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Conway Street Apartments: A Multifamily Deep Energy Retrofit

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Consortium for Advanced Residential Buildings

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

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

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Acknowledgments

The Consortium for Advanced Residential Buildings would like to thank Olive Street Development and Zaccheo Properties for consistently moving toward cost-effective, zero energy, multifamily buildings. Thanks also to New England Solar Hot Water, EWS Plumbing and Heating, Girard Heating and Air Conditioning, and Western Massachusetts Electric Company for their support in this effort.

Definitions

AFUE	Annual Fuel Utilization Efficiency
BEopt™	Building Energy Optimization Software
CARB	Consortium for Advanced Residential Buildings
CFM	Cubic Feet per Minute
CPVC	Chlorinated Polyvinyl Chloride
DHW	Domestic Hot Water
DWHX	Drain Water Heat Exchanger
HSPF	Heating Season Performance Factor
HRV	Heat Recovery Ventilator
HVAC	Heating, Ventilation and Air Conditioning
IECC	International Energy Conservation Code
LED	Light-Emitting Diode
PV	Photovoltaic(s)
R-Value	Thermal Resistance ($ft^2h°F/Btu$)
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
SPF	Spray Polyurethane Foam
U-Value	Thermal Transmittance ($Btu/ft^2h°F$)

Executive Summary

In Greenfield, Massachusetts, Olive Street Development transformed an old elementary school building into 12 high-end rental apartments. The developer aimed to get as close to net-zero performance as practical, installing:

- R-30 high-density spray foam against the brick walls
- R-50 roof assemblies
- New triple-pane windows
- Light-emitting diodes throughout
- Efficient appliances
- Ductless heat pumps for heating and cooling
- A solar thermal system providing most water heating energy
- A 30-kW photovoltaics (PV) system over the parking area.

With all these features, the developer was able to achieve Home Energy Rating System indices of 10–20 for the apartments and 72% source energy savings (50% not including PV). This translates to an annualized energy related cost (mortgage and utilities) savings of roughly $585 per apartment over a comparable code minimum built apartment. Although the building will not likely achieve zero net energy, residents will have very low energy costs—if any. Hot water (mostly provided by solar) is included in the rent, and each lease includes a specific amount of electricity (roughly 1/12 of the expected PV generation). If tenants stay within this budget, they'll pay nothing for energy; if they exceed it, the lease has provisions for them to pay for excess electricity.

Figure 1. Conway Street apartments when complete

The building was completed April 1, 2014, and all apartments were rented before this completion date. The Consortium for Advanced Residential Buildings (CARB) has begun testing and monitoring of the building's domestic hot water systems. Even though a condensing, natural gas boiler is used for water heating, the developer chose to install several features to further reduce gas consumption. Researchers are monitoring performance of these systems:

- Solar thermal
- Drain water heat recovery
- Demand-controlled hot water recirculation.

Many researchers have found that solar water heating systems are rarely cost effective in cold-climate homes, especially when efficient natural gas systems are available. In a multifamily project such as this, however, total cost for the solar thermal system was approximately $31,000 (just less than $2,600 per dwelling unit). In CARB's experience, solar water heating systems on single-family homes in the Northeast cost approximately $9,000–$10,000. There is clearly a dramatic scale effect when a single solar thermal system serves several dwellings.

Figure 2. Above the parking area, a 30-kW PV array provides electricity to the building

Because the building was completed in spring 2014, performance data are available for late May through early October only. There have been interesting preliminary findings:

- The solar thermal system has provided 88% of water heating energy.
- The drain water recovery system has provided a modest 5% of water heating energy.
- The demand-controlled recirculation system was installed incorrectly, and losses from recirculation were 38% of total water heating energy. As an interim solution, the recirculation system was shut off entirely. When shut off, heat required from the boiler dropped by 73% and the solar fraction rose from 73% to 91%.

Using some lessons learned from this project, Olive Street Development is currently planning another project in nearby Montague, Massachusetts. With more area available for PV, the developer intends that this next project will truly be zero net energy. CARB believes this Conway Street project demonstrates a viable approach to zero net energy (or "zero energy ready") in small, multifamily buildings—either for new construction or major rehabilitation.

1 Introduction

Single-family, detached homes account for 63% of households (EIA 2009); multifamily homes account for a very large and growing segment of that remaining housing stock. Through recent research efforts, the Consortium for Advanced Residential Buildings (CARB) has been evaluating strategies and technologies that can make dramatic improvements in energy performance in multifamily buildings—both for new construction and for existing buildings.

Toward this end, researchers teamed with Olive Street Development in Greenfield, Massachusetts to evaluate reproducible, cost-effective pathways to achieve dramatic energy savings in the renovation of an existing building. In 2011, prior to partnering with CARB, Olive Street Development completed construction on the Olive Street Lofts in Greenfield, Massachusetts (Figure 3). These 16 apartments, located on the upper floors of a renovated mill building, featured several advanced energy features such as triple-pane windows, R-30 closed-cell spray polyurethane foam (SPF) in walls, active solar thermal water heating, and photovoltaics (PV) on the roof. Space heating was provided hydronically with condensing boilers, and cooling was provided by ductless split air conditioners.

Figure 3. Apartments at 30 Olive Street in Greenfield, Massachusetts

The developer, whose sister company owns and leases the property, was very pleased with the energy costs and with the occupancy rate; all of the apartments were leased within a week of obtaining the certificate of occupancy. The developer endeavored to repeat—and possibly improve upon—the effort while renovating a vacant school building in Greenfield. The Building America team worked with Olive Street Development to determine the most cost-effective and feasible systems for this repurposing of the old elementary school in Greenfield, Massachusetts (climate zone 5).

This project was a gut-rehab; however, many of the strategies are relevant to new construction as well. Olive Street Development has begun to specialize in the rehabilitation of brick buildings into high-end apartments. Such buildings provide unique opportunities to achieve high performance at relatively low cost:

- Sound existing structures are dramatically less expensive than new construction.
- The gut-rehabilitation nature of the projects allow for substantial flexibility in the installation of energy systems (envelope, heating, ventilation, and air conditioning [HVAC], lighting, etc.).
- Even in relatively rural regions (such as western Massachusetts), there is growing demand for multifamily homes.
- With smaller envelope areas, multifamily homes inherently have lower space conditioning loads than single-family homes.

