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Integrating Net-Zero Energy and High-Performance Green Building Technologies into Contemporary Housing in a Cold Climate

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Abstract

The objectives of this research project are (1) to show how the sustainable resources of forest biomass, solar energy, harvested rainwater, and small-diameter logs can be integrated to a system that provides most or all of the energy and water needs of a typical cold climate residential household, and (2) to effectively interpret the results and convey the sustainable potential to the public. This project validates that (1) the combination of the BioMax® wood-pellet energy system (5 kW peak) with grid interconnected solar energy via photovoltaics (4 kW) can provide the majority of the power needs for a residential unit in a cold climate; (2) rainwater can be stored in a 2,500-gallon cistern and reliably filtered and disinfected for potable use; (3) systems to product and save energy and water are safe and reliable; and (4) these technologies are available and work well in cold climates similar to the project's location in Madison, Wisconsin, USA.

Keywords: integrated design, passive solar, active solar, rainwater harvesting, photovoltaic (PV)

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SI conversion factors

Inch–pound unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
gallons (gal)	0.003785	cubic meters (m^3)
ton	907.18	kilograms (kg)
mile	1.609	kilometers (km)
Btu	0.0002929	kilowatt-hour (kWh)

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Integrating Net-Zero Energy and High-Performance Green Building Technologies into Contemporary Housing in a Cold Climate

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Introduction

In recent years, great strides have been made in improving the energy and water efficiency of housing. "Green" building improvements include the following:

- Water-conserving plumbing fixtures
- Higher efficiency heating and cooling systems
- Improved insulation and radiant control in windows
- Better building envelope design for insulation and moisture control
- Advances in renewable energy technologies for residential applications such as photovoltaics

Acceptance and adoption of these technologies have been facilitated through incentives (public and utility) and regulatory mechanisms (building energy codes) resulting in more efficient buildings and lower costs compared with when green building improvements were first introduced. The energy challenges of recent years, combined with a better understanding of how human-produced greenhouse gases may be altering the climate, suggest that we need to do even more to reduce energy demand from traditional sources. The conservation and efficiency improvement gains that we have realized from advances in the building technologies listed are no longer enough. But, how do we raise the bar in energy- and water-use efficiency on the residential scale? Research in building energy modeling has shown that the cumulative energy performance improvements of individual building envelope components (high efficiency windows; better insulation in wall, ceiling, and foundation; and reduced infiltration rates and orientation) are greater than the sum of their individual impact. A synergy results from their integration.

Whereas conservation is critical and has provided important gains in energy and water efficiency, integrated systems are emerging that can make truly sustainable use of our natural resources. This project examines how renewable energy, rainwater harvesting, and the waste from forest thinning can be integrated for residential sustainability in cold climates and how energy and water-use reductions can be achieved.

Wood products made from small-diameter logs, harvested rainwater, the energy from wood waste, and the sun are all plentiful and renewable resources. The thesis of our research is that these resources, if effectively harvested and managed, are sufficient to provide a sustainable support system for cold-climate housing, reducing reliance on fossil resources (energy and groundwater), while making better use of forest resources. Products and technologies to harness and use these resources are available. However, putting them together requires an integrated approach to building design and engineering. This project is designed to demonstrate how currently available systems and strategies that use these resources can be integrated into contemporary housing and to test applications at the residential scale in order to validate system performance.

The Research Demonstration House was completed in 2001 on the grounds of the Forest Products Laboratory (FPL) in Madison, Wisconsin. Its purpose is to showcase innovative new wood products and wood composites, such as Southern Pine flooring and wood composite shingles; demonstrate and evaluate innovative wood products applications and durability (as evidenced by the wood floor and walls in the basement); and to study moisture migration through walls. This applied research program was expanded starting in 2003 to include investigating residential rainwater utilization and renewable energy applications.

For this research, a building (coined the Carriage House by Mark Knaebe) the scale of a contemporary double car garage or workshop (Fig. 1) has been designed and constructed adjacent to the Research Demonstration House to contain the potable rainwater and renewable energy systems. The project also showcases advanced construction methods using small-diameter lumber products. A primary objective is to introduce and build acceptance of these sustainable products and show how they can be integrated into the contemporary housing market.

