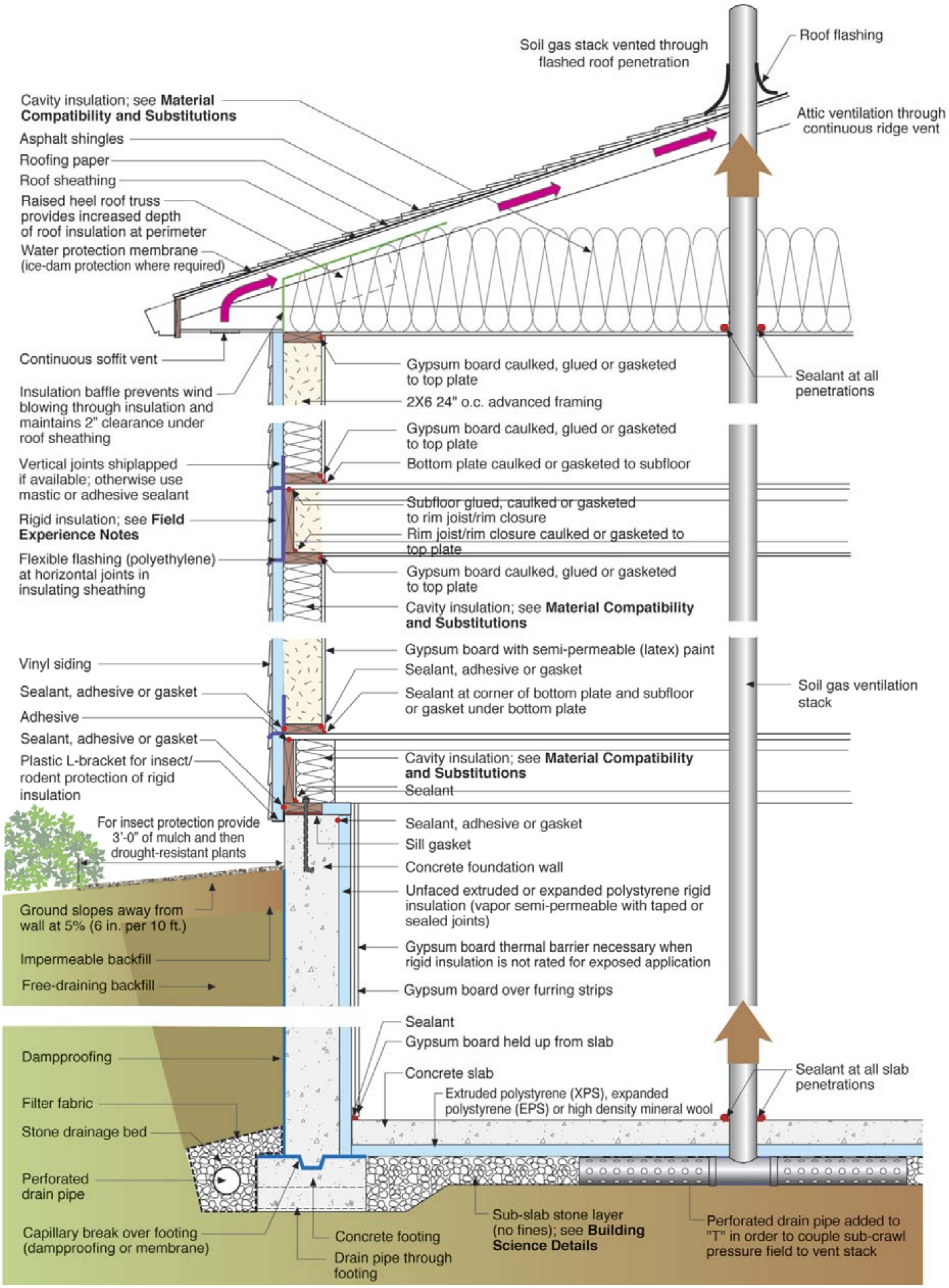

Figure 17. Example of building envelope details for Chicago, Illinois

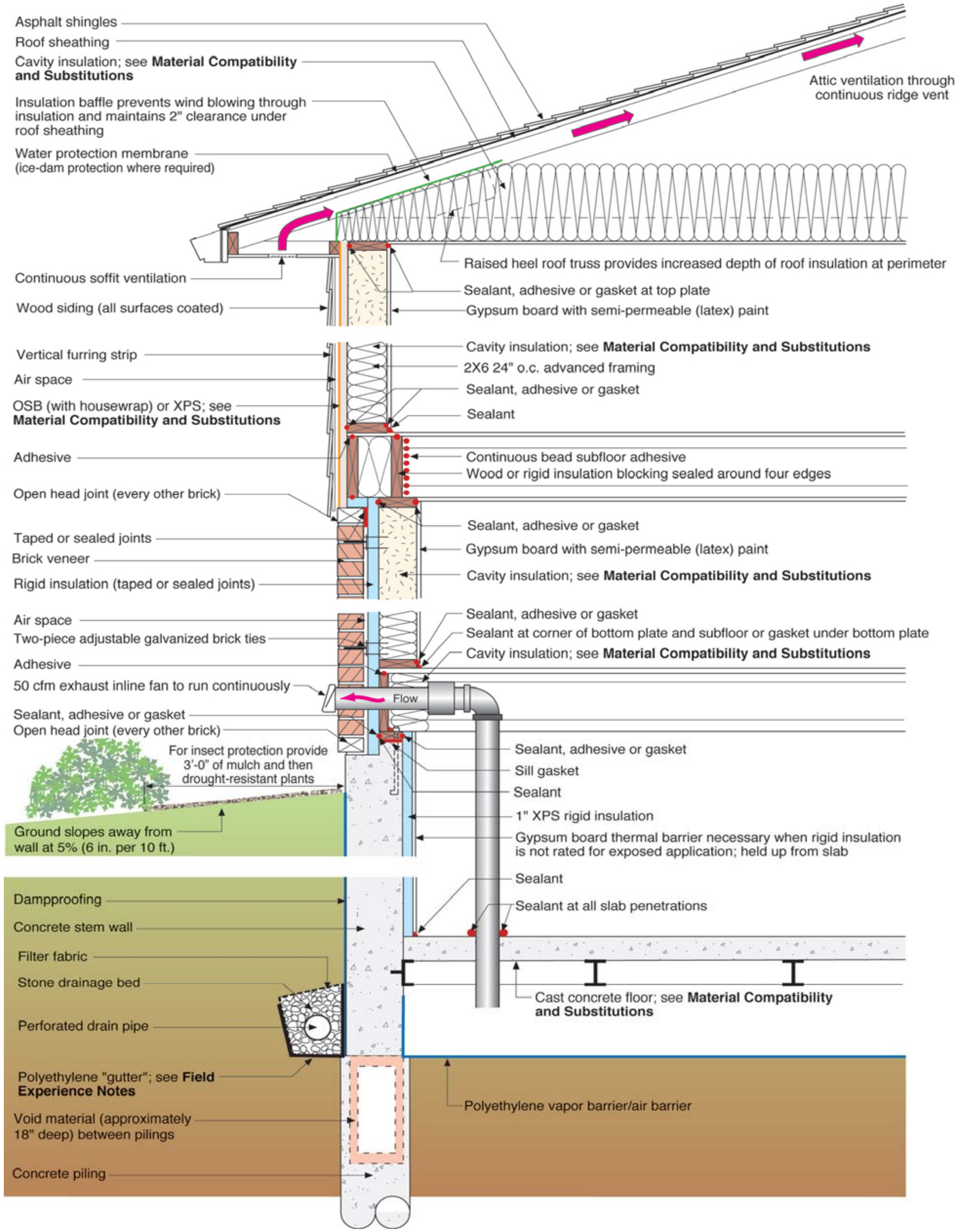

Figure 18. Example of building envelope details for Denver, Colorado

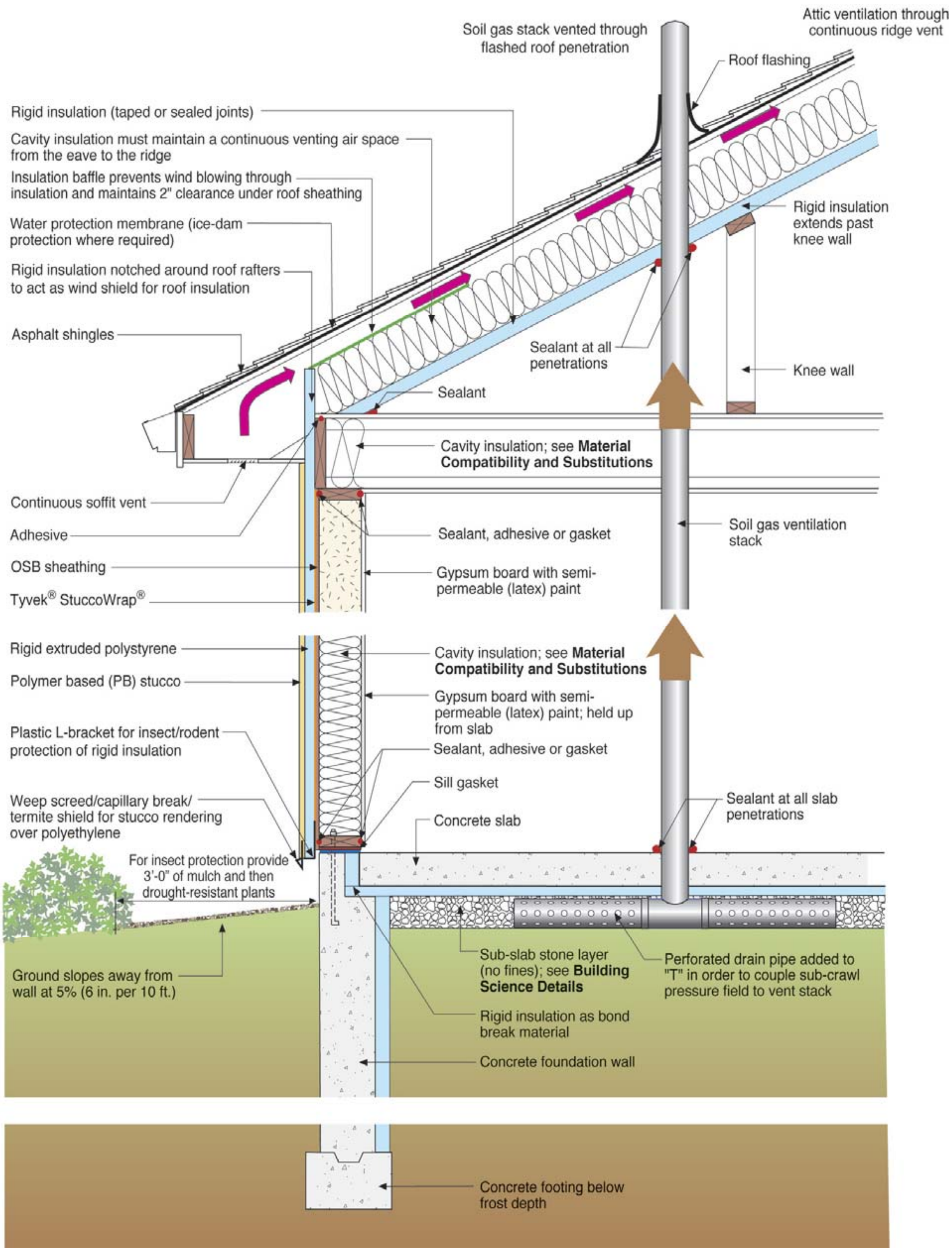

Figure 19. Example of building envelope details for Minneapolis, Minnesota

Space Conditioning and Ventilation Systems

Forced Air

Forced-air heating and cooling systems are the most predominant type of system in today's residential new-construction market. This is driven primarily by the market for central air conditioning. According to census data, 77% of the homes constructed from 1990 to 1997 had central electric air conditioning. Central natural gas-fired furnaces were used in 47% of the new homes.

To accomplish the target of 30% whole-house energy savings in the Cold Climate region, a direct-vent condensing furnace is recommended. Direct-vent furnaces use outdoor air for combustion and can be easily located within the conditioned space. This was the approach taken for each of the case studies provided.

Induced-draft furnaces draw combustion air from the surrounding space and for "unusually tight construction" (which all 30% homes should be), outside make-up air must be ducted in. These outside air ducts can lead to complaints about cold drafts and defeat many of the objectives of a tight building envelope. Induced-draft furnaces are not recommended for 30% whole-house energy-savings homes.

Locating the forced-air system (air-handler equipment and ducts) within the conditioned space is important to whole-house performance. By locating the furnace within the thermal envelope, not only is the leaky and minimally insulated cabinet within the conditioned space, but all of the ductwork is as well. This minimizes the system inefficiencies associated with air leakage and thermal losses.

Methods for locating the duct system within the conditioned space include the use of open-web floor trusses, dropped ceilings and soffits, modified roof trusses, or an unvented or "cathedralized" attic.[47] The "best" method depends upon the house plan, the type of foundation, and the builder's preferences.

Homes with basements typically have the equipment located in the basement with ducts that serve the first floor via floor registers. Duct chases should be provided in the first-floor plan to bring supply air to and return air from the second floor. The use of open-web floor trusses provides spaces for ducts to run to serve second-floor registers or up into interior walls for high wall supply registers. Space-conditioning ducts should not be run in outside walls and return ducts should not be panned. Central hard-ducted returns are recommended with passive return air paths, such as jump ducts or transfer grilles from bedrooms.

Homes with slab foundations commonly have ducts in the attic with ceiling supply registers. For these homes, the opportunity to bring the ducts into the conditioned space with dropped ceilings and/or soffits should be considered first.[48] Alternatively, Building America teams have also employed unvented attics and modified roof trusses.

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[47] Hedrick, R., Home Builders Guide to Ducts in the Conditioned Space, www.energy.ca.gov/reports/2003-11-17_500-03-082_A-16.pdf

[48] McIlvaine, Beal, and Fairey. Design and Construction of Interior Duct Systems. www.fsec.ucf.edu/bldg/baihp//pubs/interior_ducts.pdf.

With the high-performance envelope measures described in previous sections, the annual cooling load for homes in the Cold Climate region will most likely be modest. Thus, the efficiency of the air-conditioning system has a small impact on the whole-house energy performance. Air-conditioning systems with efficiencies beyond the new NAECA[49] minimum efficiency of SEER 13 are not necessary to meet the 30% whole-house goal. However, the availability of incentives for higher efficiency equipment and/or the specific design and loads of the home could make higher efficiency equipment an appropriate consideration.

Furnaces or air handlers with "variable-speed" brushless permanent-magnet DC motors are recommended.[50] These motors are more efficient at lower speeds than the more common permanent split-capacitor (PSC) type motors. Efficiency at lower-speed operation is increasingly important in systems with multiple gas-firing stages, enhanced dehumidification capability during cooling, air-cleaning equipment, or integrated ventilation.

All space-heating and cooling systems should be sized according to the procedures described in ACCA Manuals J and S.

Hydronic

Where air conditioning is not necessary or radiant heating is desired, a boiler can be considered. For space heating, standard boiler efficiencies are not as high as condensing-furnace efficiencies. Condensing boilers are available from a limited number of manufacturers, but they are expensive and their performance has not been thoroughly evaluated by the Building America teams. Never the less, when system performance is considered, including the hydronic distribution system and the use of the boiler to supply domestic hot water needs as well, the high efficiency (85%-87% AFUE) non-condensing boiler with a power vent or direct vent may be a reasonable choice.

The use of boilers and domestic hot water heaters for space heating is discussed further in the section of this report entitled Combination Systems – Space and Water Heating.

Ventilation

In addition to point-source exhaust systems that are ducted to the outdoors for bathrooms and kitchen ranges, a whole-house mechanical ventilation system that is capable of meeting the specifications of ASHRAE Standard 62.2 is recommended. For Cold Climate homes, there are several approaches with varying levels of initial cost and complexity.[51] The following three systems were used in the case studies provided:

- a balanced system using a heat-recovery ventilator (Kacin Homes, Pittsburgh, and Eastern Dakota, Grand Forks)
- an exhaust-only system with low-sone bath fans rated for continuous duty (Claretian, Chicago)

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[49] NAECA refers to the National Appliance Energy Conservation Act established in 1987.
[50] Pigg, S. The Electric Side of Gas Furnaces, Home Energy, November/December 2003, pp. 24-28.
[51] Whole-House Ventilation Systems: Improved Control of Air Quality. Building Technologies Program, Office of Energy Efficiency and Renewable Energy (EERE) (Brochure). 2002. 6 pp.; NREL/BR-840-26458; DOE/GO-102002-0778

- a supply-only system integrated with a dehumidifier and the central air-handling unit (DR Horton, Reno).

Each system has different features and benefits, and there is clearly no "best" approach that applies for all builders and homebuyers in the Cold Climate.

Balanced-heat or enthalpy-recovery systems have the advantages of heat recovery from the exhausted air, but have the highest initial cost. The extent that these systems are marketable to potential home buyers is important to the selection of this approach. These systems also provide higher outside flow rates (100 cfm or higher) than called for by ASHRAE 62.2 (60 cfm for a three-bedroom, 3000-ft^2 home). Homeowners need to understand the operation and importance of proper maintenance for these systems to perform properly.

It has been demonstrated that exhaust-only systems are the lowest in initial cost and simplest to implement.[52] However, the outside air enters the home unfiltered and through unknown locations. The circulation of the ventilation air throughout the home is also dependant upon the house plan, location of the exhaust fan(s), and the frequency of operation for the home's central air handler.

Supply-only systems provide the ability to filter the air, but pressurize the space. As stated in ASHRAE 62.2, pressurizing the space may be *unacceptable in Cold Climates* and *if delivered directly to rooms without tempering, can cause thermal discomfort*. Nevertheless, with adequate control of indoor humidity levels, a supply-only system with a passive outside air inlet to the central air-handler's return with appropriate dampers and controls has been successfully employed in Building America homes. It's important that the outside air is sufficiently mixed with and tempered by return air to avoid damaging condensation in the furnace's heat exchanger and to avoid comfort complaints. As with all mechanical systems, it is also important that the system is properly commissioned.[53]

Air Distribution

As discussed in the section of this report on System Design Approach, at the 30% improvement level, a number of general requirements apply to design of the forced-air distribution system:

- Design should be in accordance with ACCA Manual D
- Ductwork should be located within the thermal envelope of the house or in some climate zones buried within the attic insulation
- Ducts should not be located in exterior walls
- Ducts must be air-sealed using UL 181-approved mastic or equivalent for the particular duct type
- "Panning" between joists and the use of stud cavities for supply or return air is not recommended
- Ducts may be of galvanized sheet metal, duct board, or flex duct

[52] Furnace Fan Penalty, Energy Design Update, June 2005.
[53] Ventilation System Installation and Commissioning Guide. 2004. 6 pp; Record No. 35395

- There must be continuity of the vapor barrier on insulated ducts not running inside conditioned spaces
- Locate ducts within an insulated, non-vented, conditioned crawl space or basement
- Locate within an insulated "cathedralized" attic
- Locate in open-web floor trusses
- Develop chase walls to accommodate duct risers
- Design closets inside the conditioned space for locating the air handler in houses using slab-on-grade construction.

While the distribution system is important from an energy perspective, there are also health, safety, and IAQ issues to be considered. The following sections briefly discuss each, with recommended solutions.

Seal forced-air distribution systems. Leaky duct systems, in addition to the energy losses thus introduced, may result in indoor-outdoor pressure imbalances that generate significant air leakage through the building envelope. For the 30% improvement house, extensive duct sealing is typically required. For metal ducts, UL 181 mastic is the only acceptable sealing method; for duct board, UL 181 tapes are accepted; and for flex duct a combination of UL 181 mastic and strap ties should be used. The targets for total duct leakage is 5% of the high-speed system cooling airflow in CFM, as tested at 25-PA reference pressure. To further reduce duct leakage, do not pan joists or use stud cavities for supply or return air. It is virtually impossible to seal building cavities properly to achieve the target tightness for forced-air systems.

Isolate the HVAC system from areas with potential pollutants. One of the most potentially hazardous IAQ problems arises when return ducts run through garage spaces where the opportunity exists to draw CO from automobile exhausts or other pollutants from hazardous chemicals often stored in the garage into the duct system and redistribute it throughout the house. Locating the HVAC unit in the garage is not recommended in the 30% improved houses, but it is not always possible to relocate the air-handling unit. If the air handler and return-air ducts must be located in the garage, any return-air ductwork and the air handler should be thoroughly sealed with UL 181 mastic, with a target leakage between the duct system and the garage of 0 CFM@25 PA. This yields the least possible opportunity for bringing garage air into the return system.

Pressure Balance the System. Pressure imbalances can cause air movement through the envelope when the HVAC system is operating, wasting energy, and potentially causing moisture problems. Imbalanced airflows can also cause room-to-room or floor-to-floor temperature differences, leading to comfort complaints. Finally, imbalanced airflows can draw unwanted pollutants into the house, causing indoor air-quality problems. One key factor in eliminating room-room and indoor-outdoor pressure imbalances is the adequacy of the return-air path. In homes with individual-room ducted returns this is generally not a problem. Individual-room ducted return systems are historically typical in colder climates, but are losing favor because of their costs. From a cost-effectiveness standpoint, a well-designed central-return system with individual-room pressure relief is considered the standard for the 30% improvement house. To qualify as well-designed, the return system must incorporate adequate relief from each room where entry doors may be closed. Thus, return-air recommendations include the use of ceiling "jump ducts," or transfer grills located in the walls. Door undercuts are generally not considered to be acceptable because they are often inadequate in area and/or blocked by the installation of carpeting. One important consideration in the installation of "jump ducts" or transfer grilles is to maintain a satisfactory acoustic separation between spaces. This is typically accomplished by the use of flex duct, duct lining with sound-absorbent material, a slightly circuitous path, or some combination of these strategies to block sound transmission.

Supply-air Register Selection and Placement. The distribution of the heating or cooling air stream from the supply register to the return point is critical to maintaining comfort conditions within the room. In the 30% improvement house, envelope insulation (including window U-value and SHGC) and air sealing have been improved to such an extent that basic comfort needs are more easily met by the HVAC System. In particular, envelope surface temperatures are moderated to a considerable degree, which results in reduced radiant heat loss (or gain) to room occupants, improving comfort conditions. Similarly, solar gains through low-SHGC windows are reduced, considerably improving cooling-season comfort conditions. With good air sealing, houses are much less drafty than those built to older construction standards.

All these reduced loads and improved comfort conditions mean that room heating/cooling air volumes (at typical supply temperature) may be reduced. If typically sized registers are used, discharge velocities are reduced, and the air has less "throw" within the room. This is a new operating region for forced-air systems and presents a number of challenges to achieving a proper design for good comfort conditions.

In conventionally built housing in Cold Climates, supply registers are typically located in the floor or at the baseboard on the outside wall and underneath windows. When thermal losses are high and drafts are strong, such locations are logical. In the cooling season, this low position requires significant velocity and throw to engage the entire mass of air and to provide even temperatures throughout the room.

With the lower loads of the 30% improved house, such register locations may not be necessary. There are good reasons to shift supply registers out of these low floor positions. Of primary importance is to avoid blockage by furniture and draperies for better cooling performance. High wall or ceiling positions avoid this blockage potential and provide better cooling performance. To maintain comfort in the heating season, it is critical to properly select registers based on throw characteristics and the volume of air being delivered to the room. This may require designing at the upper limits of recommended face velocities and the purchase of "non-standard" register sizes. It may also require the use of registers with manually operable vanes to fine-tune air flow for optimal comfort.

In general, high sidewall applications have been used where the register is directed at the wall of dominant heat loss or gain (usually the wall with windows or glass doors) and the register is no more than 12 -13 ft away. Ceiling diffusers with curved blades to help direct the airflow along the ceiling can be used where the wall opposite the dominant load exceeds 13 ft.

Research is currently underway in the Building America Program to understand the issues of air distribution in high-performances houses and to develop recommendations for supply and return apertures to achieve the best comfort conditions consistent with a highly energy-efficient system.

There are many issues to consider including the following:

- Register location and discharge pattern
- Discharge velocity
- Discharge temperature
- Effect of return location
- Stratification and mixing patterns
- Part load operation, H/C variation
- Impact of zoning systems
- Solar load variability
- Buoyancy issues
- Sound issues
- Register/nozzle configurations
- Register approach conditions – boots
- Dampening and control.

The recommendations that are developed from these ongoing investigations will enhance the current recommendations for houses achieving 30% whole-house savings and will likely be critical for houses at the 40% and greater improvement levels.

Duct Insulation. If ducts cannot be brought within conditioned spaced, supply ducts should be insulated to R-8 minimum and return ducts to R-4 minimum. Research by the Building America Team CARB[54] has supported code credits for ducts in Hot-Dry and Mixed-Dry Climates that are buried in loose-fill attic insulation. This strategy may be applicable to areas in the Cold Climate zone with low relative humidity during the cooling season. This strategy should not be used in sections of the Cold Climate zone with high relative humidity in the cooling season because condensation can form on the outside of the duct vapor barrier and cause moisture problems in the home. Similarly, it is critical to make sure all metal fittings are well insulated to avoid condensation.

Dehumidification

Dehumidification of basement spaces in Cold Climates is not necessary if basements are correctly constructed and insulated. However, dehumidification is a powerful technology to repair and rehabilitate problem basement assemblies.

[54] Dianne Griffiths et al. Insulation Buried Attic Ducts – Analysis and Field Evaluation Findings. American Council for Energy-Efficient Economy (ACEEE). 2004 ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA. August 23, 2004

Mechanical, Electrical, and Plumbing Systems

Lighting

The development of improved efficiency in residential lighting has been pursued in a number of prototype homes. These have ranged from the simple substitution of screw-in conversion CFL lamps used in conventional fixtures to a High-Performance Lighting (HPL) approach using a full complement of hard-wired, dedicated compact and linear fluorescent fixtures. In addition to providing excellent light quality, a key objective of several HPL prototype installations has been to provide as much of the basic ambient lighting and key task lighting in the home as possible. The reason for this emphasis is to maximize the efficient light content of the house and minimize the discretionary (usually incandescent) portable lighting provided by the homeowner. This approach yields the greatest reliable lighting energy-use reduction.

With the current cost of good quality hard-wired fluorescent fixtures (those with electronic ballasts and good optics), the HPL approach does not appear to be cost effective for a house at the 30% improvement level. The industry is still lacking a family of more affordable hard-wired fluorescent fixtures that meet production-builder price points. Important steps have been taken in this regard, most notably the development by Lawrence Berkeley Labs, the California Lighting Technology Center, and Lithonia of the recessed downlight twin package. This package offers a pair of good quality recessed downlight at a reduced manufacturing and installation cost. More innovative development of this type is needed across the board for HPL cost reductions. Simple screw-in CFL substitution is a viable strategy at the 30% level; however, there are questions as to the persistence of energy savings because the homeowner is free to replace the CFL with a traditional incandescent light bulb. A website that discusses lighting options in detail has been developed and is located at www.ibacos.com/hpl1.html.

The following are near-term energy-savings opportunities for new homes. In some cases, these involve newly commercialized products that are just now entering the market, while in other cases these represent systems show great promise but need further refinement and field-testing:

- Lamps with color-rendition index (CRI) of 80 or higher and a color temperature (CT) of 3000 degrees Kelvin
- Screw-in replacement CFL bulbs with instant-on electronic ballasts. Some are available to work with conventional dimmers
- High-quality, high-output residential-grade CFL downlights for kitchens and hallways
- Linear fluorescent bathroom vanity strips (vertical and/or horizontally mounted)
- Bathroom-occupancy sensors with integrated LED nightlight
- LED porch lighting
- LED exterior security luminaire
- High-output LED walkway lighting
- Evaluation of energy-savings potential from incandescent dimming.

Residential Lighting Controls. Residential lighting controls represents a significant opportunity for energy savings. Lighting controls generally refers to technologies that turn off (or turn down) lighting systems when they are not needed. Examples include occupancy sensors, photo sensors, dimmers, and timers.

Technologically, residential controls have improved greatly over the past several years, both in terms of the types of controls options available, as well as their quality and functionality. Because the cost of these systems is decreasing by increased demand for commercial applications, they become increasingly attractive for cost-effective residential applications.