2 Building Systems

2.1 Envelope

Like the Olive Street project, the existing Conway Street school building is a brick building approximately 100 years old. The overall approach for improving the envelope was very similar. After gutting the building, a frame wall was constructed 2–3 in. inside the brick wall and 4–5 in. of closed-cell SPF was sprayed against the inside of the brick walls. The developer was evaluating steel versus wood framing for the walls. THERM modeling showed the clear-wall R-value for wood framing to be 32.9 $ft^2h°F/Btu$; clear-wall R-value for steel studs was 29.6 $ft^2h°F/Btu$. The developer actually found wood framing to be slightly less expensive, so the decision was an easy one (Figure 4).

Figure 4. Partially insulated wall

Initial plans for the roof were to insulate with closed-cell SPF beneath the deck, but the developer would not be able to achieve the desired R-value in the 2 × 8 rafters (see Figure 5). To address this, contractors installed 4 in. of polyisocyanurate board above the existing roof deck and an additional layer of sheathing (as a substrate for composition shingles). Beneath the deck is 5 in. of closed-cell SPF (for a total R-value of 50–55 $ft^2h°F/Btu$).

Figure 5. Top floor of building before renovation

Figure 6. Wall and roof insulation on top floor. Fiberglass insulation is for sound control between rooms.

There were substantial areas of windows in the building; the main floors have 11-ft ceilings and windows that are 7 ft tall (Figure 7). The existing windows needed to be replaced, however, and to provide comfort and energy performance, the developer chose to install triple-pane windows throughout the building (thermal transmittance [U]: 0.18 Btu/ft^{2}h°F, solar heat gain coefficient (SHGC): 0.27, from Paradigm Windows). These windows do carry a premium (approximately 50% more than Paradigm's high performance double-pane products), but the large window areas made the energy and comfort benefits compelling.

Figure 7. Old windows were replaced with new triple-pane windows

2.2 Heating, Ventilation, and Air Conditioning

It was not possible or practical to use the building's original heating system (oil-fired steam); its components were removed during the initial demolition stage. The developer initially planned to use the same heating and cooling strategy used at the previous project: hydronic heating (with panel radiators/convectors) and ductless split air conditioners. One of CARB's early suggestions to the developer was to investigate air-source heat pumps for both heating and cooling. This approach was likely to save considerable costs upfront for a very modest increase in heating operational costs.

After obtaining initial pricing from several contractors, the developer found that heat pumps would cost approximately $48,000 (17 ductless split heat pumps). The developer also investigated variable refrigerant flow (VRF) systems, but initial pricing for these was higher. In addition to lower costs, individual split systems also had two other benefits:

- No premium for coincident heating and cooling (as with VRF systems)
- Individual heat pumps are powered through each apartment's meter so occupants can be responsible for their own heating and cooling energy (and cost).

Hydronic system costs came in $50,000–$100,000 higher than the heat pump approach (proposed costs varied widely). As ductless air conditioners would still be used for cooling, hydronic heating carried a substantial first-cost premium.

The developer also considered ducted heat pump systems, but to simplify and to save costs ductless units were installed in all apartments. Design loads ranged from 5,500 Btu/h (one-bedroom, 700-ft^2 basement apartment) to 11,500 Btu/h (two-bedroom, 1,300-ft^2 apartment with substantial window area) at a 99% outdoor design temperature of 2°F. To obtain a balance between upfront costs and energy costs while maintaining comfort, CARB recommended the following:

- In single-story apartments (eight), install a ductless heat pump in the main living space with capacity to handle the entire apartment heating load.
- In two-story apartments (four), install a ductless heat pump in the central space on each floor with combined capacity to handle the entire apartment heating load.
- Install mixing fans to move air between the central spaces and secondary spaces (bedrooms).
- Install auxiliary electric resistance heaters in secondary spaces (bedrooms) sized to meet the rooms' design loads.
- Install ceiling fans to reduce stratification during the winter and to provide cooling benefit during the summer.
- Provide education to occupants on operation of the system to minimize electricity use without sacrificing comfort.

The developer followed the recommendations on heat pump sizing and ceiling fans. The developer chose not to install mixing fans (though wiring was run in case fans are installed in the future). While electric resistance heat was installed in all bedrooms, capacities were sometimes significantly lower than calculated design loads for those rooms. Each resistance heater has an individual control independent from heat pumps and other systems.

To reduce energy costs associated with ventilation and to minimize airflow between apartments, CARB recommended heat recovery ventilators (HRVs) instead of continuous exhaust ventilation. As with nearly all multifamily projects, however, the substantial costs and additional wall penetrations associated with HRVs were not tenable. As he had done in other projects, the developer chose to use continuous exhaust ventilation from the bathrooms in each apartment.

2.3 Water Heating

Most of the water heating energy at the Conway Street apartments is provided by a solar thermal system consisting of 372 ft^2 of evacuated tube collectors (eight Thermopower VHP25 panels) coupled with three, 110-gal storage tanks. Because the building's hip roofs and dormers do not allow for significant south-facing collector area on the roof, collectors are mounted as awnings over several of the large, south-facing windows (see Figure 8). These four collector awnings are connected in parallel. A 40% propylene glycol solution runs between the collectors and heat exchangers in the storage tanks. When glycol is not flowing, it drains into a drainback tank located in the basement mechanical room (DOE 2013 and Mehalic 2010 provide information on solar thermal and drainback operation).

Each of the three storage tanks contains two heat exchangers. The glycol solution heated by the solar system runs through the lower heat exchangers; boiler water runs through the upper heat exchangers (see Figure 10). All heat exchangers are run in parallel (reverse return).

The developer chose to install a DWHX to preheat potable city water before it enters the tanks. The manufacturer of the DWHX (Renewability) recommends that heat exchangers be installed on drain stacks from showers and that cold water to showers be warmed by this drain water. This approach, however, was not possible with the convoluted plan and plumbing layout. Instead, drain water from seven of the eight above-grade apartments as well as the communal laundry room combine in one stack located in the basement. Two C4-30 Powerpipes were installed on this stack (in parallel with respect to potable water, Figure 9). Cold water runs through the DWHX and into the mechanical room. In the mechanical room the flow divides and water enters the bottom of each storage tank. Between the DWHX and the mechanical room is approximately 20–30 ft of uninsulated copper pipe. This pipe is run above the finished ceiling of the basement level.

To reduce water waste, wait time, and energy consumption, CARB recommended a demand-controlled hot water recirculation system (Enovative Demand Controller). Instead of circulating hot water continuously or on a timer, this system uses a flow sensor to determine when hot water draws occur. When a draw occurs, the circulator turns on to prime the hot water distribution system with hot water. A temperature sensor on the recirculation return pipe in the mechanical room allows the controller to turn off the circulator when the hot water loop is primed.

The plumbing contractors installed the Enovative controller, but for some reason the flow sensor was not installed. This situation is discussed more in the Results and Discussion sections.

