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Wisdom Way Solar Village: Design, Construction, and Analysis of a Low-Energy Community

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Consortium for Advanced Residential Buildings

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Contents

List of Figures

Unless otherwise noted, all figures were created by the CARB team.

List of Tables

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Definitions

AFUE	Annual Fuel Utilization Efficiency
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
CARB	Consortium for Advanced Residential Buildings
cfm	Cubic feet per minute
DOE	U.S. Department of Energy
EGUSA	EnergyGauge USA
kW	kilowatt
kW_{STC}	kilowatt at Standard Test Conditions (PV ratings)
low-e	low emissivity
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
RDI	Rural Development, Inc.
SHGC	Solar heat gain coefficient
SWA	Steven Winter Associates, Inc.
WWSV	Wisdom Way Solar Village

Executive Summary

In 2010, Rural Development, Inc. (RDI) completed construction of Wisdom Way Solar Village (WWSV), a community of ten duplexes (20 homes) in Greenfield, Massachusetts. From the beginning of the design process and throughout construction, RDI was committed to very low energy use. Key features of the project and its homes include:

- Careful site plan so that all homes have solar access (for active and passive systems)
- Cellulose insulation providing R-40 walls, R-50 ceiling, and R-40 floors
- Triple-pane windows
- Airtight construction (~0.1 cfm50/ft^2 enclosure area)
- Solar water heating systems with tankless, gas, auxiliary heaters
- PV systems (2.8 or 3.4kW$_{STC}$);
- 2-4 bedrooms, 1,100-1,700 ft^2.

The design heating loads in the homes were so small that each home is heated by a single, sealed-combustion, natural gas room heater. The cost savings attributed to the simple HVAC systems helped to make possible the tremendous investments in the homes' envelopes. The Consortium for Advanced Residential Buildings (CARB) team monitored temperatures and comfort in several homes during the winter of 2009-2010. In the spring of 2011, CARB obtained utility bill information from 13 occupied homes.

Because of efficient lights, appliances, and conscientious home occupants, the energy generated by the solar electric systems exceeded the electric energy used in most homes. Most homes, in fact, had an annual net credit from the electric utility. Total natural gas costs averaged $377/yr (for heating, water heating, cooking, and clothes drying). Because of net credits from solar electricity generation, average total energy costs ($337/yr including all utility fees) were even less than average natural gas costs. The highest annual energy bill for all of the evaluated homes was $458; the lowest was $171.

Acknowledgements

CARB's work in this project has been funded through the Building America program, which is part of the U.S. Department of Energy Building Technologies Program. CARB would like to thank committed people at RDI, their contractors, Austin Design, Joan S. Rockwell & Associates, and also WWSV homeowners who participated in evaluation efforts. CARB is also grateful to Western Massachusetts Electric Company and Berkshire Gas for providing utility bill information.

1 Introduction and Background

The Consortium for Advanced Residential Buildings (CARB) is an industry research team funded through the U.S. Department of Energy Building America (BA) program. CARB is led by Steven Winter Associates, Inc. (SWA), a firm of architects, engineers, and building system consultants with offices in Norwalk, Connecticut; New York, New York; and Washington, D.C.

Rural Development, Inc. (RDI) has been a pioneer in developing and building affordable, efficient, and sustainable homes. RDI is a not-for-profit agency whose mission is, “to advance the right of all people in Franklin County and the North Quabbin region to occupy environmentally responsible, energy efficient, affordable housing and to improve economic independence. Further, RDI strives to promote environmental awareness, and to operate in a manner that is respectful of the rural character of our region.”

Figure 1. RDI’s prototype BA home in Colrain, Massachusetts. The home was completed in May 2007.

RDI began participating in utility-sponsored ENERGY STAR® programs in 2000. Since then, RDI has endeavored to steadily improve the performance, efficiency, and overall sustainability of its homes. The company began incorporating solar electric systems into ENERGY STAR homes in 2004 (with support from the Massachusetts Technology Collaborative) and, in 2005, RDI received the national Award of Excellence for Affordable Housing Built Responsibly from the Home Depot Foundation. Also in 2005, RDI began working with CARB to design a prototype home with exceptional energy performance. This prototype home (Figure 1) was completed in Colrain, Massachusetts, in May 2007; CARB closely observed the construction process and monitored the energy systems for three years after completion.

Building on the successes and lessons learned from this prototype home, RDI began planning a community of very low energy homes. RDI worked closely with architects at Austin Design (designers of the prototype home) and engineers at CARB to plan the community. Located on Wisdom Way in Greenfield, Massachusetts, RDI named the project Wisdom Way Solar Village (WWSV).

Wisdom Way Solar Village consists of 10 duplexes (20 dwelling units total) including two-, three-, and four-bedroom homes. Eighteen of the 20 homes are owner-occupied; RDI will rent the two fully accessible units to residents with disabilities. All homes are "visitable" by persons in wheelchairs. The first unit was completed in late 2008; the last homes were completed in September 2010. CARB has obtained utility bill information from 13 of the occupied homes.

Figure 2. One of the completed WWSV duplexes

In addition to supporting the design and construction team, CARB's goals included documenting how well—and how cost effectively—advanced systems could be implemented on a community scale. Integrating the double-wall systems, simple HVAC, and solar thermal systems were of particular interest. Finally, CARB hoped to evaluate occupied homes to determine how energy costs compared to modeling and predictions.

The CARB team hopes that the results of this effort will provide solid examples of systems that provide dramatic, cost-effective energy reductions without sacrificing comfort. The results also highlight several technology gaps and opportunities for improvement.

2 Planning and Design

2.1 Project Team

RDI found value in assembling a design team very early in the project—even before the land was acquired. In addition to several RDI staff members (the builder and developer), the design team included architects from Austin Design, a civil engineer, the landscape architect, the mechanical engineer, RDI's lawyer, solar contractors, plumbers, the electrician, site and foundation contractors, a utility representative, the home energy rater, and other specialists as needed. Not every member of the team attended every meeting, but having this group of committed professionals willing and able to address problems and meet as needed was critical to the project's success. The team continued working together to address concerns and resolve issues as the project progressed. In addition to having a professional design team, RDI also organized periodic meetings with interested members of the community and potential home buyers to evaluate concerns and gather suggestions for the project.

Many members of the design team met to discuss the potential project before the land was purchased. It was determined that the site could support 20–25 dwelling units with substantial room for open space. Designers worked with the town of Greenfield, Massachusetts, to evaluate various development options; the final plans called for a community consisting of 20 dwelling units in 10 duplexes.

2.2 Site Planning

Site planning is one of the most important, but often overlooked, elements in designing communities of high performance homes. The infill site for the community was very level and had very few trees or other obstructions. Until recently, the site had been used as overflow parking for the nearby county fairgrounds. The design team met very early in the process to consider:

- Creating a "neighborhood" rather than a typical, suburban development
- Providing open space for recreation, gardening, and other outdoor activities
- Incorporating utilities and roads efficiently
- Providing southern orientation for all homes to allow for passive and active solar
- Designing functional landscaping that would not cause detrimental shading
- Making the community accessible to people with disabilities.

The design team explored various clustered development options; the final site plan approved by town officials is shown in Figure 3. The 10 duplexes are sited to ensure solar access for all homes. Open space is preserved in the northwest corner of the site, and a narrow strip on the western edge of the block (which is shaded by tall trees to the west) is also left open. CARB worked with RDI and Joan S. Rockwell & Associates, the landscape architect, to specify maximum mature heights for plantings so that solar access to homes would not be compromised now or in the future.

Figure 3. Site and landscape plan from Joan S. Rockwell & Associates. North is toward the top of the page.

2.3 Home Plans

The community consists of 20 homes in 10 duplexes as outlined below:

- Four 2-bedroom, one-story homes (1,137 ft^2; two are fully accessible)
- Four 2-bedroom, two-story homes (1,140 ft^2)
- Nine 3-bedroom, two-story homes (1,390 ft^2)
- Three 4-bedroom, two-story homes (1,773 ft^2).

Typically, the homes feature an open downstairs plan containing living, dining, and kitchen areas as well as a powder room. Upper floors generally contain bedrooms and a full bath. In single-story homes, the living, dining, and kitchen areas are toward the southern sides of the homes, while the bedrooms and bathroom are in the northern sections. Plans for one duplex, showing a 2-bedroom and 3-bedroom unit, are shown in the appendix.

