Green, Affordable Housing Moving Toward "Zero Energy"

Robb A. Aldrich, PE **Gayathri Vijayakumar**

ABSTRACT

In Spring of 2006, a nonprofit developer and builder of affordable housing in Western Massachusetts began construction on a small home, aiming to achieve extraordinary levels of energy efficiency while incorporating active solar thermal and electric systems. Features include double-wall construction; windows with a suspended, low-emissivity film; and a radiant slab insulated with four inches of foam. A 3.2 kW PV system will provide an estimated 74% of the home's total electric needs, and 44% of the combined heating and water-heating loads will be met by the solar thermal system. Modeling predicts that energy required to operate the home, which will be completed in Spring of 2007, will be $1,030 per year—a 73% savings compared to standard construction.

INTRODUCTION

Beginning in 2000, a nonprofit builder and developer of affordable housing in Franklin County, Massachusetts, began a concerted effort to steadily improve the efficiency and sustainability of its homes. The first step in this process was meeting ENERGY STAR™ requirements through a program sponsored by the local utility. The builder then began including solar electric systems in some new homes and in 2006 they began participating in the LEED™ (Leadership in Energy and Environmental Design) for Homes pilot program administered by the U.S. Green Building Council. The subject of this paper represents the builder's next step towards creating *zero-energy homes*. Several others across the U.S. have been working toward the zero-energy goal (Farhar 2004; Keesee 2005; NAHB 2004; Norton 2005; Parker 2000; Puttagunta 2006). A zero-energy home, as the term is used here, is a home that requires no net off-site source energy to operate over the course of a year. This is achieved through a combination of energy efficiency and on-site renewable energy. The authors performed energy modeling per protocols developed by the U.S. Department of Energy's Building America Program (Hendron 2006).

The authors were involved during the design of the home, providing energy modeling and recommendations on envelope details, mechanical systems, and solar systems. The authors also visited the home regularly during construction (see Figure 1) to document details of the construction process and evaluate practicality or "build-ability" of several of the advanced building systems. The authors installed monitoring

Figure 1 *The home in Colrain, Massachusetts, nearing completion.*

Robb Aldrich *and* ***Gayathri Vijayakumar*** *are engineers at Steven Winter Associates, Inc., Norwalk, CT.*

equipment to evaluate the performance of building systems when the home became occupied in mid-May 2007.

This home also serves as a prototype for the builder. Because the builder is a nonprofit organization providing housing for lower-income buyers, they must maintain tight control of construction costs. Construction and evaluation of this home will help identify the most practical and cost-effective strategies to include in future projects.

HOME DESIGN AND SPECIFICATIONS

Site and Home Plans

The home site is on a south-facing hill in a wooded area. A few trees on the southern (downhill) side of the home were removed to provide excellent solar access. The architects deliberately designed the home along a long east-west axis to allow for both passive solar gains and a large south-facing roof area for active collectors. The home has three bedrooms, two baths, and a finished floor area of approximately 1350 ft^2 (125 m^2). Living areas generally used during daylight hours are on the south side of the house (living room, dining area, kitchen, and master bedroom), while secondary bedrooms, both bathrooms, and the mechanical room are located on the north side.

Foundation and Slab

Typically, this builder builds homes on full basements. Because there was a significant amount of rock ledge on the site, a basement foundation would have required substantial excavation. Designers opted to build a slab-on-grade home, as the slab also provided a good means for delivering radiant floor heat.

To achieve R-20 slab insulation, the builder installed four inches of extruded polystyrene at the perimeter and beneath the entire slab. For delivery of radiant heat, crosslinked polyethylene (PEX) tubing was installed at 12 in. on center at the bottom of the slab (see Figure 2). The finished floor of the home is the polished, pigmented concrete slab.