Figure 8. Evacuated tube solar collectors mounted as awnings over south-facing windows

Figure 9. DWHX installed on the main stack

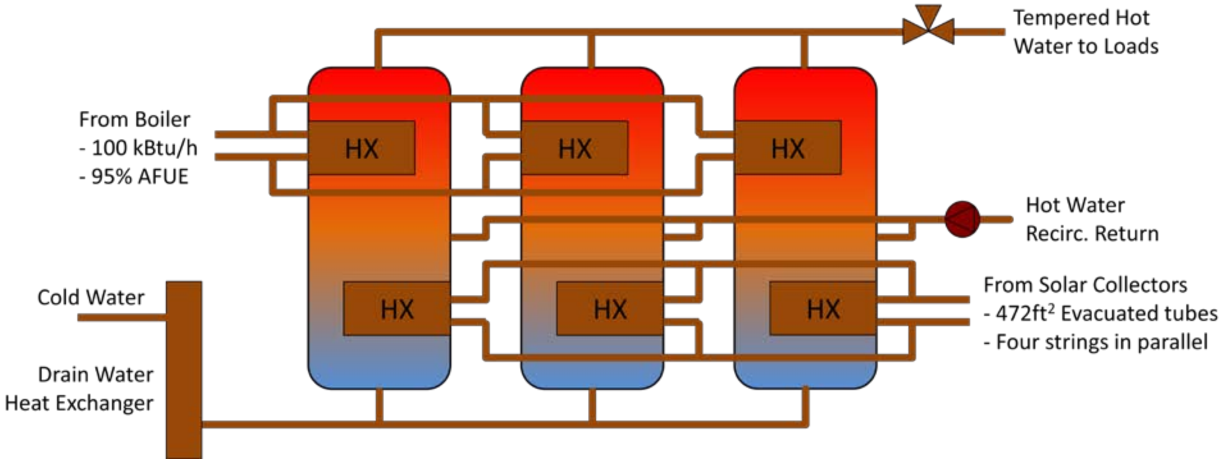

Figure 10. Simple schematic of Conway Street hot water systems. Each of the three storage tanks holds 110 gal.

2.4 Photovoltaics

Initial plans called for 40 kW of PV to power the building. With space constraints, however, only 30 kW of PV were installed. The PV is installed over the main parking area just to the east of the building (shown in Figure 2). CARB estimates this system will generate 32–36 MWh/year or 2,700–3,000 kWh/year per apartment. Building Energy Optimization Software (BEopt™) modeling predicts that a typical apartment will consume approximately 6,000 kWh/year; REM/Rate models also predicted 4,000–6,000 kWh/year. Based on past experience, however, the developer believes consumption will be somewhat less than 6,000 kWh.

2.5 Summary of Systems and Costs

Table 1 shows a summary of the building systems and approximate costs. These costs do not include incentives (except for light-emitting diode [LED] lamps which had a point-of-sale utility incentive).

2.6 Research Questions

In addition to evaluating cost-effective ways to reach 50% source energy savings targets, researchers sought to answer the following questions from this project:

- How much water heating energy is provided by the solar thermal system?
- What savings were achieved by installing drain water heat recovery?
- How much savings are achieved from the demand-controlled recirculation system? …compared to a constant circulation system? …compared to a timer-controlled system?
- How cost effective are these strategies—both considered separately and as a package?
- What are the impediments to more widespread implementation of these strategies in other projects?

Table 1. Description of Key Energy Systems With Approximate Costs

Component	Description	Approximate Cost
Spray Foam	Closed-cell SPF on all above- and below-grade walls (4–5 in.) and in roof rafter bays (5 in.)	\$44,500
Roof	4 in. of polyisocyanurate, an additional deck, and 50-year asphalt shingles	\$30,000
Windows	Triple-pane windows with vinyl frame (U: 0.18/SHGC: 0.27)	\$80,000
Ductless Heat Pumps	Mitsubishi FE12 and FE09. HSPF[a]: 10, SEER[b]: 23 17 split systems total	\$48,000
Solar Water Heating	372 ft^2 of evacuated tube solar collectors with three 110-gal storage tanks.	\$30,980
DWHX	Two 30-in. × 4-in. Renewability Powerpipes	\$2,500
Demand-Controlled Recirculation	Enovative Demand Controller	\$1,100
Lighting	189 LED lamps	\$3,780 (\$20 each)
PV	30-kW system above parking area serving all 12 apartments	\$139,000

[a] Heating season performance factor

[b] Seasonal energy efficiency ratio

3 Instrumentation and Monitoring

Soon after the building was completed and occupied, performance monitoring began on three systems: the solar thermal system, the DWHX, and the hot water recirculation system. Figure 11 and Figure 12 show the basic flow meter and temperature sensor locations on the water heating system. Short descriptions of the sensors and instruments used are in Table 2.

Table 2. List of Sensors in the Water Heating Systems

Sensor	Description	Instrument
T1	Temperature of glycol solution leaving tank heat exchangers (to solar)	Pipe strap-on thermistor Omega 44031
T2	Temperature of glycol solution entering tank heat exchangers (from solar)	Pipe strap-on thermistor Omega 44031
T3	Temperature of boiler water entering tank heat exchangers (from boiler)	Pipe strap-on thermistor Omega 44031
T4	Temperature of boiler water leaving tank heat exchangers (to boiler)	Pipe strap-on thermistor Omega 44031
T5	Temperature of cold, potable water entering DWHX	Immersion thermistor Omega ON-910-44031
T6	Temperature of potable water leaving DWHX	Immersion thermistor Omega ON-910-44031
T7	Temperature of potable water entering mechanical room	Pipe strap-on thermistor Omega 44031
T8	Temperature of potable hot water leaving tanks	Immersion thermistor Omega ON-910-44031
T9	Temperature of tempered, potable water delivered to hot water distribution system	Immersion thermistor Omega ON-910-44031
T10	Temperature of recirculated water returning to mechanical room.	Immersion thermistor Omega ON-910-44031
F1	Flow rate of propylene glycol to solar collectors	Vortex shedding, Grundfos VFS 5-100
F2	Flow rate of water from boilers to tank heat exchangers	Vortex shedding, Grundfos VFS 10-200
F3	Flow rate of domestic hot water (DHW) (not tempered)	Turbine meter, RESOL V40-15
F4	Flow rate of hot water recirculation	Vortex shedding, Grundfos VFS 10-200