Throughout the design process, CARB performed energy modeling on proposed designs and provided feedback to the team about performance and preliminary cost effectiveness. The final systems and specifications are outlined below.

3 Building Specifications

Specifications and construction details selected for the homes are described below. In addition, the decision-making processes, challenges that occurred during construction, and recommendations for improving on these construction techniques are noted.

3.1 Basement

All homes have full, unconditioned basements. The first-floor joist bays are insulated with 11.5 in. of blown cellulose for approximately R-39 ft^{2}hr°F/Btu.

Figure 4. Ceiling of a basement insulated with blown cellulose

Whenever possible, CARB recommends insulating foundation walls rather than the first floor joist cavity above the basement. Proper insulation of basement walls results in warmer, dryer, and more usable basement spaces. RDI determined, however, that insulating the floor joist area was much less costly and more practical than insulating walls. Energy modeling showed that R-18 ft^{2}hr°F/Btu rigid foam insulation (3 in. of polyisocyanurate) adhered to the walls would achieve the same overall energy performance as R-39 floors. The blown cellulose was considerably less expensive and simpler to install. In many areas, foil-faced polyisocyanurate foam is approved for basement wall application and can be left exposed in basements. At this site, however, RDI believed that the local code officials would require that the foam be covered with drywall, further increasing the cost.

3.2 Above-Grade Walls

One of the key features of RDI's previous prototype home in Colrain, Massachusetts, is double-wall construction (achieving approximately R-40), therefore, RDI chose this wall system for WWSV. Each exterior wall assembly begins with a load-bearing, 2 × 4 framed wall (framing at 16 in. on center). Carpenters then enclose the entire envelope: wall sheathing, roofing, windows, and doors. Once the home is enclosed, carpenters begin interior framing by constructing an additional 2 × 4 wall 5 in. inside of the existing, exterior wall. Fiber-reinforced polyethylene or insulation netting is stapled to the inner studs, and the entire 12-in. wall cavity is filled with dry-blown cellulose insulation at densities of at least 3.4–4 lb/ft^3. The cellulose manufacturer recommends using higher-than-average insulation densities to prevent settling in such large wall cavities.

In the first two duplexes, reinforced polyethylene was installed as a vapor barrier on the inside of the double wall. A vapor barrier is required by the Massachusetts code, but the design team felt strongly that the wall would be more durable (i.e., more forgiving of moisture intrusion) if it could dry somewhat to the interior. RDI approached the Greenfield building department to assess options for omitting the polyethylene, and the building department eventually allowed this wall system (Figure 5) after receiving stamped letters from architects and engineers.

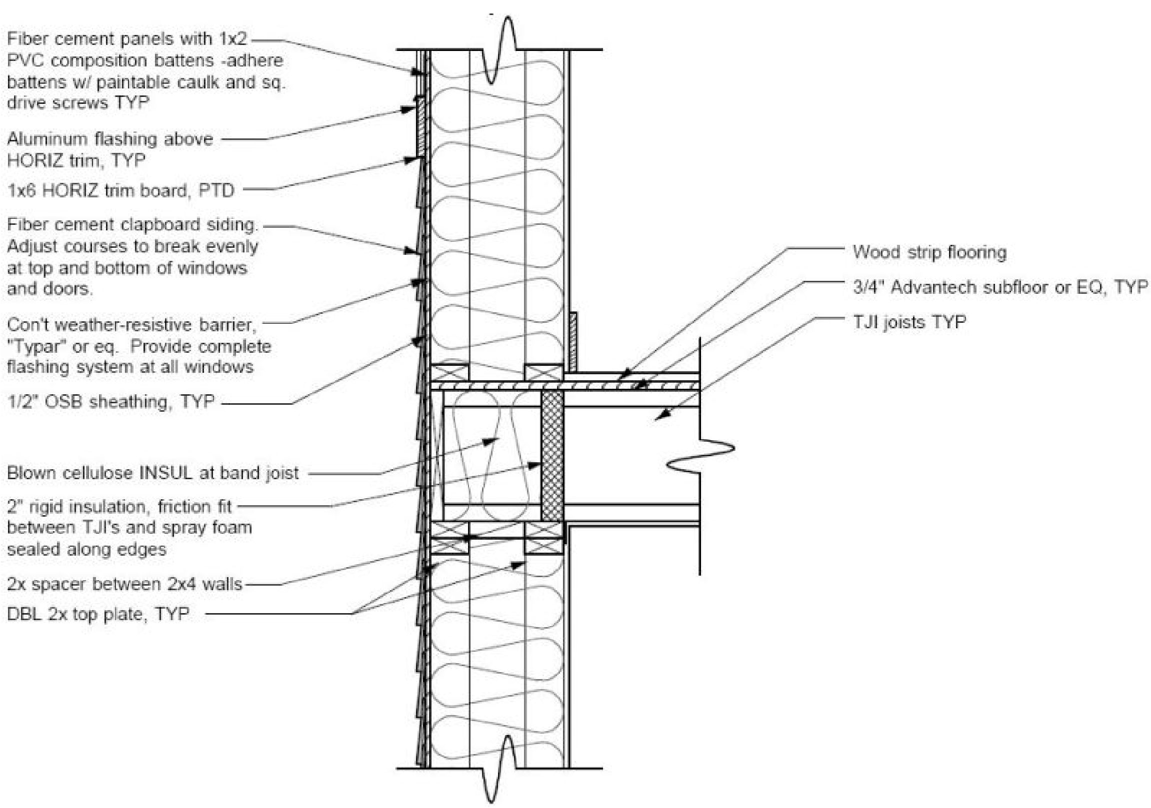

Figure 5. Typical wall section from Austin Design, Inc. Insulation netting was used instead of rigid insulation between floor joists.

Figure 6. Double walls before and after cellulose insulation

Planning for wall penetrations is critical with double-wall construction. Several venting challenges required on-site meetings to coordinate venting and insulation. Around dryer exhaust, exhaust fans, combustion venting, and other plumbing penetrations, RDI carpenters made special insulation accommodations (depicted in Figure 7). A separate compartment of insulation netting was installed around vents, and these compartments were blown separately. In this way, if these penetrations need to be accessed for any reason, only the small amount of insulation surrounding them would need to be removed. Without this provision, insulation in the entire wall could be compromised.

Figure 7. Insulation netting surrounding water heater combustion air and exhaust piping. These small areas were insulated separately to allow access if needed in the future.

The double-wall construction seems to work very well for RDI for two key reasons:

- The homes are designed with double-wall construction in mind. The perimeters of the homes are basically rectangular with very few interruptions (each home has one box bay). Employing the double-wall technique on more complicated homes with elements such as dormers, gables, angles, and bays would require additional time and materials.
- RDI had a core group of carpenter employees that built the homes, and did not have to rely on (or train) outside framing contractors for this specialized job.

Because of these key factors, the added costs for double walls were affordable. CARB surveyed RDI's carpenters and insulators to assess the added time and material needed for building double-wall systems. These estimates are shown in Table 1. The double walls provide approximately R-40 $ft^2hr°F/Btu$, which is a dramatic improvement over RDI's standard 2 × 6 (R-15) walls.

Table 1. Approximate Incremental Costs for Double-Wall Construction in a 3-Bedroom Home at WWSV. Costs are Compared to Conventional 2 × 6 Construction with Blown Cellulose.

	Increased Cost (over 2x6 wall)
Framing Labor	$2,520
Framing Materials	$256
Insulation (Time and Material)	$1,000
Total:	$3,776

3.3 Attic

Roofs of the homes are constructed with manufactured, raised-heel trusses. Vented attics incorporate full soffit and ridge vents and full insulation baffles at every truss bay. Homes are insulated with 14 in. of loose-blown cellulose for an R-value of approximately 50 $ft^2hr°F/Btu$. Incremental cost for this insulation (over the typical R-38) was approximately $300 per home.

3.4 Windows

RDI had typically obtained low-e, vinyl-framed windows from Paradigm Windows, a manufacturer based in Portland, Maine. Paradigm makes double-pane, low-e windows with foam-filled frames that achieve U-values of 0.26 $Btu/ft^2hr°F$ and solar heat gain coefficients (SHGCs) of 0.28.

At the prototype home in Colrain, Massachusetts, Paradigm provided windows with a Heat Mirror membrane. The Heat Mirror product is a low-emissivity, polymer film that is suspended between the two panes of glass, effectively acting as a third pane. These windows had a U-value of 0.20 $Btu/ft^2hr°F$ and SHGC of 0.25. While Paradigm provided these windows for the prototype at no incremental cost (above the standard double-pane windows), the normal cost of these windows was twice that of RDI's standard double-pane, low-e windows.