Recognizing these technological and market advances, as well as the potential energy savings of these technologies, energy-code officials have begun to look more closely at residential lighting controls. The new 2005 Title 24 building code in California, which will go into effect on October 1, 2005, includes strong incentives for homebuilders to utilize occupancy sensors, photo sensors, and dimmers. In fact, many market watchers now anticipate that homebuilders will choose lighting-control alternatives over energy-efficient luminaries to comply with this new code because the controls approaches are often more cost-effective.

Major Appliances

At the present time, the best practice recommendations for the 30% improvement house is to use ENERGY STAR-rated appliances. Within the ENERGY STAR-rated offerings, there are differences in performance levels, but these are probably not of significance at the 30% improvement level. It is also recommended that best-in-class appliances for non-ENERGY STAR-rated appliances be installed or recommended for purchase by the homeowner if not provided by the builder.

Program for Off-peak Operation. While not a mechanism for direct-source energy reduction, peak-load shifting is a beneficial strategy from a consumer-utility cost perspective where time-of-use rates are in effect; peak-load shifting and can have electric utility system benefits by helping to reduce the need for peak-power plants. The cost of energy consumption for appliances can be reduced by operating appliances during off-peak hours and refraining from or minimizing their use (especially simultaneous use) during peak hours.

For example, using Whirlpool's energy-management system for stand-alone Time-of-Use (TOU) appliances delays the operation of the dishwasher, washing machine, and dryer until the energy prices are lower (off-peak rate). An LED lets the consumer know if the rate is currently on- or off-peak. To delay until off-peak, the consumer can press a button and another LED illuminates to let them know that this appliance will start at a later time.

An alternative strategy is to minimize the amount of time that appliances are in the high-power mode by ensuring that the appliance is used in the lowest possible power mode whenever practical.[55]

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[55] International Energy Agency. 2001. THINGS THAT GO BLIP IN THE NIGHT Standby Power and How to Limit it. www.iea.org/textbase/nppdf/free/2000/blipinthenight01.pdf.

Water Heating and Distribution Systems

At the 30% improvement level, energy use for heating hot water becomes a significant component of total energy use. Consequently, the following guidance has been developed for the design and installation of domestic hot water (DHW) systems:

DHW Heater Sizing. The size of tank and first-hour draw pattern can have an impact on the overall energy consumption associated with hot water. Tank size is a function of first-hour rating, draw patterns, and incoming and outgoing water temperatures. The sizing method described in the next paragraph takes into account the nominal population of a house, the main supply water temperature, and the efficiency of the DHW heating equipment.

Sizing Method for Tank Type DHW Heater. Use this method for determining the size of the tank-type domestic hot water heater (Figure 20).

1. Establish the design population of the house by taking the number of bedrooms + 1
2. Multiply this by the gallons/person for the climate zone where the house is located to get the first-hour rating for the water heater
3. Using the first-hour rating from Step 2, select a DHW heater that meets or exceeds this rating
4. For a tank-type gas heater, select a heater with an energy factor greater than 0.60. For a tank-type electric heater, select a heater that meets the current NAECA standard.

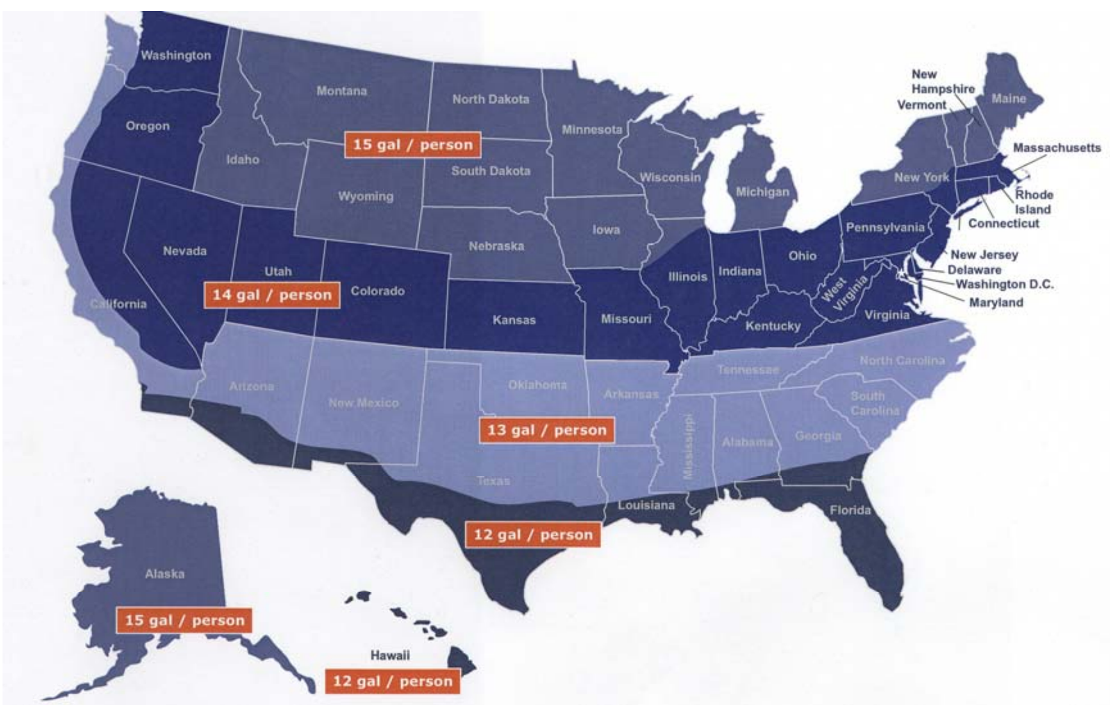


Figure 20. Domestic hot water tank sizing for 135°F tank temperature only

Heater Selection. The efficiency target for fuel-fired tank-type gas DHW heaters is 0.60 EF or higher. With the tight house construction of the 30% improvement level, these heaters should be either power vented (which forcibly discharges the products of combustion and draws combustion air from the house), direct vented with dedicated outside air for combustion, or sealed-combustion units that draw combustion air from outdoors and fan discharge combustion gasses outdoors. If electricity is used for heating water, a high efficiency tank or tankless unit should be used.

Tankless water heaters (about 0.84 EF) can provide significant advantages over the traditional storage-tank water heaters for a number of reasons:

- **Energy Savings:** Tankless water heaters have a higher energy factor compared to tank water heaters and are, therefore, a more energy-efficient option.
- **Space savings:** Tankless water heaters are dimensionally smaller and save space compared to storage tank water heater. This allows for installation in spaces with limited area or in locations closer to the point of use.
- **Longer life expectancy and favorable life cycle costs:** The tankless water heater has a life expectancy of 15 to20 years compared to a typical 9 years for storage-tank water heaters. When the replacement of a tank water heater is combined with the lower operating costs, the life-cycle costs of a tankless water heater is generally lower than a tank-type water heater.

Some builders have chosen to install multiple gas-fired tankless units, which may require upsizing of the main gas service when coupled with other gas end-uses in the house (furnace, cooking appliances, dryer, etc.). This could be a significant barrier to widespread adoption, especially in areas with low gas pressures. By installing multiple units, builders are safeguarding against a call from homeowners that there isn't enough hot water, but may be overcompensating because of lack of experience with the tankless gas-fired technology.

Tank-type heaters offer the best efficiency with relatively steady, continuous-use patterns. If electricity is the energy source for water heating, additional improvements to other areas of the house will likely be needed to achieve the 30% savings levels because there is very little room for improvement in electric water-heating efficiency compared to the possible efficiency gains using gas-fired technologies.

Stand-alone electric heat pump water heaters offer better efficiency than electric resistance heaters, but they are complex, costly, and still evolving as a standard commercial product. They provide the best efficiency when their cold-air discharge can be used to augment home air conditions, which can be a benefit in cooling-dominated climates. Conversely, they can contribute to an additional heating load during the winter. Optimizing these relationships along with this performance variation as a result of supply water temperature and load pattern is quite challenging. Primarily because of the early state of technology deployment and reliability, stand-alone heat-pump water heaters are not considered a practical choice at the 30% level. Should these units improve in reliability and volume manufacturing brings costs down, then they would be worth considering as part of the overall package.

If a ground-source heat pump is chosen for space heating and cooling, it is possible to use it to generate hot water, either through a desuperheater on the basic water-to-air heat pump or by using a water-to-water system where the heat pump can generate heated or chilled water to be used for space conditioning and domestic hot water. These systems can be effective, but the pricing varies dramatically by region and can be more complex than a traditional gas furnace with DX air-conditioning systems. In an area where no natural gas is available, this system is an option in all climate zones; however, it requires a skilled and experienced installer base and favorable pricing.

While not necessarily required to achieve the 30% whole-house energy-savings target, there are a number of reliable solar DHW heaters in the market. They represent a range of operating philosophies:

- Storage/non-storage
- Freeze-protected/drain-back
- Passive thermosystem/pumped cycle, etc.

With good design, these solar systems can all be effective sources of hot water, particularly in sunny climates. What most degrades the performance of solar DHW systems are the details of design, construction, operation, and maintenance. Research has found that simple set of characteristics such as long pipe run from the collector plate combined with a short, infrequent usage pattern can render the solar contributions nearly negligible. Primarily because of their high cost, solar DHW systems are not considered practical at the 30% improvement level.

Hot-Water Distribution Systems. The hot-water distribution system plays a surprisingly important role in the total energy efficiency of the DHW system. Thermal losses from the hot-water distribution piping system while water is flowing and the losses associated with "stranded" hot water as it cools down once faucets are turned off can amount to a very substantial portion of total hot water energy use. Thus, guidance on the configuration of the system, its insulation, and patterns of use can help reduce the piping system component of DHW energy use.

Basic guidance on the layout of DHW piping suggests that the DHW source and major use points should be as close to each other as practical. A good example of this would be the location of the DHW heater in a closet adjacent to the kitchen and a laundry that are back-to-back. Short lines will minimize "stranded" losses, which can be considered detrimental during the cooling season. Tankless water heaters can be located immediately adjacent to high-use clusters, such as a pair of bathrooms in a remote wing or a second floor, to reduce piping heat losses.

All DHW supply piping should be insulated with standard R-4 pipe insulation. It is readily available, inexpensive, and effective. This includes any hot-water lines located in concrete slabs or underground. Increasing tank insulation to a minimum of R-12 by adding a tank insulation wrap can also reduce energy consumption.

Research has also shown that "parallel-piped" or "homerun" plumbing systems using PEX piping and a central manifold can reduce energy consumption compared to traditional copper "tree and branch" plumbing systems.[56]

To avoid the waste of water as one "waits for the hot water to arrive" and to provide instantaneous hot water, there is growing use of recirculation systems that continuously circulate hot water through the entire system. This continuous circulation of hot water results in great heat

[56] NAHB Research Center, Inc. Performance Comparison of Residential Hot Water Systems. Upper Marlboro, MD: NAHB Research Center, Inc., November 2002.

loss from the piping system, even if insulated, and is strongly discouraged in an energy-efficient house of any type.

If a recirculation system must be installed, a push-button-activated on-demand recirculator is by far the best recirculation system option. While all well-designed recirculation systems reduce water waste relative to conventional main-and-branch plumbing design, the push-button-activated on-demand recirculation system minimizes the length of time the recirculation loop is kept hot.

The on-demand circulator is primarily useful for use points that are a long way from the DHW source and represent a substantial water waste while waiting for the hot water to "arrive."

Combination Systems – Space and Water Heating

For the purposes of this discussion, combination systems refer to any system that uses a single combustion appliance to provide both the space heating and the domestic hot water needs for the home. Combinations systems used by Building America teams have included

- a gas-fired boiler serving hydronic baseboard units for space heating and an indirect storage tank for domestic hot water,
- a gas-fired storage water heater for domestic hot water and serving space-heating loads via a hydronic coil in a central fan-coil unit,
- a gas-fired tankless water heater for domestic hot water and serving space-heating loads via a hydronic coil in a central fan-coil unit,
- a combination boiler that provides hot water for space heating, as well as domestic hot water via a separate heat exchanger, and
- a gas-fired boiler with one or more hydronic coils for space heating and an indirect-storage tank for domestic hot water.

The primary advantages of these systems are

- the reduced cost and complexity of only having to vent one combustion appliance. This can be significant when direct-vent equipment is desired.
- the improved energy efficiency for serving the domestic hot-water load. Indirect tanks have significantly lower losses than gas-fired storage tanks with flues. Removing the tank losses entirely with a tankless, on-demand system provides further improvements.

An important factor for success in all of these systems is that the plumbing and HVAC contractors must coordinate and cooperate. Builders are often concerned about who is ultimately responsible for the system. Ideally, one contractor would be responsible for the entire system, but if a forced-air system is used, this situation is unlikely.

Systems that use a storage water heater to serve both loads should only be considered in homes with modest space-heating loads—25 kBtu/hr or less at design. In the Cold Climate region, this probably confines their consideration to multifamily homes. Also, careful design and attention to detail is necessary for proper operation of these systems.[57] Thermo-siphoning during summer air-conditioning operation has been observed in several installations.

Common boilers for space heating will typically have lower AFUE ratings than commonly available condensing furnaces. Thus, the magnitude of space-heating loads versus domestic water-heating loads is important to the overall whole-house energy savings. Condensing boilers are available from a limited number of manufacturers, but they are expensive and their performance has not been thoroughly evaluated by the Building America teams.

Onsite Power Systems

A number of on-site power-production systems are currently available for Building America projects, and others are in the research stage. Most have been used in Building America projects. These systems include the following:

- Photovoltaics
- Engine generator/combo systems
- Fuel cells.

The 30% improvement level can be achieved most cost effectively through the improvement of the envelope, heating, cooling, domestic hot-water systems, and possibly the application of some lighting and appliance improvements. On-site power systems are very costly and are not recommended as a strategy to achieve the 30% savings level.

Cost Analysis

Life-Cycle Cost Analysis

From a purely economic point of view, building energy optimization involves finding the global optimum that balances investments in efficiency versus utility-bill savings. However, there are sometimes non-economic reasons for targeting a particular level of energy savings. Given a particular energy-savings target, economic optimization can be used to determine the optimal design (lowest cost) to achieve the energy-savings goal. The analysis presented below targets 30%-39% whole-house energy savings with respect to the Benchmark by using the BEopt analysis method to investigate cost tradeoffs associated with various residential energy efficiency and renewable-energy technology options.

Building Characteristics Considered in this Study. For the Prototype building, a two-story 3000-ft^2 and a single-story 1500-ft^2 residential building was used for this study with the front of the buildings facing east. Although complex floor-plan geometries can be analyzed, a simple square floor plan was implemented for the purposes of the current analysis. The buildings are modeled with a full basement. Both buildings were assumed to have three bedrooms and two bathrooms. The building has 1-ft eaves. Window area is assumed to be 18% of floor area with 50% of the window area facing west, 25% of the window area facing east, 12.5% of the window area facing north, and 12.5% of the window area facing south. The non-uniform window distribution was utilized in order to represent a possible "worst case" window distribution from

[57] Combo Space/Water Heating Systems – "Duo Diligence," Building Science Corporation.

the available window distribution options currently included in the BEopt analysis method. The energy options considered in the study include space-conditioning systems (up to SEER 18 and 92.5% AFUE in the current study), envelope systems, hot-water systems, lighting systems, major appliances, and residential PV. The buildings use natural gas for the following end uses: cooking, space and water heating, and clothes drying. For the Chicago example cases, the uninsulated basement case option was not included in the analysis. Air-conditioner capacities less than 1.5 tons were not considered, nor were furnace capacities less than 50kBtu/hr. SEER-10 air-conditioning equipment was included in this analysis for discussion purposes; however, after January 1, 2006, Federal minimum equipment efficiencies will mandate the use of SEER-13 air conditioners. No options that would potentially reduce miscellaneous electric loads other than major appliances were included in the study.

Occupancy/Operational Assumptions. Occupancy and operational assumptions are as defined in the Benchmark and include time-of-day profiles for occupancy, appliance and plug loads, lighting, domestic hot-water use, ventilation, and thermostat settings.

Base-Case Building. Results are calculated relative to the Benchmark. The Benchmark defines baseline features, including wall, ceiling, and foundation insulation levels and framing factors; window areas, U-values, and solar heat gain factors; interior shading; overhangs; air-infiltration rates; duct characteristics; and heating, cooling, and domestic hot water system efficiencies.

Cost Assumptions. Each option has an assumed first cost and lifetime (Appendix B). Costs are retail and include national average estimated costs for hardware, installation labor, overhead, and profit. Some are input as unit costs that are then multiplied by a category constant (e.g., ceiling insulation costs are input per square foot and multiplied by ceiling area by BEopt). Some inputs are energy-option specific (e.g., cost of solar water heating systems). Inputs can also be based on total costs (e.g., cost of wall constructions with different insulation values) because BEopt will calculate the differences between option costs.

Construction costs (wall insulation, ceiling insulation, foundation insulation, etc.) are typically based on R.S. Means[58] cost estimates. Window and HVAC costs are based on quotes from manufacturers' distributors. Appliance costs are based on manufacturers' suggested retail prices.

Building construction options (wall insulation, ceiling insulation, foundation insulation, windows, etc.) are assumed to have 30-year lifetimes. Equipment and appliance options typically have 10- or 15-year lifetimes. Lifetimes for lighting options (incandescent and compact fluorescent lamps) are modeled based on cumulative hours of use.

Utility costs are assumed to escalate at the rate of inflation (i.e., to be constant in real terms). The mortgage interest rate is 5% above the rate of inflation. The onsite power option used for this study was a residential PV system with an installed cost of $7.50 per peak Watt DC, including present value of future operation and maintenance costs. This cost is assumed to be independent of PV system size. Additional costs associated with mounting large PV arrays were not considered. For Chicago, natural gas is assumed to cost $0.8044/Therm, and the cost of electricity was modeled as $0.0771kWh.

[58] Residential Cost Data – 18th Annual Edition. 1999. Kingston, MA: R.S. Means, Company, Inc.

Simulation Limitations. Some benefits not considered by the BEopt analysis method will have an influence on the real-world design of a home, such as reduction in warrantee and liability exposure, increased customer satisfaction, and higher quality construction practices. The BEopt analysis method does not consider concerns with regard to IAQ, mold, and combustion safety. In a real world design, these factors may lead the designer, engineer, builder, or architect to use equipment or construction practices that increase first cost without reducing utility bills in order to provide better indoor air quality, combustion safety, occupant comfort or other design considerations that have high value to the builder or potential homebuyer. There are also some side effects that the simulations are not equipped to deal with, such as the costs of change in a builder's organization necessary to implement energy-efficient design approaches, the costs of moving a trade base to a different place, or termination of long-term relationships with a trade because the trade would not adopt energy-efficient practices. There is currently no methodology available to account for these effects in the simulation. Further development of a methodology to account for these effects and collection of appropriate data to inform the simulation would be necessary if there is interest in considering these effects.

The BEopt analysis method is relatively new to the Building America program, the case studies included in the Building America Systems Research Results section were not initially simulated with BEopt nor was BEopt used to guide the design process of the case study homes included in the section of this report entitled Building America Systems Research Results. The case studies are the result of years of field experience and design work done by Building America teams. Currently, this analysis method is being used for general programmatic guidance in an effort to understand at what cost and performance specifications efficiency and renewable technologies begin to look attractive when compared to other efficiency and renewable technologies. In its current form, the BEopt analysis method is useful for programmatic studies in terms of weighing the merits of certain efficiency and renewable technologies versus standard construction practices or other technologies using national average cost data, retail cost data, or projected costs for emerging technologies; however, cost of these technologies may be very different on a production or custom-builder scale. The results shown here should not be taken as representative of all builders in this climate region.

As an example of what building efficiency options would lead to a combination of options that would achieve 30-39% whole-house energy efficiency relative to the Benchmark an optimization was performed with the Chicago TMY2[59] weather file. Figure 21 shows the 35% whole-house energy efficiency point that falls on the cost-optimal curve for Chicago.

[59] Typical Meteorological Year weather data, http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/

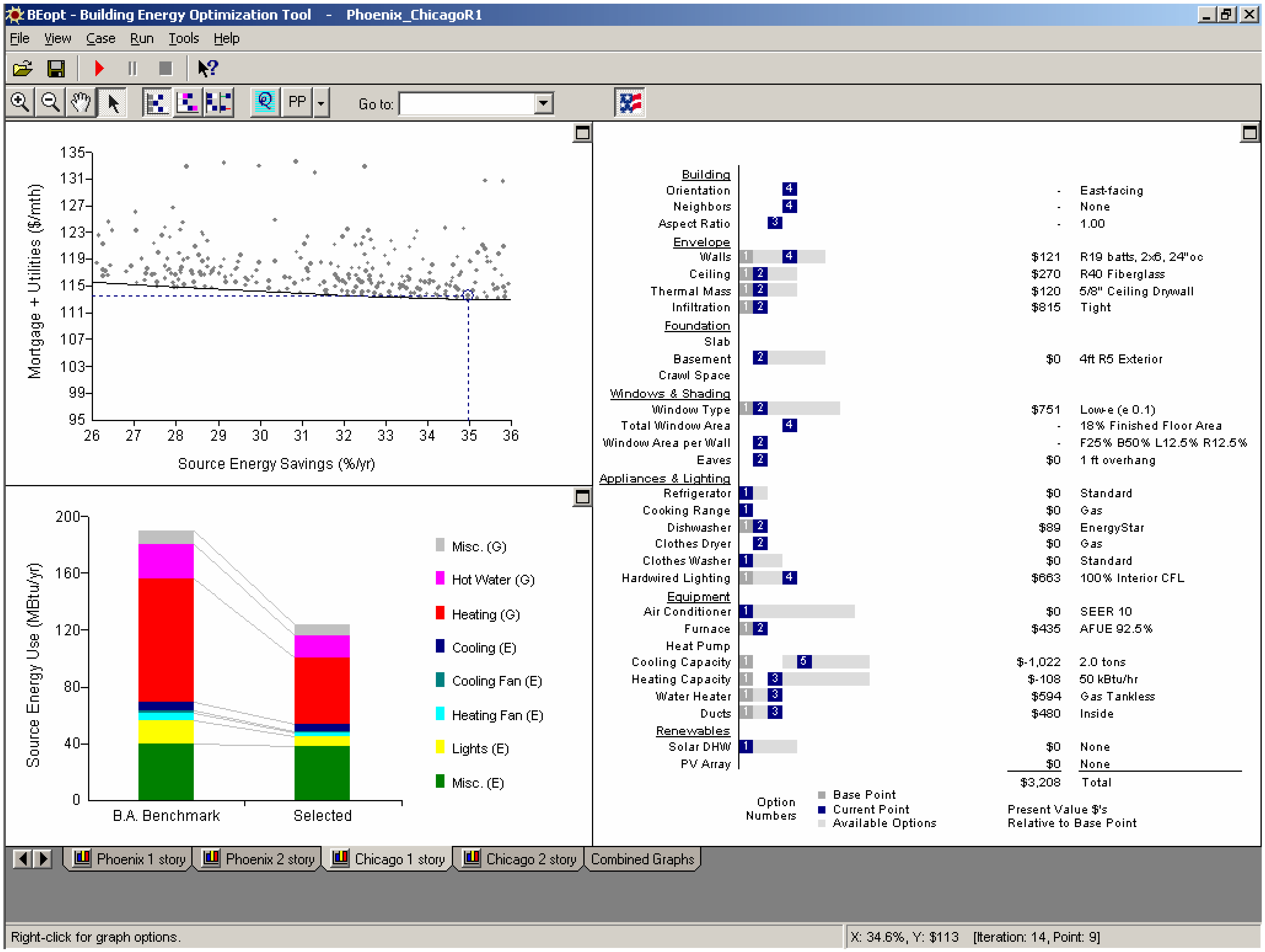


Figure 21. The 35% point for a single-story Chicago example case

Based on the costs assumed as shown in Appendix B, and within the limitations of the analysis method and the previously mentioned assumptions, the options selected in Figure 22 would represent a possible least-cost combination for 35% whole-house energy savings for a single-story residence in Chicago. Because costs may vary significantly across the Cold Climate region, from builder to builder, and over time, the above is only an example that may not reflect the actual least-cost set of options that would apply to a specific home, builder, and location.

At the other end of the building energy performance range considered here, 39% whole-house energy savings, the total monthly cost is slightly higher than the 35% example. Figure 22 shows an example combination that meets 39% whole-house energy savings compared to the 35% combination.

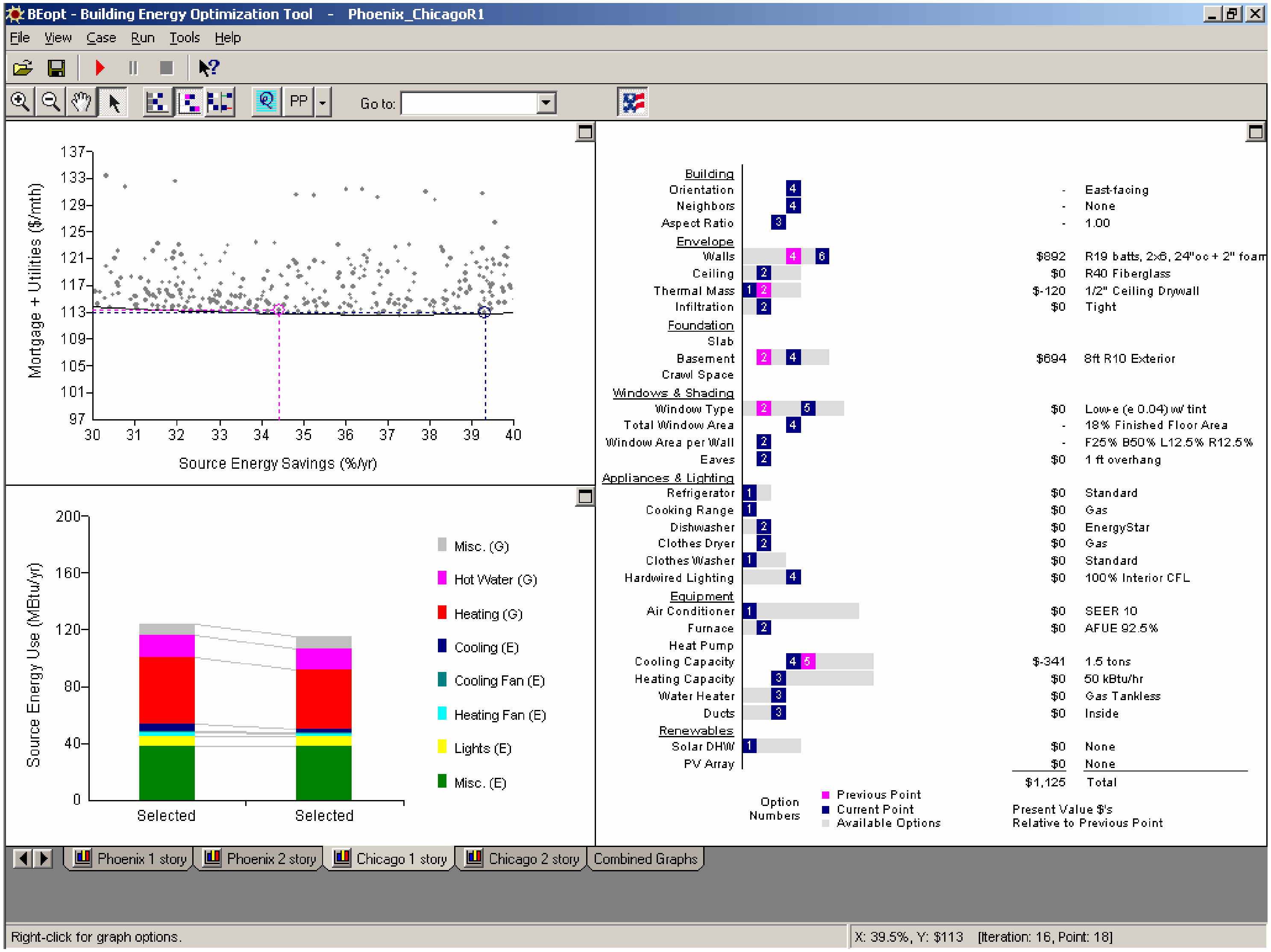


Figure 22.[60] Comparison of 39% point to the 35% point, one-story Chicago example case

[60] Note that cost show in this figure are incremental relative to the 35% energy savings point (shown in magenta)

The comparison of the 35% combination (represented in magenta) to the 39% combination (blue only) shown in Figure 23 demonstrates that by utilizing additional exterior wall insulation, basement wall insulation and a higher performance Low-e glazing, the 39% combination is slightly less expensive in terms of total cost per month than the 35% single-story example. There are some cost savings associated with downsizing of cooling equipment as a result of envelope improvements.