Wall Construction

The builder's chosen method for reducing heat loss through walls was a double-wall assembly. Once the foundation was complete, the builder erected the exterior load-bearing, 2 × 4-framed walls (see Figure 3). After the floor was poured and the home was closed in, the second 2 × 4-framed wall was installed 5.5 in. (14 cm) inside the exterior wall (a 2 × 6 spacer was used between the top plates and left in place to provide blocking). Carpenters installed this second wall very much like an interior partition. After interior framing was complete, the electrician and plumber installed rough wiring and domestic water piping.

The exterior walls were insulated with dense-blown cellulose. The insulators stapled fiber-reinforced polyethylene to the sides of the interior wall studs. Starting near the

Figure 2 *Pouring the radiant slab above 4 in. of XPS insulation and radiant piping.*

Figure 3 *Walls during construction with exterior and both interior and exterior 2 × 4 in. framed walls.*

bottom of the wall, insulators cut small holes in the polymer sheet in each stud bay through which to blow cellulose. According to the insulator, more holes were required to fill such a large wall cavity. In more common 2 × 6-framed walls, two holes are needed in each bay; here, at least three holes were needed in each bay (Figure 4). Insulating was also complicated by all the wall cavities being connected (through the 5.5 in. gap between the interior and exterior framed walls). Instead of entirely filling one stud bay at a time, insulators needed to make several circuits around the house, gradually packing the entire wall system.

When wall insulation was complete, the holes were patched with polyethylene tape. The finished walls contain 12.5 in. (32 cm) of cellulose for an approximate whole-wall R-value of 43 $ft^2 \cdot hr \cdot °F/Btu$ (7.6 $m^2 \cdot K/W$).

Drywall was attached normally to the face of the studs of the interior wall. At windows, bottom returns were made with pine sills; drywall returns were installed on the other three surfaces.

Figure 4 *Insulators attaching reinforced polyethylene before dense-blowing cavities with cellulose insulation.*

Incremental cost for the double wall system in this home was estimated at approximately $2400 when compared to the builder's standard 2 × 6 wall system (this figure includes added lumber, framing time, and increased insulation cost). The relatively low cost, however, is largely a result of this particular design and the builder's construction practices. First, the home's plan is basically a rectangle. There are four right angles in the exterior wall, simplifying framing tremendously. In more complex homes, double-wall construction could be much more expensive and impractical. Second, the builder is somewhat unique in that they are developers, builders, and carpenters. The builder's own crews perform much of the construction, including framing, so much of the extra work required for double-wall framing was done in-house at a modest premium. The builder estimated that framing of the double wall would require an additional 32 person-hours when compared to their conventional 2 × 6 wall framing.

Modeling shows that the fuel savings achieved by the wall system in this home—when compared to the builder's standard 2 × 6 construction—is 107 gals of propane per year. At current propane prices of $2.30 per gal, this is an annual savings of $246.

Siding

Three types of fiber-cement siding were used on the exterior of the home: lap siding, shingles, and panels (4 × 10 ft. [1.2 × 3.0 m] panels are used to achieve a board-and-batten appearance). This siding is considerably more costly than vinyl siding, which, because of its lower cost, is the standard siding material on many of the builder's homes. In an attempt to reduce costs at this home, the builder and architect chose to use the siding manufacturer's published procedures for installing the fiber-cement siding to serve as both sheathing and siding, eliminating the standard OSB sheathing in most of the builder's homes. Sheathing was not required for structural reasons, as 2 × 4 bracing is installed between the two 2 × 4 walls where required.

On the outside face of the outer 2 × 4 wall, polypropylene house wrap was stapled to studs. Fiber-cement siding was attached, flashed, and sealed per the manufacturer's instructions. Unfortunately, the elimination of sheathing resulted in unforeseen delays. Time needed to attach the siding increased significantly, as carpenters were not able to drive any fasteners into OSB sheathing; all fasteners needed to be used at studs. Time required to install the battens on the board-and-batten sections was also increased. Because battens did not align with studs (they are aesthetic elements only), installing these required a carpenter on each side of the wall: one inside holding furring strips to serve as backing for the nails, and a carpenter outside driving the nails.