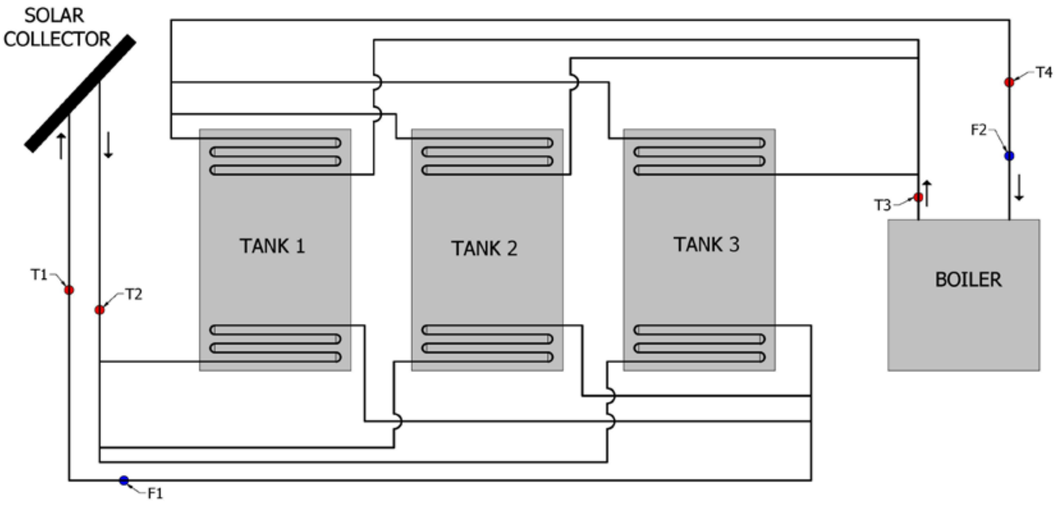

Figure 11. Schematic of sensor locations on the boiler and solar loops

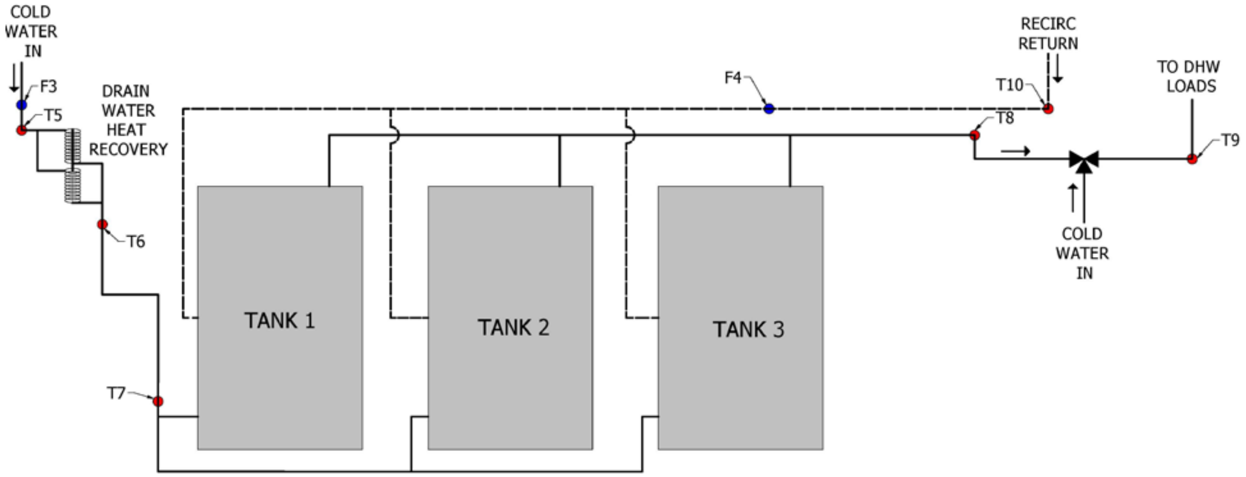

Figure 12. Schematic of sensor locations in potable water

Data are collected from a Campbell Scientific data logger via cellular modem. The data logger is programmed to take readings from sensors every 5 seconds. Data are stored in memory every 15 minutes (as averages, sums, minimum, or maximum values as appropriate). At each 5-second interval, thermal energy transfer (Equation 1) is calculated based on liquid flow and temperature differentials during the interval:

$$Q = F\rho c_p \Delta T \qquad (1)$$

where,

Q = thermal energy transfer (Btu)
F = volume of liquid in interval (gal)
ρ = density of liquid (lb_m/gal)
c_p = heat capacity of glycol solution (Btu/lb_m-^{o}F)
ΔT = temperature differential (°F)

Thermal energy is calculated every 5 seconds for each of these values (with the associated flow meter and temperatures):

- Solar energy delivered to the tanks (F1, T2-T1)
- Energy from the boiler delivered to the tanks (F2, T3-T4)
- Energy transferred from the DWHX to the potable water stream (F3, T6-T5)
- Energy gain in the potable water line between the DWHX and the mechanical room (F3, T7-T6)
- Energy gain from the tanks (F3, T8-T7)
- Energy lost from recirculation (F4, T9-T10).

The accuracy of the temperature sensors is quite good (± 0.2°F); however, the accuracy of the energy measurements is rather limited by the flow meters. A compromise was required between flow meter accuracy or resolution and pressure drop. The solar contractor installed a vortex shedding flow meter in the solar loop; these have low pressure drop but relatively poor accuracy (see Table 3). Adding redundant meters would have added more cost and pressure drop and was not tenable.

The DHW flow meter is a turbine meter with pulse output. Manufacturer literature for this meter does not list accuracy or standard error. The resolution, however, is very poor: 10 liters per pulse (2.6 gal/pulse). As many hot water draws are smaller than 2.6 gallons, this may lead to larger errors. Here again CARB explored adding a redundant flow meter, but the plumbers were very sensitive to added pressure loss.

Table 3. Published Accuracy for Flow Meters

Measurement	Published Accuracy	Typical Flow Rates
Solar Flow Rate (F1)	± 1.5 l/min (± 0.39 gpm)	2–5 gpm
Boiler Flow Rate (F2)	± 3.0 l/min (± 0.80 gpm)	10 gpm
Hot Water Recirculation Flow Rate (F4)	± 3.0 l/min (± 0.80 gpm)	5 gpm
DHW Consumption (F3)	NA—see below	Varies widely

4 Results

Because of many types of delays, this building was completed approximately 18 months later than originally scheduled. Construction was completed April 1, 2014, and occupants began moving in shortly thereafter. Data collection began in May.