Figure 23 and Figure 24 look at the same energy-performance levels for the two-story case.

The comparison of the 35% combination (represented in magenta) to the 39% combination (blue only) shown in Figure 24 demonstrates that by investing in additional basement wall insulation, an ENERGY STAR dishwasher and a SEER-15 air conditioner results in the 39% point being only slightly more expensive in terms of total cost per month for the two-story example. Table 7 shows detailed features for the 35% and 39% example cases. A more comprehensive table of examples that include energy end-use results and comparison to the Benchmark is shown in Appendix B for single- and two-story cases.

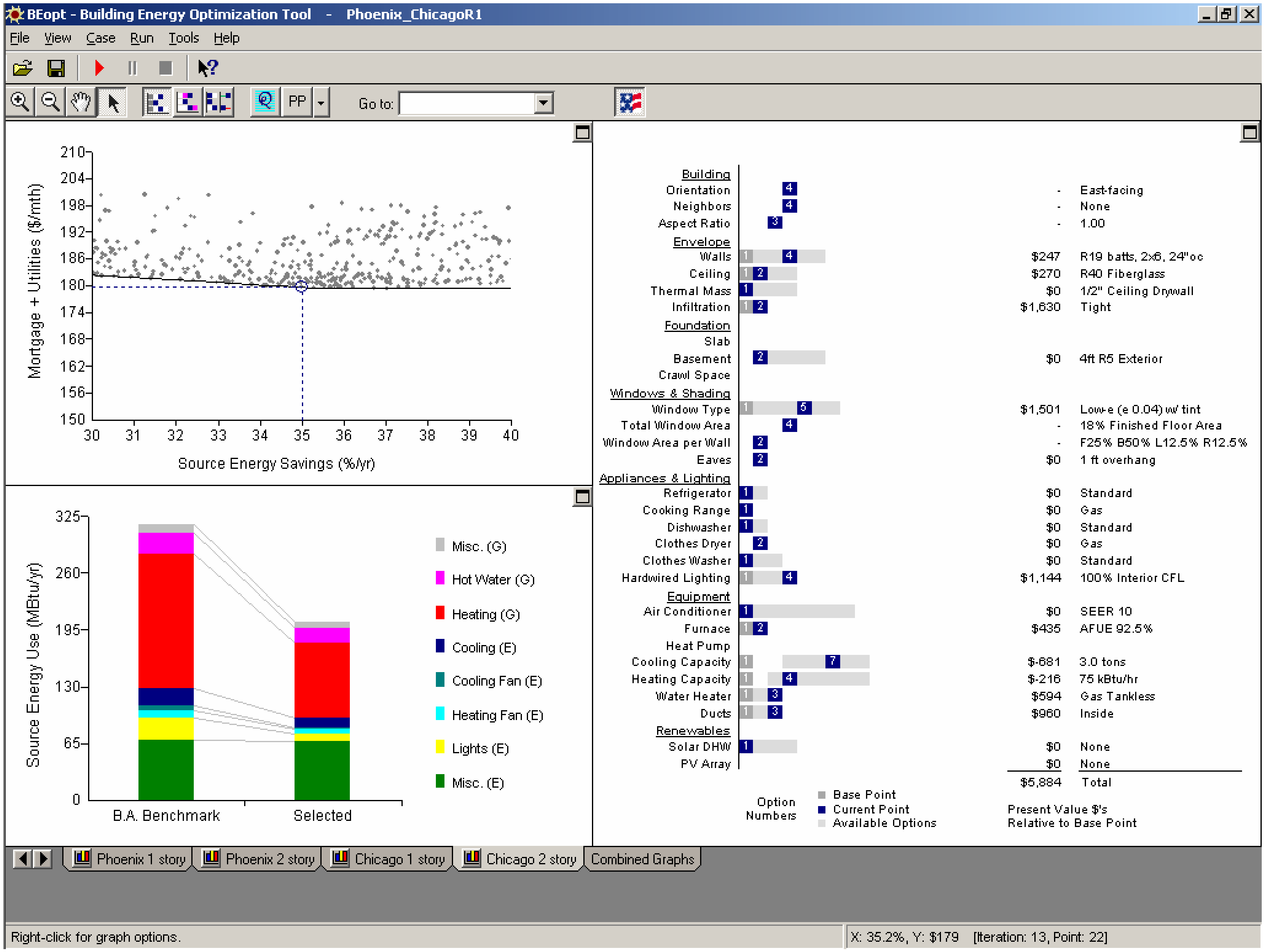


Figure 23. The 35% point for the two-story Chicago example case

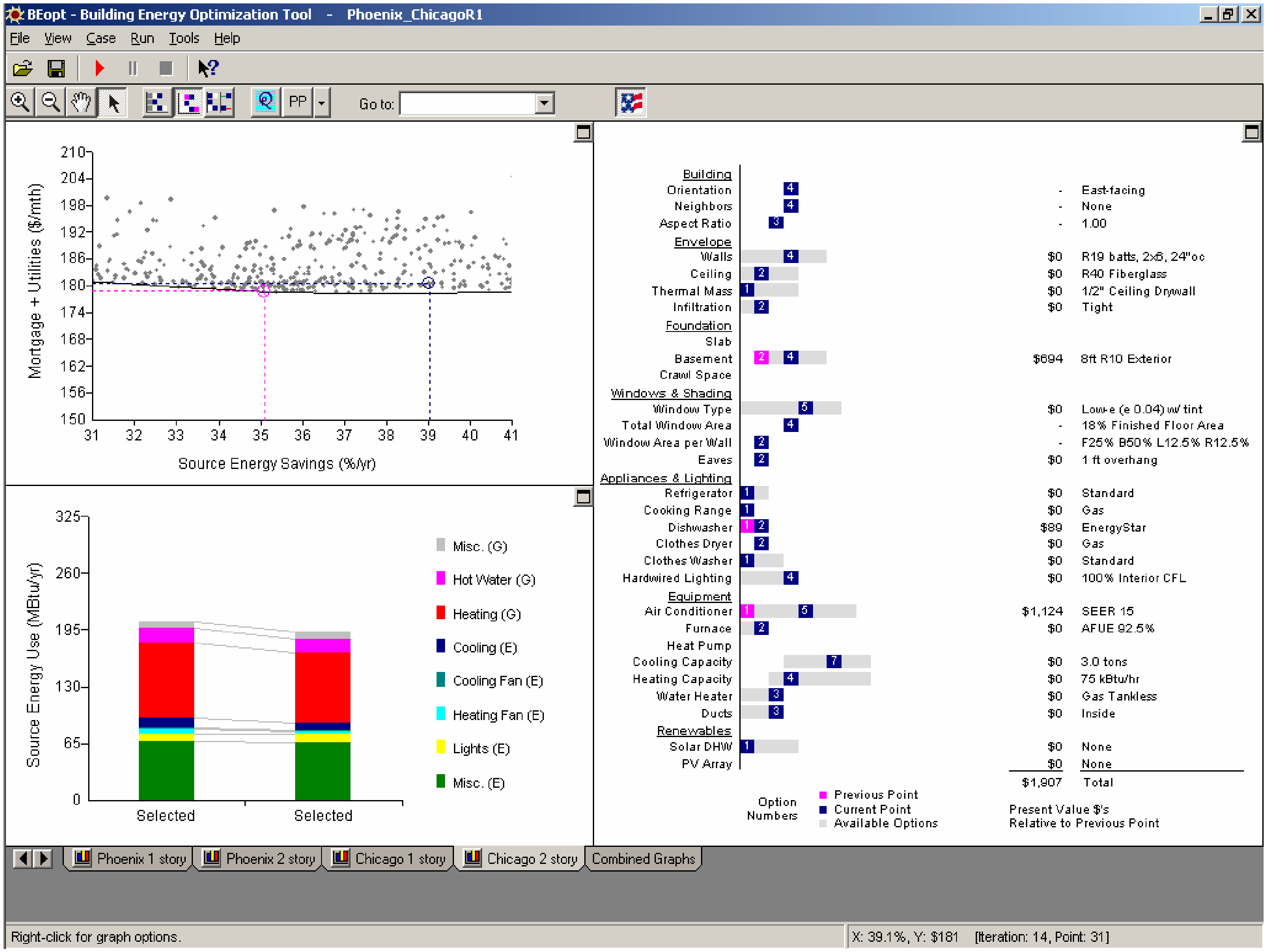


Figure 24.[61] **Comparison of the 39% point to the 35% point, two-story Chicago example case**

[61] Note that costs shown are incremental relative to the 35% energy savings point.

Table 7. Comparison of Single- and Two-Story Cases

CATEGORY	35% EXAMPLE		39% EXAMPLE	
Number of Floors	One Story	Two Stories	One Story	Two Stories
Walls	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc + 2-in. polyiso (R-14)	R-19, 2x6, 24 in. oc
Ceiling	R-40 FG	R-40 FG	R-40 FG	R-40 FG
Thermal Mass	5/8-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall
Infiltration	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003
Basement	4-ft R-5 Exterior Insulation	4-ft R-5 Exterior Insulation	8-ft R-10 Exterior Insulation	8-ft R-10 Exterior Insulation
Glass Type	Two-pane, Low-e, U = 0.32, SHGC = 0.64 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame
Window Area per Wall	270 ft^2, 12.5% N&S, 50% W, 5% E	540 ft^2, 12.5% N&S, 50% W, 25% E	270 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E
Refrigerator	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr
Cooking Range	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr
Dishwasher	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW
Clothes Dryer	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr
Clothes Washer	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW
Lighting	100% CFL, 439 kWh/yr hard-wired, 331 Plug in	100% CFL, 707 kWh/yr hard-wired, 571 Plug in	100% CFL, 439 kWh/yr hard-wired, 331 Plug in	100% CFL, 707 kWh/yr hard-wired, 571 Plug in
Air Conditioner	SEER 10, 2 Tons, 0.365 W/CFM AH Fan	SEER 10, 3 Tons, 0.365 W/CFM AH Fan	SEER 10, 1.5 Tons, 0.365W/CFM AH Fan	SEER 15, 3 Tons, 0.256 W/CFM AH Fan
Furnace	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 75 kBtu/hr	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 75 kBtu/hr
Ducts	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow
Water Heater	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF

Table 7 shows very small differences in the options selected between the one- and two-story cases for the energy-savings levels and combinations selected. The differences between one- and two-story examples at the 35% and 39% energy-savings level are limited to air-conditioner SEER, glazing types, dishwashers, and exterior-wall insulation levels. Within the limitations of the economic model included in the BEopt analysis method, the above example cases would represent a reduction in total monthly cost (mortgage cost – utility cost) when compared to the neutral cost line shown in Figure 6.

First-Cost Impacts

For all of the 30%-39% energy-savings level example cases shown here and in Appendix B the first costs are increased. Many builders are reluctant to design first-cost increases into their standard products. To many potential homebuyers, the first cost of a home can make or break a home sale. In order to address first-cost concerns associated with energy-efficient home designs, some builders have implemented guaranteed energy-bill programs that may influence some potential homebuyers such that they would be more willing to absorb the additional first cost into a 30-year mortgage knowing that their monthly cash flow will ultimately be reduced when the utility bill is considered:

> Builders who guarantee their homes are willing to tell buyers how much energy the home should use, and they guarantee these levels will not be exceeded. These guarantees are backed up with payments if limits are exceeded. Builders can work with insulation companies or other partners to offer guarantees or caps on their home's energy costs, or they may develop their own programs. Some cover room comfort by guaranteeing that the temperature at the thermostat will not vary by more than 3 degrees at the center of any room served by that thermostat. A Building America team helped to develop these programs. Information on three of these programs can be found at
>
> - Environments for Living – www.eflhome.com/index.jsp
> - Engineered for Life – www.us-gf.com/engineered.asp
> - The Energy Use and Comfort Guarantee – www.artistichomessw.com/guarantee.htm.[62]

In some cases, homebuyers may be eligible for energy-efficient mortgages that allow potential home buyers to qualify for larger loans in order to compensate for additional first costs associated with energy-efficient options that are designed into a home. The case study of the Foothills at Wingfield, Reno, Nevada, shows an example of a guaranteed energy-bill program.

> The following features for energy-efficient loans are taken from Fannie Mae, the nation's largest source of funding for mortgages. You can learn more about Fannie Mae at www.fanniemae.com.
>
> - Energy-efficient mortgages (EEM) are available for both purchase and refinance in conjunction with most Fannie Mae first-mortgage products, including conventional fixed-rate and adjustable-rate mortgages.

[62] Building America Best Practices Volume 3, Builders and Buyers Handbook for Improving New Home Efficiency, Comfort and Durability in the Cold and Very Cold Climates, October 2004, NREL/TP-550-36960, Page HOM-5.

- Monthly savings resulting from energy efficiency can be used to qualify borrowers for a larger mortgage. This means consumers can buy more home in the form of energy efficiency or other upgrades.
- The EEM can be used with many Fannie Mae mortgage products. The guidelines of the selected Fannie Mae mortgage apply, with the EEM allowing for the projected energy savings to provide an adjustment to the loan-to-value and qualifying ratios that favor the borrower.[63]

Table 8 shows the first costs associated with the 35% and 39% two-story example cases.

At a 7% mortgage interest rate, an additional $7,794 first cost associated with energy efficiency measures only represents an additional $52 per month for a 30-year loan term. It is important to note that the cost data used in this analysis may not be representative of actual builder or consumer costs in the Chicago area or other Cold Climate areas. The actual first cost for energy efficiency options for a particular builder and potential homeowner in the Cold Climate area may vary substantially from Table 8. Variations in costs would affect the outcome of the analysis method. Other examples of actual first costs associated with the construction of homes that meet the 30% - 39% savings criteria are found in the case studies section of this report and also in the section entitled First Costs, Cost Tradeoffs, and Owner Annualized PITI + Energy.

Table 8. Incremental First-Cost for Two-Story Chicago Case

Category	**Chicago, Two-story**	
	Incremental First-Cost 35% Example	**Incremental First-Cost 39% Example**
Walls	$247.00	$1,959.00
Ceiling	$270.00	$270.00
Infiltration	$1,630.00	$978.00
Basement/ Slab	$0.00	$694.00
Window Type	$1,501.00	$1,501.00
Dishwasher	$0.00	$60.00
Lighting	$376.00	376.00
Air Conditioner	-$460.00	$299.00
Furnace	$75.00	$75.00
Ducts	$960.00	$960.00
Water Heater	$622.00	$622.00
Total	$5,221.00	$7,794.00

[63] Building America Best Practices, Volume 3: Builders and Buyers Handbook for Improving New Home Efficiency, Comfort, and Durability in the Cold and Very Cold Climates, October 2004, NREL/TP-550-36960, Page HOM-4.

Key Cost Tradeoffs

The analysis for a single- and two-story home in the Chicago climate shows the main trends that result in a home that saves 30%-39% whole-house energy relative to the Benchmark. These trends are improved exterior-wall constructions, basement wall insulation, ceiling insulation, high-performance glazing, air-sealing measures to reduce infiltration, ducts in conditioned space, condensing furnaces, tankless gas water heaters; a number of the selected points used elevated levels of compact fluorescent lighting. The results indicate that the main driver for energy and cost savings in the Chicago climate are heating-load reduction strategies (high levels of insulation) coupled with high efficiency furnaces. While most of these measures add to first cost, the total monthly cash flow is actually reduced in terms of a 30-year mortgage when utility bills are considered. In some cases, envelope improvements cause a significant cooling-load reduction that can reduce the cost of the air-conditioning unit. Envelope measures, such as improved exterior wall constructions, basement wall insulation, ceiling insulation, high-performance glazing, air-sealing measures to reduce infiltration, and ducts in conditioned space make it possible to reduce heating and cooling loads such that investment in high efficiency reduced-capacity mechanical equipment is possible. The interaction between improving the building envelope and forced-air duct system to reduce the required capacity of mechanical equipment is the primary cost tradeoff for Cold Climates, as shown in the case studies and supported by the results from the BEopt analysis method. The case studies at Selkirk Twin Homes, Grand Forks, North Dakota, and Foothills at Wingfield, Reno, Nevada, show detailed examples of cost tradeoffs for energy-performance options

Research Results and Conclusions

Through the use of systems engineering and operations research, the Building America program has shown that homes that save 30% whole-house source energy in Cold Climates can be built on a cost-neutral basis by production builders. Table 9A shows a summary for energy-related features for the case studies included in the following section of this report and examples of results from use of the BEopt analysis method for Cold Climates. While the specific combinations of technologies used in the case studies or shown in BEopt results may not be cost-optimal solutions for all areas and housing types covered by the Cold Climate, the key features of the approaches demonstrated in each of these examples can be adapted as needed to provide homes that save 30% whole-house energy savings.

It should be also noted that the BEopt analysis method is subject to the limitations as described in the Cost Analysis – Life-cycle Cost Analysis section of this report. The case studies are the result of 3 years of field experience and design work done by Building America's research teams.

Table 9A. Summary of Energy Features for Case Studies and BEopt Results

	Case Studies					BEopt results			
Category	**Eastern Dakota Housing Alliance, Grand Forks, North Dakota**	**Foothills at Wingfield Reno, Nevada, Plans 1-4**	**CDC of Utah, Magna, Utah**	**Claretian Associates, Chicago, Illinois**	**Kacin Homes, Pittsburgh, Pennsylvania**	**35% Point**	**Neighbor 5**	**35% Point**	**Neighbor 4**
Floor Area (ft^2)	1230 living / 600 unfinished	Not Described	1540/1635	2592	1815	1500	1500	3000	3000
Number of Floors	2	Not Described	2	2	2	1	1	2	2
Number of Bedrooms	Not Described	Not Described	3/4	3	3	3	3	3	3
Number of Bathrooms	Not Described	Not Described	3	Not Described	3	2	2	2	2
Walls	2x6, R-19 or 2x4, R-15 + 2-in. foam for ~ R24	2x6, R-23 blown in cellulose + 1-in. R-4 EPS stucco	2x6, 24 in. oc, R-23 blown-in fiberglass	SIP, 6.5-in. R-24.7	R-5 sheathing, 2x4 16 in. oc, R-15 batt	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc + 1 in. polyiso (R7)
Ceiling	R-49 unvented attic	R-38 blown in fiberglass	R-40 blown in fiberglass	SIP, 10.25-in. R-42.5	R38	R-40 FG	R-30 FG	R-40 FG	R-30 FG
Thermal Mass	Not Described	Not Described	Not Described	Not Described	Not Described	5/8-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall
Infiltration	2.4 ACH_{50}	2.5 $in.^2$ per 100 ft^2 of envelope	0.21 ACH_{ann} = unit 1, 0.22 ACH_{ann} = unit 2, 0.18 ACH_{ann} = unit 3	300-350 CFM_{50}	0.27 ACH_{ann}	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003
Basement/Slab/ Crawl space	Basement = R-22 forms	Slab, R-10, 2-in. XPS slab-edge insulation	Basement, 2-in. Polyisocyanurate, R-13, ½-height interior insulation	Basement, interior 4-in. Rigid EPS	Crawl space - unvented, R-3, rigid fiberglass, exterior; R-10 fiberglass, interior	4-ft, R-5, Exterior Insulation	4-ft, R-5, Exterior Insulation	4-ft, R-5, Exterior Insulation	4-ft, R-5 Exterior Insulation
Glass Type	Double-Pane, High-Performance	Vinyl, Low-E^2, U = 0.35, SHGC = 0.33	Double-pane, low-e vinyl, U = 0.35, SHGC = 0.30	Low-e Vinyl U = 0.30, SHGC = 0.45	Wood-framed, double-glazed, U = 0.33, SHGC = 0.31	Two-pane, Low-e, U = 0.32, SHGC = 0.64 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.32, SHGC = 0.64 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame
Window Area per Wall	Not Described	Not Described	Not Described	Not Described	Not Described	270 ft^2, 12.5% N&S, 50% W, 25% E	270 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E

Table 9A. Summary of Energy Features for Case Studies and BEopt Results (continued)

	Case Studies					BEopt results			
Category	Eastern Dakota Housing Alliance, Grand Forks, North Dakota	Foothills at Wingfield, Reno, Nevada Plans 1-4	CDC of Utah, Magna, Utah	Claretian Associates - Chicago, Illinois	Kacin Homes - Pittsburgh, Pennsylvania	35% Point	Neighbor 5	35% Point	Neighbor 4
Refrigerator	ENERGY STAR	Best electric	Not Described	Not Described	Not Described	Standard, 671 kWh/yr	Standard, 671 kWh/yr	Standard, 671 kWh/yr	Standard, 671 kWh/yr
Cooking Range	Not Described	Best electric	Not Described	Not Described	Not Described	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr
Dishwasher	ENERGY STAR	Best electric	ENERGY STAR	Not Described	Not Described	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW	Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW
Clothes Dryer	Not Described	Best electric	Not Described	Not Described	Not Described	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr
Clothes Washer	ENERGY STAR	Best electric	Not Described	Not Described	Not Described	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6k Wh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW
Lighting	85% Fluorescent	Not Described	70% CFL	Many fluorescent	69% fluorescent	100% CFL, 439 kWh/yr Hardwired, 331 Plug in	100% CFL, 439 kWh/yr Hardwired, 331 Plug in	100% CFL, 707 kWh/yr Hardwired, 571 Plug in	14% CFL, 2534 kWh/yr Hardwired, 571 Plug in
Cooling	Not Described	SEER12	OAsys indirect/direct evaporative cooler - unit 1/Freus water cooled condenser - unit 2/SEER12 - unit 3	SEER10	SEER13, 2.5 tons	SEER 10, 2 Tons, 0.365 W/CFM AH Fan	SEER 14, 2 Tons, 0.383 W/CFM AH Fan	SEER 10, 3 Tons, 0.365 W/CFM AH Fan	SEER 10, 3 Tons, 0.365 W/CFM AH Fan

Table 9A. Summary of Energy Features for Case Studies and BEopt Results (continued)

	Case Studies					BEopt results			
Category	**Eastern Dakota Housing Alliance, Grand Forks, North Dakota**	**Foothills at Wingfield, Reno, Nevada Plans 1-4**	**CDC of Utah, Magna, Utah**	**Claretian Associates - Chicago, Illinois**	**Kacin Homes - Pittsburgh, Pennsylvania**	**35% Point**	**Neighbor 5**	**35% Point**	**Neighbor 4**
Heating	92% AFUE	92% AFUE	96% AFUE furnace direct-vent, ECM motor, two-stage gas	92.5% AFUE	93% AFUE, direct-vent 60,000 Btu/h	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 75 kBtu/hr	92.5% AFUE, 75 kBtu/hr
Ducts	Not Described	Inside conditioned space, R4.2, less than 5% leakage to outside	Mastic Sealed, 76 CFM @ 25 Pa - unit 1; 59 CFM @ 25 Pa; unit 2 total to outside	Inside conditioned space	Inside conditioned space, sheet-metal w/ UL181 mastic, 30 CFM total leakage to outside	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow
Water Heater	Tankless 0.83 EF	0.62 EF 50 gallon gas water heater in garage	50 Gallon, 0.61 EF Power Vented	50-gallon 0.58 EF sealed combustion	Tankless EF = 0.82, HW recirculation system	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF
On-site Power system	None	None	None	1.2-kW grid tied	None	None	None	None	None

Table 9B summarizes the source of the energy savings by end use. Figure 25 shows the location of the case studies presented in this report. Locations are indicated with stars.

Table 9B. Summary of Source Energy Savings by End-use as a Percentage of Total Energy Use for the Cold Climate Case Studies

	Percent Source Energy Savings				
End Use	Eastern Dakota Housing Alliance: Grand Forks, North Dakota, Phase 2	Foothills at Wingfield: Reno, Nevada Plans 1 through 4	CDC of Utah: Magna, Utah	Claretian Associates: Chicago, Illinois	Kacin Homes: Pittsburgh, Pennsylvania
Space Heating	58%	52/55/57/58%	53%	63%	53%
Space Cooling	27%	46/50/48/54%	68%	0%	43%
DHW	38%	28%	16%	7%	54%
Lighting	40%	0%	49%	57%	37%
Appliances + MEL	8%	3%	3%	5%	5%
Total Energy Use	**38%**	**33/35/35/37%**	**32%**	**36%**	**38%**
Number of Homes	12	165	3	26	117

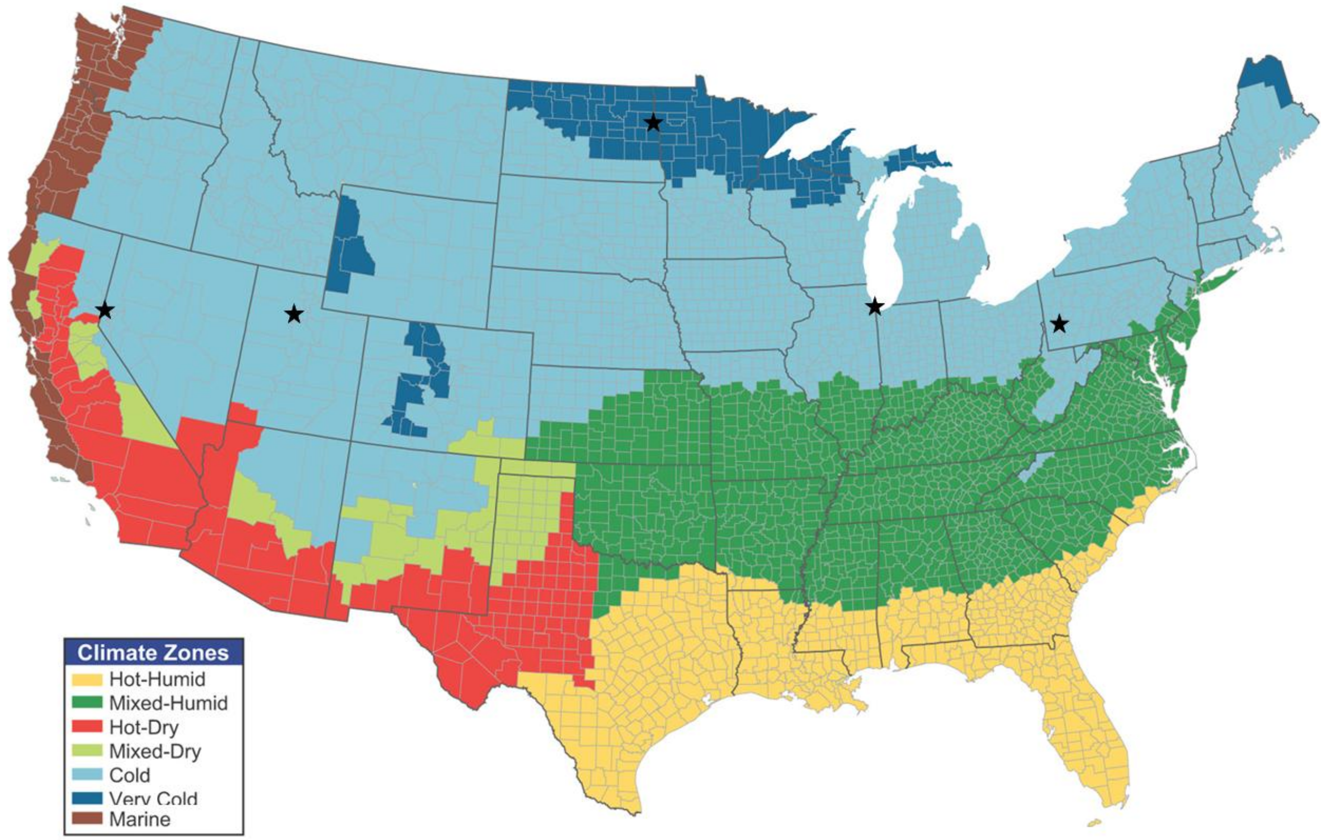


Figure 25. Location of 30% Cold-Climate case studies

House Case Studies

Development: Selkirk Circle Twin Homes
Builder: Applegren Construction
Location: Grand Forks, North Dakota

Fueled by Crises

In 1997, a flood in Grand Forks, North Dakota, destroyed or damaged two-thirds of the houses in this town of 49,000. The average value of the homes lost in the flood was $72,000, which resulted in a shortage of affordable housing. In addition, severe winters in 2000 and 2001 coupled with rising natural gas prices sent utility bills through the roof for low-income families. These crises galvanized the not-for-profit Eastern Dakota Housing Alliance (EDHA) to team with other non-profit organizations, cities, counties, and for-profit developers to build more affordable housing in eastern North Dakota. EDHA's clients consisted of households earning below 80% of the area median income. Many of EDHA's home buyers earn less than $30,000 per year. Lisa Rotvold, the Director of EDHA and an architect, explained it in this way:

> We became interested in teaming with Building America because of the severe weather here. We needed a way to make heating and cooling more affordable. In the winter months, we have severe weather months with temperatures below minus 20 degrees. In the summer, we have temperatures in the 90s with high humidity. We get both extremes. In the last few years, we have seen significant jumps in the utility costs for natural gas. Our low-income families do not have the money to pay the heating and cooling bills, so we needed to build houses that use less energy. This was our motivation.