For WWSV, RDI again planned to use Heat Mirror windows, despite the cost. There were supply issues with the Heat Mirror product, however, and Paradigm began offering a triple-pane product with similar thermal performance (U-value of 0.18 $Btu/ft^2hr°F$, SHGC of 0.23). While these windows would provide excellent thermal performance, the visible transmittance (VT) of the windows was rather low at 0.37.

Partly because of the low VT, RDI sought windows that would transmit more visible light and—at least for the southern elevations—would admit more solar heat. While these homes do not have a tremendous amount of southern glazing (88 ft^2 in the 3-bedroom unit), higher solar gain in southern windows can offset some gas use.

CARB worked with RDI to find windows with higher solar gain (ideally 0.50 or above) and VT, but with U-values near 0.20 Btu/ft^2hr°F. Unfortunately, the search was not fruitful; CARB and RDI contacted approximately 20 different window manufacturers (many in Canada), but none was able to provide vinyl-framed windows with the desired properties (only windows with very low SHGC were found). Several manufacturers of custom, fiberglass windows could meet the desired performance criteria, but their products were prohibitively expensive. CARB also contacted window researchers at Lawrence Berkeley National Laboratory, who provided contacts of several glazing manufacturers. These contacts, however, failed to lead to providers of affordable triple-pane windows with the desired properties.

RDI also worked with Paradigm to see if they could manufacture a window with these properties, but Paradigm was not able to do so. Paradigm did, however, provide double-pane windows with the low-e coating on surface 3 (basically the reverse of the company's typical low-e product), which raised the SHGC to 0.37. The final specification for windows at WWSV is shown in Table 2.

Table 2. Window properties at Wisdom Way Solar Village

Orientation	Manufacturer	Description	U-value [Btu/ft^2hr°F]	SHGC	VT
South	Paradigm	Double-pane, low-e on surface 3	0.26	0.37	0.53
North, East, West	Paradigm	Triple-pane, low-e on surfaces 2 and 5	0.18	0.23	0.37

The triple-pane windows cost approximately \$35/ft^2, 55% more than the \$23/ft^2 for double-pane windows. Total increased cost of windows for a 3-bedroom WWSV home was $1,436.

3.5 Air Sealing

Since RDI began building ENERGY STAR homes, it has paid increasing attention to creating airtight envelopes. Careful sealing, including joints in sheathing, around windows and doors, and all penetrations in plates and walls, is standard practice. Blower door testing on the WWSV homes showed leakage in the range of 200 to 350cfm when homes were depressurized to 50 Pa.

3.6 Heating Systems

Because of the superb envelope, the design heat loads of these units are very small: 9,000–13,500 Btu/h (calculated per ACCA Manual J procedures). To satisfy the very small loads, RDI specified a very small, simple heating system—a sealed-combustion, natural gas-fired room heater located in the central area on the first floor of every unit. The unit is a Monitor Products model GF1800; capacity is 10,200 Btu/h at low fire, 16,000 Btu/h on high fire, and the Annual

Fuel Utilization Efficiency (AFUE) is 83%. The location of the heater is shown on the floor plans in the appendix.

In previous projects, RDI has typically used an ENERGY STAR boiler (either gas or oil) and hydronic baseboard convectors. Compared with the standard boiler, the unit heater results in initial cost savings of approximately $4,000, which helps to offset the significantly higher envelope costs. CARB and RDI have discussed home comfort at length. To alleviate concerns about temperature differentials, and to improve ventilation performance, CARB worked with RDI to design a very simple air distribution system. This is described further in the 3.7 Ventilation Systems section below. To assure comfort in bathrooms, each full bathroom upstairs contains a small, 500-watt electric resistance heater. The electric heaters are wired to a crank timer so they cannot be left on for long periods of time.

In conjunction with the National Renewable Energy Laboratory (NREL), CARB performed short-term thermal comfort testing on one of the first completed WWSV homes in February 2009. As expected, testing found that unoccupied upstairs bedrooms with doors closed were substantially cooler than the downstairs living room. However, when doors were opened or when a small load (a 60-W lamp) was introduced, bedroom temperatures were much closer to downstairs temperatures.

CARB followed this short-term testing with tests of four occupied homes during the winter of 2009–2010. This monitoring revealed that upstairs bedrooms were usually slightly cooler than downstairs spaces (where the heater was located). None of the occupants, however, had major complaints about comfort. Some occupants surveyed were quite pleased, saying that comfort in the home exceeded expectations. Much more information about these heating systems, test results, occupant interviews, and other implications of these systems can be found in CARB's report "Point-Source Heating Systems in Cold-Climate Homes: Wisdom Way Solar Village" (CARB 2010a).

3.7 Ventilation Systems

As with most of RDI's homes, the WWSV dwellings use an exhaust-only ventilation strategy. In the primary bathroom of each home (the bathroom with a shower), a Panasonic WhisperGreen exhaust fan (model FV-08VKSL1) is installed and programmed to run continuously to meet the whole-building ventilation requirements of ASHRAE Standard 62.2-2007 (30–60 cfm, depending on the home size). The fan is also equipped to boost to high speed (80 cfm) for an adjustable amount of time when the bathroom is in use.

Exhaust-only ventilation is a common, affordable ventilation system for small homes in northern climates where air conditioning and duct systems are not always installed. For RDI—a developer of affordable housing for many first-time homeowners—an additional benefit of exhaust-only systems is the very low maintenance requirements. From an energy standpoint, new exhaust fans with brushless, permanent-magnet motors typically draw 5–11 watts. With such low power consumption, the overall energy and operating costs of these exhaust-only systems are less than operating costs of some heat recovery and energy recovery ventilators. CARB and NREL conducted tracer gas testing at the RDI prototype home; this home also had exhaust-only ventilation. The researchers found that when all interior doors are closed, some parts of the home experience much less fresh air exchange than do other areas. While it's unclear if this presents a problem with indoor air quality, it is not ideal.

In homes at the WWSV, CARB worked with RDI to incorporate a simple air distribution system to minimize discrepancies in fresh air delivery to rooms. As an added benefit, the system also helps to equalize air temperatures between spaces in the home. Each home contains an additional Panasonic WhisperGreen fan which draws air from the ceiling of the first floor and distributes a small amount of this air (20–25 cfm) to each bedroom. Mechanical plans showing equipment and duct layouts are included in the appendix.

Figure 8. The exhaust fan and simple duct distribution system installed between the first and second floors

In conjunction with NREL, CARB performed multipoint tracer-gas testing to evaluate air change rates throughout the homes. Test results showed that the simple air distribution system improves fresh air mixing. During one tracer gas test, in which all interior doors were closed and the distribution system was turned off, the reciprocal age of air ranged from 0.15 h^{-1} in one bedroom to 0.30 h^{-1} in the living room. With the mixing system turned on, reciprocal average age of air ranged only from 0.27 h^{-1} in one bedroom to 0.32 hr^{-1} in the living room (in a home with perfect mixing, reciprocal age of air would be equal in all rooms).

For more information on these tests, see CARB (2010a). For more information about reciprocal age of air tests and analysis methods, see Barley et al. (2007).

3.8 Lights and Appliances

RDI participated in an ENERGY STAR program sponsored by the local utility (Western Massachusetts Electric Company, WMECO). As part of this program, RDI received screw-in compact fluorescent lamps for all fixtures in the homes. All appliances supplied by RDI (refrigerators and dishwashers) were ENERGY STAR rated.

3.9 Water Heating

Most of the domestic water heating energy needs in the homes is provided by solar thermal systems. Flat-plate solar collectors are mounted on the southern roof of each home, and a propylene glycol solution is circulated between the collectors and a heat exchange coil in a 110-

gal storage tank in the basement. A direct current pump circulates the glycol; the pump is powered by a dedicated 20–30 watt photovoltaic (PV) module. A sealed-combustion, natural-gas-fired, tankless water heater provides auxiliary water heating in each home. Three- and four-bedroom homes have three, 29-ft^2 solar thermal collectors; the 2-bedroom units have two collectors.

As Figure 2 and Figure 12 show, southern roof space was limited in these homes. RDI's original plans called for solar thermal systems to provide a portion of the space heating load as well as water heating. However, to provide a substantial portion of the space heating load, one or two additional solar thermal collectors would be needed, and there was insufficient roof space to support additional collectors.