4.1 Source Energy Savings

Building America goals call for 30%–50% source energy savings (not including PV) in new construction when compared to the Building America benchmark (Wilson et al. 2014). To model these savings CARB used BEopt. Modeling results are summarized in Table 4 and Figure 13. The annual source energy savings were predicted to be 50% not including PV and 72% including PV.

Table 4. Summary of BEopt Results for a Typical Apartment

Home	Adjusted Source Energy Savings	Annualized Energy-Related Costs
Reference	NA	$1,936
Conway Street Apartment—No PV	50%	$1,279
Conway Street Apartment	72%	$1,351

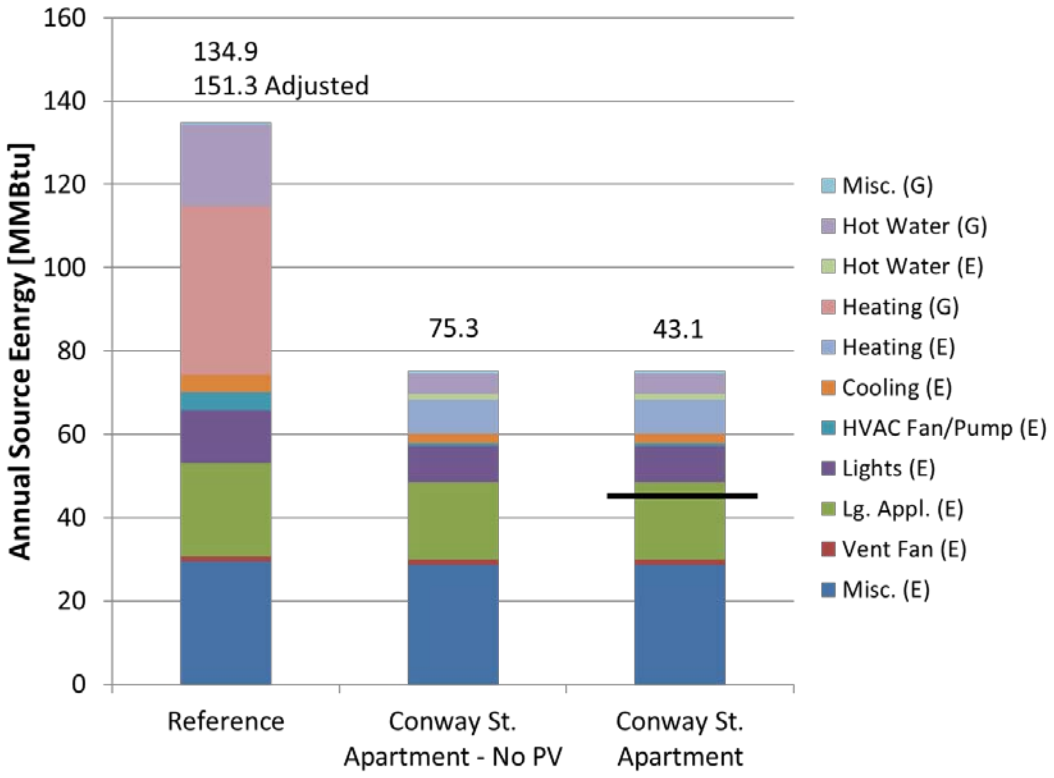

Figure 13. Source energy summary for a typical Conway Street apartment. The "adjusted" reference value normalizes consumption based on number of occupants and floor area.

(Wilson et al. 2014)

4.2 Hot Water Consumption

During the monitored period to date, average hot water consumption has been 19 gal/day per apartment. All of the apartments were rented upon completion, and there are 19 full-time residents in the entire building (12 apartments).

4.3 Drain Water Heat Exchanger

CARB has consistently seen higher water temperatures leaving the DWHX than entering the DWHX. The typical temperature rise, however, is rather modest (approximately 3°–5°F; see Figure 14). Data show that these temperature gains have provided 5% of total energy added to hot water.

Initially, CARB did not install a separate temperature sensor in the cold water pipe entering the mechanical room. Early results, however, indicated that there were likely significant energy gains between the DWHX and inlet to the water tanks. After adding this sensor, data showed that the temperature rise between the DWHX outlet and the mechanical room (approximately 20–30 ft of 1-in. pipe run above the finished ceiling in the basement level) was similar to (if not greater than) the temperature rise across the DWHX.

In hindsight, installing potable water temperature sensors at the inlets of the tanks may have provided more useful information. Between the mechanical room inlet sensor (T7) and the tanks there is approximately 15 ft of uninsulated, 1-in. copper pipe (containing approximately 0.6 gal). As the mechanical room is consistently near 93°F, CARB suspects heat gains through this section of pipe may be significantly larger than gains from the DWHX. However, the poor resolution of the DHW flow meter (2.6 gal/pulse) would make this rather difficult to assess during small water draws.

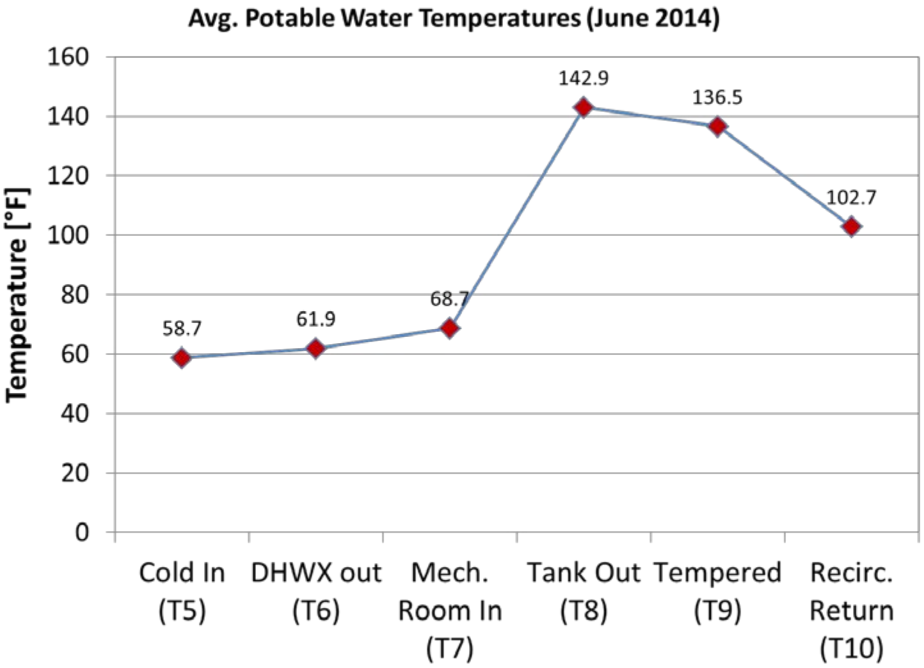

Figure 14. Typical temperatures of potable water in DHW system. Sensor numbers refer to Figure 12 and Table 2.