In March 2003, EDHA completed its first of four housing phases working to Building America standards. Each of the four planned phases includes four twin-home (duplex) units. Each two-story home within the duplex unit has 1,230 ft^2 of living space with a 600- ft^2 unfinished basement. The living space includes three bedrooms, 1.5 bathrooms, and a detached double-car garage (Figure 26 and Figure 27).

Figure 26. Phase-1 and Phase-2 Twin Home design

Figure 27. Twin home unit energy efficient affordable homes

"A great thing I appreciate about Building America is that they test the houses upon completion for energy efficiency and give them ENERGY STAR and Building America certification," said Rotvold.

Testing and certification is performed by Building America's Industrialized Housing Partnership. HERS scores on four Phase I units completed in March 2003 were between 88 and 90 with whole-house savings of 25% to 30% against the Benchmark. Four Phase II units completed in January 2004 had an average HERS of 92.5 and whole-house savings of 39%. The higher efficiency in Phase II comes from the addition of a whole-house tankless gas water heater and R10 sheathing on exterior walls. Lower HERS scores (88.3 – 89.5) on the Phase III units was primarily a result of electric resistance water heating and slightly higher duct and envelope leakage. All units have ventilation air brought to the air-handler return plenum with 10 of 12 units utilizing heat recovery ventilators (HRVs). Rotvold said:

> Our goal is that every house we build in this neighborhood will be built following Building America principles. In this process, the value that Building America has provided is the technical assistance and the systems approach to design. For example, we could have simply increased the insulation or done some other piecemeal things to improve energy efficiency, because we didn't understand how to look at all of the systems of a house and how they can impact energy usage.
>
> Building America provided us with a lot of technical assistance. They guided us through the process. We stressed that we wanted practical solutions. They ran estimates to determine the financial payback of the energy efficiency measures we were considering. These estimates proved to be invaluable because we were getting lots of pressure to consider innovative methods (like geothermal heating from groundwater). However, the energy analysis Building America ran proved that these methods would not provide a payback for our small houses, so we learned that innovative is not always effective.
>
> We wanted a common sense package of features.

Innovations

As with all Building America homes, these features begin with super-tight construction, which during the testing phase must demonstrate an air-sealed interior. Because of this tight design, builders incorporated the Lifebreath mechanical ventilation system for bringing clean air into the house and expelling stale air (Table 10).

According to Rotvold: "We are building healthy houses. When you build a house so tight, you must consider systems for getting clean air in—which in the winter can be very cold. Therefore, we installed 'air-to-air' heat exchangers." An air-to-air heat exchanger uses outgoing warm air to heat the incoming air stream.

Another energy-efficient feature is increased insulation. The Phase I homes have 2x6 walls at 16 in. on center (o.c.) insulated with R-19 batt insulation (Figure 28). The vented attic is insulated to R-49.

Table 10. Builder Profile: Applegren Construction

Where:	**Price Range:**
Grand Forks, North Dakota	From $115,000 to $120,000
Founded:	**Key Features:**
1978	• High-efficiency GMC natural gas furnace
Employees:	• Lifebreath air-to-air heat exchanger
10 employees	• R-15 spray-on fiberglass insulation
Development:	• Tight construction envelope
Selkirk Circle	• R-22 insulated basement forms
Size:	• R-49 attic insulation
Space for 22 units in the development	• High efficiency tankless gas water heater
Square footage:	• Efficient lighting system
Duplex with each unit 1,230 ft^2 with a 600-ft^2 unfinished basement and either an attached or detached garage.	• Programmable thermostat • ENERGY STAR appliances • Double-pane high-performance windows

Figure 28. The houses feature 1-1/2-in. XPS foam at corners

The wall exterior is OSB sheathing, building paper, and vinyl siding. All electrical boxes on the exterior walls are sealed to prevent air seepage. The basement can be upgraded in the future to a living space with two windows at grade level provided for each of two future bedrooms.

The homes are heated with a 92%-efficient gas furnace. The thermostat is programmable to allow specific temperatures to be set for specific times of the day.

Each home is sold with ENERGY STAR appliances, including a horizontal-axis clothes washer, dryer, dish washer, and refrigerator.

Finally, considerable effort focused on replacing incandescent bulbs and fixtures with fluorescent lighting. EDHA increased the use of fluorescents from a typical 10% of the home's lighting to 85% by installing linear fluorescent fixtures and providing compact fluorescent (CFL) bulbs for appropriate standard fixtures.

Rotvold explains that they are learning and applying what they learn with each phase. In addition, she notes that more energy-efficient products and options are available on the market now than when they started with Phase 1 a few years ago. For example, in Phase 2, they switched to a tankless gas water heater. Tankless means that the hot water is not stored; instead, it is heated on-demand by powerful gas burners. Because the heater is not heating the whole tank, just the water needed at that moment, it uses less energy. Another change was to switch from 2x6 walls with R-19 batt insulation to 2x4 walls with blown-in fiberglass to R-15. Two in. of extruded polystyrene (R-10) is installed except in areas where ½-in. OSB bracing is required. These corner-braced areas received 1-1/2 in. of insulated sheathing (R-7.5). This gave an overall R-value of approximately R-24. "The water heater made a very big difference," said Rotvold. "It was a costly item but it has a good payback for us."

Comfort, Durability, and Health

"We are really proud of these houses," explained Rotvold. "The quality is so much higher than the market is producing. Also, anecdotally, I am hearing that the heating bills are much less in our homes." The homes are sold for $115,000 to $120,000, which is the appraised value. Seven of the first eight buyers earn less than $30,000 per year. For the buyers, the North Dakota

Housing Finance Agency's Community Partners program provides a 1% to 2% interest rate buy-down. The city provides up to $7,500 in down-payment assistance. The developer provides a subsidy of between $2,000 and $20,000. Finally, Rotvold relies on grant funding to help fund the energy efficiency upgrades. "Without the grants, we would be losing money doing the upgrades, partly because we are pricing affordably and not pushing the market to make these upgrades appraise," said Rotvold. She believes in the quality of the homes and the value of the energy-efficient features for their lower income buyers.

The Bottom Line

"This is a model project," said Rotvold. "It is a tremendous cooperative effort. I would tell other companies who are considering Building America that if you can get in the door, do! Get the technical assistance they provide because it helps you to make good decisions. We didn't do everything David [the Building America Technical Assistant from Florida Solar Energy Center] suggested because we had to balance dollars; however, David thinks from a systems approach, so we just didn't increase insulation we made small improvements to many of the systems within the homes. Attention was provided to every little detail in relation to the whole."

Economics

Excerpts from a 2004 ASHRAE publication provide an economic comparison of the Selkirk twin homes (Table 11) with a theoretical regional base case using DOE2 simulations. Energy measures from the Phase II units were evaluated progressively by adding one measure at a time to the base case in the order listed in Table 12 arrive at estimated savings numbers. Major construction components or equipment were added first, such as envelope measures and the gas furnace. ENERGY STAR appliances were added before the water heater upgrade to highlight their savings with respect to electrically heated water.

One row in Table 12 shows the cumulative effect of all measures added to the base-case home. Estimated saving in this row includes the cumulative effect of all measures incorporated together in the DOE2 simulation. The heat recovery ventilator (HRV) is broken out from the other measures to provide a meaningful simple payback and first-year cash-flow figures for the other cumulative measures. The HRV is considered an essential component for the indoor air quality of these homes but comparing it to a base-case home without ventilation means no relative savings are attained, thus this measure is added in a separate row. With the exception of the HRV all measures show a positive cash flow on a 6%, 30-year fixed rate mortgage beginning in the first year.

Table 11. Completed Selkirk Homes

	Phase 1	Phase 2	Phase 3
Number of Homes	4	4	4
Completion Date	Mar-03	Jan-04	Aug-04
HERS range	88 – 90	92.5	88 – 89.5
Benchmark range	30%	38%	TBD

Table 12. Economic Assessment of Phase-2 Measures

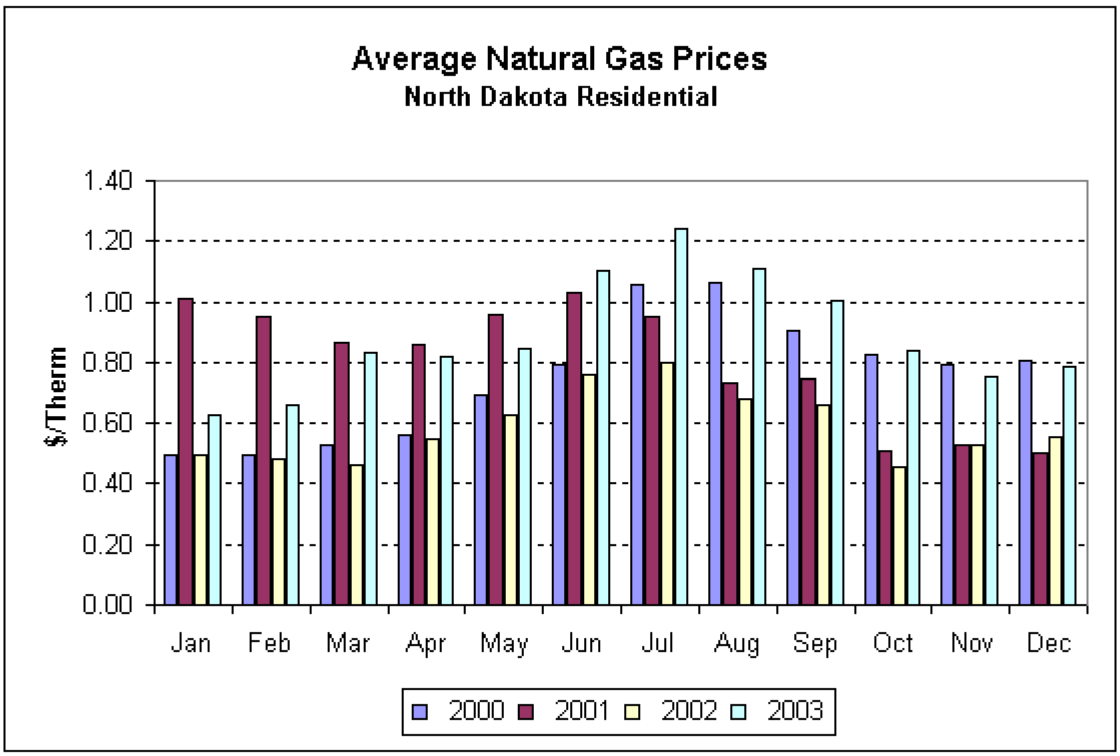
Energy Measure	Annual Savings	Installed Cost	Simple Payback	First Year Cash Flow
Upgrade walls to (R10 sheath + R15 FG batt)	$72	$600	8.3	$31
Reduce infiltration from 5.0 to 2.4 ACH50	$106	$325	3.1	$82
Upgrade from 78% to 92% direct vent furnace	$40	$600	15.0	-$1
Switch to Programmable Thermostat	$18	$130	7.2	$6
Upgrade to ENERGY STAR appliances[a]	$60	$730	12.2	$12
Electric tank to EF-0.83 tankless gas water heater	$94	$1,250	13.3	$10
Increase from 10% to 85% fluorescent lighting	$31	$200	6.5	$18
All Measures	**$421**	**$3,835**	**9.1**	**$158**
Heat recovery ventilation @75cfm, 33% RTF	($43)[b]	$1,400	N/A	-$134
All Measures with HRV	**$378**	**$5,235**	**13.8**	**$24**

Notes:

[a] ENERGY STAR appliances include refrigerator, dishwasher, and h-axis clothes washer

[b] First-year cash flow based on 30-year fixed rate mortgage with interest rate of 6%, down payment of 5%, and discount rate of 5%. A general inflation rate of 3% per year was applied to the upgrade cost of measures replaced at end of lifetime. Final value of equipment is determined by linear depreciation over lifetime. Interest paid on mortgage is considered tax deductible using a tax rate of 28%. Energy costs escalate at 3% per year. A property tax rate of 0.8% was applied to the energy upgrade cost and is inflated at 3% per year.

The 2003 average local natural gas ($0.748/therm) and electric ($0.06/kWh) rates were obtained from the serving utility for these calculations. The economics, however, become difficult to quantify for both the furnace and tankless gas water heater upgrades in light of recent natural gas price fluctuations. In the 10 years before 2000, gas prices (Figure 29) were relatively stable with a slight rise in the summer months when heating demand is reduced. This trend was interrupted in the winter of 2000-2001 when prices remained high throughout the winter as shown in the bar chart. Such fluctuations would impact furnace upgrade savings, making the high efficiency unit look more favorable against a standard efficiency furnace. For the gas water heater, on the other hand, increasing gas prices would reduce its cost effectiveness relative to an electric model typically installed in this area. Historically, more stable electric costs in North Dakota were 26% below the national average of $0.0813/kWh in 2003 (EIA 2004).



Source: U.S. Energy Information Administration (converted to $/therm from $/Mcf using estimated heat content of 1,029 Btu/cubic foot)

Figure 29. Average natural gas prices for North Dakota residences

Development: **Magna, Utah**

Builder: **Community Development Corporation of Utah**

Location: **Magna, Utah**

The Community Development Corporation of Utah (CDCU) is a 501(c)3 non-profit organization established in 1991. Their mission is to help low-income families achieve homeownership and become stable partners in the community. People with disabilities, those living in substandard housing, those on public assistance who are seeking self-sufficiency, and people in danger of being homeless or institutionalized receive priority attention.

To date, the CDCU has assisted more than 1,400 families in 97 Utah communities. In addition to keeping the first cost of the homes low, the CDCU recognizes the importance of reducing operating costs. For families to thrive, low-income homeowners must be able to operate and maintain their homes.

Initially, the CDCU partnered with Building America under the Existing Residential Buildings Program. After successfully completing a low-income rehab project in January 2004, the CDCU was anxious to apply the lessons learned to new construction. The CDCU acquired three lots adjacent to the completed Magna rehab project.

Three Building America prototype homes were built on the adjacent lots in Magna, Utah. These homes demonstrate the CDCU's ongoing commitment to building safe, durable, and energy-efficient housing. The CDCU is working to transform the small city of Magna and improve the quality of housing available to low-income families. The plans developed meet the needs of the future families, fit into the site and surrounding community, comply with local codes, and achieve high energy performance.

A site plan for the project is shown in Figures 34 through 37). The first- and second-floor plans of Unit #2 are shown on the following page. Also included is an overlay of the two floors. In the overlaid drawing, the alignment of bearing walls and location of mechanical chases can be identified.

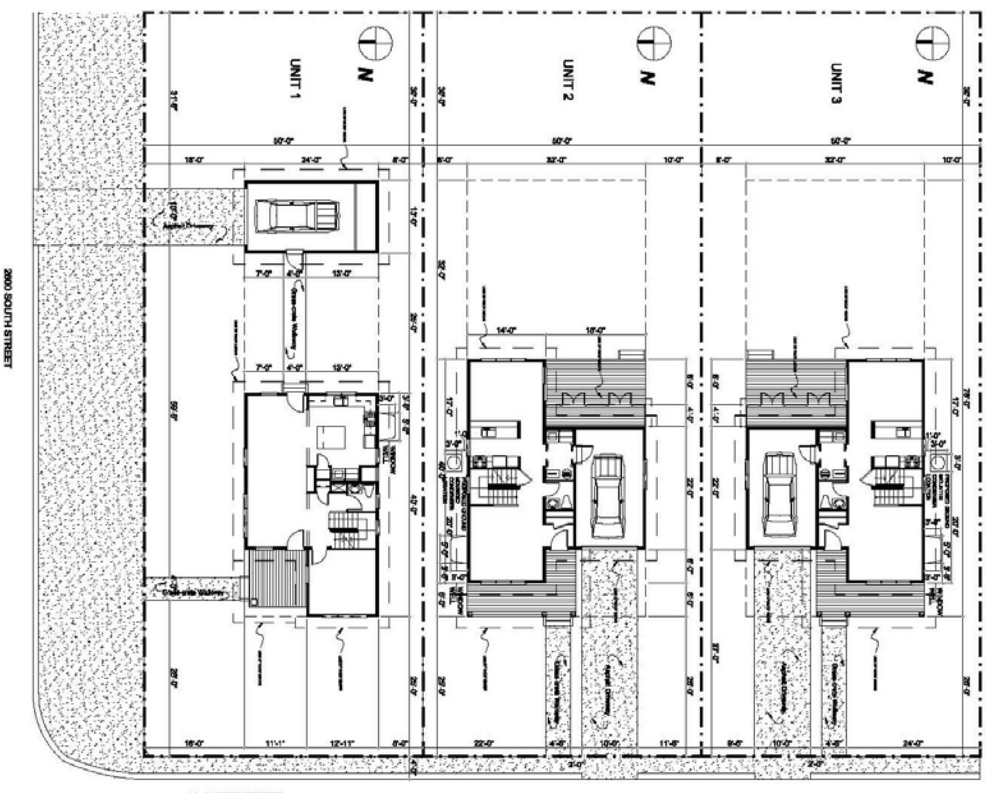


Figure 34. Magna site plan

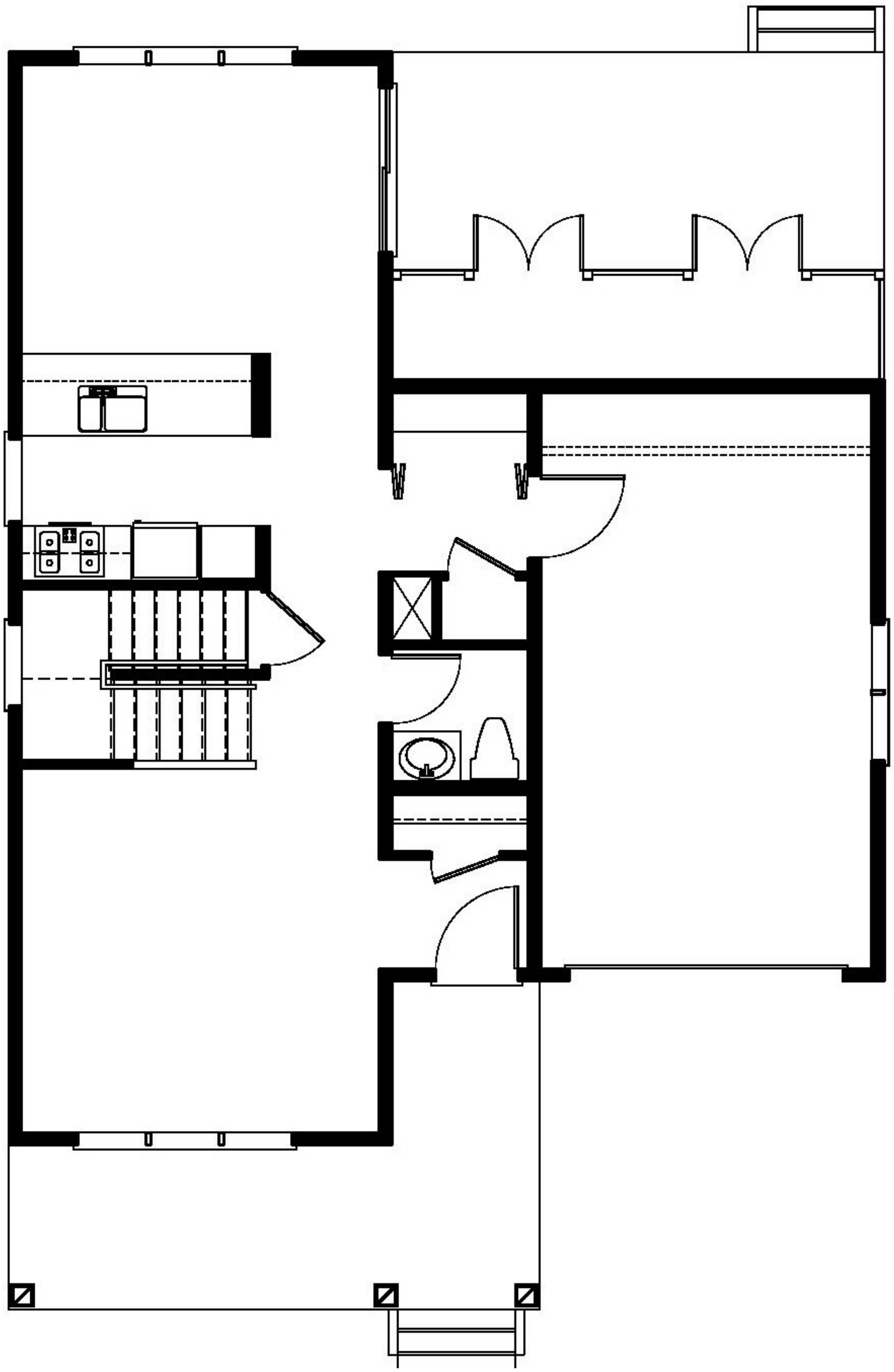


Figure 35. Unit #2 first-floor plan

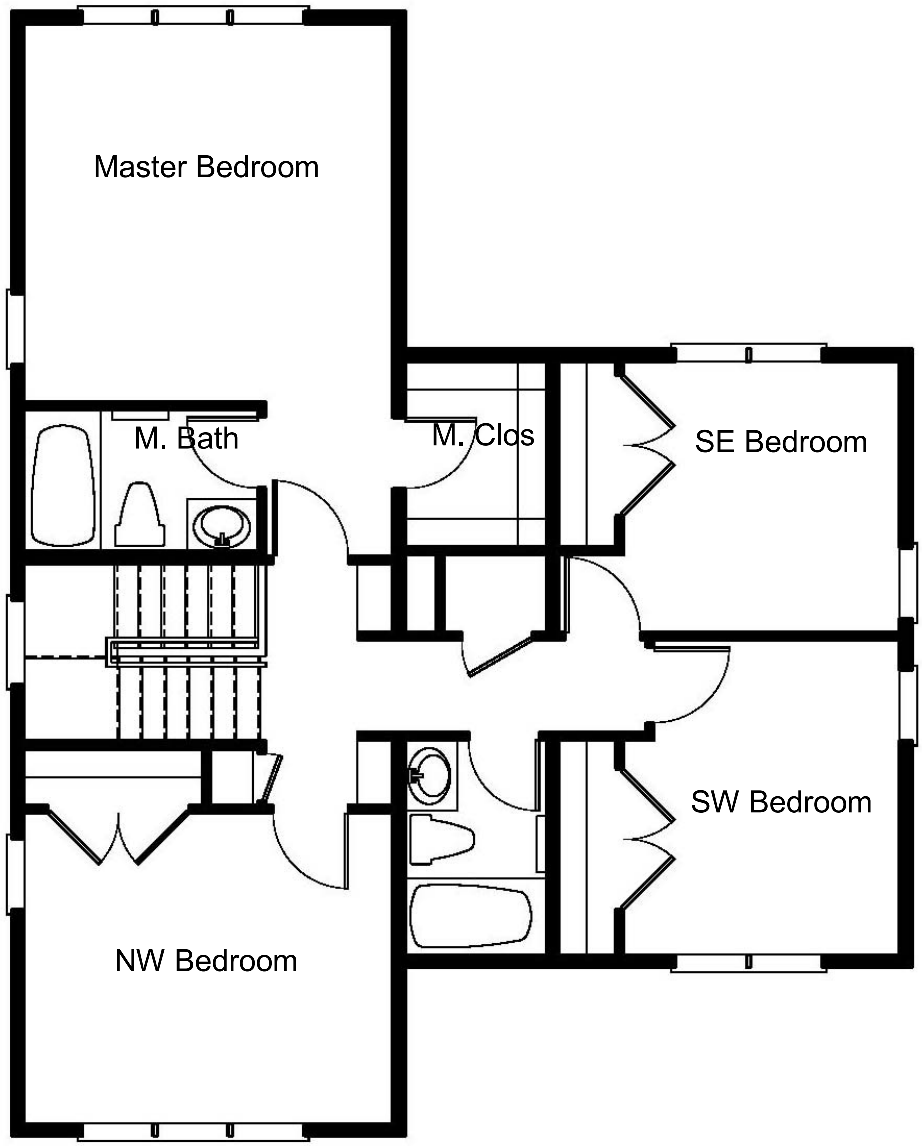


Figure 36. Unit #2 second-floor plan

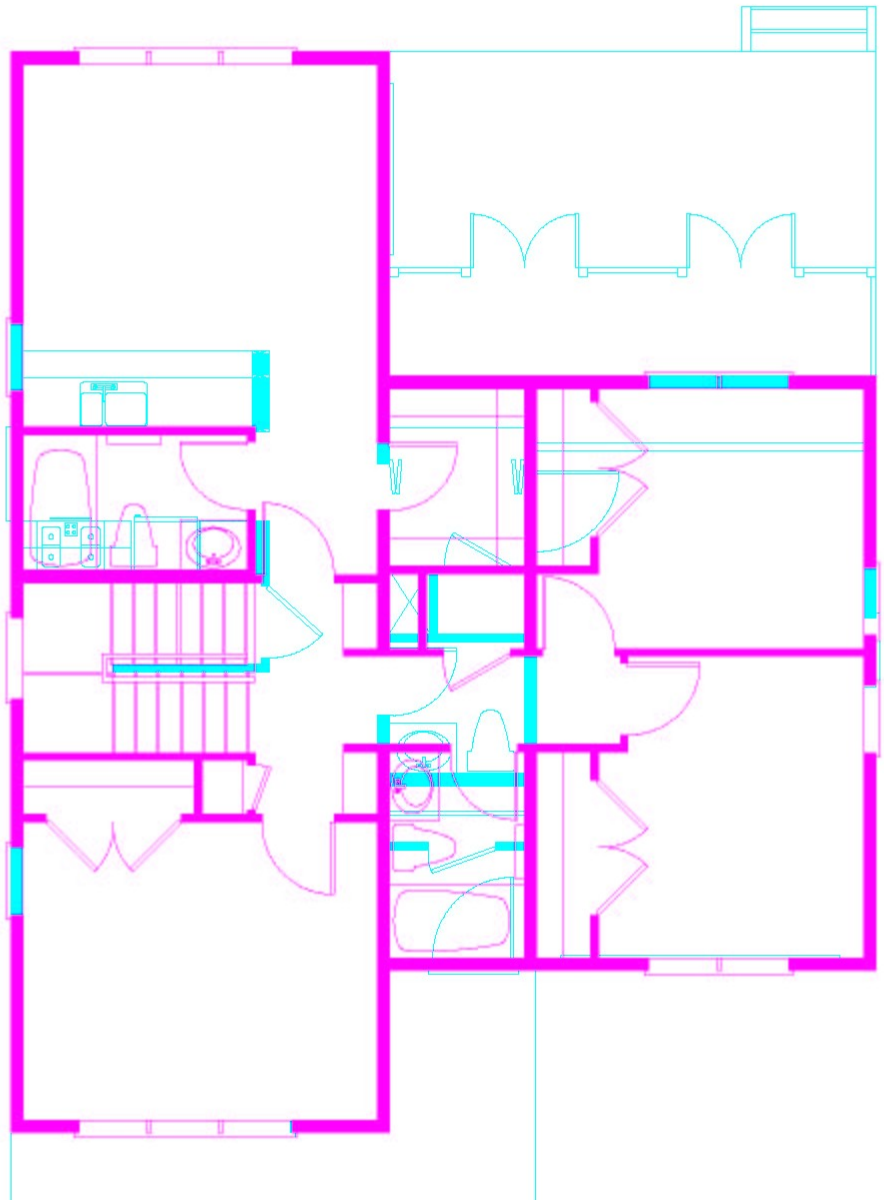


Figure 37. Magna first- and second-floor overlay

Specifications for All Units

Square Footage	1,540 ft^2 and 1,635 ft^2 with 770-ft^2 and 670-ft^2 basements, respectively
No. of Bedrooms	Three and four bedrooms
Foundation Walls	2-in. foil-faced polyisocyanurate insulation (R-13), half-height installation
Exterior Walls	2x6 wood framing, 24 in. OC, advanced framing
Wall Insulation	R-23 blown-in fiberglass
Vapor Retarder	Poly-vapor barrier on the interior
Floor System	Space joist TE open-web trusses
Rim/Band Joists	Insulated with two-component spray-foam
Floor over Garage	R-19 batt insulation
Windows	Low-e, double-pane, vinyl frame (U = 0.35, SHGC = 0.30)
Ceiling Insulation	R-40 blown-in fiberglass
Duct System	Engineered duct system, sealed with mastic
Transfer Grilles	R.A.P. transfer grilles
Space Heating	Carrier infinity, 96% AFUE furnace, direct-vent, ECM motor, two-stage gas
Thermostat	Programmable
Water Heating	Power-vented, A.O. Smith Powershot, 50 gallon, EF = 0.61
Lighting	70% compact fluorescent
Appliances	ENERGY STAR dishwasher
Ventilation	Upgraded bath fan and Grasslin pin timer

In addition to the above specifications, each unit features a different high performance cooling system:

- Unit 1: OASys Indirect-Direct Evaporative Cooler (IDEC) integrated with a Dynamic Ceiling System
- Unit 2: Freus Evaporative Condenser combined with oversized indoor evaporator coil to maximize sensible cooling capacity and the Energy Efficiency Rating
- Unit 3: SEER 12 Condenser combined with oversized indoor evaporator coil to maximize sensible cooling capacity and the Energy Efficiency Rating (EER).