3.10 Solar Electric Systems

Each home has a solar electric system installed on the roof. Two-bedroom homes have 2.84-kW_{STC} PV systems; three- and four-bedroom homes have 3.42-kW_{STC} systems. All systems are installed flush on the roof (10/12 pitch, 40° tilt) and facing within 10° of true south. Each system has one inverter located in the basement of each home.

4 Modeling Methods

4.1 Building America Benchmark Analyses

CARB conducted building energy analyses to compare the energy use of WWSV homes to the BA Research Benchmark Definition (Hendron 2009) and to a code-compliant home. The BA Benchmark used is consistent with mid-1990s standard building practice for the climate zone. Greenfield, Massachusetts, falls in the cold climate zone (DOE climate zone 5) with approximately 7,200 heating degree-days (HDD) per year (65°F base) and 2,200 cooling degree-hours (74°F base). The 99% heating design temperature is 2°F.

CARB used EnergyGauge USA v2.7.03 (EGUSA), an hourly energy simulation tool, to model the energy performance of a 3-bedroom home. Performance of the solar thermal system was modeled with F-Chart software, and PV generation was estimated with NREL's PVwatts tool. The modeled 3-bedroom unit is midsized for the development, and it is also the most common (accounting for 9 of the 20 homes). According to these analyses, the home will require 57% less source energy to operate than a home built to the benchmark definition. When the PV generation is included, source energy savings is 77% when compared to the benchmark home. Table 3 shows the modeled site energy by end use, and Table 4 shows the estimated source energy for a 3-bedroom home at WWSV.

Table 3. Modeled Site Energy of 3-Bedroom Home Compared to the Building America Benchmark

	Annual Site Energy			
	Benchmark		Prototype	
End Use	kWh	Therms	kWh	Therms
Space Heating	739	1,024	212	258
Space Cooling	851	0	547	0
DHW	0	242	0	53
Fixed Lighting	1,490		415	
Appliances	1,056	98	937	98
Plug Load	2,578	11	2,578	11
Plug-in Lighting	309		86	
OA Ventilation	190		53	
Total Usage	7,213	1,375	4,828	420
Site Generation			4,060	
Net Energy Use	7,213	1,375	768	420

Table 4. Modeled Source Energy of 3-Bedroom Home Compared to the Building America Benchmark (2007).

			Soruce Energy Savings		
	Annual Source Eenrgy		Percent of	Percent of	Component
	Benchmark	Proto	End-Use	Total	%
End Use	MMBtu/yr	MMBtu/yr	Prototype	Prototype	Prototype
Space Heating	120.3	30.6	74.6%	38.5%	68.1%
Space Cooling	9.8	6.3	35.7%	1.5%	2.7%
DHW	26.4	5.8	78.2%	8.9%	15.7%
Fixed Lighting	17.1	4.8	72.1%	5.3%	9.4%
Appliances	22.8	21.5	6.0%	60.0%	1.0%
Plug Load	30.8	30.8	0.0%	0.0%	0.0%
Plug-in Lighting	3.5	1.0	72.2%	1.1%	1.9%
OA Ventilation	2.2	0.6	72.3%	0.7%	1.2%
Total	233.0	101.4	56.6%	56.5%	100.0%
Site Generation		46.6	20.0%	20.0%	
Net Energy Use	233	54.7	76.5%	76.5%	

4.2 REM/Rate Modeling

Steven Winter Associates performed REM/Rate analyses in addition to BA Benchmark modeling. REM/Rate is the modeling tool used by most home energy raters in the region, and SWA has found that it provides accurate predictions of heating energy use. Models assumed infiltration of 350 cfm50 for all homes; blower door testing ultimately revealed that infiltration was below this value for most (if not all) homes.

While REM/Rate typically produces very accurate predictions of heating energy, it has less success with predictions that depend more heavily on behavior of home occupants. A summary of the REM/Rate results is presented in Table 5 and Table 6. Table 7 shows the associated costs predicted at current utility rates.

Table 5. Results of REM/Rate Modeling on Natural Gas Use in Each Home Type

	Modeled Annual Gas Use [Therms]			
	2-BR (1-story)	2-BR (2-story)	3-BR	4-BR
Space Heating	177	182	185	242
Water Heating	14	14	24	20
Other	74	74	89	104
Total:	265	270	298	366

Table 6. Results of REM/Rate Modeling of Electricity Use and Generation in Each Home Type

	Modeled Annual Electricity [kWh]			
	2-BR (1-story)	2-BR (2-story)	3-BR	4-BR
Consumption	1,765	1,769	1,935	2,300
Generation	3,394	3,394	4,087	4,087
Net	(1,629)	(1,625)	(2,152)	(1,787)

Table 7. Modeled Energy Costs from REM/Rate*

	2-BR (1-story)	2-BR (2-story)	3-BR	4-BR
Total Utility Fees	$218	$218	$218	$218
Gas Cost	$398	$405	$447	$549
Electricity Cost	-$228	-$228	-$301	-$250
Net Cost	$388	$395	$364	$517

* Utility fees include $9.65 per month for gas and $8.53 per month for electricity. Gas rates used here are $1.50 per therm and $0.14 per kWh.

REM/Rate energy consumption predictions are notably less than BA Benchmark analyses using EGUSA software. This is discussed further in the 6.2 Modeling Comparisons section below.

5 Results

5.1 Electric Bills

All buyers of the WWSV homes agreed to allow RDI and SWA to access their utility bill information. CARB was able to access natural gas and electricity consumption data from 13 homes that have been occupied for one year or more.

From the electric utility, CARB was usually able to obtain net energy consumption (or generation); details about actual consumption and PV generation were not available. Figure 9 shows average net daily energy use in each of the homes for which data were available.

For the most recent 12 months (mid-June 2010 through mid-June 2011), CARB obtained net electricity consumption data for 11 occupied homes. Of these homes, nine generated more energy than was consumed. Six homes generated enough excess electricity to offset all utility fees; these six homes have net credits from the electric utility. Table 8 shows an annual summary for these 11 homes. The average home generated an excess 1.6 kWh/day, and the average annual electric utility cost was $8.

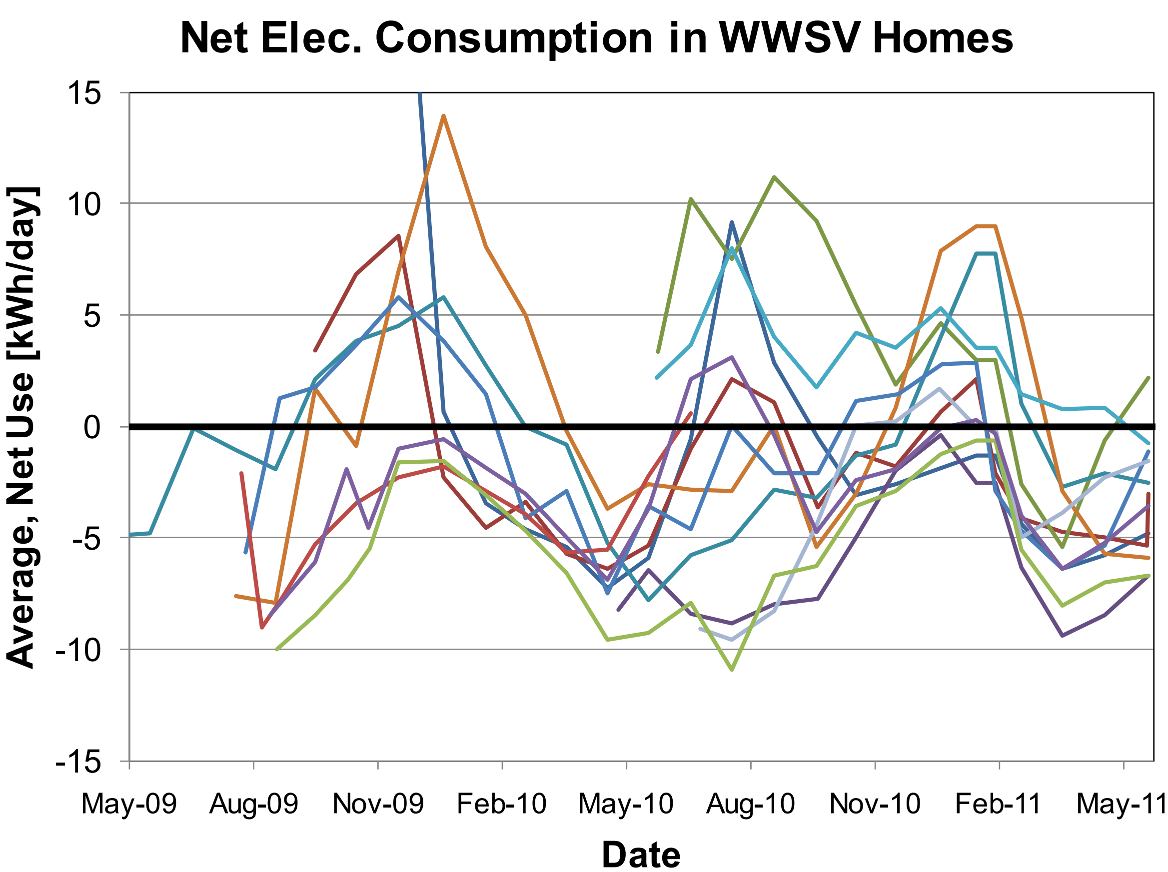

Figure 9. Average net electricity consumption in WWSV homes from monthly utility bills. Negative values indicate net generation.