Together the Research Demonstration House and the Carriage House typify a house in the suburban upper Midwest of the United States. By combining state-of-the-art

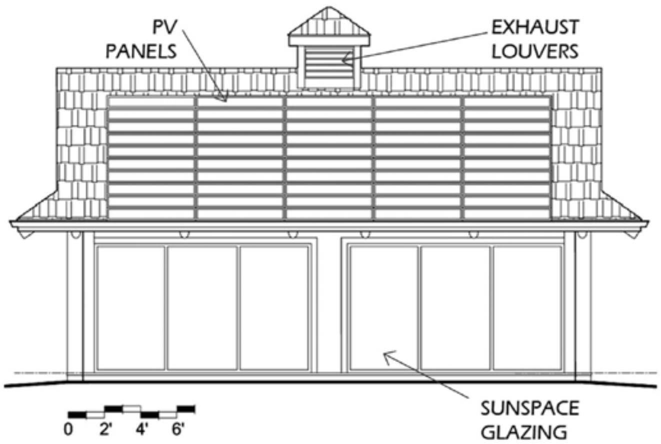

Figure 1. Carriage House south elevation.

renewable energy technologies and innovative rainwater harvesting systems, the research assesses whether net-zero energy and optimal rainwater use is achievable in a cold climate. The cost, efficacy, and reliability of these systems are being evaluated while their potential is demonstrated.

The primary question addressed by this applied research program is whether contemporary building technologies and systems can be effectively integrated to accomplish a much higher level of residential energy and water efficiency in a cold climate similar to that of Madison, Wisconsin. The energy and water efficiency targets for this research evolved through our analysis of efficiency improvement opportunities associated with the wood products from the Research Demonstration House, conditions of the project site, and through discussions about complementary ongoing FPL research programs. The project's energy performance target was modeled after those being developed and promoted by the Department of Energy's Energy Efficiency and Renewable Energy Program (DOE 2010).

The water efficiency goal was developed through ongoing research by the author based on work conducted in the southwestern United States. The use of renewable wood products came out of research conducted by FPL on the potential for small-diameter lumber products from fire-wise forest thinning. These targets were reaffirmed in the October 2008 report from the National Science and Technology Council Subcommittee on Building Technology Research and Development (NSTC 2008), which shows that designs of new buildings and retrofits of existing buildings over their life cycle accomplish the following:

- Produce as much energy as they consume (net-zero energy) and significantly reduce greenhouse gases.
- Double the service life of building materials, products and systems, and minimize life-cycle effects.
- Halve the use of domestic water (to 50 gallons per day per person or less), maximize water recycling and rainwater harvesting, and minimize storm water runoff.
- Achieve breakthrough improvements in indoor occupant health, productivity, and comfort.

Through the FPL Advanced Housing Research Center's cooperative effort with the University of Arizona's Environmental Research Laboratory, this project was developed to examine how using an integrated design approach that incorporates energy efficiency, renewable energy, harvested rainwater, and the waste from forest thinnings can improve residential sustainability in cold climates.

Methodology

This project used an iterative research, programming, design, and development model to integrate renewable energy production, rainwater harvesting, and new advances in wood product utilization into the FPL Research Demonstration House. Initial research in water and energy use requirements for a typical energy-efficient residence in Madison were gleaned from the literature and usage assessments from local utilities for both energy and water. Renewable energy technology and rainwater harvesting systems options were evaluated to determine the most strategic approach toward the project goal of net-zero energy use and a 50% reduction of potable water use for an existing single family residence in a cold climate. The results of these investigations were used to develop a design program appropriate for the house and site in function, performance, aesthetics, interpretive potential, and associated FPL research.

Design development and engineering of the systems proceeded from the results of the research and systems evaluation phase. Through a series of design iteration and review meetings with FPL researchers, we determined the scope and scale of the project and prepared design development documents.

To effectively address ongoing systems integration details, funding, and the weather, we used a design-build approach to construction. The design-build process allowed for innovative problem solving to occur during construction. This approach also allowed for the data monitoring and controls associated with ongoing research to evolve and be integrated into the building.