In future projects using similar siding, the builder plans to install house wrap over OSB sheathing to simplify siding installation. This detail has the added benefit of including a redundant, rigid, weather-drainage plane, which is a desirable durability feature.

Windows

Throughout the home, the builder installed vinyl-framed, Krypton-filled windows with a low-emissivity polymer film suspended between the windows' two panes. The windows have U-factors of 0.20 Btu/ft^2·hr·°F (1.1 W/m^2·K) and solar heat-gain coefficients (SHGC) of 0.34. Modeling shows that these windows provide annual propane savings of 43 gals per year compared to the builder's standard windows: double-pane low-e with U-factors of 0.30 Btu/ft^2·hr·°F (1.7 W/m^2·K). For this home, the windows were provided to the builder by the manufacturer at no incremental cost (over the cost of the standard windows used by the builder).

To take advantage of direct solar gain during the winter, windows with larger solar heat-gain coefficients would have been desirable on the southern elevation. According to simulations, raising SHGC from 0.34 to 0.50 would result in a 10% decrease in the annual space-heating load. The windows used, however, are the only products available from this manufacturer with suspended low-e film.

Attic and Roof Insulation

The roof is supported with prefabricated trusses at 24 in. on center. A polyethylene vapor barrier was stapled to the bottom chords of the trusses, and 1 × 3 strapping is attached below the vapor barrier perpendicular to the truss chords (Figure 5). Installing strapping perpendicular to the truss chords is a practice very common in Massachusetts home construction. With the polyethylene installed between the truss chords and strapping, the insulator can install attic insulation before drywall is installed. This allows the insulator to make a single site visit to insulate both attic and walls. The attic is a conventional vented attic with continuous soffit and ridge vents; baffles were installed at each truss bay to keep insulation away from the soffit vents. Fourteen inches of loose cellulose were blown into the attic for an R-value over 50 ft^2·hr·°F/Btu (8.8 m^2·K/W).

Infiltration and Air Sealing

The simple plan, the slab foundation, the continuous polyethylene vapor barriers, and dense-blown insulation all contribute to a very tight home. In addition, the builder employed meticulous air sealing details (such as sealing all penetrations made for wires, pipes, and ducts; sealing around window and door jambs; and caulking seams in top plates). A blower door test performed when the home was nearing completion (before plumbing fixtures were installed and before all finish work was complete) showed envelope leakage of 1.9 ach$_{50}$ (air changes per hour when the house was depressurized to 50 Pa.)

MECHANICAL AND ENERGY SYSTEMS

Space Heating and Domestic Water Heating

Energy for space and water heating is provided largely by a solar thermal system; auxiliary heat for both applications is provided by a single, propane-fired, tankless water heater. A schematic of the system is shown in Figure 6

Solar Thermal Collection

Figure 1 shows three evacuated-tube solar thermal collectors (each with a total area of 28 ft^2 [2.6 m^2]) and two small photovoltaic modules (40 W$_{DC}$ total) on the eastern end of the home's south-facing roof. These PV modules power a DC differential temperature controller and a DC circulating pump. This pump moves a 50% propylene glycol solution between the solar thermal collectors and a heat exchanger coil in the 119 gal (450 L) storage tank. The heated antifreeze heats potable water in the tank to be used for both space heating and domestic water heating.

Domestic Water Heating

The energy to heat domestic hot water is provided primarily by the solar thermal system. Auxiliary water heating is provided by a sealed-combustion tankless water heater with a modulating, propane-fired burner. Upon a domestic hot-water draw, preheated water is drawn from the top of the solar tank then passed through the tankless heater. If the water from the solar tank is below the hot water set point (adjustable around 120°F [49°C]), the water heater fires to bring the water up to the set point temperature. Because water in the solar storage tank can get very hot (at or above 160°F [71°C]), a tempering valve is installed to mix cold water into the stream and reduce water temperature to below scalding levels. To replace the hot water drawn from the top of the solar tank, cold water from the well enters near the bottom of the tank to maintain some stratification.

During summer months, the propane water heater may not be needed at all. In this case, a summer bypass valve can be opened and the propane water heater turned off entirely.