Table 8. Summary of Electricity Bills for 11 Homes

	12 Mo. Net Electric Use		
Unit	kWh	kWh/day	Cost
2-1 A	-707	-1.9	-$6
2-1 B	1112	3.0	$245
2-2 A	-708	-1.9	-$73
2-2 B	-2256	-6.1	-$216
2-2 C	-180	-0.5	$68
3 A	-738	-2.0	-$6
3 B	1446	3.9	$289
3 C	-427	-1.2	$35
3 D	-2062	-5.6	-$189
4 A	-624	-1.7	$12
4 B	-1163	-3.3	-$68
	Average	-1.6	$8

"Unit" designation refers to the number of bedrooms in each home. The second number – when present – indicates the number of stories. For example, Unit 2-2 B is a 2-bedroom, 2-story home; multiple units of the same plan are labeled A, B, C, etc. All 3- and 4-bedroom homes have two stories.

5.2 Natural Gas Bills

CARB obtained gas consumption data for 13 occupied homes. Daily average gas consumption from each billing period is shown in Figure 10. Because of a lag in utility bill availability, CARB has a full 12 months of data for only nine occupied homes. Table 9 shows that the average annual gas consumption for these homes was 203 therms resulting in average annual gas costs of $377, including all utility fees. Total annual gas costs ranged from $183 to $485.

The data for one home (2-2C) appear suspect in that gas consumption is extremely low and hardly rises during the winter (note the purple line in Figure 10). However, CARB has been assured by RDI and neighbors that this home is occupied. It is RDI's understanding that the occupants keep the home very cool and use electric resistance heaters to consume electric utility credits.

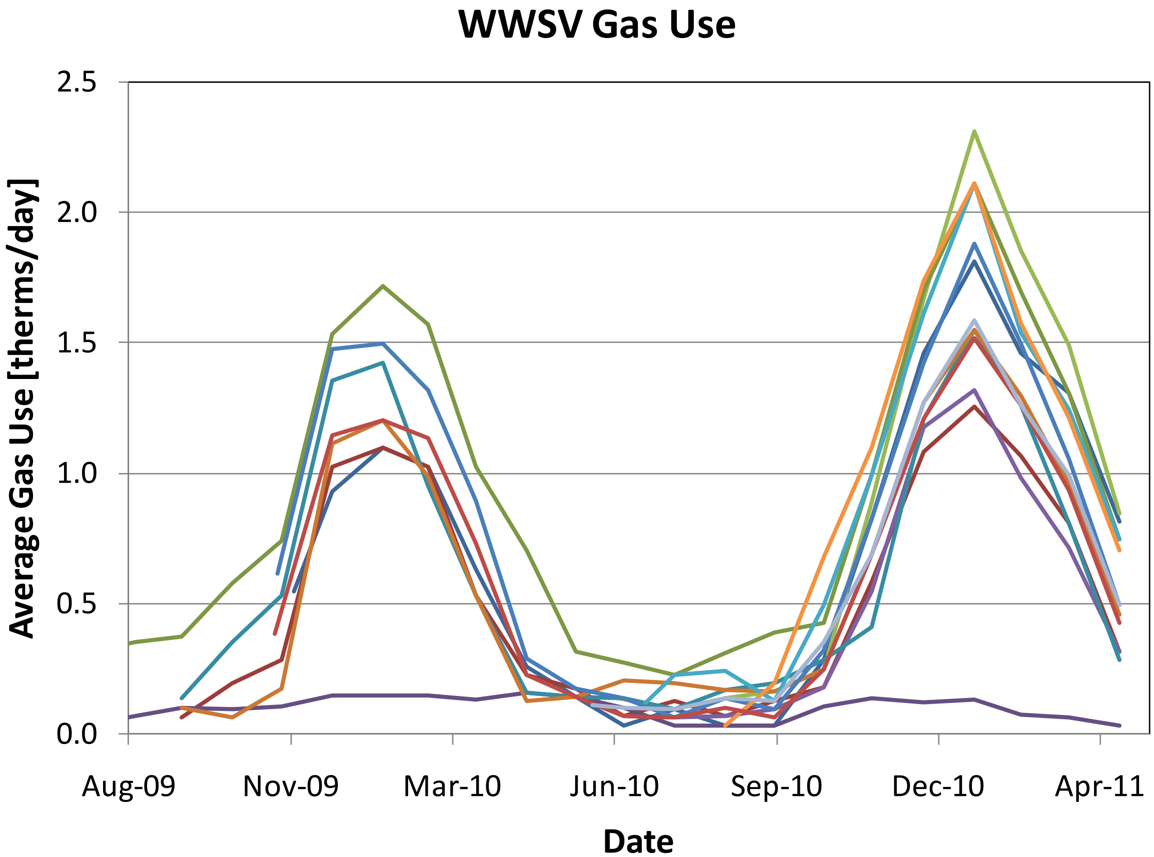

Figure 10. Average natural gas use in 13 occupied WWSV homes

Table 9. 12-Month Gas Consumption for Nine Occupied WWSV Homes

	12 Mo. Gas Use		
Unit	Therms	Therms/day	Cost
2-1 A	204	0.6	$427
2-2 A	252	0.7	$358
2-2 B	174	0.5	$386
2-2 C	31	0.1	$183
2-2 D	224	0.6	$324
3 A	179	0.5	$390
3 C	319	0.9	$422
3 D	246	0.7	$485
4 A	199	0.5	$418
Average	203	0.6	$377

While data from a full year are available from nine homes, data from the previous heating season (October 2010–April 2011) are available from all 13 occupied homes plus two additional unoccupied homes. As Figure 10 shows, gas consumption from May to September was minimal.

It is worth noting that the gas consumption in the two unoccupied homes—which were kept at approximately 55°F with no water heating, cooking, or clothes drying—was only 30% less than the average consumption for the occupied homes. Internal gains in the occupied homes clearly provide much of the energy needed for space heating.

Table 10. Summary of Gas Consumption during Heating Season

	7 Heating Months (Oct'10-Apr'11)		
Unit	Therms	Therms/day	Cost
2-1 A	191	0.9	$ 351
2-1 B	202	1.0	$ 366
2-2 A	242	1.1	$ 314
2-2 B	160	0.8	$ 307
2-2 C	21	0.1	$ 111
2-2 D	197	0.9	$ 265
2-2 E	277	1.3	$ 349
3 A	161	0.8	$ 309
3 B	283	1.3	$ 431
3 C	273	1.3	$ 346
3 D	228	1.1	$ 403
4 A	176	0.8	$ 330
4 B	265	1.3	$ 337
2-1 Unocc.	154	0.7	$ 299
2-1 Unocc.	144	0.7	$ 285
Average (Occ'd):	206	1.0	$ 325

5.3 Total Energy Costs

Between the two data sets, there are eight occupied homes for which CARB has complete energy bill data for an entire 12 months. As Table 11 shows, average annual energy costs – including all utility fees – ranged from $171 to $458. The average cost for energy was $337, or $28 per month.

5.4 Energy Improvement Costs

CARB worked with RDI, its contractors, and its suppliers to determine incremental costs of the advanced energy features as accurately as possible. An overview of these costs is shown in Table 12. Some estimates are unavoidable, especially with respect to time needed to install or implement some strategies (e.g. the double wall). These costs are specific to energy systems only. For example, RDI spent substantial resources making the homes more accessible and including sustainable materials; these costs are not reflected in Table 12.