Research and Systems Evaluation

This research program, initially focused on rainwater harvesting opportunities at the FPL house, evolved into a more comprehensive integrated look at residential sustainability in a cold climate. The physical design and ongoing research at the Research Demonstration House combined with the need for a space to house the BioMax®, a pilot-scale biomass system that converts biomass energy to thermal or electrical power, or both); a requirement for rainwater storage that would not freeze; and an opportunity to demonstrate the use of new wood products from forest thinnings led to the decision to develop another facility adjacent to the Research

Table 1—Estimated average annual energy use[a] (typical 2,000 ft^2 energy-efficient house)

Type	Use	Equation[a]	Therms	kWh	kBtu	kBtu/ft^2
Natural gas	Heating	$0.20 \times ft^2 + 150$	550	15,950	54,982	27
	HW and cooking		360	10,440	35,988	18
	Total	$0.20 \times ft^2 + 510$		26,390	90,970	45
Electricity	Cooling	$0.40 \times ft^2 + 800$	54	1,600	5,459	3
	Plug loads		244	7,164	24,444	12
	Total	$1.06 \times ft^2 + 6,684$	298	8,764	29,903	15

[a]Because the Research Demonstration House is largely unoccupied, we used energy use data from MG&E that is representative of a typical residence in Madison, Wisconsin. The energy use values and equations shown in this chart are from research conducted by MG&E through their Good Cents Program. The breakdown between energy type and use show that 75% of the annual energy requirement for a typical house in Madison is for heating. The factors in the equations column are from MG&E. The energy values in shaded cells are conversion by author, unshaded by MG&E.

Demonstration House. The Carriage House provides a platform to address the broader residential sustainability issues in association with the Research Demonstration House without affecting ongoing research.

The expanded scope of the research program addresses energy, water, and better utilization of forest resources. In addition, new wood products, developed from material traditionally considered as waste, are being evaluated for integration.

Energy

To address the energy-use question and to create a benchmark for the Carriage House systems design and performance evaluation, we used electric and gas use formulas developed by Madison Gas and Electric (MG&E) based on data from their Good Cents certified homes program (personal communication with Robert K. Stoffs, Community Energy Manager at MG&E, May and June, 2009). Table 1 shows estimated average annual energy use.

Natural gas is the primary source for residential heating and comprises about 75% of the annual average residential energy use. While coal-fired powers stations supply the majority of the electricity, MG&E has a strong commitment to renewable energy sources and energy efficiency (City of Madison 2008).

Options for achieving net-zero energy at the residential scale include demand reduction and on-site electrical generation. Because the majority of the energy use in housing is for heating, building envelope improvements to decrease heat loss (better insulation and reduced infiltration) and passive or active solar thermal systems to improve heat gain in the building can be effective at reducing energy demand. These strategies were employed to optimize the thermal energy performance of the Carriage House. For the electricity use requirement, a number of renewable energy systems are available for onsite generation. The electric production systems evaluated include photovoltaics, wind power, hydrogen fuel cells (methane reformer), and biomass energy conversion systems.

Wind was insufficient at the site, and hydrogen fuel cells are an emerging technology that has potential and may be considered for later inclusion. Photovoltaic systems have become widely available and incentives for their application are readily available. Biomass systems for electric and heat energy production, while in the emerging technology category, are a sponsored research initiative of FPL. One such system, the BioMax®, was being evaluated by FPL and made available for inclusion into the project. The BioMax® together with an appropriately sized photovoltaic system will be evaluated to assess their capacity to provide the electric power requirements of a typical energy-efficient house on a net annual production basis.

Water

The residential sector accounts for 22% of the annual energy consumption in the United States. Average per capita water consumption exceeds 100 gallons per day nationally. Nationally, the daily indoor water use per capita is 69.3 gallons. Conservation measures such as installing low water use toilets, flow controls, and high-efficiency clothes and dishwashers can reduce water use by about 35% to 45.3 gallons. See per capita daily water use in Table 2 (AWWA 2009).

In the City of Madison, the residential average daily use per capita (indoor and outdoor) is about 73 gallons per day. For an average household of 2.5 persons, this is about 184 gallons per day (City of Madison 2008). Residential water use (indoor and outdoor) in Madison is 25% less than the national average on a gallons per capita day (gpcd) basis (73 gpcd versus 100 gpcd nationally). This variance from the national average is due in part to the region’s rainfall frequency and total volume, offsetting demand for outdoor irrigation.

The use of harvested rainwater for toilets and clothes washing could net a 60% reduction in indoor use per capita from the municipal water supply. Managing on-site rainwater and using greywater for irrigation would further reduce municipal water use.