4.4 Solar Thermal and Boiler Heat

During afternoons in full sun, the solar system typically delivers approximately 4 gpm of glycol to the storage tanks at 140°–160°F. The typical glycol temperature rise from the solar collectors is 5°–15°F. In the period monitored to date, the solar thermal system has provided 88% of the heat put into the storage tanks (average of 115 kBtu/day); the gas boiler has provided the remaining 12% (16 kBtu/day). During June, both the solar contractor and CARB were surprised to see substantial boiler operation. Two recommendations were provided to reduce boiler use:

- Address hot water recirculation losses.
- Reduce the boiler aquastat set point (142°F) by 5°–10°F.

The building owner addressed the recirculation issue first. These losses, and their effect on solar effectiveness, are discussed below.

4.5 Hot Water Recirculation

Inspections of the DHW system quickly showed that there was a significant problem with the demand-controlled recirculation system: the flow sensor (indicating DHW demand) was not installed. It remains unclear why the flow sensor was not installed; it’s likely that the plumbers were not familiar with the system and the flow sensor was simply misplaced during construction. Initial data showed immediately that recirculation energy losses were dramatic. During the first few weeks that the system was monitored, recirculation accounted for 38% of thermal energy from the hot water tanks.

The data also clearly showed that—without the demand sensor installed—the circulator operated very frequently. It appeared that the controller was simply operating as a thermostat: running the circulator to keep return water temperature at approximately 103°F. The manufacturer confirmed that the controller might operate in this way without the flow sensor installed.

Figure 15. Hot and cold water manifolds in the mechanical room. Copper hot water piping was ultimately insulated; chlorinated polyvinyl chloride (CPVC) piping was not.

The recirculation losses were exacerbated by the layout of the plumbing system. When inspecting the mechanical room, CARB was surprised to find a homerun plumbing configuration. From a manifold in the mechanical room, 12 CPVC pipes run to apartments (see Figure 15). Twelve separate recirculation pipes run back to the mechanical room and combine at a manifold before the circulator. All of this plumbing has two key implications:

- There is much more surface area through which heat loss can occur.
- With the homerun configuration, delays and water waste would likely be rather small without any recirculation.

The developer began coordinating with the plumbing contractors about installing the flow sensor. But on June 17, the building owner turned off the recirculation system entirely. There have been no complaints from residents, and researchers examined water consumption data to see if there was an increase in consumption as a result of longer hot water waiting times. As Table 5 shows, there was a negligible change (actually a drop) in hot water consumption when the recirculation was turned off.

Table 5. DHW Consumption With and Without Recirculation

	No. Days	DHW Consumption (gal/day per unit)
With Recirculation	19.3	19.2
No Recirculation	108	18.7

The energy effects of disabling recirculation were pronounced. Table 6 shows that thermal energy provided by the boiler dropped dramatically (and solar fraction rose correspondingly) when the recirculation system was disabled. This difference is more dramatic when considering the "with recirculation" period was in June; the "no recirculation" period runs through early October.

Table 6. Solar Energy and Boiler Energy in DHW Tanks With and Without Recirculation

	No. Days	Solar Energy into Tank (kBtu/day)	Solar Fraction	Boiler Energy Into Tank (kBtu/day)	Boiler Fraction
With Recirculation	19.3	113	73%	42	27%
No Recirculation	108	115	91%	11	9%

5 Discussion

5.1 Heating and Cooling Systems

As discussed above, the developer investigated two heating strategies:

- Hydronic heating with a high-efficiency natural gas boiler
- Ductless air-source heat pumps with some auxiliary electric resistance.

Because the former would require separate, split cooling systems, initial costs for the heat pump approach were $50,000–$100,000 lower. Comparing operating costs, however, is more difficult because it's hard to predict the amount of electric resistance heat. Table 7 shows modeled heating costs with an efficient gas system and a heat pump with varying amounts of resistance heat.

Table 7. Predicted Heating Costs for a Typical Apartment From BEopt for Various Heating Systems

Heating System	Annual Heating Cost
Heat Pump, No Resistance	$113
Heat Pump, 10% Resistance	$136
Heat Pump, 25% Resistance	$169
Heat Pump, 50% Resistance	$225
Gas - Hydronic	$97

Because of the very good thermal envelope, the heating costs are quite modest. Even if the heat pump provided 100% of heating needs, however, BEopt predicts that an efficient natural gas system would be less expensive to operate ($16 less per year). Heating costs rise dramatically, however, with significant electric resistance use. Studies of heat pump and electric resistance combinations in single-family homes (e.g., Rosenbaum 2011) show that electric resistance use can vary by a factor of 10 in identical homes with different occupants. An evaluation of temperature, thermal comfort, and electricity consumption in several of these apartments could be a very interesting study.

5.2 Cost Effectiveness of Solar Thermal

In several past studies (Aldrich and Vijayakumar 2006; Aldrich et al. 2006; CARB 2010), researchers have found that solar water heating systems are rarely cost effective in single-family homes in colder climates. The installed costs (averaging $9,000–$10,000) rarely are justified by water heating savings, especially when homes have efficient appliances, low-flow plumbing fixtures, and efficient natural gas water heating.

In small multifamily buildings such as this, however, there may be a growing niche for solar thermal systems for projects attempting to attain net zero energy. The main reason is simply one of scale. The total installed cost of the solar thermal system for the 12 Conway Street apartments was approximately $31,000. The cost per dwelling unit—just under $2,600—is approximately 70% less than the cost of a typical system on a single-family home. Part of this lower cost is simply system size. The collector area and storage capacity of the Conway Street system are 4–5 times larger than those of many single-family systems (i.e., not 12 times larger).

Initial RETScreen modeling estimates showed the solar thermal system would provide approximately 50% of the total water heating load assuming average consumption of 30 gal/day per apartment. At natural gas rates of $1.50/therm, this results in savings of approximately $800/year for the entire building. With lower consumption (initial monitoring shows average use near 20 gal/day per apartment), modeling shows savings of $700/year. Without incentives, $700–$800 annual savings does not justify a $31,000 investment. State incentives, the 30% federal tax credit, and accelerated depreciation reduce the cost by 71% (see Table 8). With these incentives, the solar thermal costs appear more practical (6% internal rate of return, 12-year simple payback).