Table 11. Actual Annual Energy Costs for Eight Occupied WWSV Homes

	Annual Cost		
Unit	Gas	Elec.	Total
2-1 A	$427	$ (6)	$421
2-2 A	$358	$ (73)	$285
2-2 B	$386	$(216)	$171
2-2 C	$183	$ 68	$251
3 A	$390	$ (6)	$385
3 C	$422	$ 35	$458
3 D	$485	$(189)	$297
4 A	$418	$ 12	$430
Average:	$384	$ (47)	$337

Table 12. Approximate Costs for Energy Improvements to a 3-Bedroom RDI Home. Incremental Costs are Compared to Building America Benchmark Specifications

	Incremental Costs		
Measure	Without subsidies	With Subsidies	Notes
Double-wall construction	$3,776	$3,776	From builder calculations and estimates.
R-50 attic insulation	$300	$300	Builder cost calculation.
R-40 floor insulation	$540	$540	From BEopt cost estimates.
Triple-pane windows	$1,436	$1,436	Actual incremental window costs
Heating System	($4,500)	($4,500)	Plumber and builder estimates, including savings from the standard central boiler with baseboard.
Water Heating System	$0	$0	Cost of tankless comparable to standard indirect tank.
Ventilation System	$600	$450	Cost estimates for distribution system; the electric utility provided the fan at no cost.
100% CFL	$114	$0	BEopt estimate of $3.79 per lamp; utility provided all CFLs at no cost.
ENERGY STAR Appliances	$190	$190	BEopt incremental costs for ENERGY STAR refrigerator and dishwasher.
Solar water heating system	$9,750	$0	Pricing from solar contractor plus additional RDI labor. RDI obtained DOE funding for solar thermal systems.
3.4-kW Photovoltaic system	$24,827	$4,574	State incentives provide funding for PV systems.
Total:	$37,033	$6,766	

As Table 12 shows, RDI received substantial subsidies for the energy improvements that went into the home. It's also worth considering the relative incremental costs of the envelope improvements ($6,052), mechanical systems (savings of $3,900), and solar systems ($34,577).

6 Discussion

6.1 Home Size and Energy Use

Results in the previous section show that there is a weak, if any, relationship between net energy use and home size (i.e. number of bedrooms). Figure 11 shows average energy use for homes of each size. CARB does not have information about the occupancy of all homes; number of occupants can certainly be a better indicator of energy use than can number of bedrooms. The results in Figure 11 also include the effects of different PV systems. The 3- and 4-bedroom homes have 3.4-kW PV systems; the 2-bedroom homes have 2.8-kW PV systems.

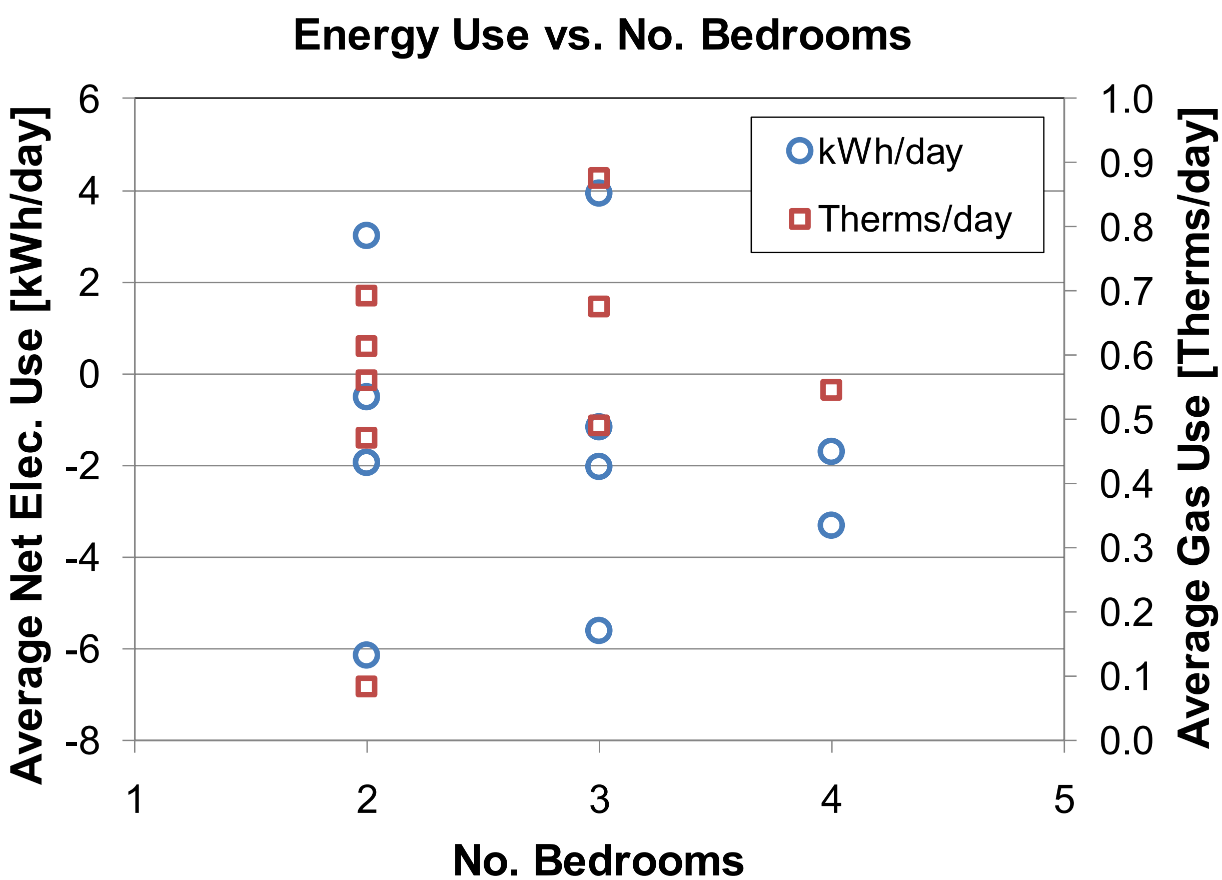

Figure 11. Average energy use for each home vs. number of bedrooms.

6.2 Modeling Comparisons

Energy modeling is by necessity approximate, and it cannot account for variations in occupant behavior. However, when data are available from homes such as these, comparisons to modeling results can be valuable in evaluating general accuracy and possible model shortcomings.

6.2.1 Natural Gas

Table 13 compares modeled natural gas consumption and average measured gas used in each type of home. In these homes, predictions were consistently higher than actual usage.

Table 13. Annual Natural Gas Consumption Predicted by Modeling and Actual Gas Consumed in the Homes.

	Natural Gas Use [therms]			
	2-BR (1-story)	2-BR (2-story)	3-BR	4-BR
REM/Rate	265	270	298	366
EGUSA/Benchmark			420	
Utility Bills	204	217*	248	199
No. Homes	1	3*	3	1

* Home 2-2C, which had abnormally low gas use, was not included in the average.

For 2- and 3-bedroom homes, REM/Rate predictions are 20%–30% higher than actual consumption. In the one 4-bedroom home evaluated, REM/Rate's prediction is 84% higher than measured gas consumption. The predictions made with EnergyGauge USA and the Building America Benchmark procedures were 69% higher than the average of the three, 3-bedroom homes evaluated.

6.2.2 Electricity

Looking at the modeled electricity use (Table 14), EnergyGauge USA and the BA Benchmark procedures again predicted higher energy use than was observed. REM/Rate modeling, however, resulted in predictions lower than those observed.

Table 14. Modeled and Measured Electricity Consumption in the WWSV Homes. The EnergyGauge USA Values are from the 3-Bedroom Home.

	Annual, Net Electricity Use [kWh]
EGUSA/BA	768
REM/Rate	-1847
Utility Bills	-575

6.2.3 Reasons for Modeling Discrepancies

With respect to predicted electricity use, the disparity between the REM/Rate and EGUSA / BA Benchmark models are substantial. Measured electricity consumption fell between the two models. There are two key differences in these two modeling procedures that likely explain most of the discrepancies:

- The BA Benchmark requires that a minimum-efficiency, central air conditioner be modeled in homes in which the builder does not provide air conditioning. This modeled air conditioning results in an additional 1.5 kWh/day (547 kWh/yr). REM/Rate models, on the other hand, include no cooling. While many homeowners did install window air conditioners, it is unlikely that air conditioning energy consumption was as high as what was predicted in the BA Benchmark analyses.