Table 2—Per capita daily water use (typical single family home, indoor only)

	Without conservation measures		With conservation measures[a]	
Use	Gpcd[b]	Percentage	Gpcd	Percentage
Shower	11.6	16.8	8.8	19.5
Clothes washer	15.0	21.7	10.0	22.1
Dishwasher	1.0	1.4	0.7	1.5
Toilets	18.5	26.7	8.2	18.5
Baths	1.2	1.7	1.2	2.7
Leaks	9.5	13.7	4.0	8.8
Faucets	10.9	15.7	10.8	23.9
Other	1.6	2.2	1.6	3.4
Total	69.3		45.3	

[a]Water conservation measures can lower consumption by 35%. Using rainwater for clothes and toilets (shaded cells) nets a 60% reduction in municipal water use.

[b] Gallons per capita day.

Wood

New forest-management programs to remove excessive undergrowth and smaller trees (ladder fuels) have been initiated in response to the increasingly large and destructive forest fires. These programs generate a large volume of small-diameter logs, slash, and wood chips that have little or no value in the traditional timber industry. Product development research for these waste materials includes investigations on the use of wood chips as a fuel for electric generation, and initiatives to develop products from the small-diameter logs. One small-diameter log product is the direct use of the small-diameter logs for construction (FPL has sponsored a number of projects demonstrating the use of this material). Another higher value product, laminated tongue and groove decking, has been developed by a manufacturer in Northern Arizona. See sidebar below.

Small-Diameter Log Background

The frequency and devastation of large forest fires have necessitated changes in the management of forest resources in the United States. Essentially, forests are being cleared of smaller understory trees to prevent them from laddering fires to the larger trees. This new management strategy has increased the availability of small-diameter logs. Incentives for producing products made from small-diameter logs are needed, and FPL is leading in this market development effort. The Carriage House is a small part of this program and was designed to showcase the use of small-diameter logs and new small-diameter log products in the construction. Both wood waste energy generation and the use of small-diameter log materials are at a level of development suitable to be demonstrated and evaluated in this project.

Figure 2. On-site structural assembly of small-diameter logs and trusses.

Program and Design Development

These new initiatives broadened the research agenda for the Research Demonstration House. Rainwater harvesting and management required a cistern for water storage, pressurization and filtration that was protected from freezing temperatures. A solar photovoltaic system required a south-facing rooftop, and the orientation and shading of the Research Demonstration House's south roof was not optimal. In addition, an on-site, residential scale BioMax® being tested by FPL was re-commissioned as a component of the renewable energy program for this project. To accommodate these a new building, the Carriage House, was required.

These program requirements, the cistern location, a south-facing roof for photovoltaics, and a space for the BioMax® determined the size of the new building. The Carriage House was sited in response to the solar access requirements, infrastructure proximity, and contextual relationship to the Research Demonstration House. The Carriage House was designed with exterior detailing and roof line that was sympathetic with the Research Demonstration House, appearing as a detached double car garage.

The following sections address (1) the integration of the small-diameter log structural system with contemporary construction, (2) the passive solar design and building thermal performance in response to cold-sensitive systems that will be housed in the space, (3) the renewable energy systems employed, and (4) the rainwater harvesting and management systems.

Structural System and Assembly

A reinforced concrete grade beam set on piers to prevent frost heaving forms the building foundation. A 2,500-gallon precast cistern is located under the floor of the Carriage House's east bay. The structure is made from small-diameter log columns and trusses (peeled ponderosa pine). For winter space heating (frost protection), a sunspace was integrated into the south façade. Figure 2 depicts the building frame during construction. The building cross section in Figure 3 details the sunspace and location of the cistern. Between the perimeter log columns, the infill walls use traditional 2 by 4 framing and insulation systems. The small-diameter log roof trusses are exposed on the interior and a laminated tongue-and-groove decking also made from small-diameter logs forms the roof system (Fig. 4).

Construction Systems and Assemblies as Simulated

Foundation: Concrete grade beam on piers with 1-1/2-in. rigid perimeter insulation (R7.5) vertical on the grade beam and 2 ft to the interior under the concrete paver flooring.

Structure: Small-diameter log 6-in. diameter posts and trusses with custom 1/4-in. steel plate connectors.

Walls: Wood–plastic composite siding, Tyvek building wrap, 2-in. Hunter H-Shield-NB rigid insulation with nailable sheathing (R9.1), 1/2-in. oriented strandboard (OSB) structural sheathing, 2 by 4 framing in between the structural posts with fiberglass batts (R-13), and 1/2-in. gypsum board.

Steel Roof: 3-1/2-in. Hunter H-Shield-NB rigid insulation with nailable sheathing (R19.1), 1/2-in. OSB structural sheathing, 2 by 4 small-diameter log laminated tongue and groove decking.