Prototype Features

The winning bid fell within the range of typical construction costs for past CDCU projects. Although these homes include high-performance envelopes and upgraded mechanical equipment, the bid was competitive with standard practice construction. A number of factors helped to keep the bid low, including: economies of scale for three homes, advanced framing drawings detailing the reduction in materials, minimized ductwork, and complete drawings and specifications.

Foundation Insulation

Two inches of foil-faced polyisocyanurate insulation (R-13) was installed on the interior upper half of the wall, which accounts for the greatest amount of heat loss (Figure 38). The rigid insulation board was adhered horizontally on the upper portion of the wall and using a quick-setting construction adhesive. The seams between each sheet were sealed with metal tape and the corners were caulked. Because the insulation is foil faced, it did not have to be covered to meet building code requirements. The insulation was installed tight to the floor trusses. This created a lip at the top of the foundation, which was useful when applying spray-foam insulation to the band joist.

Figure 38. Foil-faced polyisocyanurate insulation

Compact Duct System

The HVAC system was coordinated with the advanced framing. The system was designed to minimize ductwork, to keep all ducts within the conditioned space, and to provide balanced supply and return airflows. Chases were provided for supply trunks and central returns, eliminating the need for ductwork in exterior walls. No panned ductwork was permitted, and the system was sealed with mastic to reduce duct leakage.   Homes have central returns on the first and second floor and a separate return from the master suite.

Space Cooling

A unique feature of Unit #2 is the Freus evaporative condenser (Figure 39). As standard practice, the CDCU typically installs SEER 10 air conditioning systems in their homes. CARB researched equipment incentives available and found that Utah Power was offering $250 for the installation of SEER 12 equipment. Higher SEER equipment, such as the Freus unit, qualified for a $350 incentive.

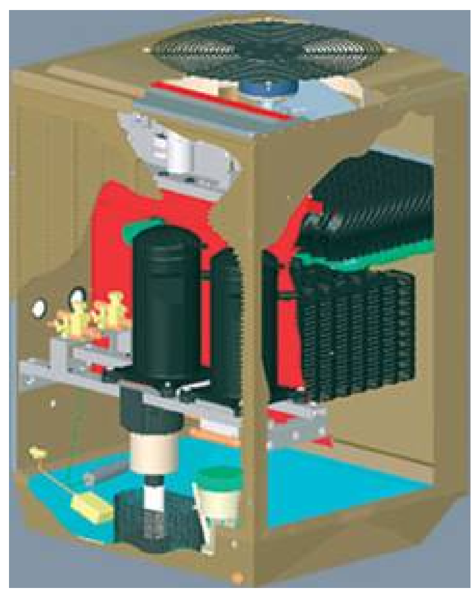


Figure 39. Freus evaporative condenser (left) and a cut-away sketch of the Freus unit (right)

Figure 40. Nutone fan and Grasslin pin timer

Mechanical Ventilation

These homes were air-sealed to reduce infiltration, making mechanical ventilation extremely important. These homes feature an "exhaust-only" ventilation strategy. An upgraded low-sone, energy efficient bath fan rated for continuous duty was installed in the main bathroom of each home. To control the fans, a pin timer was installed in a nearby closet. A manual switch in the bathroom allows the occupants to use the fan for local exhaust, while the timer ensures adequate run time to provide ventilation for the home. These prototypes are capable of complying with the guidelines set forth by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) in Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-rise Residential Buildings. Figure 40 shows the Grasslin Timer (Model # KMA ST-1G) installed in a closet off the bathroom.

Energy Modeling

Using Energy Gauge USA 2.10 software, the energy performance of Unit #2 was modeled and compared to the "Building America Research Benchmark Definition version 3.1." The energy modeling included in this report is based on the floor plan, specifications, and mechanical equipment installed in Unit #2. It also includes data obtained during the performance testing of the homes, such as infiltration and duct leakage rates.

Based upon the actual specifications, the prototype will have an estimated 32% total energy reduction compared to the Benchmark and use 26% less than the CDCU's standard practice. For further details, see Table 21.

Table 21. Energy Consumption by End-Use and End-Use Source Energy and Savings

Summary of Energy Consumption by End-Use

	Annual Site Energy						Annual Site Cost		
	Benchmark		Builder		Prototype		Benchmark	Builder	Prototype
End-Use	kWh	Therms	kWh	Therms	kWh	Therms	$	$	$
Space Heating	306	439	320	445	119	247	$ 406	$ 412	$ 225
Space Cooling	2663	0	2093	0	864	0	$ 168	$ 132	$ 54
DHW	0	271	0	269	0	228	$ 238	$ 237	$ 201
Lighting	2100		1548		1080		$ 132	$ 98	$ 68
Appliances	1121	162	1121	162	1039	162	$ 213	$ 213	$ 208
Plug Load	2704		2704		2704		$ 170	$ 170	$ 170
OA Ventilation	212		122		36		$ 13	$ 8	$ 2
Total Usage	9105	872	7908	876	5841	637	$ 1,341	$ 1,269	$ 929
Site Generation					0				
Net Energy Use	9105	872	7908	876	5841	637	$ 1,341	$ 1,269	$ 929

Summary of End-Use Source-Energy and Savings

	Annual Source Energy			Source Energy Savings: Percent of End-Use		Source Energy Savings: Percent of Total		Component %	
	Benchmark	Builder	Proto	Builder	Prototype	Builder	Prototype	Builder	Prototype
End-Use	MBtu/yr	MBtu/yr	MBtu/yr						
Space Heating	48.1	48.8	26.5	-2%	45%	0%	12%	-6%	37%
Space Cooling	28.7	22.6	9.3	21%	68%	3%	10%	49%	33%
DHW	27.6	27.4	23.3	1%	16%	0%	2%	2%	7%
Lighting	22.6	16.7	11.6	26%	49%	3%	6%	48%	19%
Appliances	28.6	28.6	27.7	0%	3%	0%	0%	0%	1%
Plug Load	29.2	29.2	29.2	0%	0%	0%	0%	0%	0%
OA Ventilation	2.3	1.3	0.4	42%	83%	1%	1%	8%	3%
Total	187.1	174.6	128.0	7%	32%	7%	32%	100%	100%
Site Generation			0.0						
Net Energy Usage	187.1	174.6	128.0	7%	32%	7%	32%		

Notes: The "Percent of End-Use" columns show how effective each building is in reducing energy use over the Benchmark in each end-use category.
The "Percent of Total" columns show how the energy reductions in each end-use category contribute to the overall savings.

energy costs	$0.0630	/kWh for electricity	Utah Power
	$0.88	/therm for natural gas	Questar Gas

	equipment sizing		
Benchmark	49.8 kBtu/hr for heating		
	34.5 kBtu/hr for sensible cooling	-->	4.5 nominal tons
Builder	42.5 kBtu/hr for heating		
	29.7 kBtu/hr for sensible cooling	-->	4.0 nominal tons
Prototype	36.9 kBtu/hr for heating		
	19.2 kBtu/hr for sensible cooling	-->	2.0 nominal tons

*Sizing of cooling nominal tons is based on a SHR of 0.7, 0.7, 0.85, respectively

	HERS rating
Benchmark	81.0
Builder	81.7
Prototype	89.7

Community-Scale Case Studies

Development: New Homes for South Chicago, Illinois

Builder: Claretian Associates, South Chicago Workforce

Location: South Chicago, Illinois

Introduction

In South Chicago, Illinois, Claretian Associates, a non-profit community development organization, and South Chicago Workforce, a non-profit local builder, are in the process of building “New Homes for South Chicago III” (Figure 41): 26 efficient, affordable homes on empty lots in the South Chicago neighborhood. Energy efficiency, sustainability, and the health of the homes are the prime concerns of the developer and the builder.

The Consortium for Advanced Residential Buildings (CARB) began working with Claretian Associates and South Chicago Workforce as part of DOE’s Zero Energy Homes program. The primary goals were to monitor the energy performance of the homes’ solar energy systems and to evaluate the performance of several ventilation systems in the first three homes.

General Features and Specifications

Each three-bedroom single-family home has 2,592 ft^2 of living space, including the conditioned basement. The baseline specifications of these homes achieve the Building America 30%-40% total energy savings level. An additional 5% total energy savings is provided by site generated power, in the form of photovoltaic (PV) panels on the roof.

Figure 41. Two of the “New Homes for South Chicago, Illinois

Figure 42. SIPs installed in the first home

Foundation

Each home has a walk-out basement with poured concrete walls. The foundation walls were insulated on the interior with 4 in. of rigid expanded polystyrene (EPS) insulation.

Walls and Roofs

Structural insulated panels (SIPs) were used for all above-grade walls and roofs of the homes (Figure 42). Wall SIPs are 6.5 in. (R-24.7) and ceiling SIPs are 10.25 in. (R-42.5). Open-webbed floor trusses support the first and second floors, and rock-wool was blown into these rim-joist cavities (R-20 or higher). It is believed that these buildings are the first SIP homes allowed within the city of Chicago. The SIP envelopes, combined with meticulous air sealing, resulted in very tight envelopes. Blower door tests on the three homes that were monitored showed infiltration between 300 and 350 CFM50.

Windows

The selected ENERGY-STAR® windows are manufactured by Certainteed with low-emissivity glazing and vinyl frames. U-values are 0.30 $Btu/ft^2hr°F$ and solar heat gain coefficients are 0.45.

Heating

The homes are heated by condensing, sealed combustion furnaces (Armstrong, 92.5% AFUE). Sheet-metal duct systems distribute air throughout the homes.

Figure 43. Sealed-combustion furnace and water heater in the first home.

Water Heating

To eliminate any chance of back-drafting in these very air-tight homes, all combustion appliances (with the exception of the kitchen ranges) are sealed combustion (Figure 43). The AO Smith "Sealed Shot" water heaters (50 gallon, EF 0.58) draw combustion air through a PVC vent and send exhaust directly out through the wall.

Cooling

When homeowners purchase the air-conditioning option, SEER-10 Armstrong air conditioners provide cooling. Though few homebuyers chose this option, energy analyses presented here assume that the air conditioning is installed.

Ventilation

Providing fresh air for occupants is a key component of the developer's commitment to high Indoor Environmental Quality (IEQ) and healthy homes overall. South Chicago Workforce approached CARB with a proposal to evaluate several types of ventilation systems. In the spring of 2003, CARB completed the installation of monitoring systems in the first three homes.

Starting in November 2003, CARB collected data for approximately 18 months. CARB monitored three different ventilation systems in the first three homes:

- Energy recovery ventilation (ERV)
- Air cycler (outdoor air duct to return plenum)
- Exhaust only ventilation (timers on efficient bath exhaust fans)

CARB monitored temperature, humidity, and CO_2 levels at three points inside each house, plus one point outside the homes. CARB has begun to evaluate the energy and IEQ ramifications of each of the ventilation systems.

Solar Electricity

On the first 12 homes in the scattered development, South Chicago Workforce is installing 1.2-kW PV systems. The Spire modules are mounted on the south-facing roofs of the homes. Sunny Boy inverters are located near the electrical panel in the basement.

Lighting

Most fixed lighting in the homes is fluorescent. Overhead fixtures in the kitchen, dining rooms, and bathrooms are fluorescent, and recessed cans all contain compact fluorescent lamps (CFLs).

Energy Modeling and Benchmark Analysis

Energy modeling – primarily using Energy Gauge USA – predicted a total energy savings of 33% for these homes, compared to the Benchmark. The modeled savings rose to 38% when energy from the solar electric systems was factored in. Most of the savings was achieved by reducing the space-heating loads, by upgrading both the building envelope and the equipment efficiency. A review of the utility bills found that the expected heating energy use closely matched the actual use.

Modeling predicted the following energy use:

- Space heating: 424 therms/year
- Cooling: 2017 kWh/year
- Water heating: 218 therms/year
- Lighting, appliances, and misc. electric loads: 6910 kWh/year.

Lessons Learned

In all homes using forced air for heating and cooling, CARB strongly recommends the use of air handlers with ECM-driven fans. Such air handlers generally consume nearly 200-250 Watts. Furnaces in this home, while very efficient in burning gas, consumed between 700 and 800 Watts. This led to staggering electricity consumption, especially in the homes where central air handlers were used for fresh air ventilation.

The HVAC contractor informed CARB that the incremental cost for more electrically efficient furnaces would be approximately $1,000. This was not possible with the project's budget. But even when the furnaces provide heating alone (no cooling or ventilation), an efficient fan could save homeowners $75-$100 each year. An efficient air handler fan is absolutely essential when part of an efficient, whole-house ventilation system.

Awards

In part because of the efficiency and green features of these homes, the "New Homes for South Chicago" project received Chicago's 2005 award for "Outstanding Non-Profit Neighborhood Real Estate Project." More information on the award is available at:

http://www.lisc-cnda.org/2005.php?recipient=claretian

Development:	**Foothills at Wingfield**
Builder:	**D.R. Horton**
Location:	**Reno, Nevada**

D.R. Horton has constructed a Building America development aimed at achieving overall energy savings of 30%. This builder is responsible for Sierra Valley Oaks, the 30% community of 2004. A total of 165 Building America homes will be constructed. The switch to a Cold Climate in Reno created new design issues to overcome (Figure 30).

The homes are designed with high levels of insulation in the walls, using the R-23 Optima blown cellulose in 2x6 framing and with high-performance vinyl windows. The air handler and ductwork are located in conditioned space and outside ventilation is provided.

This development is unique because it is the first DR Horton development in Reno, Nevada, with slab-edge insulation. Figure 31 is a picture of the detail for the insulation.

Figure 30. From left to right, the Foothills at Wingfield Models, Plans 1, 2, 3, and 4

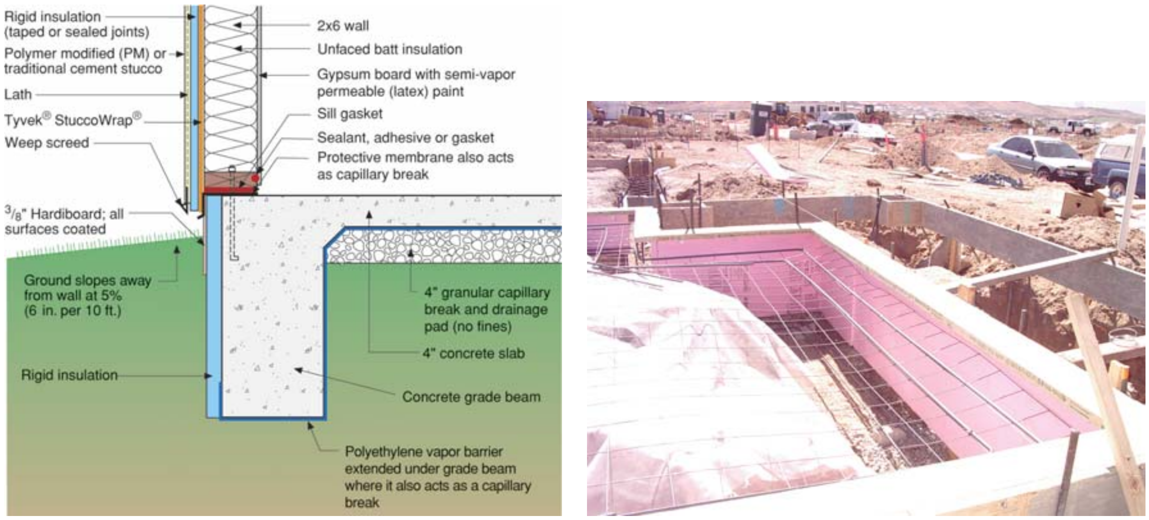


Figure 31. Slab-edge insulation detail

This insulation should protect the slab from cold temperatures and will lower heating costs for the development. The exterior configuration with the monolithic pour was an economical strategy for DR Horton to insulate their slabs. The photos below show the sheet-metal protection for the finished product (Figure 32).

Initially, there was some confusion with regards to the sequencing of the slab-edge construction. Concern was raised as to the vulnerability of the exposed XPS getting destroyed on-site before the pour. There is a possibility that a design may be implemented in future developments that has the XPS installed on top of the slab below a sub-floor to further simplify the construction process.

Figure 32. Edge insulation properly protected with sheet metal

Energy Analysis

Energy consumption simulations were done for each of the floor plans to compare the total end-use energy-consumption reduction of the prototype characteristics to the Benchmark. The energy analyses were completed using EnergyGauge USA USRRPB v 2.42 modeling software. The prototype models were based on the design criteria in Table 13.

Table 13. Foothills at Wingfield Building Characteristics

Building envelope	
Ceiling	R-38 Insulsafe 4 flat attic blown fiberglass
Walls	R-23 Optima 16 o.c. 2X6 walls + 1-in. R-4 EPS Stucco
Frame Floors	R-30 Insulsafe 4 flat attic blown fiberglass
Foundation	Slab, R-10 2-in. XPS on perimeter
Windows	Milgard Classic Vinyl Spectrally Selective LoE2
	Weighted Average U = ~0.35, SHGC = ~0.33
Infiltration	2.5 in.^{2} leakage area
	per 100 ft^2 envelope
Mechanical systems	
Heat	Sealed-combustion 92% AFUE gas
	furnace in conditioned space (closet)
Cooling	12 SEER split system in conditioned space
DHW	0.62 EF 50-gallon gas water heater in garage
Ducts	R-4.2 flex runouts in dropped ceiling or in floor joists
Leakage	none to outside (5% or less)
Ventilation	Aprilaire VCS 8126 Supply-only system integrated with AHU
	33% Duty Cycle: 10 minutes on; 20 minutes off
	60-80 CFM continuous average flow
Return Pathways	Transfer grilles/jump ducts at bedrooms

Table 14. Foothills at Wingfield Source Energy-Use Summary

Plan Number	Annual Energy Use Benchmark (10^6 Btu/y)r	Annual Energy Use Prototype (10^6 Btu/yr)	Percent Savings (%)
1	222	148	33%
2	246	159	35%
3	274	177	35%
4	329	207	37%

The results of the source-energy consumption reduction analyses are highlighted in Table 14

The average reduction was 35% over the Benchmark for the community.

In addition, a series of parametric changes were applied to Plan 1 to see how each change from the Benchmark affected the overall source energy use reduction.

The incremental parametric changes done in the simulation (EnergyGauge USA USRRPB v 2.42) are described below. The abbreviation IOSEU is used to replace "incremental overall source energy use." A negative value reflects an increase in energy use, and a positive value reflects a decrease (Figure 33 and Table 15).

1. **Benchmark:** This step applies the Benchmark criteria to the floor plan used in the energy simulation. The energy consumption result is used as the basis for comparison for the rest of the parametric study.
2. **Envelope, Window Configuration Changes:** The Benchmark basis the window areas of the house on 18% of the finish floor area. The distribution of the windows on each elevation is based on the same ratio of window distribution of the prototype house. This step resets the window configurations back to the prototype design. The resultant IOSEU was -0.2%.
3. **Overhangs:** Overhangs and shading devices were added back into the design. There was a negligible energy savings from this step. The resultant IOSEU was 0.0%.
4. **Upgrade to Vinyl LoE windows U = 0.35, SHGC = 0.33:** The windows used in the project were very similar in efficiency compared to the Benchmark. The resultant IOSEU was 0.1%.
5. **Increase ceiling insulation from R-36 to R-38:** The increase in insulation level from the Benchmark was fairly small, resulting in a small energy savings. The resultant IOSEU was 0.3%.

6. **Increase wall insulation from R-17.5 to R-27:** Optima blown cellulose insulation, 2x6 wall construction, and exterior rigid insulation sheathing was used on this project. The resultant IOSEU was 3.6%.
7. **Air tightness:** the Building America air tightness goal of 2.5 square inches per hundred square feet of envelope area was applied to the prototype model. The resultant IOSEU was 6.8%.
8. **Ducts inside and duct leakage to 5%:** All the ducts were moved into the interior of the conditioned space. This reduces the amount of duct leakage potential to the outside. The resultant IOSEU was 12.6%.
9. **12 SEER air conditioner:** The air-conditioner efficiency was upgraded from 10 SEER to 12 SEER. Because of the relatively low air-conditioning load, only a small energy savings was realized. The resultant IOSEU was 0.3%
10. **92% Furnace:** The furnace was upgraded to a 92% sealed-combustion condensing furnace. The resultant IOSEU was 4.2%.
11. **0.62 EF Water Heater:** The water heater was upgraded to a 0.62 EF gas water heater located in the garage. The resultant IOSEU was 2.1%.
12. **Best Electric Appliances:** High-efficiency appliances were used in the energy analysis. The resultant IOSEU was 2.4%.

The total energy savings over the Benchmark was 32.3%. The results of the energy consumption analyses are highlighted Tables 16, 17, 18, and 19.

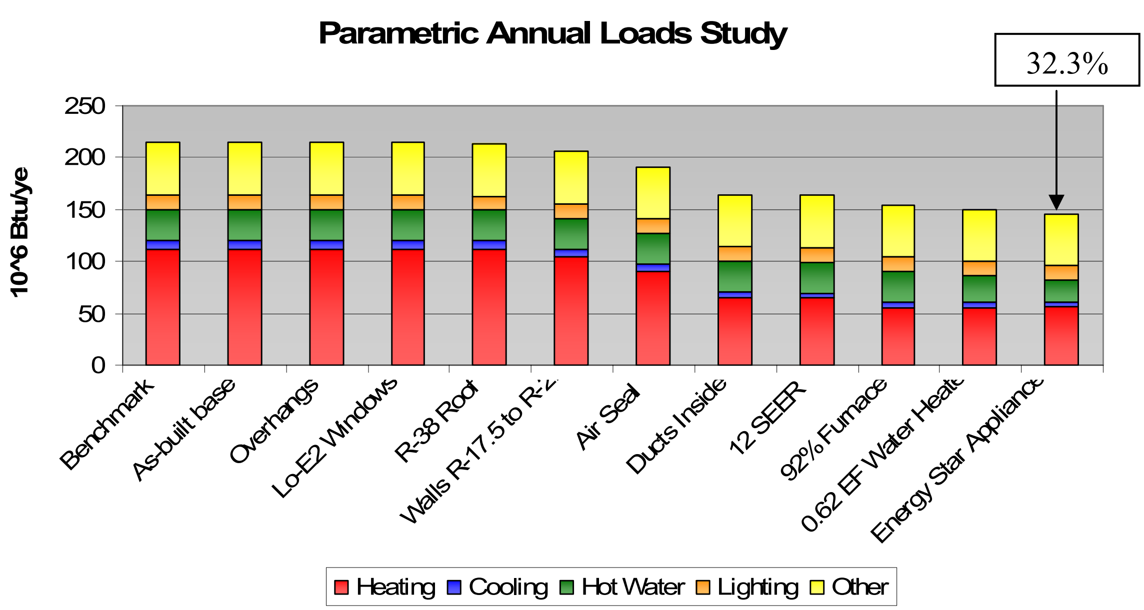


Figure 33. Foothills at Wingfield effects of incremental improvement steps

Table 15. Foothills at Wingfield Parametric Analysis Results

Description of change	Total Source Energy Savings (H/C/DHW/Lights/Appliances/Plug) Over BA Benchmark[1]	Incremental Over Benchmark	Annual Energy Cost	Item Savings
Benchmark	n/a	n/a	$1,291	n/a
Envelope, window configuration changes	-0.2%	n/a	$1,294	n/a
Overhangs	-0.2%	0.0%	$1,293	($2)
Upgrade to vinyl LoE windows U = 0.35, SHGC = 0.33	0.0%	0.1%	$1,290	$3
Increase ceiling insulation from R-36 to R-38	0.3%	0.3%	$1,285	$5
Increase walls from R-17.5 to R-27	3.9%	3.6%	$1,248	$37
Air seal	10.7%	6.8%	$1,180	$68
Ducts inside and duct leakage to 5%	23.3%	12.6%	$1,045	$135
12 SEER	23.7%	0.3%	$1,038	$7
92% Furnace	27.9%	4.2%	$999	$39
0.62 EF Water Heater	30.0%	2.1%	$980	$19
Best electric appliances	**32.3%**	2.4%	$948	$32

Table 16. Foothills at Wingfield Plan 1 Building America Benchmark Performance Report

Summary of End-Use Site-Energy

End-Use	Annual Site Energy: BA Benchmark kWh	BA Benchmark therms	BA Prototype kWh	BA Prototype therms
Space Heating	766	925	455	436
Space Cooling	789	0	425	0
DHW	0	251	0	182
Lighting*	1716		1716	
Appliances + Plug	3768	99	3598	99
OA Ventilation**				
Total Usage	7039	1275	6195	716
Site Generation	0	0	0	0
Net Energy Use	7039	1275	6195	716

Summary of End-Use Source-Energy and Savings

End-Use	Estimated Annual Source Energy: Benchmark 10^6 BTU/yr	Proto 10^6 BTU/yr	Source Energy Savings: Percent of End-Use Proto savings	Percent of Total Proto savings
Space Heating	117	56	**52%**	**27%**
Space Cooling	8	4	**46%**	**2%**
DHW	30	21	**28%**	**4%**
Lighting*	18	18	**0%**	**0%**
Appliances + Plug	50	49	**3%**	**1%**
OA Ventilation**	0	0	**0%**	**0%**
Total Usage	222	148	**33%**	**33%**
Site Generation	0	0		0%
Net Energy Use	222	148	33%	33%

Table 17. Foothills at Wingfield Plan 2 Building America Benchmark Performance Report

. Summary of End-Use Site-Energy

End-Use	Annual Site Energy: BA Benchmark kWh	BA Benchmark therms	BA Prototype kWh	BA Prototype therms
Space Heating	858	1039	490	458
Space Cooling	928	0	462	0
DHW	0	251	0	182
Lighting*	1934		1934	
Appliances + Plug	4343	99	4178	99
OA Ventilation**				
Total Usage	8062	1390	7064	738.75
Site Generation	0	0	0	0
Net Energy Use	8062	1390	7064	738.75

Summary of End-Use Source-Energy and Savings

End-Use	Estimated Annual Source Energy: Benchmark 10^6 BTU/yr	Proto 10^6 BTU/yr	Source Energy Savings: Percent of End-Use Proto savings	Percent of Total Proto savings
Space Heating	131	59	**55%**	**29%**
Space Cooling	10	5	**50%**	**2%**
DHW	30	21	**28%**	**3%**
Lighting*	20	20	**0%**	**0%**
Appliances + Plug	56	54	**3%**	**1%**
OA Ventilation**	0	0	**0%**	**0%**
Total Usage	246	159	**35%**	**35%**
Site Generation	0	0		0%
Net Energy Use	246	159	35%	35%

Table 18. Foothills at Wingfield Plan 3 Building America Benchmark Performance Report

. Summary of End-Use Site-Energy

	Annual Site Energy			
	BA Benchmark		BA Prototype	
End-Use	kWh	therms	kWh	therms
Space Heating	911	1088	510	460
Space Cooling	1566	0	812	0
DHW	0	279	0	201
Lighting*	2219		2219	
Appliances + Plug	5164	105	4975	105
OA Ventilation**				
Total Usage	9860	1472	8516	765.5
Site Generation	0	0	0	0
Net Energy Use	9860	1472	8516	765.5

Summary of End-Use Source-Energy and Savings

	Estimated Annual Source Energy		Source Energy Savings	
			Percent of End-Use	Percent of Total
	Benchmark	Proto	Proto savings	Proto savings
End-Use	10^6 BTU/yr	10^6 BTU/yr		
Space Heating	137	59	**57%**	**28%**
Space Cooling	16	8	**48%**	**3%**
DHW	33	24	**28%**	**3%**
Lighting*	23	23	**0%**	**0%**
Appliances + Plug	65	63	**3%**	**1%**
OA Ventilation**	0	0	**0%**	**0%**
Total Usage	274	177	**35%**	**35%**
Site Generation	0	0		0%
Net Energy Use	274	177	35%	35%

Table 19. Foothills at Wingfield Plan 4 Building America Benchmark Performance Report

. Summary of End-Use Site-Energy

	Annual Site Energy			
	BA Benchmark		BA Prototype	
End-Use	kWh	therms	kWh	therms
Space Heating	1121	1339	616	550
Space Cooling	1997	0	911	0
DHW	0	312	0	220
Lighting*	2589		2589	
Appliances + Plug	6204	111	6003	111
OA Ventilation**				
Total Usage	11911	1762	10119	880.5
Site Generation	0	0	0	0
Net Energy Use	11911	1762	10119	880.5

Summary of End-Use Source-Energy and Savings

	Estimated Annual Source Energy		Source Energy Savings	
			Percent of End-Use	Percent of Total
	Benchmark	Proto	Proto savings	Proto savings
End-Use	10^6 BTU/yr	10^6 BTU/yr		
Space Heating	169	71	**58%**	**30%**
Space Cooling	20	9	**54%**	**3%**
DHW	37	26	**29%**	**3%**
Lighting*	27	27	**0%**	**0%**
Appliances + Plug	77	75	**3%**	**1%**
OA Ventilation**	0	0	**0%**	**0%**
Total Usage	329	207	**37%**	**37%**
Site Generation	0	0		0%
Net Energy Use	329	207	37%	37%

*Lighting end-use includes both interior and exterior lighting
**In EGUSA there are currently no hooks to disaggregate OA Ventilation

Table 20 shows the energy bill guarantee for the various floor plans.