- The Benchmark modeling procedures result in a miscellaneous plug load of 7.3 kWh/day (2,664 kWh/yr) in addition to the lights and appliances load of 3.7 kWh/day (1,352 kWh/yr). The REM/Rate model puts all lights, appliances, and plug loads at 5.3 kWh/day (1,935 kWh/yr)—less than half of the BA Benchmark prediction. From the utility data, it seems average loads are between the two.

Reasons for the gas discrepancies are more difficult to identify. Water use in the homes, including hot water use, is likely much lower than the default values used in the models. In addition to very efficient appliances, low-flow lavatory faucet aerators (0.5 gpm) and showerheads (1.5 gpm) are installed throughout the homes. Neither model accounts for these factors, but the main discrepancy in gas use was observed during the heating season.

The winter of 2010–2011 was not mild. The weather site used in REM/Rate modeling (Vernon, Vermont) has a heating design temperature of 2°F and 7,229 heating degree days (HDD, base 65°F). Weather data obtained from a nearby weather station in Orange, Massachusetts (Weather Underground 2011) show 7,172 HDD and 21 days where temperatures dropped below the 2°F design temperature. The design data for Albany, New York, which was used for EGUSA modeling, shows 6,929 HDD and a design temperature of 2°F. Warmer temperatures cannot explain the lower-than-expected gas consumption.

CARB suspects one of the main reasons for the lower-than-predicted energy usage—for both gas and electricity—is conscientious home occupants. For many buyers of homes in this community, energy efficiency and sustainability were major selling points. It stands to reason that people interested in efficiency would operate their homes more efficiently.

7 Conclusions

Overall, RDI and CARB have been very pleased with the utility bills from the Wisdom Way Solar Village homes. The commitment and attention to detail on the part of RDI, the design team, and contractors was impressive, and it is gratifying to see average energy costs of $337/yr. Below are discussions of several systems or issues that were very successful, challenging, or merit more investigation.

7.1 Cost Effectiveness

As Table 12 shows, total incremental costs for energy improvements in a 3-bedroom WWSV home, above BA Benchmark specifications, were $37,033. After considerable subsidies, RDI's net incremental costs were $6,766. Modeled cost savings (Table 15) were $2,335/yr. When subsidies are included, energy savings provide an effective rate of return of 35% on the efficiency investments (over a 30-year evaluation period). Without subsidies, the modeled rate of return is a much more modest 4.7%.

Table 15. Summary of Modeled and Measured Energy Costs for a 3-Bedroom WWSV Home Electricity Costs are $0.14/kWh and $8.63/month. Gas Costs are $1.40/therm and $9.65/month.

	Annual Energy Cost
Modeled - Benchmark Ref. Home	$ 3,292
Modeled - EGUSA	$ 957
Modeled - REM/Rate	$ 365
Measured - Average Bills	$ 380

As discussed previously, measured energy cost of the occupied homes was significantly lower than modeled costs (using EGUSA and BA Benchmark procedures). It is also worth noting that most of the incremental costs—93% before subsidies—were associated with the solar electric and solar thermal systems (Table 12). The solar systems are responsible for approximately 50% of the energy cost savings. If the envelope, HVAC, lighting, and appliance savings are considered separately from the solar systems, investments in these systems have a 47% effective rate of return.

7.2 Double-Wall System

RDI found that the double-wall system worked quite well for them. While the system is labor-intensive, it was a buildable, cost-effective way to dramatically improve the homes' envelopes. One of the reasons the double-wall system worked especially well for RDI is that the homes were designed with double walls in mind. The footprint of each home is essentially rectangular, and there are no dormers, kneewalls, or variations in wall height on the same floor. During the design phase, the architects were very conscious of simplifying framing to accommodate the double walls.

RDI found that good planning for wall penetrations, especially appliance venting, is important. During construction, there were on-site meetings to find solutions for venting problems as they occurred. Planning for venting is always important, but with double walls, mistakes that require moving penetrations are much more involved. Venting issues were further complicated by accessibility goals of the homes, as discussed below.

7.3 Accessibility

RDI's goal was to make two of the homes fully accessible and the first floors of all homes visitable by people with disabilities. To lower the level of the first floor with respect to grade, the floor joists were hung from the sill at the top of the foundation (rather than set on top of the sill plate). This change had two important impacts: it eliminated the band joist and would have made window wells extremely deep.

Eliminating the band joist (through which vent piping is traditionally run for basement appliances) meant that water heater vent pipes and dryer exhaust pipes had to be run up into the double walls, to 90° elbows, and then to the exterior terminations. In several instances, the first floor wall thicknesses were increased (to approximately 15 in.) to accommodate vent pipes. In other cases, basement appliance venting was run behind cabinets or in small chases. These venting challenges were not entirely clear until construction began.

Because of the low level of the first floor, basement windows would have required very deep window wells. The initial cost and ongoing maintenance of these deep wells moved RDI to eliminate basement windows. The elimination of the windows triggered a requirement for basement ventilation in the first four homes (with code changes part-way through construction, ventilation was not required in the later 16 homes). The building department required both air intake and exhaust to the unconditioned basements; this requirement was met with an exhaust fan and passive intake duct. The exhaust fan operated when basement lights were turned on.

While the goal of having capability to remove pollutants from the basement air is laudable, the effect of this ventilation requirement was the introduction of substantial amounts of moisture into the basements during the summer. CARB and RDI foresaw this, and RDI provided dehumidifiers for these first four homes. The dehumidifiers were intended to be located on shelves so that the condensate could be routed to the washer drain. Homeowner operation of the dehumidifiers, however, proved to be inconsistent. The basement ventilation resulted in very humid conditions in some basements and high electricity use from the dehumidifiers.

7.4 Siding

The architects made great efforts to create simple floor plans to limit the framing time and cost associated with the double-wall system. This resulted in homes that were basically boxes; to make the homes more aesthetically appealing, the architects used several different siding styles and colors. Most agree that these aesthetics work very well, but the details involved in integrating fiber-cement clapboard, shingle, and panel proved to be more challenging, time-consuming, and expensive than planned. CARB was not able to quantify incremental siding costs, but these could be considered indirect costs related to the double-wall system.

Figure 12. Completed WWSV homes

7.5 Mechanical Plans

CARB provided mechanical plans for each home plan, with an understanding that plans might need to be altered based on plan variations, utility locations, or other factors. CARB did not always get timely notification of these variations, and some quick decisions were required on site during construction. In two or three homes, this led to solar thermal tanks being located far from the auxiliary water heaters. With this configuration, there may be more than one gallon of water in the pipe between the two. This leads to reduced solar effectiveness and higher gas use, especially for short hot water draws. This highlights the importance of upfront planning and quality control.

7.6 Room Heaters

RDI was able to save several thousand dollars in each home by installing a single room heater. This is a nonconventional strategy, and CARB performed both short and long-term testing to evaluate the effectiveness of the heating system. Based on monitoring results and interviews with occupants, the systems appear to provide adequate comfort with very low gas costs. Based on the findings, CARB believes this strategy may offer a cost-effective pathway to meet aggressive energy goals and that more detailed investigations are called for. CARB has reported on these results in much more detail in CARB (2010a).

7.7 Solar Thermal Systems

As described above, each home has a solar thermal system that can provide most of the energy for domestic water heating. From the gas bills, it is clear that, during the summer, solar energy provided most (or all) water heating in the homes. In August 2010, CARB began monitoring performance of one system in some detail. Preliminary monitoring results—and details about the many challenges experienced with installing and commissioning the solar systems—are discussed in CARB (2010b).