Windows: Vinyl covered wood, fixed and operable; south windows (interior and exterior) have double pane clear glass, other windows have double pane low-E glass.

Building Performance

The Carriage House is an unoccupied space; however, the interior temperature does need to maintain temperatures above freezing because of the exposed rainwater disinfection system inside. To provide this frost protection passively, an air-fed solar collector referred to and modeled as a sunspace was incorporated into the south façade of the Carriage House. CALPAS3 hourly simulation software with the generic COLD.GMY weather file was used to assure the building would remain above freezing in winter (Berkeley Solar Group 1984). This program was selected because it will simulate the impact of the attached sunspace as a heat source for the building. The model was adjusted to reflect the materials actually installed and to optimize the design for the desired performance (interior temperature not below 35 °F (1.7 °C)).

Iterative simulations were conducted to assess and optimize the effect of strategic design and materials applications on building energy performance. As a base case, the building was first simulated like a utility building without insulation

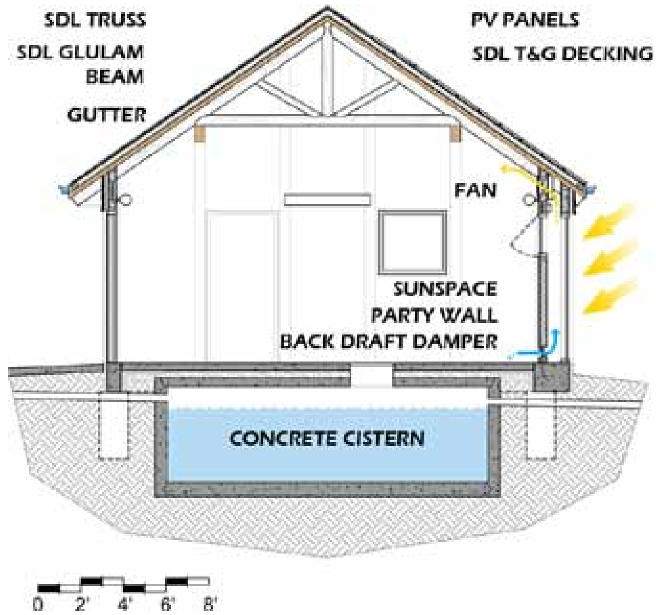

Figure 3. Carriage House cross section showing integration of structural components, solar energy (passive-thermal and active-electricity), and water storage.

Figure 4. Interior view of the small-diameter log (SDL) structure, glulams, and tongue-and-groove decking.

and minimal windows. Then insulation, south windows, and the sunspace were incrementally added to the model to parametrically assess and optimize building thermal performance.

Building parameters were adjusted as noted below for these various simulation schemes:

1. Base case building without insulation in the walls, roof, or foundation; omit south windows (at party wall to sunspace); omit sunspace (at party wall to sunspace modeled as exterior wall).

2. Building without insulation in the walls, roof or foundation; include south windows; omit sunspace.
3. Building without insulation in the walls, roof, or foundation; include sunspace.
4. Base building as-built with insulation; omit south windows and sunspace.
5. As-built with insulation and sunspace.

Table 3 delineates the insulation values of wall systems and materials used for the simulation schemes. Clear glazing is used on the south elevation and low-E glazing elsewhere. Heat pump heating was modeled in the simulation and no cooling was required. When modeling the sunspace, direct gain through the south windows of the sunspace party wall is not included (See Figs. 1 and 3.).

Table 3—Insulation values for five energy performance modeling scenarios

	Insulation (U) values				
Scenario	Wall	Roof	Foundation [F2]	Clear window	Low-E window
A	0.2669	0.2483	0.73	–	0.37
B	0.2669	0.2483	0.73	0.49	0.37
C	0.2669	0.2483	0.73	0.49	0.37
D	0.0431	0.0432	0.70	0.49	0.37
E	0.0431	0.0432	0.70	0.49	0.37

Installing 32 square feet of clear-glass south-facing windows produces a 7.5% improvement in building performance. Converting the windows to an attached sunspace with 163 square feet of glazing and a temperature-operated fan to heat the building in scheme C produces a 10.9% (1,247 kBtus) improvement over the base case. Scheme D models the building with the insulation added as installed and at 61.3% (6,160 kBtus) creates the greatest jump in building energy performance. However adding the sunspace and insulating the building creates a synergistic improvement of 80.5% (9,231 kBtus) over the base case building, which is greater than the additive improvements would indicate. Figures 5 and 6 show the progressive improvement in building performance for simulation schemes A through E. The Carriage House was constructed per scheme E. A small electric heater is present to prevent freezing in an emergency.