Figure 5 *Insulated ceiling before drywall.*

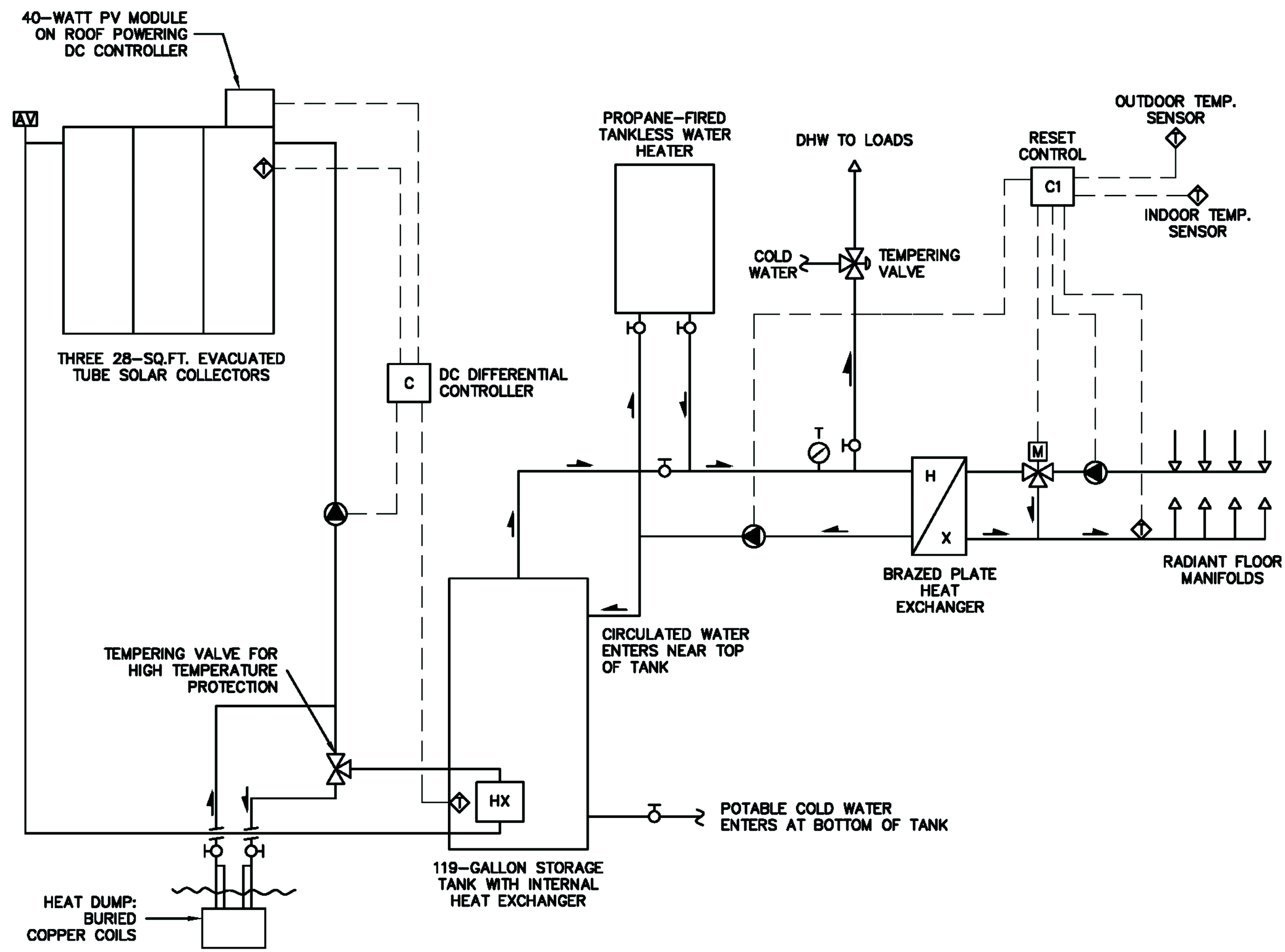

Figure 6 *Schematic of the home's thermal systems to provide space heat and domestic hot water. Heat sources are active solar and an auxiliary tankless water heater.*

Space Heating

With the superior thermal envelope of the home, engineers calculated the design heat load of 11,800 Btu/hr (3.46 kW). Heat to meet this load is delivered through the radiant floor slab. There is a single zone in the home, and a single circulating pump moves warm water through PEX tubing within the concrete slab. These pipes run to and from the radiant manifolds located in the mechanical room.