Table 8. Summary of Approximate Solar Thermal Costs and Incentives

Gross Solar Thermal Cost	$(31,000)
MA Solar Thermal Incentive	$8,664
Federal Tax Credit	$6,701
Pres. Value of Depreciation Benefits (30% Tax Rate)	$6,695
Net Solar Thermal Cost (Present Value)	$(8,940)
Additional Mass Save Tier III Performance Incentive	$24,000

Massachusetts utilities, however, had additional incentives for high performance homes based on space heating, cooling, and water heating energy savings (Mass Save 2014). The Conway Street apartments qualified for the highest level of incentives (Tier III) of $4,000 per apartment. Tier III incentives would never have been achieved without the solar thermal system; the excellent envelope systems and efficient heat pumps would have resulted in Tier II incentives of $2,000 per apartment. Although this is not a direct solar thermal incentive, the additional incentives of $24,000 for overall building efficiency helped to make the solar thermal costs viable.

Over the next several months, monitoring of the solar thermal system will allow for a more accurate cost-benefit analysis. In the meantime, Olive Street Development is using lessons learned from the Conway Street apartments to plan for its next project: converting an empty school building in nearby Montague, Massachusetts into 20 zero net energy apartments. Unlike the Conway Street project, this next project will have no access to natural gas. When compared to fuel oil, propane, or electric water heating, the savings from solar thermal will be 2–4 times greater. Even without the substantial incentives, solar thermal systems on low-rise multifamily buildings may be cost effective when offsetting propane, oil, or electric water heating systems.

5.3 Hot Water Recirculation

Past studies have shown substantial savings from demand-controlled hot water recirculation (HMG 2006, 2007; Zobrist 2012). In some multifamily buildings near New York City, Steven Winter Associates, Inc. has found that heat loss from continuous DHW recirculation can account for approximately half of water heating energy.

The monitoring strategy at the Conway Street apartments allows for heat leaving the storage tanks to be broken down into two categories: recirculation heat loss and heat going to hot water draws (standby losses could not be measured directly). During the 3 weeks when the recirculation system was operating and monitored, recirculation heat loss accounted for 38% of the energy leaving the storage tanks.

As discussed above, the recirculation heat losses were exacerbated by two factors:

- The plumbers did not install the flow sensor for the demand recirculation controller. Without the flow sensor, the controller seemed to operate as a thermostat—turning the circulator on to maintain return temperature of approximately 103°F.
- Unbeknownst to the developer or to CARB, the plumber installed homerun plumbing to each apartment. Instead of one or two recirculation loops, there are 12.

Clearly, better communication would have resulted in more efficient hot water distribution systems. It appears, however, that the homerun system without recirculation may be the lowest energy approach. Hot water to each apartment is provided through a ½-in. CPVC pipe. Pipe lengths vary, typical hot water runs are likely 30–60 ft. Volume in this length of pipe is approximately 0.3–0.6 gal. This relatively small volume is unlikely to result in long wait times for hot water or significant water waste. Since the recirculation system was deactivated, monitoring has shown no increase in water consumption.

5.4 Drain Water Heat Recovery

Drain water heat recovery is a low-cost, low-maintenance system that has shown to have modest savings in single-family homes (5%–10%, Puttagunta and Shapiro 2012); studies have shown savings in multifamily homes can sometimes be higher (CMHC 2007). The original plan for the Conway Street apartments, and the recommendation of the manufacturer (Van Decker 2013), was to install multiple DWHXs on stacks serving one or two bathrooms. Cold water coming to these bathrooms would be heated by the drain water, and—especially when showering—the volume of hot water used could be reduced. Installing several DHWXs on bathroom drains, however, was not practical with the building plan and layout of the bathrooms.

The installed cost of the DWHX was approximately $2,500. The cost of the heat exchanger was approximately $1,700; installation by the plumbers is somewhat hard to quantify because some extra plumbing was required on both the sanitary and potable sides.

During the initial monitoring period, the DWHX has typically raised the temperature of incoming potable water by 3°–5°F and provided preheating of 8 kBtu/day on average (5% of the water heating load). A full year of data will lead to much more meaningful results; however, Table 9 shows an annual extrapolation of these values if the DWHX heat gains entirely offset heat provided by the boiler.

Table 9. Extrapolation of DWHX Performance If All DWHX Heat Offsets Boiler Heat

Daily Thermal Energy Savings	**8 kBtu**
Annual Thermal Energy Savings	2,920 kBtu
Annual Natural Gas Savings	34 therms
Annual Gas Savings ($1.50/therm)	$51

This extrapolation is oversimplified. On one hand, DWHX gains may be more significant during the winter; on the other hand, with such large solar thermal contributions, not all DWHX gains will offset heat needed from the boiler.

The preliminary results do indicate, however, that this DWHX application on its own is likely not cost effective. The estimated savings in Table 9 do not justify the installed cost. More compelling is an examination of heat gain in the pipe between the DWHX outlet and the preheated water entering the mechanical room. Data collected to date show that temperature rises and average heat gains in this section of pipe are slightly higher than DWHX heat gains: 11 kBtu/day.

In hindsight, an additional immersion temperature sensor very near the potable water inlet of one of the tanks could have provided more information. With a great deal of hot water piping and storage tanks in a small space, the mechanical room is very hot—93°F on average. CARB suspects that heat gains in the uninsulated 1-in. pipe within the mechanical room could be substantially larger than gains from the DWHX. In hindsight, the developer has suggested that a small (approximately 30-gal), uninsulated tank in the mechanical room might be a much more effective and lower cost method of preheating water entering the tanks.

5.5 Overall Effectiveness of Energy Systems

This project had its share of delays and cost overruns. Many of these, however, were not related to the energy systems in the building. Most of the problems were related to renovating a 100-year old building (e.g., more structural improvements than anticipated, replacing sewer lines, removing the basement slab). Table 10 outlines the systems used to achieve the modeled energy performance of 50% source energy savings (72% when including PV).

As discussed above, these features result in higher construction costs. Even though good state, utility, and federal incentives certainly help defray the costs, there is still a substantial construction premium. The most obvious benefit of these systems is, of course, reduced energy cost. BEopt modeling shows that, for a typical apartment, the 72% source energy savings is accompanied by an 81% reduction in annual energy costs ($1,936 to $363). When PV is not included, the 50% source energy savings translates into a 40% reduction in operating costs ($1,936 to $784).

Each apartment has its own electric meter, and tenants may have zero energy costs over the course of a year. Each apartment has an electricity budget based on REM/Rate models and the total expected PV generation. If occupants stay within this budget, they pay no electricity fees. If they exceed the energy budget, their leases have provisions for tenants to pay for the excess consumption. Gas costs (used for auxiliary water heating) are included in rent.