Renewable Energy Systems

Two renewable energy systems are being employed and evaluated. One is a 3.7-kW roof integrated photovoltaic array mounted on the south-facing roof and is shown in Figure 1. Power is conditioned with a 4,000-W inverter. The electricity will be metered back into the local utility grid, taking advantage of a photovoltaic installation incentive program. The annual estimated energy production is ~4,500 kWh. The photovoltaic system was sized to power most of the plug loads of a typical residence.

The second renewable energy system, housed in the west bay of the Carriage House, is a carbon neutral, wood-pellet gasification–electrical generation system (Walt 2004). The BioMax® is a 5-kW household scale system that uses wood pellets from wood waste to produce electricity (up to 30 kW per day) and thermal energy in the form of heat that can be used for hot water or space heating. The manufacturer's claim of up to 30 kW per day has not been verifiable in field evaluations. Systems evaluation and testing is ongoing. The electricity produced by the BioMax® complements the photovoltaic systems when electric use is more than solar production. The use of the thermal energy from the BioMax® for residential heating was not included in the Research Demonstration House but may be added as a retrofit.

> Unlike fossil fuels, biomass fuels like wood pellets are largely carbon neutral, as they do not add CO^2 to the atmosphere. This is because the same amount of CO^2 released during the burning process is stored in the pellet's source plant material while growing. The energy used to produce and transport wood pellets must be considered in their carbon footprint. The electrical power used to make pellets requires about 10% of the electricity produced by a given quantity of pellets. Were the electricity produced by the BioMax® (Community Power Corporation, Littleton, CO) used to charge batteries in an electrically powered vehicle, the transportation would be removed from the fossil fuel equation. Hauling wood chips 50 miles from forest to manufacturing site costs approximately $10 per ton for fuel and driver. If the costs for transporting pellets (higher density equals less expense per ton) to the BioMax® were on par with hauling chips from the forest, it would require another 10%. If the harvesting equipment and other energy users were all electric, it could be said that if 10 tons of pellets were produced it would require 2–3 tons of that material's energy to make it honestly (not including producing the vehicle, equipment, or paving roads) carbon neutral. The electricity produced is net and not attributed to specific power producers.

Table 1 shows that the estimated average annual electric use for an energy-efficient home in Madison is 8,764 kWh. Together, these renewable energy systems (photovoltaic and BioMax®) can produce all of the electricity required including air conditioning on a net annual basis (PV ~4,500 kWh, BioMax® plus ~4,500 kWh at 50% of rated capacity) for a typical energy-efficient residence. Ongoing evaluation on the performance of the PV and BioMax® will be compared with the Research Demonstration House's annual electrical energy use.

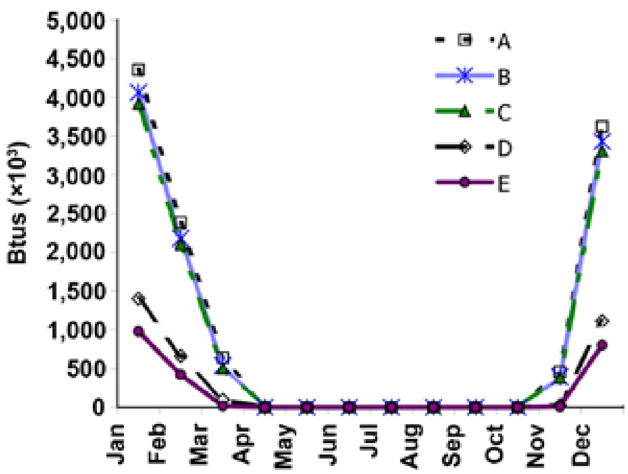

Figure 5. Carriage House monthly heating demand for the energy simulation scenarios.