The temperature of the water flowing through the radiant piping is determined by a reset controller. The controller senses indoor temperature, outdoor temperature, and temperature of water sent to the radiant floor. To raise the water temperature, the controller adjusts a three-way mixing valve to divert water through a flat-plate heat exchanger (where it picks up heat from the hot domestic water stream). When lower radiant-floor water temperatures are needed, the three-way valve bypasses the heat exchanger and directs more water back to the floor piping.

On the other side of the plate heat exchanger, a circulator moves potable water from the top of the solar storage tank, through the tankless water heater (which fires if water temperature is below the domestic hot-water set point), through the heat exchanger, and back to the solar tank. To help maintain tank stratification, circulated water re-enters the storage tank approximately 1 ft (30 cm) from the top of the tank.

Ventilation

In both bathrooms, efficient, quiet exhaust fans are installed to run continuously at 25 CFM (0.71 m^3/min) to meet the minimum ventilation requirements of *ANSI/ASHRAE Standard 62.2-2004, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings* (ASHRAE 2004). This constant flow rate is adjustable, and override switches installed in the bathrooms boost the fans to high speed (80 CFM [2.3 m^3/min]) when the bathrooms are in use.

Makeup air enters the home through envelope leakage. Heating of this air is the largest single component of the annual space-heating load; modeling shows that 129 gals of propane will be required annually to heat ventilation air. While the heating load is quite large, the electric consumption of these two exhaust fans is very small; the authors field verified the manufacturer's listed power consumption of 5 W for each fan at low speed.

Lighting and Appliances

As part of the home energy-rating program sponsored by the local utility, compact fluorescent lights were provided at no cost to the builder. All fixed lighting in the home uses ENERGY STAR certified compact fluorescent lamps. The refrigerator, clothes washer, and dishwasher also have ENERGY STAR ratings.

Solar Electricity

On the western side of the south-facing roof, an array of 28 photovoltaic (PV) modules is installed with a total DC rating of 3.22 kW at standard test conditions. Because there are numerous trees near the home, the authors performed a shading analysis at the PV array and found that shading should reduce irradiance on the array by less than 6% over the course of a year. The inverter is located in the mechanical room and the homeowners will have a net-metering agreement with the local utility.

MODELED ENERGY PERFORMANCE

The authors modeled the energy performance of the home using the Building America Research Benchmark Definition (Hendron 2006) guidelines developed by the U.S. Department of Energy Building America program. The benchmark procedure compares the modeled energy performance of the home to that of a reference home with similar geometry but with baseline specifications typical of mid 1990s construction. These specifications are in line with the *2003 International Energy Conservation Code* (ICC 2003).

The basic hourly energy simulations were performed using the EnergyGauge USA modeling tool. To model the contributions of the solar thermal system to space and domestic water heating, the authors used F-Chart software. These solar thermal modeling results show that the solar thermal system will provide 44% of the combined space and water heating loads for an annual propane reduction of 218 gals. A summary of modeling results of the key loads for the benchmark home and the home as-built is shown in Table 1. While no cooling system is installed in the home, the benchmark procedure requires the assumption that occupants will install cooling with minimum efficiency.