In part because of these energy savings, the owner finds that efficiency and renewable energy features help to keep occupancy rates high. The features (especially the prominent solar systems) also provided good publicity from local newspapers[1] and television.[2] An open house drew approximately 300 visitors, and the apartments were all rented before April 1 (the first day tenants were able to move in). Even though the developer is not entirely convinced that near-zero energy projects such as this are more economically viable than more conventional projects, the next project in the works is another deep energy retrofit. Olive Street Development is currently planning another major renovation of a vacant school building in nearby Montague,

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[1] www.recorder.com/home/11346185-95/old-school-transformed-net-zero-apartments-built-by-zaccheo

[2] www.wggb.com/2014/04/04/old-greenfield-school-building-transforms-to-modern-green-living/

Massachusetts. Many of the same systems will be used and, without access to natural gas and with more space for solar collectors, the developer plans for this next project to truly be zero net energy.

Table 10. Summary of Conway Street Apartment Specifications

Component	2009 IECC and Building America Benchmark Specifications	Conway Street Apartments
Foundation Insulation	R-10 continuous	R-28 closed-cell SPF
Above-Grade Wall Assembly	R-17 inside massive wall	2 × 4 wood stud wall (16 in. on center) inside brick, R-28 closed-cell SPF (2-in. continuous insulation)
Ceiling Insulation	R-38	4 in. polyisocyanurate above deck, 4-to 5-in. closed-cell SPF between rafters (approximately R-50 to 55)
Windows	U: 0.35 Btu/ft^{2}h°F	Triple-pane windows with vinyl frame (U: 0.18/SHGC: 0.27)
Infiltration	7 ACH$_{50}$	2–3 ACH$_{50}$
Ventilation	Exhaust only	Exhaust only
Heating System	78 annual fuel utilization efficiency (AFUE) natural gas furnace	Ductless heat pumps 10.6 HSPF, auxiliary electric resistance in bedrooms
Cooling System	SEER 13 air conditioner	Ductless heat pumps, SEER 23; ceiling fans in all rooms
Ductwork	R-6, total leakage of 12 CFM$_{25}$/100 ft^2	None
Water Heating	0.59 energy factor natural gas 50-gal storage water heater	Central water heating: 372 ft^2 of evacuated tube solar collectors; auxiliary heat from 95% AFUE gas boiler.
Lighting	34% fluorescent	100% LEDs and compact fluorescent lamps
Appliances	ENERGY STAR® refrigerator, dishwasher, clothes washer, and exhaust fan; gas cooking range and clothes dryer	ENERGY STAR refrigerators, dishwashers, clothes washers, exhaust fans, and ceiling fans; electric cooking ranges and clothes dryers.
PV	None	30-kW system above parking area serving all 12 apartments

6 Conclusions

Because of substantial construction delays, monitoring of the water heating systems has only just begun. Preliminary answers to the research questions are below.

How much water heating energy is provided by the solar thermal system?

When the recirculation system was operating, the solar thermal system provided 73% of DHW energy (113 kBtu/day). When the recirculation system was deactivated, the solar system provided 91% of water heating energy (115 kBtu/day).

This preliminary monitoring period was from late May to early October; results from the rest of the year are necessary to accurately gauge performance.

What savings were achieved by installing drain water heat recovery?

Initial results show that the DWHX is not providing substantial energy gains. While extrapolating over an entire year is not possible with much accuracy, it seems that maximum gas savings possible will be 34 therms/year or $51/year.

It is worth noting that the preferred installation method (at bathroom stacks to preheat cold water to showers) was not possible or practical at the Conway Street apartments. This application could result in more significant savings.

How much savings are achieved from the demand-controlled recirculation system? …compared to a constant circulation system? …compared to a timer-controlled system?

During construction the demand controller was not installed properly. In addition, the plumbers installed a home-run distribution system where each apartment has a dedicated, ½" CPVC hot water line.

When the recirculation system was operating (in effect as a thermostat to maintain return water temperature), 38% of the heat leaving the tanks was lost through recirculation. When the system was deactivated and these losses were eliminated, solar fraction rose substantially (73% to 91%) and heat delivered to the tanks from the boiler dropped by 79%.

Certainly better coordination on DHW distribution is desirable. The home-run system without recirculation, however, seems like an efficient system with minimal energy loss, water waste, and no occupant complaints (to date). For this building, at least, the homerun system seems appropriate. The homerun system does require more material and labor, and in larger buildings hot water delays could certainly be more significant.

How cost effective are these strategies—both considered separately and as a package?
Initial results show the DWHX is not cost effective. More data are needed to asses this, however. These systems may be more cost effective if installed as recommended by the manufacturer: on bathroom stacks to preheat cold water during showers.

Because of the communication and integration problems, the demand-controlled recirculation system was certainly not cost effective in this building. CARB still believes that this technology can be very cost effective in some applications with better coordination during design and construction.

The solar system does seem to be cost effective here for two key reasons:

- The multi-family scale allows per-dwelling unit costs below $2,600 (approximately 30% of the cost of single-family solar water heating systems).
- Massachusetts solar rebates, the federal tax credit, accelerated depreciation, and utility efficiency incentives cover most—if not all—of the solar system's cost.

It is not practical to extrapolate a full year of solar savings from initial results during the summer, but CARB expects the solar thermal system to offset approximately $700 per year in natural gas costs.

Even without such generous incentives, solar thermal systems such as these could be cost-effective in regions (or buildings) without natural gas. While energy prices vary dramatically over time and across regions, heating water with oil, propane, or electricity is generally 2-4 times more costly than with natural gas. In buildings with natural gas and without significant incentives, it's unlikely solar thermal is a cost-effective option.

What are the impediments to more widespread implementation of these strategies in other projects?

Preliminary results show that this is not a good application for the DWHX.

The key impediment to the demand-controlled recirculation system being effective was clear: poor coordination between developers, designers, and contractors. Bad assumptions in the type of DHW distribution system and the plumber's lack of familiarity with the controller led to a very poor installation.

Because of substantial incentives and multi-family scale, the solar thermal system seems to be a viable system for this and similar buildings. The contractor was very knowledgeable and experienced, and the system has been working more-or-less as designed since CARB began monitoring. Up-front costs and modest energy savings (when offsetting efficient natural gas water heaters) remain the biggest barrier to more wide-spread adoption of solar thermal. However, there is growing interest in achieving zero net energy in many types of buildings, and solar thermal in multi-family buildings can certainly help achieve this. Solar thermal may be especially viable in multi-family buildings without natural gas, as savings from solar will typically be 2-4 times greater.

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