Table 20. Energy Bill Guarantee Summary for Foothills at Wingfield Models

Plan Name	Energy Star	Annual Cost	Monthly Cost	MMBtu Heating	MMBtu Cooling	Heating	Cooling
Plan 1	89.2	$491	$41	41.3	4.0	413 therms	1172 kWh
Plan 2	89.4	$542	$45	46.6	4.0	466 therms	1172 kWh
Plan 3	90.0	$597	$50	49.7	5.0	497 therms	1465 kWh
Plan 3 Bed 6	89.7	$676	$56	54.7	6.2	547 therms	1817 kWh
Plan 4	89.9	$682	$57	57.1	5.6	571 therms	1641 kWh
Plan 4 Bed 6	89.7	$684	$57	56.3	5.9	563 therms	1729 kWh

Development:	**Summerset at Frick Park**
Builder:	**A. Richard Kacin Inc.**
Location:	**Pittsburgh, Pennsylvania**
Founded:	**1960**
Employees:	**30**
Size:	**Three bedrooms, three bathrooms**
Square Footage:	**1,815**
Price Range:	**$310,000 - $360,000**

As a builder in the Summerset at Frick Park community in Pittsburgh, Pennsylvania, Kacin Inc. has benefited from learning how to build energy-efficient, durable, and comfortable homes. Summerset's performance standards require the homes to achieve the Environmental Protection Agency (EPA) ENERGY STAR® level of energy efficiency and to meet quality-control objectives related to house durability, occupant comfort, and occupant health and safety. To manage the learning curve involved, Kacin has worked with Building America team member IBACOS since 2001 to understand the standards and to become proficient at implementing the innovative construction practices necessary to achieve the performance goals set forth in the standards. As a result, all of Kacin's homes in the community's first phase of construction meet the standard.

Demand for the first 52 homes to be built was so strong that a lottery was held in which all the homes were sold within 1 hour and 15 minutes. For the second-phase lottery, more than 400 buyers signed up for a chance to buy one of 65 homes. In addition to strong sales, Kacin has built a reputation of building high-performance homes, which gives them an edge in the competitive Pittsburgh marketplace.

Kacin Inc. didn't want to rest on their laurels, though. In the second phase of construction at Summerset, Kacin was interested in researching what greater levels of energy efficiency could be achieved at a cost-effective level. Kacin and IBACOS chose to build a pilot home to research cost-effective energy-efficient construction. The pilot home is a two-story building, with a two-car attached garage in the rear and a porch on the front. The house is built on a crawl space foundation and has 1,815 ft^2 of living space. It has three bedrooms (one on the first floor), three bathrooms, 10-ft first-floor ceilings, and 9-foot second-floor ceilings.

Figure 44. The front of the Kacin Construction pilot home faces southeast. Fiber-cement siding covers the exterior walls of the house not pictured. The attached garage is at the rear.

Innovations

The pilot home (Figure 44) was built to achieve a minimum of 40% savings in total energy using three primary system strategies: improve the thermal performance of the building enclosure; use high performance equipment to handle space heating, domestic hot water, and mechanical ventilation; and install high efficiency lighting and appliances .

To achieve these strategies, this pilot home featured several advanced systems that Kacin Construction had seldom or never before implemented in the field. These included high-density fiber-glass insulation within exterior walls; practices to enhance building-enclosure airtightness even further; a high efficiency tankless hot water heater system; energy efficient lighting; and a balanced heat-recovery mechanical-ventilation system. In addition, Kacin was already familiar with many energy efficiency practices and technologies, including the following:

- Building an unvented and conditioned crawl space with foundation walls insulated on the inside with R-10 fiber glass insulation with a perforated facing and R-3 semi-rigid fiberglass insulation board on the exterior face (to grade) (Figure 45).
- Increasing building airtightness through draft-stopping and careful air sealing around penetrations
- Installing R-5 insulating sheathing on exterior walls to improve wall airtightness, thermal performance, and durability
- Using high efficiency heating and cooling equipment (Figure 46)
- Increasing the performance of the air-distribution system.

The Bottom Line

Kacin Inc. has been committed to building energy-efficient, high-performance homes because they realize the value to customers and to their business. They chose to partner with the Building America Program initially to meet Summerset's performance standards, but didn't want to stop there. Through the construction of this pilot home, they've been able to research cost-effective measures to continue to build high-quality homes. By following the specifications for this pilot home, a homeowner may realize $387 or 22% in energy savings over other homes in Summerset. With respect to the Benchmark, energy savings are 38% and energy cost savings are $915.

Figure 45. Once the HVAC subcontractor recognized the need to condition the crawl space, a register in the main trunk line was put in. This register was sealed up because it had the potential to divert too much air to the crawl space,, and a ducted register was installed in a more central location in the crawl space.

Figure 46. Over-cabinet (fluorescent) and under-cabinet (halogen) lighting was used at the Kacin Construction project. Cove lighting, consisting of strip fluorescent lamps and recessed downlights with CFLs, were used in the adjacent dining room.

Key Features

- Unvented, conditioned crawl space. The crawl space (block) walls were insulated to-grade on the exterior with R-3 semi-rigid fiber glass insulation. On the inside R-10 fiber glass insulation batts with a perforated-vinyl facing cover the full height of the wall
- R-38 attic insulation
- Exterior walls consist of 1 in. (R-5) extruded polystyrene insulating sheathing with joints taped; 2x4 framing at 16 in. centers; R-15 kraft-faced fiber glass insulation batts in cavities; and drywall finish. Band joists are insulated with R-15 unfaced fiber glass insulation batts in cavities.
- Long-term durability of the wall system was enhanced with a continuous drainage plane to shed water, which was created by taping the joints of the insulating sheathing and using flexible-flashing membrane around window and door rough openings.
- To improve building airtightness, a great deal of emphasis was placed on draft-stopping large holes to ensure air-barrier continuity. In particular, draft-stopping was conducted at exterior

wall locations where there was normally no drywall, such as behind tubs and at the fireplace. The numerous penetrations through the enclosure were sealed as well, particularly those connected to the attic and the crawl space.

- Windows are wood-framed, double-glazed, argon-filled units (U = 0.33, SHGC = 0.31).
- The high efficiency mechanical equipment consists of a 93% AFUE, direct-vent natural gas furnace with 60,000 Btu/h input and a 13 SEER (nominal) condensing unit. The cooling system uses Carrier's Puron minimal ozone depleting refrigerant and has a 2.5-ton capacity.
- A direct-vent gas tankless (EF = 0.82) hot water system was used. A hot-water recirculation system was installed to reduce time waiting for hot water.
- The entire air-distribution system is fully ducted and within conditioned space. The furnace is located horizontally in the conditioned crawl space. Ductwork serving the second floor travels through first-floor interior walls to floor and high wall register locations on the second floor. A fully ducted return system draws air from each floor and each bedroom. The basement is fully conditioned. Ductwork was sheet metal and sealed with UL 181-approved water-based mastic sealant.
- The results from the final duct-tightness test are 450 cfm total system leakage. The ductwork associated with ERV was included to permit testing. Of the 450 cfm total duct leakage, 30 cfm of the leakage was to the outside. The total amount of air leakage exceeded the target value of 100 cfm, but the air leakage to the outside target of 30 cfm was met.
- The pilot home has an airtightness value of 3.8 ACH at 50 Pa, which is approximately equivalent to an average annual natural infiltration rate of 0.27 ACH. The airflow induced by the blower door at 50 Pa was 1555 cfm.
- A heat-recovery ventilator provides balanced mechanical ventilation. The system runs continuously, drawing outdoor air that is mixed with return air that draws from the second floor. The treated air then enters a main return air trunk before being distributed throughout the house.
- A total of 69% of all hard-wired indoor lighting in the home is from fluorescent fixtures—compact and linear.
- Major appliances meeting ENERGY STAR® requirements were installed.

Estimated savings for different advanced system design improvements to the pilot home with respect to the builder standard are noted in Tables 22 and 23. Energy costs are based on Duquesne Light Company average rate for electricity of $0.0876/kWh and Equitable Gas average rate for natural gas of $1.158/therm.

By following the specifications for the pilot home a homeowner may realize $387 or 22% in energy savings. A discussion on the costs of different advanced system improvements follows.

Table 22. Energy Simulation Results: Summary of Predicted End-use Site Energy for the Kacin Construction Project

	Annual Site Energy					
	BA Benchmark		Builder Standard Home		Pilot Home Design	
End-Use	kWh	Therms	kWh	Therms	kWh	Therms
Space Heating	843	1016	694	602	563	460
Space Cooling	1101	0	797	0	625	0
DHW	0	215	0	208	0	99
Lighting	1876	0	1876	0	1173	0
Appliances	1206	98	1206	98	1096	98
Subtotal	**5026**	**1329**	**4572**	**908**	**3457**	**657**
Plug Loads	3412	0	3412	0	3412	0
Total Usage	**8438**	**1329**	**7984**	**908**	**6869**	**657**

Table 23. Summary of Estimated End-use Source Energy for the Kacin Construction Project

End-Use	Annual Source Energy			Estimated Source Energy Savings			
				Percent of End Use		Percent of Total	
	BA Benchmark (Mbtu)	Builder Standard (Mbtu)	Pilot Home (Mbtu)	BA Benchmark	Builder Standard	BA Benchmark	Builder Standard
Space Heating	113	69	53	53%	23%	26%	9%
Space Cooling	12	9	7	43%	22%	2%	1%
DHW	22	21	10	54%	52%	5%	6%
Lighting	20	20	13	37%	37%	3%	4%
Appliances	23	23	22	5%	5%	1%	1%
Subtotal	**190**	**142**	**104**	**45%**	**27%**	**38%**	**21%**
Plug Loads	37	37	37	0%	0%	0%	0%
Total Usage	**227**	**179**	**141**	**38%**	**21%**	**38%**	**21%**

Appendix A: Passive Solar Design Considerations

There are three primary passive design systems: direct gain, indirect gain, and sunrooms.

Direct Gain. In direct gain (Figure A-1), the sun shines directly into the house through windows, skylights, and clerestories. Depending on the amount and orientation of glazing, thermal mass materials may be needed to be incorporated in walls and floors to absorb the solar radiation and re-release it during the evening. Direct gain can also utilize a strategy called "sun tempering" where glazing is favored on the south side, but limited so that additional thermal mass is not necessary to prevent overheating of south-facing rooms.

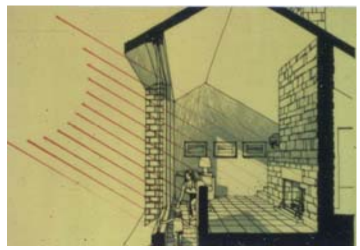


Figure A-1. Direct Solar Gain

Indirect Gain. Indirect gain (Figure A-2), also called thermal storage wall and Trombe Wall, consists of a thermal mass wall, with direct southern exposure. For example, a thermal storage wall could be a poured-in-place concrete wall or a concrete masonry block wall with the cores filled with concrete. One or more panes of glazing are located immediately on the outside of these mass walls. The outside surface of the mass wall is painted a dark color or coated with a selective surface, such as those used in active solar collectors.

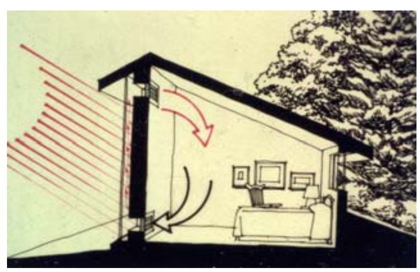


Figure A-2. Indirect Solar Gain

Sunroom. Passive solar sunrooms (Figure A-3) can either be isolated or open to the rest of the home. Because of the large areas of glass, it is usually recommended that they include doors and windows that can be closed to isolate them from the rest of the house. In this configuration, the temperature in the sunroom can be permitted to go higher and lower than would be permitted within the home.

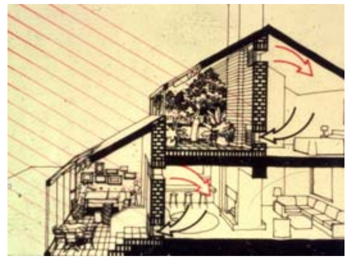


Figure A-3. Passive Solar Gain

To optimize the solar design of the house, which includes size of aperture, glazing performance characteristics (U-value and SHGC), by orientation, inclusion of mass, and house configuration, it is recommended that detailed energy simulations be undertaken. In general, if passive solar design is to be implemented, the following issues should be addressed, in the following order of importance:

- Site planning to allow for optimizing house orientation
- Orienting the house to optimize solar gains for heating and limiting solar gains during the cooling season. Simply by orienting homes with longer sides with larger glazing areas facing north-south helps to minimize unwanted heat gain in summer and maximize beneficial solar heat gains in winter (Figure A-4).

Builders seeking to optimize individual home and lot orientation can follow these guidelines.

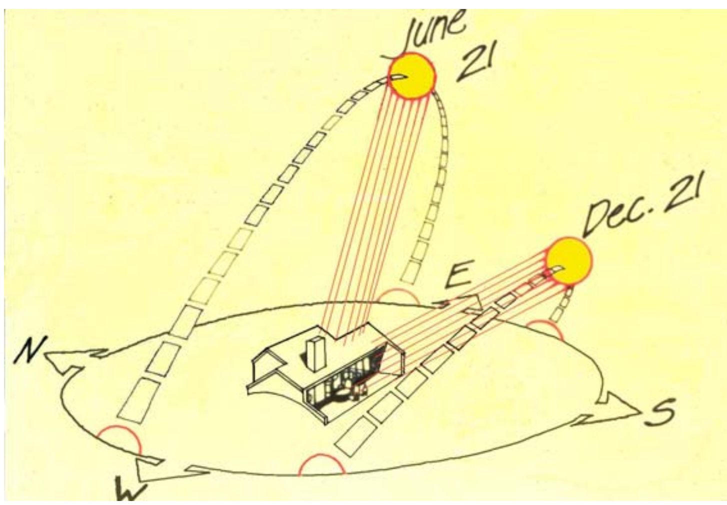


Figure A-4. The paths of the sun in winter and summer over a home with long sides facing north and south

- **Minimize East and West Glazing.** Orienting homes so that the sides with the least glazing face east and west can significantly reduce cooling loads and reduce glare. Typically, afternoon sun shining in west windows is most important to minimize or to shade.
- **North-South Orientation.** Having the longer sides of homes facing north-south is beneficial for reducing both heating and cooling loads. In Cold Climates, having more glazing face south with adequate shading can minimize cooling and heating loads significantly; however,

this must be carefully designed to prevent overheating and comfort complaints. South windows can most easily be shaded with overhangs.

- **Architectural Design.** Shape the architectural form and solar apertures of the houses to optimize passive solar heating, including appropriate mass to avoid localized overheating, and summertime shading to mitigate cooling loads. This is best done in conjunction with hourly energy and room-temperature modeling to assure energy savings and occupant comfort. Passive designs typically employ increased use of dense materials like concrete-slab floors with tile and increased thickness of drywall or interior brick or concrete walls that have high conductivity to heat and high heat capacities. The increased mass can be as simple as replacing carpeted floors with inexpensive tile floors in slab-on-grade construction. If mass materials are warmed by winter sun and cooled with night ventilation systems in summer, they can add to comfort and reduce use of and consumption by conventional heating and cooling systems.
- **Night Cooling:** Locate openings to optimize airflow during temperate conditions and to facilitate "night flushing" of heat built up over the day during the relatively cooler evening hours.

Passive design may have a significant impact on the architectural character of the house and may be viewed in a positive or negative manner by builders and homebuyers. Passive strategies may be pursued as a trade-off for other energy improvements; however, careful consideration of occupant comfort must be taken into account. Effective passive solar heat gain can be very beneficial during the heating season, but it is challenging to design well and requires proper linkage of aperture and thermal storage in order to be useful and to avoid discomfort. Overheating is a significant problem. Passive cooling, both by window shading and glass transmission characteristics, is very beneficial during the cooling season. Window shading can be very effective, but its proper design is critical, and the shading elements may have a strong visual impact on the exterior of the house. Thus, it is not a strategy that is thought to be universally appropriate at the 30% improvement level. For more information on passive design strategies, see the Passive Solar Industries Council's passive solar design guidelines.[64]

Architectural Shading Considerations. Shading, like orientation, is not required to achieve 30% savings, particularly with low-SHGC glazing. However, studies have shown that shading can cut solar heat gain by anywhere from 10% to 50%. Blocking the sun's rays from striking glazing areas and heating up a home is much more efficient than using air conditioning to cool down an already overheated house.

"Architectural shading" is simple, does not need any maintenance, and may reduce costs compared to sophisticated shading devices. Incorporating shading methods into the home during the design phase ensures that a home receives the most effective shading. For example, providing properly designed overhangs shading the south glass adequately can reduce the heat gain during the summers while allowing for heat gain during the winters. Shading the west glass can also minimize the unwanted heat gains. A wide range of shading options is available, including the following:

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[64] Sustainable Building Industries Council. *Passive Solar Design Strategies: Guidelines for Home Building.* Sustainable Building Industries Council Website: www.psic.org.

- **Overhangs on South Sides.** Extending the roofline a few feet can create shade for a home's south-facing windows. Because sun angles drop in the winter months, south-facing overhangs will let the warming sun into the home when it is needed. Because of low sun angles in summer mornings and afternoons, overhangs on the east or west have little to no affect. Shades for east- or west-facing windows must have some vertical dimension, such as awnings or shade screens.
- **Decks and Porches.** Adding a covered deck or porch is an excellent way to shade a home and to add living space, too. Porches and covered decks should have enough of an overhang to shield the area from the high sun and still offer a view outside from the interior spaces.
- **Awnings.** Awnings provide excellent shading for south-, east-, and west-facing windows; awnings will block as much as 65% of the summer sun's heat (77% on an east- or west-facing window), but they have the disadvantage of blocking the top half of the view from the window and reducing ventilation when windows are opened. Retractable canvas awnings can overcome this problem to some extent because they can be extended only when they are needed. This is especially helpful in winter months, when occupants want to let the sun in to warm their home.
- **Louvers.** Exterior louvers are attractive because their adjustable slats control the level of sunlight entering the building and, depending on the design, can be manually adjusted from inside or outside. The slats can be vertical or horizontal. Louvers remain fixed and are attached to the exteriors of window frames. Careful attention to the louver angle can allow significant winter sun penetration whilst still excluding all sun in summer.
- **Exterior Shade Screens.** Retractable shade screens are a good choice for windows that receive direct sunlight. They work much like an inside window shade, except that they are attached to the outside of the window. Most shade-screen manufacturers offer automatic controls for these products. The screens are installed at the top of the window and can be lowered during sunny days and retracted when not needed. Shade screens are generally custom-made. They are a good choice for a homeowner who wants to retrofit for energy efficiency but still wants to see out of a window that gets lots of sun throughout the day. The downside of shade screens is that they can darken the view when pulled down.

Designing Shading Systems. The following design recommendations generally hold true for properly designed shading devices:

- Use fixed overhangs on south-facing glass to control direct-beam solar radiation. Indirect (diffuse) radiation should be controlled by other measures, such as low-e glazing.
- To the greatest extent possible, limit the amount of east and west glass because it is harder to shade than south glass. Consider the use of landscaping to shade east and west exposures, awnings, exterior shade screens, or interior highly reflective shades.
- Do not worry about shading north-facing glass because it receives very little direct solar gain.
- Shading effects daylighting; consider both simultaneously. For example, a light shelf bounces natural light deeply into a room through high windows while shading lower windows.

- Do not expect interior shading devices such as Venetian blinds or vertical louvers to reduce cooling loads because the solar gain has already been admitted into the work space. However, these interior devices do offer glare control and can contribute to visual acuity and visual comfort.
- An understanding of sun angles is critical to selecting shading devices.
- Carefully consider the durability of shading devices. Over time, operable shading devices can require a considerable amount of maintenance and repair.
- When relying on landscape elements for shading, be sure to consider the cost of landscape maintenance and upkeep on life-cycle cost.
- Shading strategies that work well at one latitude, may be completely inappropriate for other sites at different latitudes. Be careful when applying shading ideas from one project to another.

Appendix B: Detailed *BEopt* Analysis Results

Table B.1. BEopt Option Results for Single-Story Case

Category	Benchmark	35% Point	Neighbor 1	Neighbor 2	Neighbor 3	Neighbor 4	Neighbor 5	Next Point on Optimization Curve	39% Point
Walls	U = 0.052, 23% FF 2x6, R-19 batt, R-6 sheathing	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc + 2-in. polyiso (R-14)
Ceiling	U = 0.026, 11% FF, R-38.5	R40 FG	R-50 FG	R-30 FG	R-30 FG	R-30 FG	R-30 FG	R-40 FG	R-40 FG
Thermal Mass	8 lbs/ft^2 - furniture, standard light-frame construction	5/8-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall
Infiltration	SLA = 0.00057	SLA = 0.0003	SLA = 0.0005	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003
Basement	Wall U = 0.095, R-10	4-ft R-5 Exterior Insulation	8-ft R-10 Exterior Insulation	4-ft R-5 Exterior Insulation	4-ft R-5 Exterior Insulation	4-ft R-5 Exterior Insulation	4-ft R-5 Exterior Insulation	4-ft R-5 Exterior Insulation	8-ft R-10 Exterior Insulation

Table B.1. BEopt Option Results for Single-Story Case (continued)

Category	Benchmark	35% Point	Neighbor 1	Neighbor 2	Neighbor 3	Neighbor 4	Neighbor 5	Next Point on Optimization Curve	39% Point
Glass Type	U = 0.39, SHGC = 0.32	Two-pane, Low-e, U = 0.32, SHGC = 0.64 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.32, SHGC = 0.64 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC=0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.32, SHGC = 0.64 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame
Window Area per Wall	270 ft^2, Equal dist. On 4 sides	270 ft^2, 12.5% N&S, 50% W, 25% E	270 ft^2, 12.5% N&S, 50% W, 25% E	270 ft^2, 12.5% N&S, 50% W, 25% E	270 ft^2, 12.5% N&S, 50% W, 25% E	270 ft^2, 12.5% N&S, 50% W, 25% E	270 ft^2, 12.5% N&S, 50% W, 25% E	270 ft^2, 12.5% N&S, 50% W, 25% E	270 ft^2, 12.5% N&S, 50% W, 25% E
Refrigerator	669 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr
Cooking Range	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr
Dishwasher	206 kWh/yr, 5 gal DHW/day	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW
Clothes Dryer	Gas - 71.6 kWh/yr, 31.3 Therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 57.8 kWh/yr, 26.2 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr

Table B1 BEopt Option Results for Single-Story Case (continued)

Category	Benchmark	35% Point	Neighbor 1	Neighbor 2	Neighbor 3	Neighbor 4	Neighbor 5	Next Point on Optimization Curve	39% Point
Clothes Washer	105 kWh/yr, 15 gal/day	Standard, 3.15 ft^3, 533kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	ENERGY STAR, top loader, H-axis, 2.9 ft^3, 273 kWh/yr, 1.68 MEF, 72.9 kWh/yr machine energy, 3.71 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW
Lighting	14% CFL, 1574 kWh/yr Hard-wired, 331 Plug in	100% CFL, 439 kWh/yr Hard-wired, 331 Plug in	100% CFL, 439 kWh/yr Hard-wired, 331 Plug in	100% CFL, 439 kWh/yr Hard-wired, 331 Plug in	100% CFL, 439 kWh/yr Hard-wired, 331 Plug in	100% CFL, 439 kWh/yr Hard-wired, 331 Plug in	100% CFL, 439 kWh/yr Hard-wired, 331 Plug in	100% CFL, 439 kWh/yr Hard-wired, 331 Plug in	100% CFL, 439 kWh/yr Hard-wired, 331 Plug in
Air Conditioner	SEER 10, 0.55 W/CFM AH Fan	SEER 10, 2 Tons, 0.365 W/CFM AH Fan	SEER 10, 2 Tons, 0.365 W/CFM AH Fan	SEER 10, 1.5 Tons, 0.365 W/CFM AH Fan	SEER 10, 1.5 Tons, 0.365 W/CFM AH Fan	SEER 10, 1.5 Tons, 0.365 W/CFM AH Fan	SEER 14, 2 Tons, 0.383W/CFM AH Fan	SEER 10, 1.5 Tons, 0.365W/CFM AH Fan	SEER 10, 1.5 Tons, 0.365W/CFM AH Fan
Furnace	78% AFUE	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 50 kBtu/hr	92.5% AFUE, 50 kBtu/hr
Ducts	Basement, 5% AH fan flow leakage to the outside	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow
Water Heater	Gas, 40 gal, 0.54 EF, 0.76 RE	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF + 32 ft^2 ICS	Gas Tankless, 0.84 EF + 32 ft^2 ICS	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF