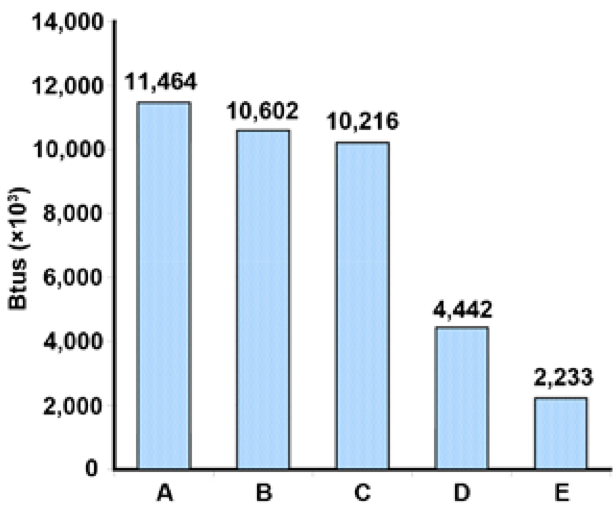

Figure 6. Total annual heating use from the energy simulation scenarios.

An analysis of the BioMax®'s potential to offset the winter heating demand indicates that the waste heat (thermal energy) generated by the BioMax® when it is producing electricity at half its rated capacity (15 kW per day) is equal to the one-half of a mid-winter day's heating requirements for a typical energy-efficient home (~200,000 btu/day) when the outside temperature is 10–15 °F (–12°– –9 °C). At 50% heat recovery efficiency, the BioMax® would provide about a quarter of the peak winter day heating requirement for an average energy-efficient residence. In the summer, this thermal energy can supply all of the hot water needs, and since the BioMax® would be typically located in an outbuilding, the excess heat would dissipate via natural ventilation through building vents or open windows. Figure 7 shows the systems and equipment locations.

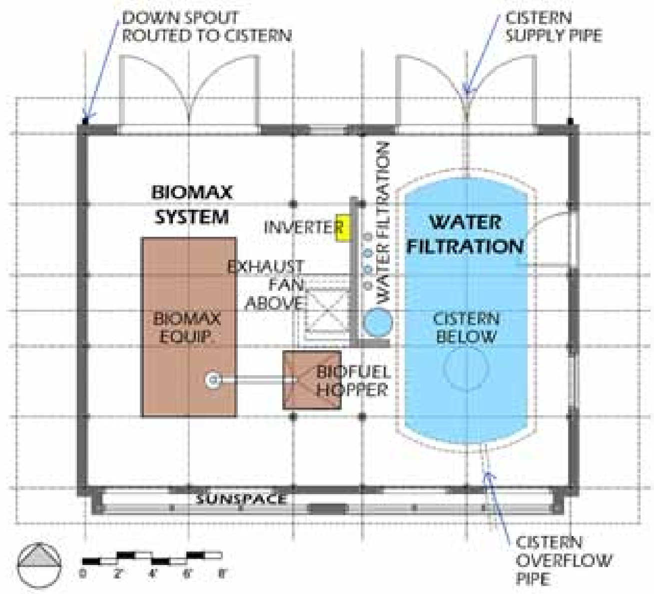

Figure 7. Carriage House floor plan showing location and relationship of systems.

Rainwater Harvesting and Management

Rainwater harvesting is used to offset municipal water supply demand. The rainwater harvesting, management, filtration, and disinfection systems incorporated into the Research Demonstration House and Carriage House are designed to provide a secure and reliable water supply for all typical household water needs. Most of the water can be supplied by the harvesting system.

Both the literature and vernacular examples have validated the efficacy for using rainwater for all typical household uses. In cold climates like Madison, Wisconsin, irrigation needs are limited; therefore, harvested rainwater can be managed for potable and non-potable uses. Non-potable uses include washing clothes, flushing toilets (Fewkes 1999), and bathing. Potable uses of rainwater have been shown to be viable with disinfection and quality monitoring.

Any comprehensive rainwater harvesting and management program must consider the climate, physical and site constraints, and technical considerations including water quality and local regulations in addition to cost. All will have an effect on system design.

The duration of storage in a cistern coupled with first-flush systems, which divert the first few gallons of catchment runoff, have been shown to produce water with quality measures that meet or exceed municipal drinking water standards. However, disinfection technologies are recommended for potable use of this water. Disinfection methods include thermal (Birch and Thomas 1998), chemical (chlorination), ultraviolet treatment (Abbaszadegan and others 1997), or a combination of these.