At current energy prices of $0.15 per kWh and $2.30 per gal of propane, these energy savings equate to annual cost savings of $2,368. The authors and the builder attempted to quantify added costs to reach these levels of energy savings. Unfortunately, accurate accounting proved elusive for several reasons. As the builder is a nonprofit developer of affordable housing, they are able to take advantage of several state and utility incentives for advanced energy systems. Other building components were donated or provided at no incremental cost for this prototype home. Because there were many changes from the builder's standard practice, significant time was spent on site learning how to integrate systems effectively. Finally, the construction was delayed for several months because of problems extending power lines. In future projects (see below), the authors and the builder hope to more accurately assess incremental costs for reaching high energy performance levels.

To assess progress towards the zero-energy goal, the authors compared source energy consumption of the as-built home to that of the benchmark home. As with the modeling discussed above, source-energy calculations were made according to protocols in the *Building America Research Benchmark Definition* (Hendron). Source energy calculations are intended to take into account inefficiencies in energy

Table 1. Summary of Annual Modeling Results for the Home and Comparison to the Benchmark Home

End Use	Benchmark Home		As-Built Home	
	Electricity, kWh	Propane, gal	Electricity, kWh	Propane, gal
Space heating	312	663	141	233
Space cooling	643	—	259	—
DHW	—	234	—	42
Fixed lighting	1570	—	618	—
Appliances	1815	119	1523	86
Plug load	2258	—	2258	—
Plug-in lighting	307	—	307	—
OA ventilation	172	—	82	—
Total usage	7077	1016	5188	361
Site generation	—	—	3855	—
Net energy use	7077	1016	1333	361
Percent savings			81%	64%

Table 2. Summary of Source Energy Comparisons of the Home and Comparison to the Benchmark Home

End Use	Source Energy Consumed (kBtu/yr)		Percent Reduction
	Benchmark	As-Built	
Space heating	64.2	22.9	64%
Space cooling	6.9	2.8	60%
DHW	21.5	3.9	82%
Fixed lighting	16.9	6.7	61%
Appliances	30.5	24.3	20%
Plug load	24.3	24.3	0
Plug-in lighting	3.3	3.3	0
OA ventilation	1.8	0.9	52%
Total usage	169.5	89.1	47%
Site generation	0	–41.6	0
Net energy use	169.5	47.5	72%

generation and transmission. Table 2 shows that overall source energy consumption of the home is reduced by 72%.

MONITORING

During construction, the authors installed instrumentation to monitor longterm performance of the home energy systems. Sensors are connected to a datalogger that can be accessed through a telephone modem. Key monitored parameters include the following:

- Thermal systems
  - solar energy collected
  - solar energy delivered to radiant floors for space heating
  - solar energy used for water heating
  - propane used by tankless heater for space heating
  - propane used by tankless heater for hot water
- Electrical systems
  - electricity consumed within the home
  - DC and AC electricity generated by the solar PV system
  - electricity usage of thermal systems (circulators, water heater, etc.)
- Environment
  - indoor and outdoor temperature and humidity
  - solar radiation incident upon solar collectors

FUTURE PROJECTS

This home in some ways served as a prototype for the builder. The builder is working with the authors and the architect of this prototype home to design a 20-unit development of affordable homes in Greenfield, MA, using many of the same systems. While this new development is still in the design phase, building of the prototype has provided direction for several building systems:

- *Double-wall construction.* The double-wall system proved to be builder friendly and was relatively simple to implement by the builder's own crews. With the convenience and modest incremental cost of this system (approximately $2400 in the prototype home), the builder plans to use this wall system in the upcoming 20-unit development.
- *Exterior wall sheathing.* As described above, the expected savings from limiting or eliminating OSB sheathing were not achieved. Instead, construction time and costs were increased and concerns were raised over

lack of a rigid, secondary drainage plane. Exterior OSB wall sheathing will be used in the upcoming project.