Table B.2. BEopt Energy and Savings Results for Single-Story Case

	Benchmark	35% Point	Neighbor 1	Neighbor 2	Neighbor 3	Neighbor 4	Neighbor 5	Next Point on Optimization Curve	39% Point
Energy End Use (MBtu/yr)									
Miscellaneous (E)	39.85	38.24	38.24	38.74	38.24	38.68	38.23	38.23	38.23
Lights (E)	16.13	6.34	6.34	6.34	6.34	6.34	6.34	6.34	6.34
Heating Fan (E)	5.26	2.73	2.61	3.28	3.28	3.28	3.00	2.75	2.39
Cooling Fan (E)	1.43	0.76	0.87	0.35	0.35	0.35	0.75	0.41	0.37
Cooling (E)	6.14	5.52	6.17	2.44	2.44	2.44	3.74	2.84	2.56
Heating (G)	87.50	47.10	45.20	55.50	55.50	55.50	49.00	47.20	41.50
Hot Water (G)	23.69	15.32	15.32	10.37	10.05	14.42	15.32	15.32	15.32
Miscellaneous (G)	9.79	8.10	8.10	8.10	8.10	7.47	8.10	8.10	8.10
Total	189.79	124.10	122.85	125.12	124.29	128.46	124.47	121.18	114.81

Table B.2. BEopt Energy and Savings Results for Single-Story Case (continued)

	Benchmark	35% Point	Neighbor 1	Neighbor 2	Neighbor 3	Neighbor 4	Neighbor 5	Next Point on Optimization Curve	39% Point
End Use Savings									
Miscellaneous (E)		4.0%	4.0%	2.8%	4.0%	2.9%	4.1%	4.1%	4.1%
Lights (E)		60.7%	60.7%	60.7%	60.7%	60.7%	60.7%	60.7%	60.7%
Heating Fan (E)		48.1%	50.4%	37.7%	37.7%	37.7%	43.0%	47.7%	54.5%
Cooling Fan (E)		46.5%	39.2%	75.5%	75.5%	75.5%	47.5%	71.3%	74.1%
Cooling (E)		10.2%	-0.5%	60.3%	60.3%	60.3%	39.2%	53.8%	58.3%
Heating (G)		46.2%	48.3%	36.6%	36.6%	36.6%	44.0%	46.1%	52.6%
Hot Water (G)		35.4%	35.4%	56.2%	57.6%	39.2%	35.4%	35.4%	35.4%
Miscellaneous (G)		17.2%	17.2%	17.2%	17.2%	23.7%	17.2%	17.2%	17.2%
Total Energy Savings		34.6%	35.3%	34.1%	34.5%	32.3%	34.4%	36.2%	39.5%

Table B.3. BEopt Option Results for Two-Story Case

Category	Benchmark	35% Point	Neighbor 1	Neighbor 2	Neighbor 3	Neighbor 4	Neighbor 5	Next Point on Optimization Curve	39% Point
Walls	U = 0.052, 23% FF 2x6, R-19 batt, R6 sheathing	R-19, 2x6, 24 in. oc	R-13, 2x4, 16 in. oc	R-19, 2x6, 24 in. oc	R-11, 2x4, 16 in. oc	R-19, 2x6, 24 in. oc + 1-in. polyiso (R7)	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc	R-19, 2x6, 24 in. oc
Ceiling	U = 0.026, 11% FF R-38.5	R-40 FG	R-40 FG	R-30 FG	R-50 FG	R-30 FG	R-40 FG	R-40 FG	R-40 FG
Thermal Mass	8 lbs/ft^2 - furniture, standard light frame construction	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall	Two ½-in. Ceiling Drywall Layers	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall	½-in. Ceiling Drywall
Infiltration	SLA = 0.00057	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003	SLA = 0.0003
Basement	Wall U = 0.095, R-10	4-ft R-5 Exterior Insulation	8-ft R-10 Exterior Insulation	4-ft R-5 Exterior Insulation	8-ft R-10 Exterior Insulation	4-ft R-5 Exterior Insulation	4-ft R-5 Exterior Insulation	4-ft R-5 Exterior Insulation	8-ft R-10 Exterior Insulation
Glass Type	U = 0.39, SHGC = 0.32	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.32, SHGC = 0.64 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e , U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame	Two-pane, Low-e, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, Vinyl frame
Window Area per Wall	540 ft^2, Equal distance on four sides	540 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E	540 ft^2, 12.5% N&S, 50% W, 25% E
Refrigerator	669 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr	Standard - 671 kWh/yr
Cooking Range	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr	45 Therms/yr

Table B.3. BEopt Option Results for Two-Story Case (continued)

Category	Benchmark	35% Point	Neighbor 1	Neighbor 2	Neighbor 3	Neighbor 4	Neighbor 5	Next Point on Optimization Curve	39% Point
Dishwasher	206 kWh/yr, 5 gal DHW/day	Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW	Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW	Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	ENERGY STAR, 384 kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	ENERGY STAR, 384kWh, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW
Clothes Dryer	Gas - 71.6 kWh/yr, 31.3 Therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr	Gas - 5.7 ft^3, 2.75 EF, 70.1 kWh/yr, 31.8 therms/yr
Clothes Washer	105 kWh/yr, 15 gal/day	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW
Lighting	14% CFL, 2534 kWh/yr Hard-wired, 571 Plug in	100% CFL, 707 kWh/yr Hard-wired, 571 Plug in	100% CFL, 707 kWh/yr Hard-wired, 571 Plug in	76% CFL, 1206 kWh/yr Hard-wired, 571 Plug in	100% CFL, 707 kWh/yr Hard-wired, 571 Plug in	14% CFL, 2534 kWh/yr Hard-wired, 571 Plug in	100% CFL, 707 kWh/yr Hard-wired, 571 Plug in	100% CFL, 707 kWh/yr Hard-wired, 571 Plug in	100% CFL, 707 kWh/yr Hard-wired, 571 Plug in
Air Conditioner	SEER 10, 0.55 W/CFM AH Fan	SEER 10, 3 Tons, 0.365 W/CFM AH Fan	SEER 13, 3 Tons, 0.365 W/CFM AH Fan	SEER 15, 3 Tons, 0.256 W/CFM AH Fan	SEER 13, 3 Tons, 0.365 W/CFM AH Fan	SEER 10, 3 Tons, 0.36 W/CFM AH Fan	SEER 10, 3 Tons, 0.365 W/CFM AH Fan	SEER 10, 3 Tons, 0.365 W/CFM AH Fan	SEER 15, 3 Tons, 0.256 W/CFM AH Fan
Furnace	78% AFUE	92.5% AFUE, 75 kBtu/hr	92.5% AFUE, 75 kBtu/hr	92.5% AFUE, 75 kBtu/hr	92.5% AFUE, 75 kBtu/hr	92.5% AFUE, 75 kBtu/hr	92.5% AFUE, 75 kBtu/hr	92.5% AFUE, 75 kBtu/hr	92.5% AFUE, 75 kBtu/hr
Ducts	Basement, 1.5% AH fan flow leakage to the outside	Inside Conditioned Space, SA leakage = 1%, OA leakage 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow
Water Heater	Gas, 40 gal, 0.54 EF, 0.76 RE	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF	Gas Tankless, 0.84 EF

Table B.4. BEopt Energy and Savings Results for Two-Story Case

	Benchmark	35% Point	Neighbor 1	Neighbor 2	Neighbor 3	Neighbor 4	Neighbor 5	Next Point on Optimization Curve	39% Point
Energy End Use (MBtu/yr)									
Miscellaneous (E)	67.94	66.83	66.33	66.85	66.33	66.84	66.33	66.33	66.32
Lights (E)	25.98	9.08	9.08	13.66	9.08	25.98	9.08	9.08	9.08
Heating Fan (E)	9.18	5.15	5.44	3.78	5.47	4.56	4.47	5.15	3.46
Cooling Fan (E)	4.81	1.59	1.66	1.08	1.43	1.72	3.09	1.59	1.10
Cooling (E)	20.59	11.20	9.30	7.64	8.00	12.09	22.29	11.20	7.80
Heating (G)	153.40	86.80	91.10	88.10	91.40	77.50	77.80	86.80	80.90
Hot Water (G)	23.69	15.75	15.32	15.75	15.32	15.75	15.32	15.32	15.32
Miscellaneous (G)	9.79	8.10	8.10	8.10	8.10	8.10	8.10	8.10	8.10
Total	315.38	204.50	206.33	204.95	205.12	212.54	206.48	203.56	192.08

Table B.4. BEopt Energy and Savings Results for Two-Story Case (continued)

	Benchmark	35% Point	Neighbor 1	Neighbor 2	Neighbor 3	Neighbor 4	Neighbor 5	Next Point on Optimization Curve	39% Point
End Use Savings									
Miscellaneous (E)		1.6%	2.4%	1.6%	2.4%	1.6%	2.4%	2.4%	2.4%
Lights (E)		65.1%	65.1%	47.4%	65.1%	0.0%	65.1%	65.1%	65.1%
Heating Fan (E)		43.9%	40.7%	58.8%	40.4%	50.3%	51.2%	43.9%	62.3%
Cooling Fan (E)		66.9%	65.4%	77.5%	70.3%	64.2%	35.8%	66.9%	77.0%
Cooling (E)		45.6%	54.8%	62.9%	61.2%	41.3%	-8.3%	45.6%	62.1%
Heating (G)		43.4%	40.6%	42.6%	40.4%	49.5%	49.3%	43.4%	47.3%
Hot Water (G)		33.5%	35.4%	33.5%	35.4%	33.5%	35.4%	35.4%	35.4%
Miscellaneous (G)		17.2%	17.2%	17.2%	17.2%	17.2%	17.2%	17.2%	17.2%
Total Energy Savings		35.2%	34.6%	35.0%	35.0%	32.6%	34.5%	35.5%	39.1%

BEopt Cost and Performance Input Assumptions

As with any analysis study, the results of the analysis are subject to the assumptions used during the study. The cost and performance assumptions used in the present study are documented in this Appendix. These assumptions will be updated on a regular basis as new information becomes available from residential field studies. The use of specific manufacturer names in this Appendix does not represent an endorsement or recommendation for use of a specific product. This Appendix is limited to categories that include multiple options specific to the optimizations performed and may not representative of all the possible options currently available within BEopt.

Table B.5. Utility and Onsite Power Inputs

Group	Input Variable	Value	Units
Economics	Electricity Source/Site Ratio	3	
	Electricity Cost	0.0771	$/kWh
	Natural Gas Cost	0.8044	$/therm
	Discount Rate	0.05	
	Mortgage Interest Rate	0.07	
	Marginal Income Tax Rate	0.28	
	Analysis Period	30	years
	Net Metered Excess Sellback Rate	Local electric rate	$/kWh
	Efficiency Cost Multiplier	1	
Photovoltaics	Module	Sharp NEH120E1	
	Installed Cost	7.5 (unless noted otherwise)	$/rated W
	Derate Factor	Determined by location	%
	Daily Incident Solar	Determined by location	kWh/m^2
	Average System Efficiency	Determined by location	%

Table B.6. BEopt Cost Assumptions

Category/Option	Unit Cost
Basement Insulation	**($/ft)**
Uninsulated	$0.00
4-ft R-5 Exterior	$1.68
4-ft R-10 Exterior	$3.08
8-ft R-10 Exterior	$6.16
8-ft R-15 Exterior	$8.96
8-ft R-20 Exterior	$9.84
Wall Construction	**($/ft^2)**
R-11 batts, 2x4, 16 in. oc	$3.15
R-13 batts, 2x4, 16 in.oc	$3.17
R-11 batts, 2x4, 16 in.oc + 1-in. foam sheathing	$3.92
R-19 batts, 2x6, 24 in. oc	$3.28
R-19 batts, 2x6, 24 in. oc + 1-in. foam sheathing	$4.05
R-19 batts, 2x6, 24 in. oc + 2-in. foam sheathing	$4.24
Ceiling Insulation	**($/ft^2)**
R-30 Fiberglass	$0.55
R-40 Fiberglass	$0.73
R-50 Fiberglass	$0.92
R-60 Fiberglass	$1.10

Table B.6. BEopt Cost Assumptions (continued)

Category/Option	Unit Cost
Thermal Mass	**($/ft^2)**
Standard ½-in. Ceiling Drywall	$0.19
5/8-in. Ceiling Drywall	$0.27
2 x ½-in. Ceiling Drywall	$0.38
2 x 5/8-in. Ceiling Drywall	$0.54
Infiltration	**($/ft^2)**
Typical (SLA = 0.0005)	$0.00
Tight (SLA = 0.0003)	$0.54
Windows	**($/ft^2)**
Two-pane clear, U = 0.49, SHGC = 0.76, Center of Glass, insulated spacer, vinyl frame	$21.99
Low-e (e = 0.01), double-pane, U = 0.32, SHGC = 0.64 Center of Glass, insulated spacer, vinyl frame	$24.77
Low-e (e= 0.1 w / tint), double-pane, U= 0.31, SHGC = 0.37, Center of Glass, insulated spacer, vinyl frame	$24.77
Low-e (e = 0.04), double-pane, U = 0.3, SHGC = 0.44 Center of Glass, insulated spacer, vinyl frame	$24.77
Low-e (e = 0.04 w / tint), double-pane, U = 0.29, SHGC = 0.29 Center of Glass, insulated spacer, vinyl frame	$24.77
Heat Mirror (HM22), U = 0.21, SHGC = 0.14, Center of Glass, insulated spacer, Vinyl frame	$30.32
Heat Mirror (HM TC88), U=0.18, SHGC=0.48, Center of Glass, insulated spacer, vinyl frame	$30.32

Table B.6. BEopt Cost Assumptions (continued)

Category/Option	Unit Cost
Refrigerator	**($/unit)**
Standard - 671 kWh/yr	$1,099.99
ENERGY STAR – 572 kWh/yr	$1,219.99
Dishwasher	**($/unit)**
Standard, 462 kWh, eight place setting capacity, 131.6 kWh/yr machine energy, 5.39 gal/day DHW	$239.00
ENERGY STAR, 384 kWh/yr, eight place setting capacity, 82.2 kWh/yr machine energy, 3.76 gal/day DHW	$299.00
Clothes Washer	**($/unit)**
Standard, 3.15 ft^3, 533 kWh/yr, 1.16 MEF, 65.6 kWh/yr machine energy, 4.63 gal/day DHW	$419.00
ENERGY STAR, top loader, H-axis, 2.9 ft^3, 273 kWh/yr, 1.68 MEF, 72.9 kWh/yr machine energy, 3.71gal/day DHW	$799.00
Lighting	**($/bulb)**
Incandescent	$0.25
CFL	$7.99

Table B.6. BEopt Cost Assumptions (continued)

Category/Option	Unit Cost
Air Conditioner SEER value	**Efficiency Cost ($) = 0.817*((186*SEERvalue)-1535)**
10	$265.53
12	$569.45
13	$721.41
14	$873.37
15	$1,025.34
16	$1,177.30
17	$1,329.26
18	$1,481.22
Air Conditioner Capacity (tons)	**Capacity Cost ($) = 0.817*(563*tons)**
0.5	$229.99
1.0	$459.97
1.5	$689.96
2.0	$919.94
2.5	$1,149.93
3.0	$1,379.91
3.5	$1,609.90
4.0	$1,839.88

Table B.6. BEopt Cost Assumptions (continued)

Category/Option	Unit Cost
Furnace Efficiency (% AFUE)	**Efficiency Cost ($) = (23.57*AFUE%*100)-1621**
80%	$264.60
92.5%	$559.23
Furnace Capacity (kBtu/hr)	**Capacity Cost ($) = 2.92*kBtu/hr**
25 kBtu/hr	$73.00
50 kBtu/hr	$146.00
75 kBtu/hr	$219.00
100 kBtu/hr	$292.00
125 kBtu/hr	$365.00
150 kBtu/hr	$438.00
175 kBtu/hr	$511.00
200 kBtu/hr	$584.00
Water Heater	**($/unit, install + equip)**
Gas Standard, 40 gallons, 0.55 EF	$428.00
Gas Premium, 40 gallon , 0.62 EF	$624.08
Gas Tankless, 0.84 EF	$1,050.00
Ducts	**($/ft^{2}FFA)**
Typical, SA leakage = 10%, OA leakage = 2.3% of fan flow	$0.45
Improved, SA leakage = 2.3%, OA leakage = 0.5% of fan flow	$0.69
Inside Conditioned Space, SA leakage = 1%, OA leakage = 0.23% of fan flow	$0.77

Appendix C. List of Key Trade-based Certifications

Preferred Contractors Program Draft

Below is a preliminary list of the different trade classifications and the sub-specializations that could be associated with a new-home certified contractors program. The concept is to have a broad range of specialist classifications, to acknowledge the fragmentation and specialization that is inherent in the construction industry. This encourages even those trades who do a very limited scope of work (i.e., just window installation or just duct rough in) to become certified specialists in their field, which requires them to also have a broader understanding of how that piece fits into the bigger house as a system. This concept will need to be discussed with manufacturers and trade contractors to determine its practicality.

1. HVAC
   A. Space-Conditioning System-Design Specialist
   B. Duct-Design Specialist
   C. Air-Distribution System-Installation Specialist
   D. Equipment-Installation and Start-up Specialist
      i. Fossil and electric heating
      ii. Refrigeration – AC / Heat Pump
   E. Airflow-Balancing Specialist
2. Carpentry
   F. Framing Specialist
3. Thermal envelope
   G. Insulation Specialist
   H. Air-sealing Specialist
4. Above-grade Moisture Management
   I. Window- and Door-Installation Specialist
   J. Wall-Drainage-Plane Specialist
   K. Roof-Drainage and Flashing Specialist
5. Below-grade Moisture Management
   L. Below-Grade Moisture-Management Specialist
6. Designers
   M. Architect / Residential Designer
   N. Engineer

Within each of the specializations is a more detailed description of the probable roles and competencies required.

1. HVAC
   - Space-Conditioning System-Design Specialist
     - Load-calculation, Ventilation, and Equipment-selection Specialist
       - Proficiency in ACCA Manual J method for load calculation and how to account for higher performance when calculating heating and cooling loads
       - Understands relationship between high-performance house (thermal-envelope strategies to achieve high-performance homes) and heating and cooling loads to be satisfied by the space-conditioning equipment
       - Surface-area competencies and understanding of thermal-envelope assemblies (i.e., framing factors, window properties, etc.)
       - Understands the types of ventilation systems and their interaction with the heating and cooling equipment
       - Understands dedicated humidity-control options and how to integrate with space-conditioning systems
       - Understands the internal gains and latent loads associated with people and ventilation
       - Understands the impact of climate, shading, and other environmental impacts on the building
     - Duct-Design Specialist
       - Understands the impact of duct friction with respect to airflows (equivalent length methods – ACCA Manual D)
       - Familiarity with structural systems and limitations regarding using running-duct systems within structural systems (floor framing systems, walls, etc.)
       - Air-distribution options in higher performance homes (high sidewall, central return, etc.)
       - Acoustics of air-distribution systems
   - Air-Distribution System-Installation Specialist
     - Follows layout by Duct-Design Specialist
     - Understands duct-dealing techniques
     - Understands ventilation-system concepts as they relate to ducts and equipment-installation issues
     - Certified in duct-system leakage testing
     - Sets furnace and inside AC coils as part of air system

- Equipment-Installation and Start-up Specialists
    - Installation of equipment and associated refrigeration
    - Start-up and commissioning of heating, cooling, and ventilation systems
- Airflow-Balancing Specialist
    - Airflow at the equipment
    - Total-system duct-leakage testing
    - Room-by-room airflow balancing and measurement

2. Carpentry
    - Framing Specialist
        - Optimum-value engineering of wood-frame structures
            - Stack framing
            - Wall layout and value-engineering wall-framing techniques
            - Floor framing and interaction with HVAC system and plumbing system
            - Structural and code limitations
    - Air-sealing techniques incorporated during framing (i.e., band-joist gluing and sealing, mud-sill sealing, cantilevers, floors over garages, chases, etc.)
3. Thermal envelope
    - Insulation Specialist
        - Insulation basics
        - How insulation works
        - Encapsulation requirements
        - Types of insulation products, limitations, and applications
        - Insulation and flame-spread issues
        - Blown-in wall techniques (new and retrofit)
        - Damp spray
        - Net and fill cavity
        - Two-hole method
        - Hole and tube (dense pack)
        - Blown attic and horizontal cavity (floor, cantilever, etc.)
        - Batt installation
        - Below-grade insulation systems (interior)
        - Crawl-space vapor-barrier installation

    - Sub-Specialist designation
- Air-Sealing Specialist
    - Envelope air-tightening techniques
    - Window and door rough openings
    - Framing intersections
    - Bypasses / chases / soffits
    - Cantilevers, floors over unconditioned spaces
    - Fire codes and safety
    - Diagnostics
    - Blower door
    - Pre- and post-testing
    - Blower-door directed air-sealing techniques
    - Infrared imaging
    - Pressure diagnostics

4. Above-grade Moisture Management
    - Window- and Door-Installation Specialist
        - Flashings
        - Integration to drainage plane
    - Wall-Drainage-Plane Specialist
        - Drainage-plane installation
        - Integration with windows and doors
        - Integration with roof-flashing systems
        - Roof-flashing systems at wall intersections
    - Roof-Drainage and Flashing Specialist
        - Roof-penetration flashings
        - Roof-wall flashing systems
        - Integration to wall systems
        - Gutter and downspouts

5. Below-grade Moisture Management
    - Below-Grade Moisture Management Specialist
        - Perimeter drainage systems
        - Sub-slab capillary break and vapor-diffusion control
        - Capillary break at footing
        - Vapor barrier at crawl spaces
        - Foundation damp-proofing systems
    - Foundation waterproofing systems
6. Designers
    - Architect / Residential Designer
    - Engineer

Appendix D: National Housing Quality Rating Table

Table D.1. Leadership

Leaders align everyone in the organization with a common purpose, values, and priorities.

	Level 1	Level 2	Level 3	IBACOS Level 3	Level 4	*IBACOS Level 4*	Level 5	*IBACOS Level 5*
1.1 Company Mission, Vision, and Values	Company's main quality goal is to avoid customer disappointment and complaints.	Quality and customer satisfaction is important to the company but not included in a written mission statement.	Written company mission statement includes a commitment to quality and customer satisfaction.	Quality is defined in the five key performance metrics (Health, Safety, Durability, Efficiency & Comfort) with measurable attributes associated with the definition.	In addition to level 3, values or principles important to the company are included in a written statement.	Performance metrics of competition is Benchmarked and three of five area exceed Benchmark industry standards	In addition to level 4, there is a compelling future vision of what the company can become.	Vision is created with stretch goals for all five performance metrics
1.2 Senior Management Involvement	Senior managers get involved with quality to handle customer complaints.	Senior managers like the idea of quality but are not involved in improvement activities.	Senior managers demonstrate personal commitment to the company's quality mission and are often involved in quality-related activities	Performance attributes are given equal weight to other quality criteria. Quality Management is a cross-cutting management function	Senior managers constantly communicate the company's quality mission to customers, employees, and trade contractors.	One point of contact for managing the performance attributes of the home from pre-design through warrantee. Goals of all Senior managers tied to achieving performance metrics	In addition to level 4, managers and supervisors at all levels are actively engaged in reinforcing the company mission, vision, and values.	All team members are reinforcing performance attributes at all phases and stages of product
1.3 Leadership Feedback and Improvement	Senior management uses their experience to guide the company toward their vision for the future.	Senior managers actively seek employee feedback to gauge the organization's alignment toward the company mission, vision, and values.	In addition to level 2, surveys measure the alignment of employee values and beliefs toward those of the organization.	Performance metrics are included in survey	In addition to level 3, senior managers plan initiatives to reinforce the company mission, vision, and values.	Performance metrics are included in initiatives	In addition to level 4, the leadership function is managed as a process that is continuously improved through evaluation, adjustment, and verification of results.	Performance achievements in homes is used as one measure of leadership success

Table D.1. Leadership (continued)

	Level 1	Level 2	Level 3	IBACOS Level 3	Level 4	IBACOS Level 4	Level 5	IBACOS Level 5
1.4 Living the Mission	Employees may have different priorities but there is a general understanding of what the company is trying to accomplish.	Most employees know key elements of the company mission, values, and vision for the future and could explain how it relates to their job.	Most employees recognize and support organizational mission, values, and vision, and use them to guide their decision making.	Performance metrics are instilled as one component that is used in decision making	In addition to level 3, survey data shows that most employees embrace the company mission, vision, and values. There is a strong feeling that everyone is working toward common goals.	Survey includes performance metrics and evaluates employee understanding and implementation of performance attributes	In addition to level 4, employees actively reinforce the company mission, vision, and values among themselves during the course of everyday work.	Employees are empowered and rewarded for achieving performance metrics.
1.5 Public Responsibility	Some people at the company are personally involved in activities that benefit the community, the public, or the housing industry.	When asked, the company supports activities to benefit the community, the public, or the housing industry.	Being a responsible corporate citizen is regarded as good for the company. The company is actively involved in activities to benefit the community, the public, or the housing industry.	Company involvement is related to performance metrics	In addition to level 3, the company creates opportunities to be actively involved in activities to benefit the community, the public, or the housing industry.	Company initiatives action that related to performance metrics	For its size, the company is one of the area's leading business supporters of activities to benefit the community, the public, or the housing industry.	Company is a regional or national leader in supporting initiatives related to performance metrics

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Table D.2. Strategic Planning

Achieving a future vision of what the company can become requires creating and executing a strategic plan for getting there.

	Level 1	Level 2	Level 3	*IBACOS Level 3*	Level 4	*IBACOS Level 4*	Level 5	*IBACOS Level 5*
2.1 Company-wide Success Drivers and Performance Measures.	Measures of company performance are limited to sales and profit.	In addition to level 1, customer satisfaction is important, but performance data is not tracked.	The current customer satisfaction rating is one of the company's monthly performance measures communicated to all employees.	Customer satisfaction measurements include consumer feedback on performance metrics, and limited testing to verify performance metrics are being achieved	In addition to level 3, company-wide performance measures link directly to key success drivers for achieving the company mission and vision.	Level 3 is supplemented with statistically valid sampling plan is in place to test performance metrics	In addition to level 4, operational performance measures through all levels of the company fully support company-wide performance measures.	100% testing and commissioning strategy
2.2 Strategic Plans	Company improvement strategy is to increase sales and reduce costs, but specific action plans are not in place.	The company's competitive business strategy includes improving customer satisfaction and products that enhance homeowner value.	In addition to level 2, written improvement plans are in place with measurable goals. Plans explain how performance improvement goals will be achieved.	Written improvement plans include performance standards and testing requirements. Plan outlines cross functional leader for performance-based quality initiative	In addition to level 3, strategic plans link directly to improvement of company-wide performance measures and fully support the company's mission and values.	Performance measures are based in integrated design and construction approach.	In addition to level 4, a systematic approach is in place for using factual information and data to plan improvements to organizational performance and competitive position.	Measured data form preplanning through warrantee costs are tracked to evaluate total system design strategies and implementation results
2.3 Plan Deployment	The senior managers who make the strategic plans also carry out the improvement initiatives. Employees are involved on an as-needed basis.	Senior managers develop the strategic plan with some employee input. The plan is used to set departmental objectives.	In addition to level 2, senior managers organize employee teams to carry out improvement projects that may involve multiple departments.		A systematic process is in place for involving most employees in the development of strategic objectives, carrying out action plans to achieve them, and monitoring progress.	Most employees are involved in the performance standards setting process, and understand the role these standards play within the context of a larger quality initiative	In addition to level 4, trade contractors, product suppliers, and business partners are involved in the company's strategic improvement process.	Outside partners are an integrated part of the performance standard setting and execution process, particularly in the design process and construction phase.
2.4 Monitoring Progress to Plan	Progress is monitored on an as-needed basis.	Quarterly review meetings monitor improvement progress.	Monthly review meetings monitor actual versus planned improvement activities. Adjustments to plans are made to accommodate current status.	Measurements of key performance attributes are made to judge achievement of goals	In addition to level 3, measurement data is used to monitor performance toward strategic objectives.	Track data as a function of design effectiveness and construction improvements	In addition to level 4, root causes of plan variances are systematically analyzed, understood, and used to prevent future problems and project future performance.	Data is used to feedback into design process and records are kept of unsuccessful designs and reasons for failure.

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Table D.3. Customer Satisfaction

Sustaining high levels of customer satisfaction requires performing well from the customer's point of view.