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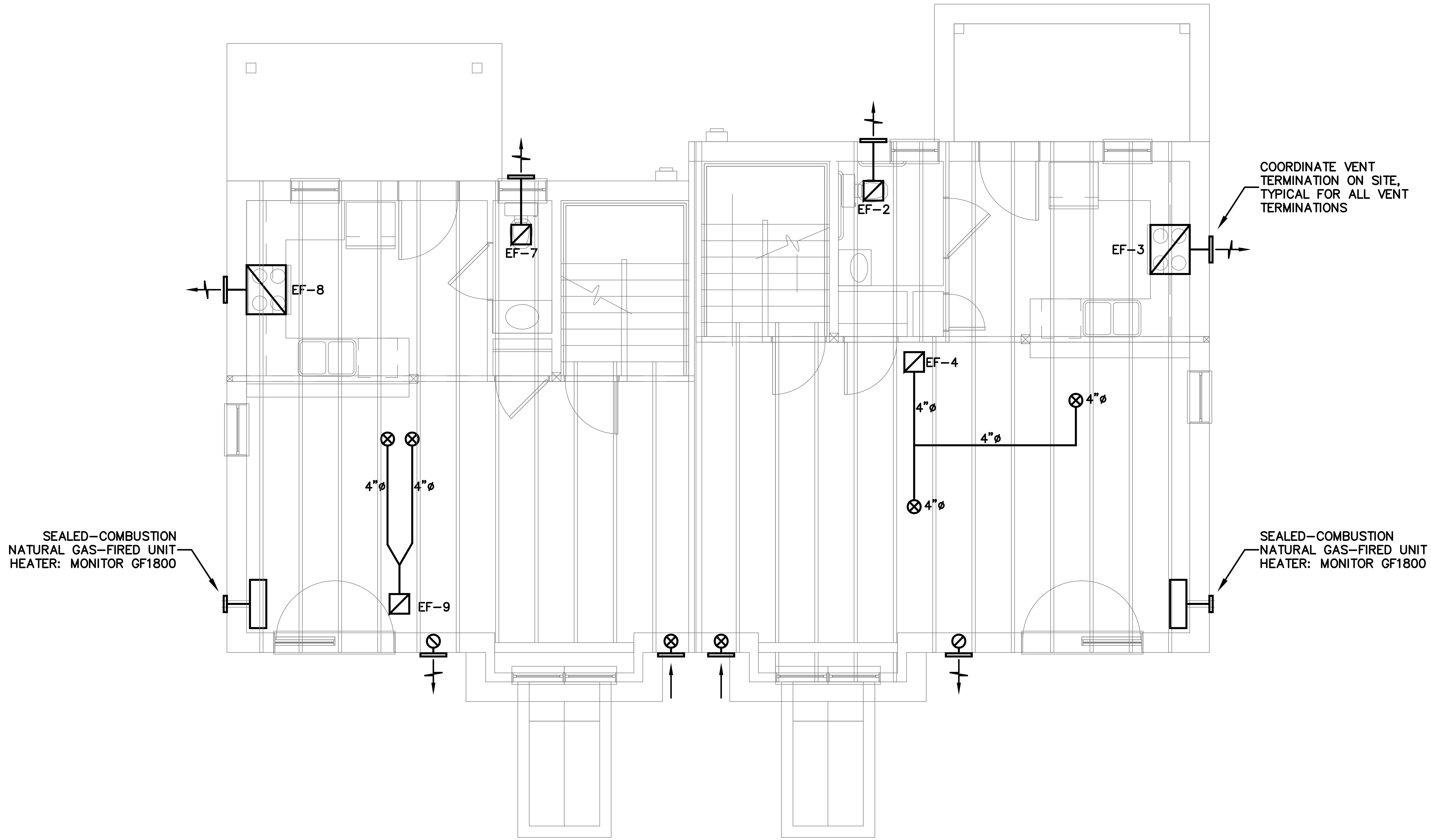
Appendix: Sample Floor Plan

Following is the floor plan of one duplex from Austin Design, Inc. with mechanical layouts provided by CARB.



SHEET 2 OF 4

M-101

SHEET NO:

CHECKED BY: RA
DRAWN BY: RA
FILE:
PROJECT NO: NETL01F

RDI WISDOM WAY SOLAR VILLAGE - LOT 10

GREENFIELD, MA

MARK	DATE	DESCRIPTION
1	4/25/2008	ISSUED FOR REVIEW
2	5/14/2008	MODIFIED FAN SCHEDULE

FIRST FLOOR MECHANICAL LAYOUT

Steven Winter Design, Inc.
50 Washington Street
Norwalk, CT 06854
Telephone: (203) 857-0200
Telefax: (203) 852-0741
www: swinter.com

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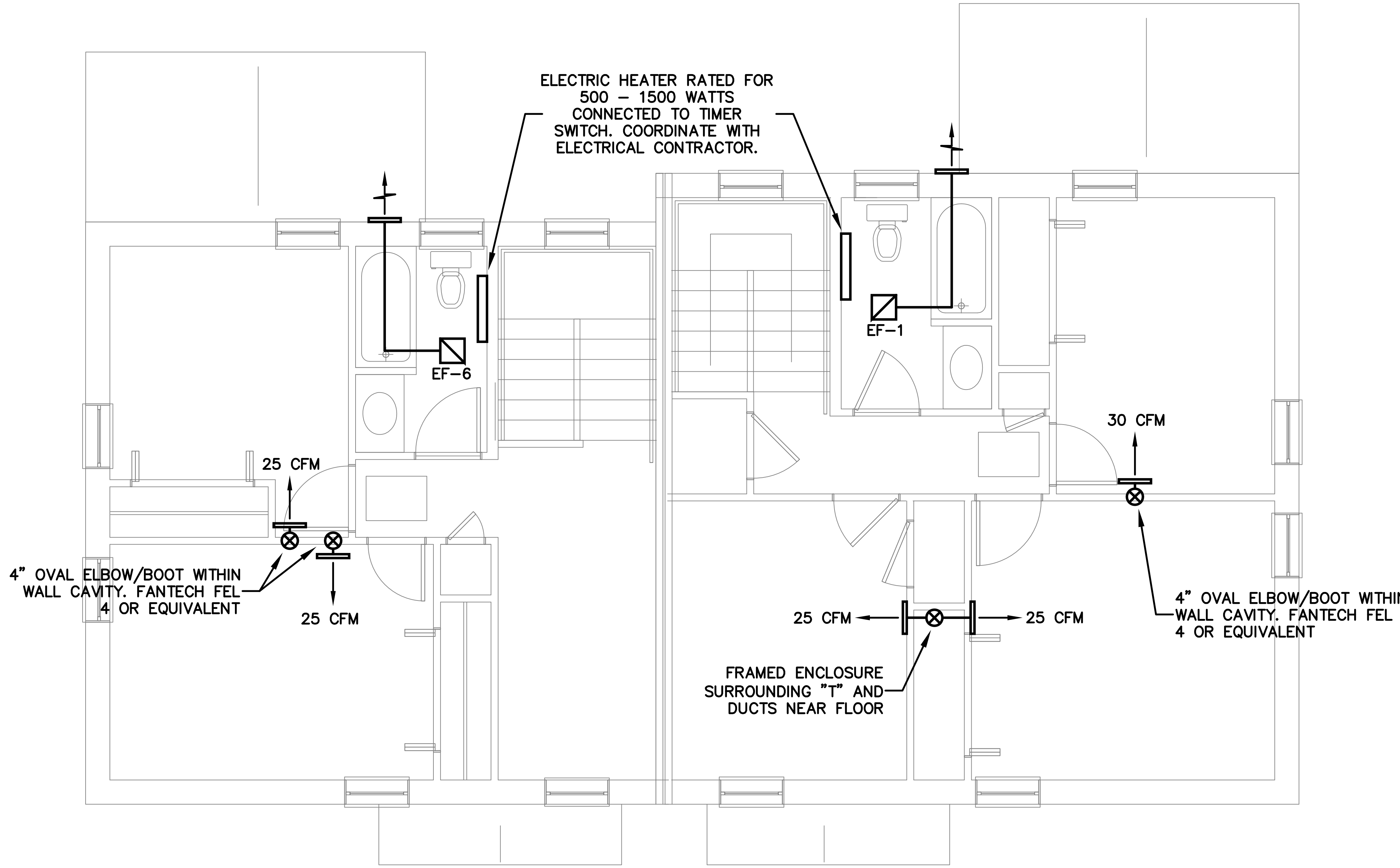

SHEET 3 OF 4

M-102

SHEET NO:

CHECKED BY: RA
DRAWN BY: RA
FILE:
PROJECT NO: NETL01F

RDI WISDOM WAY SOLAR VILLAGE - LOT 10

GREENFIELD, MA

MARK	DATE	DESCRIPTION
1	4/25/2008	ISSUED FOR REVIEW
2	5/14/2008	MODIFIED FAN SCHEDULE

SECOND FLOOR MECHANICAL LAYOUT

Steven Winter Design, Inc.
50 Washington Street
Norwalk, CT 06854
Telephone: (203) 857-0200
Telefax: (203) 852-0741
www: swinter.com

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