- *Windows.* Modeling showed that windows with the suspended, low-e film and U-values of 0.20 Btu/ft^2·h·°F (1.1 W/m^2·K) provided savings of 43 gals of propane each year compared to the builder's standard double-pane, low-e windows with U-values of 0.30 Btu/ft^2·h·°F (1.7 W/m^2·K). Windows were no more difficult to install; in fact, the insulated glazing units for both windows are installed in identical sashes, but because the suspended-film window was a low-volume product for this manufacturer, lead times were long and prices were high. Still, the builder plans to work with window providers and project funders to include these high-performance windows in the upcoming development.
- *Tankless water heaters.* These water heaters are straightforward to install and operate, and costs are comparable to the builder's standard practice: an indirect water heater making use of a gas or oil boiler. Tankless water heaters will likely be standard in the upcoming 20-unit development and in future projects where boilers are not installed.
- *Radiant heating.* Radiant floor heating will likely not be included in the upcoming development. These 20 homes will be built on basements, and the design team is exploring lower-cost heat-delivery systems.
- *Solar thermal systems.* Installation of the solar thermal system in the prototype home was straightforward, and, after commissioning, it was operating well. Modeling shows that this system will offset 218 gals of propane each year for space and domestic water heating. The solar system for this home was donated by the collector manufacturer with support from the local utility; the estimated equivalent installed cost of the system was \$12,000. The builder hopes to include solar thermal systems in the upcoming development, but they may be cost prohibitive. Simpler systems providing only domestic water heating are also being considered.
- *Solar electric systems.* With Massachusetts' incentives for solar electric systems on affordable and low-income housing, photovoltaic systems have become standard for the builder. This will continue in the upcoming development as long as funding is available.

The first homes in this new 20-unit development are scheduled for completion in winter of 2007–2008.

ACKNOWLEDGMENTS

Rural Development Inc. (RDI), the builder and developer of these high-performance homes, has shown great leadership in creating housing that is efficient, sustainable, and truly affordable to own. The authors would also like to acknowledge Austin Design, Inc. who donated architectural design services for this home. Work performed by the authors at Steven Winter Associates, Inc. (SWA) was funded by the U.S. Department of Energy Building America Program through the Consortium for Advanced Residential Buildings (CARB).

The authors would also like to acknowledge Western Massachusetts Electric Company for financial and logistical support of the project, especially with the installation and funding of the solar thermal system; American Solar Works, who donated solar thermal equipment to the project; the Massachusetts Technology Collaborative, who provided funding for the solar electric system; and Lawrence Berkeley National Laboratory, who coordinated the Heat Mirror® window procurement with Southwall Technologies and Paradigm Windows. The authors also received a great deal of assistance from Western Massachusetts Insulators, Whittier Plumbing & Heating, and James Electric during design of the energy systems and installation of monitoring equipment.

REFERENCES

ASHRAE. 2004. *ANSI/ASHRAE Standard 62.2-2004, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Farhar, Barbara, T. Coburn, and M. Murphy. 2004. Large production home builder experience with zero energy homes. *Proceedings of the ACEEE 2004 Summer Study on Energy Efficiency in Buildings*, *Pacific Grove, CA* 8:98–109.

Hendron, R. 2006. Building America research benchmark definition. NREL/TP-550-40968, National Renewable Energy Laboratory, Golden, CO.

ICC. 2003. International energy conservation code. International Code Council, Washington, DC.

Keesee, M. 2005. Setting a new standard—The zero energy home experience in California. Solar World Congress, August 8–12, Orlando, FL.

NAHBRC. 2004. Zero energy home armory park Del Sol. Final Report, National Association of Home Builders Research Center, Upper Marlboro, MD.

Norton, P., E. Hancock, G. Barker, and P. Reeves. 2005. Hathaway "solar patriot" house: A case study in efficiency and renewable energy. NREL/TP-550-37731. National Renewable Energy Laboratory, Golden, CO.

Parker, D., J. Dunlop, S. Barkaszi, J. Sherwin, M. Anello, and J. Sonne. 2000. Towards zero energy demand: Evaluation of super efficiency housing with photovoltaic power for new residential housing. *Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA*.

Puttagunta, S., R.A. Aldrich, D.K. Owens, and G. Vijayakumar. 2006. The winding road towards "zero" energy: Lessons from monitoring efficient solar homes. *Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA* 1:235–46.