	Level 1	Level 2	Level 3	*IBACOS Level 3*	Level 4	*IBACOS Level 4*	Level 5	*IBACOS Level 5*
3.1a Market Research	Market requirements are learned mainly from customer requests.	In addition to level 1, market trends are learned from tours of other builders' products and builder magazines.	In addition to level 2, detailed price and feature comparisons with other builders are used to analyze competitive position and uncover unfilled market niches. Feedback from lost customers is used to analyze unfilled needs.	Product is Benchmarked compared to national and local standards. Feedback strategies also capture data regarding performance attributes	In addition to level 3, markets are analyzed by demographic groups. Surveys or focus groups identify customer preferences for features and services.	Focus groups also include exploration of key performance features in housing according to company 5-year stretch performance goals	In addition to level 4, the design of products and services anticipate market trends. They are planned through analysis of changing demographics, economic forecasts, emerging technologies, style trends, and other leading indicators.	Predictive analysis of trends in building performance, world energy, and builder litigation inform market trends
3.1b Product Design Processes	A company expert or consultants create new home designs.	In addition to level 1, select employees provide some input into the design process.	A new home design team includes construction and sales personnel.		In addition to level 3, homeowners, employees, and trade contractors are systematically included in the home design process.	Pre-design and schematic design phase activities are used to incorporate a integrated design process that embraces a systems approach to performance	In addition to level 4, a process is in place to regularly review existing designs and feedback from customers to make design improvements.	Existing product is redesigned over time to include more cost effective implementation of performance metrics
3.2 Customer Satisfaction Drivers	Avoiding homeowner disappointment with the constructed product is the main customer satisfaction priority.	Completing the home on time with a short punch list at final inspection is the company's main focus for satisfying customers.	In addition to level 2, the customer experience and relationship with the builder are important customer satisfaction drivers. Meeting customer expectations is recognized as the key to reliably satisfying customers.	Builder monitors expectation set by other builders, and seeks to set similar consumer expectations through sales process	Exceeding customer expectations is an important company priority. Employees understand how their team and department performance contributes to overall customer satisfaction.	Builder sets higher customer expectations than competition in sales process, by making performance attributes explicit.	In addition to level 4, anticipating individual needs is recognized as the means to achieve the highest levels of customer satisfaction.	Builders guarantee certain key success drivers that are related to the performance standards and attributes of the home (i.e., energy costs and supply, comfort, durability, etc.)

Table D.3. Customer Satisfaction (continued)

	Level 1	Level 2	Level 3	*IBACOS Level 3*	Level 4	*IBACOS Level 4*	Level 5	*IBACOS Level 5*
3.3 Customer Relationship Management	Maintaining good customer relationships through final inspection is the main priority. Everyone has his or her own way of working with customers, with varying degrees of effectiveness.	Maintaining good customer relationships through the end of the warranty period is the main priority. Policies for dealing with customers are in place for the sales process.	Relationships with customers are recognized as a key customer satisfaction driver. A process is in place for creating positive customer relationships in sales, construction, and service phases.		In addition to level 3, customer expectations for key customer satisfaction drivers are systematically managed throughout the customer relationship. Customers are viewed as customers for life.	Key Satisfaction Divers include Performance standards	In addition to level 4, the customer relationship process is designed to systematically exceed customer expectations. Customer satisfaction data on each customer contact point is used to set standards and improve the relationship process.	Performance Standards are designed to set a higher level of customer expectation, and process is in place to exceed those expectations
3.4a Customer Satisfaction Measurement	Customer satisfaction feedback data consists of final inspection punch lists and warranty callbacks.	Customer satisfaction is measured occasionally by surveys or by asking customers. Some questions ask customers to rate employee performance.	All customers are surveyed on their satisfaction with the home and the customer experience during the sales, construction, and warranty service periods. Questions focus on process performance rather than employee ratings.	Survey links expectations of housing performance compared to actual experience of living in home (i.e., comfort, energy performance, durability, noise, etc.)	In addition to level 3, customer satisfaction survey questions are directly linked to known customer satisfaction drivers.	Measurements for customer satisfaction include questions on key performance drivers.	In addition to level 4, feedback from customers and employees is used to refine survey questions and improve the survey process.	New metrics for satisfaction are developed for the industry
3.4b Sharing of Customer Satisfaction Feedback	Customer complaints are shared with the persons responsible.	Customer letters and surveys are routinely circulated among employees.	In addition to level 2, Summary customer satisfaction data is available to all employees. Trends are tracked and posted for all to see. Senior managers frequently discuss customer feedback with employees.		Customer satisfaction ratings are routinely communicated to the organization as one of the company-wide performance measures. Relevant customer satisfaction data is shared with suppliers and trade contractors.	Performance data is included in these survey results	Customer satisfaction is one of the company's vital few key success measures that are tracked monthly by the company's performance management system.	Customer satisfaction is linked to performance of housing, not just buying and construction process

Table D.3. Customer Satisfaction (continued)

	Level 1	Level 2	Level 3	IBACOS Level 3	Level 4	IBACOS Level 4	Level 5	IBACOS Level 5
3.5 Customer Satisfaction Results	Percentage of customers who would recommend the company to a friend is not measured.	More than 75% of customers surveyed would recommend the company to a friend. Customer satisfaction seems to be improving.	More than 85% of customers surveyed would recommend the company to a friend. There are measured improvements in customer satisfaction.	More than 85% of customers surveyed feel home meets the company standard of performance	More than 90% of customers surveyed would recommend the company to a friend. Customer satisfaction shows measured improvements in most products and services.	More than 90% of customers surveyed feel home meets the company standard of performance	More than 95% of customers surveyed would recommend the company to a friend. Customer satisfaction shows strong improvements in most products and services.	More than 95% of customers surveyed feel home meets the company standard of performance

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Table D.4. Performance Management

	Level 1	Level 2	Level 3	IBACOS Level 3	Level 4	IBACOS Level 4	Level 5	IBACOS Level 5
4.1a Creating High-Performance Work Processes	Meeting minimum performance expectations is an important priority for most employees.	Most employees have well-defined responsibilities. Finding ways to reduce costs is the main focus of work improvement activities.	Key work processes are well defined. Customer satisfaction and cost are important work improvement priorities.	"Building performance quality management" has been identified as a key work process, and has been assigned within the organization	Customer needs drive work systems design and improvements. Some work systems are modeled on industry best practices.	The integrated design process has been mapped and assigned	Key processes have high-performance approaches and goals based upon world-class Benchmarks. Key performance metrics are tracked and used for the control and improvement of processes.	All processes associated with key building-performance standards have been identified and documented
4.1b Bench-Marking Business Processes	Information on how other builders do things is obtained mostly from publications and seminars.	Occasional visits to other builders are made to get some good ideas.	Regular visits to other builders are made to compare performance results and set improvement objectives.	Those builders visited include others who are improving building performance at Level 3 and at least one at Level 4	In addition to level 3, detailed studies of other builders' operations are used to design operational improvements.	Those builders visited include others who are improving building performance at Level 4 and at least one at Level 5	In addition to level 4, a systematic approach is used to study organizations outside the construction industry, make improvements, and set long-range goals.	Outside organizations studied reflect similar core values of performance in the product developed
4.2 Performance Management	Performance is managed by monitoring the productivity of individual employees.	In addition to level 1, conformance to department budgets is used to manage financial performance.	Performance management focuses on the productivity of key business processes. Results are tracked and reviewed monthly.	Building to a predefined performance standard is identified as a key business process	In addition to level 3, key work processes have performance measures that link directly to company-wide key success measures. Results are shared with all employees.	Performance attributes are measured and used in this process	In addition to level 4, employees, teams, and trade contractors have performance measures for their own processes that support company-wide key success measures.	Trades perform performance measurements during work
4.3 Process Improvement	Problems are handled as they occur to avoid customer complaints.	Changes to company processes are made occasionally to prevent recurring problems. Some employees are involved in improvement projects.	Improving company processes is an important part of everyone's job. There are many improvements made throughout the company. The company uses a systematic method to make improvements.	Process of designing and building for performance is identified as a key process improvement area	An effective strategy and goals are in place for involving the entire workforce in problem solving and quality improvement. Most employees have been trained in the company's process improvement methods.	Quality Process management involves workforce to continually improve performance	In addition to level 4, all major trade contractors participate in the company's problem-solving and quality improvement system.	Performance measures are part of trade feedback and design process involving trades

Table D.4. Performance Management (continued)

	Level 1	Level 2	Level 3	IBACOS Level 3	Level 4	IBACOS Level 4	Level 5	IBACOS Level 5
4.4 Improvement Results	Some company work processes seem to be improving, but there are no measures of progress.	Some company work processes show measured quality improvements.	*Most* company work processes show measured quality improvements.		Most company work processes show measured quality improvements and excellent quality results.	Performance metrics are included in this measurement	Most measures of organizational effectiveness are considered Benchmarks for the industry.	Performance standards are considered Benchmarks as well
4.5 Financial Improvement Results	Some improvements have resulted in cost reductions.	Substantial cost reductions have been made but have not yet helped improve home sales.	Home sales and company profitability show improvement.	Profitability is in some way attributable to performance standards (reduction in callbacks, improved value, etc.)	Company's share of home sales is increasing. Company profitability shows excellent results with positive trends.	Metric is developed to measure overall cross cutting impact of performance on Value, cycle, and operations to measure overall profitability	In addition to level 4, company profitability is consistently among the best among builders in the area.	

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Table D.5. Human Resources

The human resources system must develop the full potential of employees and drive the right behaviors in support of company performance and learning objectives.

	Level 1	Level 2	Level 3	*IBACOS Level 3*	Level 4	*IBACOS Level 4*	Level 5	*IBACOS Level 5*
5.1a Employee Satisfaction	The company shows a general concern for employee well-being and morale.	Company shows that employee well-being and morale are priorities in making business decisions. There are occasional morale-building activities.	In addition to level 2, employee satisfaction is recognized as important for the company's success. Senior managers take initiatives to do what they think will improve the work environment.		The company understands which factors drive employee satisfaction. Employee surveys measure employee satisfaction and the information is used to improve the work environment.	Relationship to performance standards and end product is measured as a component of employee satisfaction	In addition to level 4, employee satisfaction is integrated into the company's strategic planning process with long-range goals and action plans.	Performance is one metric used in the strategic planning process
5.1b Jobsite Safety	There are occasional safety-related training activities.	Health and safety training is provided to all field employees.	Company shows that employee health and safety are priorities in making business decisions.		In addition to level 3, there is an organized approach to analyzing causes of injuries and preventing accidents.		In addition to level 4, trade contractors are involved in an organized approach to prevent injuries.	
5.1c Job Responsibilities	Employees learn job responsibilities from on-the-job experience.	Job descriptions define job responsibilities.	In addition to level 2, most employees clearly understand their job responsibilities and how their job contributes to company performance.	Job Responsibilities are also tied to Building Performance	In addition to level 3, employees feel responsible for performing their job to meet the needs of other employees who depend on them.	One measure is in relation to building performance by internal survey of employees and trades	In addition to level 4, employees are expected to take initiatives that exceed customer expectations or solve their problems.	
5.1d Teamwork	Individual effort is the main way things get done.	Some natural work groups are formed into operating teams with shared responsibilities.	Most employees are part of an operating team with a well-understood purpose. Teams are the main way that day-to-day work gets done.	Performance attributes and standards are part of the purpose within a team	In addition to level 3, teamwork is the primary mechanism for solving problems and making performance improvements.	Problem solving and improvements include building performance standards related issues	In addition to level 4, employees are actively engaged in teams that perform key management functions for the company.	Integrated design process brings team members in from all levels of the organization and trade partners

Table D.5. Human Resources (continued)

	Level 1	Level 2	Level 3	IBACOS Level 3	Level 4	IBACOS Level 4	Level 5	IBACOS Level 5
5.2 Workforce Development	Skills are learned on the job.	Work-related training is delivered as needed when time and budget allows.	There is a company training budget. Most employees receive some training. Most employees have personal training and development plans.	Key general training on issues related to building-performance standards is provided and specifically related to company performance standards	In addition to level 3, the company's training and hiring plan is aimed at developing the skills necessary for achieving the long-range company vision.	Training for building performance is specialized by employee and function,	In addition to level 4, the company has a systematic skills-development program for key job positions.	Key positions are targeted for more in-depth building-science training
5.3 Employee Evaluation and Compensation Systems	Most employees receive an annual performance review.	Annual employee performance reviews have well-defined evaluation criteria. Bonuses and recognition reward individual efforts.	In addition to level 2, employee performance evaluation criteria are linked to job descriptions. Bonuses focus on *team* efforts.	Evaluation criteria include measurement of achievement of building-performance standards	Employee performance evaluation criteria are based on fulfillment of personal development plans and key elements of the company mission, vision, and values.	Building Performance standards are one of the Key elements	In addition to level 4, employee bonuses are linked directly to performance of the company's key success measures.	Building performance is one Key success measure

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Table D.6. Quality Construction Processes

Systematic quality management approaches are necessary to ensure high performing, trouble-free products and services.

	Level 1	Level 2	Level 3	*IBACOS Level 3*	Level 4	*IBACOS Level 4*	Level 5	*IBACOS Level 5*
6.1 Setting Quality Expectations	Informal standards exist. "We know if it's OK when we see it."	Construction details and workmanship specifications control known problem areas.	In addition to level 2, the builder, contractor, and other trades collaborate to set quality requirements. Contract scopes of work reference specific construction standards and workmanship tolerances.	Performance standards are selected and adopted by builders to meet or exceed Benchmark levels in region	In addition to level 3, requirements analysis of building codes, construction standards, product installation instructions, and industry guidelines are used to set quality specifications.	Building standards exceed Benchmark levels, and are based on a whole-house building-science approach	In addition to level 4, construction detail drawings are provided for nearly every aspect of the home.	Design documentation includes performance aspects and integrates a significant amount of means and methods descriptions to assist trades in implementation, including detailed scopes of work
6.2 Assuring Quality Results	The company fixes any defects the homeowner may find at final walk-through or during the warranty process.	Construction personnel use their experience to catch defects.	There are inspection checklists for most trades. Formal inspections are performed for each phase of construction by the builder.	Performance standards are included on checklists, some performance testing is included	In addition to level 3, trade contractors use checklists to perform quality self-inspections. The main function of builder inspections is to monitor quality performance rather than screen out defects from trade contractors.	Performance standards are included on checklists, a higher level of performance testing is included	Key trades have ISO 9000-based quality assurance systems. Conformance to specifications is a well-documented process. Company generally needs only to spot check trade contractor or product quality.	Performance standards are included on checklists, a higher level (up to 100%) of performance testing is included, but may be done as part of the trade contractors work.
6.3 Quality Problem Prevention	Quality problems are corrected as needed.	In addition to level 1, actions are taken to prevent chronic problems.	Defect data is recorded, trends monitored, and improvement objectives are set. Actions to solve defect problems occur regularly.	Troubleshooting activities use building science basis for performance based defect analysis	In addition to level 3, systematic analysis of root causes are routinely used to prevent defects. Defect prevention focuses on improving processes.	Mechanisms in place to integrate root cause prevention into design process	In addition to level 4, employees and trade contractors are actively engaged to continually refine processes toward zero defect goals.	Zero defect goals include performance attributes of buildings. Zero Defect is well defined relative to performance standards

Table D.6. Quality Construction Processes (continued)

	Level 1	Level 2	Level 3	IBACOS Level 3	Level 4	IBACOS Level 4	*Level 5*	IBACOS Level 5
6.4 Warranty Service	Service callbacks are handled but not tracked.	Systems are in place to track warranty complaints and their completion.	In addition to level 2, warranty service data is used to set priorities for solving quality problems.	Warrantee service data is broken down to capture root causes	In addition to level 3, response time and customer satisfaction with each service call are important performance measures.	Key performance drivers are identified, tracked and fed back to reduce warrantee calls and improve customer satisfaction	Warranty service excellence is among the best of builders in the area and a competitive advantage of the company.	Warranty specialist are trained in building science approach and use diagnostic skills to improve product
6.5 Product and Service Quality Results	Product and service quality seems to be improving, but there are no measures of progress.	Problems found at final inspection are decreasing. There are fewer callbacks.	Data shows that constructed quality is improving.	Quality is defined according to building science based performance metrics	Most product and service quality performance indicators show excellent results with positive trends. Zero defect final inspections are commonplace.	Defects are also measured by building science performance measurements, and are measured by testing	*All* major product and service quality performance indicators show positive improvement *trends* and *excellent* results. Most homes have zero defect final inspections.	Defects are also measured by building-science performance measurements and are measured by higher levels (up to 100%) testing

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Table D.7. Supplier Partnerships

Partnering approaches are essential for high performance relationships with trade contractors and product manufacturers.

	Level 1	Level 2	Level 3	*IBACOS Level 3*	Level 4	*IBACOS Level 4*	Level 5	*IBACOS Level 5*
7.1 Trade Contractor and Supplier Relationships	Difficult quality problems are usually solved by changing contractors or suppliers.	A systematic process is in place for the selection of trade contractors. Trades and suppliers participate in solving problems.	Key trade contractors and suppliers are considered partners. Company helps them improve quality and reduce costs.	Performance standards are a metric of quality, testing measures improvement	In addition to level 3, most major trade contractors and suppliers participate in a systematic approach to problem-solving and quality improvement.	Company has integrated design process for contractors to participate in new construction and building-science-based solution / redesign process for existing product	In addition to level 4, trade contractors and suppliers participate in planning and implementing long-term quality improvements.	Trades are actively involved in identifying proper scopes of work, sequencing, and even-flow scheduling with builder
7.2 Trade Development	There are no formal initiatives to develop the capabilities of trade contractors.	Improving trades is focused on solving problems.	A general strategy is in place to develop the capabilities and performance of trade contractors.	Builder provides general training on Performance standards and trades relation to standards	The company's trade development plans are linked directly to achieving the company's long-range vision.	Trades are trained to understand building science approach and integrated designs, and interrelationship of their work to the overall performance standards and company goals	In addition to level 4, Key trades have their own development plans that support the company vision. The builder provides incentives for trades participating in training improvement programs.	Builder required certified trades in all key performance standards areas
7.3 Trade Contractor Performance Management	Trade performance is evaluated when problems arise or when contracts are renewed.	Trade performance data consists of inspection punch lists and callbacks, but trend data is not tracked.	Trade performance trend data is tracked and reviewed regularly with the key trades and used to improve quality and prevent defects.	Primary use is checklists, some performance test data used to gauge trade against performance standards	Customer satisfaction survey data on construction workmanship is used as a trade performance indicator.	Performance testing is used as another metric for trade performance	Trades use builder performance data to monitor and improve performance. Trades are recognized and rewarded for outstanding performance.	Performance testing is used as another metric for trade performance
7.4 Trade Contractor and Supplier Results	Trade contractor quality seems to be improving, but there are no measures of progress.	Some trade contractors show *measured* quality improvements.	*All* major trade contractors show measured quality improvements.	Measurement system includes key performance attributes	All major contractors show *excellent quality results*. Most trade contractors routinely meet quality standards.	Quality standards include Performance standards	In addition to level 4, all major trade contractors show positive quality improvement *trends*.	Performance testing shows improvement trends.

NHQ Rating Form							
		Rating (circle your choice)					
1.	**Leadership**						
1.1	Company Mission, Vision and Values	1	2	3	4	5	?
1.2	Senior Management Involvement	1	2	3	4	5	?
1.3	Leadership Feedback and Improvement	1	2	3	4	5	?
1.4	Living the Mission	1	2	3	4	5	?
1.5	Public Responsibility	1	2	3	4	5	?
2.	**Strategic Planning**						
2.1	Company-wide Success Drivers and Performance Measures	1	2	3	4	5	?
2.2	Strategic Plans	1	2	3	4	5	?
2.3	Plan Deployment	1	2	3	4	5	?
2.4	Monitoring Progress to Plan	1	2	3	4	5	?
3.	**Customer Satisfaction**						
3.1a	Market Research	1	2	3	4	5	?
3.1b	Product Design Processes	1	2	3	4	5	?
3.2	Customer Satisfaction Drivers	1	2	3	4	5	?
3.3	Customer Relationship Management	1	2	3	4	5	?
3.4a	Customer Satisfaction Measurement	1	2	3	4	5	?
3.4b	Sharing of Customer Satisfaction Feedback	1	2	3	4	5	?
3.5	Customer Satisfaction Results	1	2	3	4	5	?
4.	**Performance Management**						
4.1a	Creating High Performance Work Processes	1	2	3	4	5	?
4.1b	Benchmarking Business Processes	1	2	3	4	5	?
4.2	Performance Management	1	2	3	4	5	?
4.3	Process Improvement	1	2	3	4	5	?
4.4	Improvement Results	1	2	3	4	5	?
4.5	Financial Improvement Results	1	2	3	4	5	?
5.	**Human Resources**						
5.1a	Employee Satisfaction	1	2	3	4	5	?
5.1b	Jobsite Safety	1	2	3	4	5	?
5.1c	Job Responsibilities	1	2	3	4	5	?
5.1d	Teamwork	1	2	3	4	5	?
5.2	Workforce Development	1	2	3	4	5	?
5.3	Employee Evaluation and Compensation Systems	1	2	3	4	5	?
6.	**Quality Construction Processes**						
6.1	Setting Quality Expectations	1	2	3	4	5	?
6.2	Assuring Quality Results	1	2	3	4	5	?

NHQ Rating Form							
		Rating (circle your choice)					
6.3	Quality Problem Prevention	1	2	3	4	5	?
6.4	Warranty Service	1	2	3	4	5	?
6.5	Product and Service Quality Results	1	2	3	4	5	?
7.	**Supplier Partnerships**						
7.1	Trade Contractor and Supplier Relationships	1	2	3	4	5	?
7.2	Trade Development	1	2	3	4	5	?
7.3	Trade Contractor Performance Management	1	2	3	4	5	?
7.4	Trade Contractor and Supplier Results	1	2	3	4	5	?

NHQ Survey information	**Information Champion**
Company Mission, Vision and Values	
• What are the company mission statement, core values, and vision for the future? How is this documented and communicated amongst the staff?	
• How do senior managers demonstrate a commitment to the company mission, values, and vision, and to what extent does this translate to the actions of others throughout the organization?	
• What feedback mechanisms exist from field to management relating to company's ability to deliver to the company mission, values, and progress towards vision?	
• How does the company understand if employees are in alignment with the company mission, values, and vision, and are there activities that specifically encourage and reinforce that alignment?	
• Does the company facilitate and coordinate opportunities to benefit the local community in alignment with the mission, values, and vision?	
Strategic Planning	
• What measurement mechanisms exist to evaluate if the company is achieving the mission, progressing towards the vision, and achieving customer satisfaction and operational performance metrics?	
• Is there a written strategic plan that documents the improvement process in different operational areas, the tools and systems used to identify areas of weakness and measure company-wide operational improvements, a detailed strategic plan for improvements in key areas, and who is involved in developing specific strategic improvement plans?	
• What process is in place to implement the plan, and how far throughout the organization does implementation reach?	
• What mechanisms are used and how often is review performed to monitor how well the organization is improving relative to the strategic plan? How often is the strategic plan updated?	

NHQ Survey information	Information Champion
Customer Satisfaction	
• What market research mechanisms are in place to understand customers, position relative to local competition, and forward positioning of products based on leading indicators (e.g., demographics, economic, style, etc.)	
• What is the design process? Who is involved? What feedback mechanisms exist?	
• What importance is placed on customer satisfaction, and how is that expressed in the company mission, values, and vision?	
• What process is in place to guide the customer through the sales and construction process?	
• How is customer satisfaction measured and used throughout the company to improve the customer relationship process?	
Performance Management	
• How does the organization set up work processes, identify work process improvements, and Benchmark against other industry and non-industry top performers?	
• How are work processes measured, and do they support key company wide success measures?	
• How are work-processes evaluated and improved?	
• How are work-processes tied to the quality of the house?	
• How are company financial results measured, and tied to work processes?	
Human Resources	
• Are employees are surveyed on job satisfaction and have input on improving employee satisfaction?	
• What is the company safety plan, and how far into the organization does it reach?	
• How empowered are employees with respect to their job and achieving key success metric?	
• How are teams utilized to perform management functions within the organization?	
• What kind of the training and employee development program exists in the company?	

NHQ Survey information	**Information Champion**
• How are employees and teams evaluated, compensated, and given incentive toward key success measures for the company	
Quality Construction Process	
• What are the company's quality standards, and how are these communicated throughout the organization and to trades?	
• How do management, field, and trades monitor consistency and delivery of product that meets quality standards?	
• How do the company and the trades monitor and evaluate quality problems and develop process improvements to eliminate problems?	
• How is warranty service used to identify and fix root causes of quality problems?	
• How have these improvements contributed to zero defect at final inspection, and show positive trends in quality improvement and excellent results	
Supplier Partnerships	
• How are trade contractors and suppliers engaged in the company's quality initiatives?	
• What strategies are in place to align trade contractors with the company mission, values, and vision; develop the trades to achieve quality standards; and provide financial rewards for achieving quality goals?	
• How is trade contractor performance tracked, and how is that data used to continually improve the trade contractor's performance?	
• What are the results associated with the trade contractor initiatives?	

Appendix E. SNAPSHOT Form

SNAPSHOT© "The Form"

Lot #:	Subdivision:	Address:	Date and time:
Model:			

INITIALIZATION

	Square feet	sq. ft.
	Surface area (all outside surfaces, including foundation)	sq. ft.
	Volume	cu. ft.
	Windspeed (approximate mph)	mph
	Outside temperature (estimated)	° F
	Check that all registers and bedroom doors are open.	Yes☐ No☐
	Measure static pressure in return between fan & filter.	pa
	Static pressure in Supply and Return	S Pa / R Pa
	Is there a ventilation system?	Yes☐ No☐
	Type of ventilation system (e.g., exhaust-only, HRV, ERV)	
	If there is an AirCycler™, enter the off / on times.	off on
	Enter outside air duct pressure.	pa
	Type of outside air duct (flex/sheet metal; diameter)	
	Is there an adjustable outside air damper?	Yes☐ No☐
	Is there a fireplace or wood stove?	Yes☐ No☐
	Duct location (approximate % in attic, conditioned space, basement, etc.)	

PRESSURE TESTING

	Stack Pressure (baseline with blower door installed; covers on)				pa
	Dominant Duct Leak Effect (baseline with HVAC system running)				pa
	Master Bedroom Door Closure Effect (ÄP from main space to outdoors)				pa
	All Doors Closed Effect (ÄP from main space to outdoors)				pa
	Fireplace/Wood Stove Zone HVAC Test				pa
	Pressure In Each Closed Room (room label and pressure)		pa		pa
			pa		pa
			pa		pa
			pa		pa
			pa		pa

BLOWER DOOR TESTING (BDT)

	Blower Door Location	
	Total CFM50 (add C & n values if available on multipoint test)	CFM50= C= n=

DUCT AIRTIGHTNESS TESTING (DAT)

	DAT CFM25 TOTAL	
	DAT CFM25 OUTSIDE	

MECHANICALS

	Furnace or air handler	Make:	Model:
	Air Conditioning	Make:	Model:
	Domestic hot water	Make:	Model:

Building Science Corporation

Snapshot Form

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
August 2006	Subcontractor Report	January 2005 - November 2005

4. TITLE AND SUBTITLE
Building America Residential System Research Results: Achieving 30% Whole House Energy Savings Level in Cold Climates

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

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14. ABSTRACT *(Maximum 200 Words)*
The Building America program conducts the system research required to reduce risks associated with the design and construction of homes that use an average of 30% to 90% less total energy for all residential energy uses than the Building America Research Benchmark, including research on homes that will use zero net energy on annual basis. To measure the program's progress, annual research milestones have been established for five major climate regions in the United States. The system research activities required to reach each milestone take from 3 to 5 years to complete and include research in individual test houses, studies in pre-production prototypes, and research studies with lead builders that provide early examples that the specified energy savings level can be successfully achieved on a production basis. This report summarizes research results for the 30% energy savings level and demonstrates that lead builders can successfully provide 30% homes in Cold Climates on a cost-neutral basis.

15. SUBJECT TERMS
Building America; U. S. Department of Energy; systems research; cold climates; 30% energy savings level; energy efficient housing

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER *(Include area code)*

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A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

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