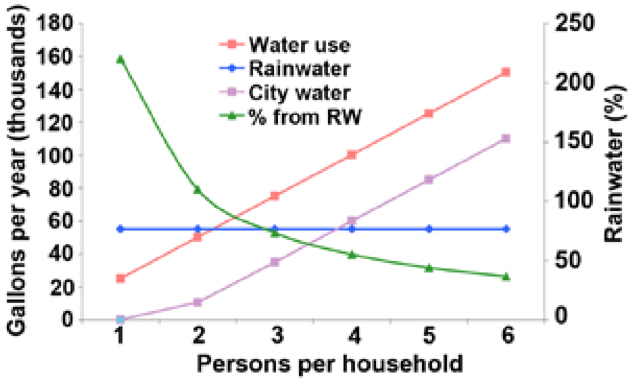

Figure 8. Chart of rainwater harvest potential by number of persons in household showing the percent of harvested rainwater that would be available as the number of persons in the household increases. The Madison average indoor use rate is gallons per day at 68.7, with 3,200 ft^2 catchment.

The water harvesting systems in this project demonstrate state-of-the-art technologies for using rainwater to offset municipal water demand and potentially provide all household water needs in emergency situations, providing a level of water security. Average total household use (family of 3) in Madison is 192 gallons (0.73 m^3) per day (Madison Water Utility 2001). On an annual basis, this is 70,080 gallons. The rainfall harvest potential for this project's 3,200 ft^2 (297 m^3) house is approximately 61,835 gallons (234 m^3) annually, given Madison's 31-in. (0.79-m) average annual rainfall. Average rainfall was calculated from Madison, Wisconsin, 1960–1995 rainfall data (NCDC 2010). Thus, effective management of rainwater harvest could supply over 75% of the water demand for a family of three in Madison (Fig. 8).

Because of rainfall variability, volume, and the cost for constructing storage, the Carriage House cistern was size optimized via an input–output model that considers rainfall frequency and volume from the rooftop collection area with the water use rate for a typical Madison residence. When rainfall is in excess of use rate and storage capacity, it overflows into a subsurface drain field south of the Carriage House.

The rainwater management systems in this residential demonstration project are designed to address potable and non-potable uses separately.

Non-Potable System

Since toilets and clothes washing comprise about half of the average daily use (Table 2), the non-potable rainwater system can reduce water use significantly depending on rainfall frequency and duration and the size of the associated storage compared to demand. This system (Fig. 9) was designed and configured to be compact for installation inside the Research Demonstration House. The close proximity to the laundry area and bathroom facilitated connection to these non-potable uses. It includes a 300-gallon tank that stores rainwater from a portion of the adjacent roof. The tank is fitted with an overflow for excess rainfall. The control system includes a demand-activated pump and relayed valve connection to the municipal supply with appropriate back-flow prevention. A low water level sensor in the tank connects to the control relays. When rainwater in the tank falls below the sensor level, the control system closes the tank output valve and opens the valve from the municipal supply. This system is designed to be used in areas where rainfall frequency does not provide a reliable supply. Maintenance and management of this system is limited to seasonal cleaning of the tanks and testing of the back flow preventer that isolates rainwater from the municipal system.

Figure 9. Non-potable rainwater storage and management systems for flushing toilets and washing clothes.

Filtration/Disinfection System

This rainwater collection system was specifically designed to determine the efficacy of producing high-quality water via a point-of-use (POU) water treatment device. It is comprised of six components, collection, detritus removal, transport, storage (see sidebar on rainwater quality), filtration/disinfection and operable connection to the household supply. Rainfall is collected from the roof into gutters and gravity fed to downspouts. The downspouts are fitted with leaf diverters and equipped with first-flush devices to remove particulates as described in the sidebar on first-flush devices.

Overflow from the first-flush devices is piped (underground) to the cistern. The main cistern (2,500 gallons, 9.5 cubic meters) is located under the east bay of the Carriage House (Fig. 7). Rainwater is pumped from the cistern through a filtration/disinfection apparatus. Figure 10 is a diagram of the filtration/disinfection systems and Figure 11 illustrates the actual system with interpretive materials. The filtered and disinfected water is routed back to the Research Demonstration House and connected into the municipal water supply line with appropriate valving and back flow prevention so that either municipal water or filtered/disinfected rainwater is supplied for the household uses. Rainwater in excess of the cistern storage capacity overflows to a subsurface leach field south of the Carriage House.

Potable Water

The point-of-use filtration/disinfection system was assembled from off the shelf filtration and UV disinfection units as shown in Figures 10 and 11. The components of the system included a typical pressure pump/tank system, a 20-µm spun polypropylene progressive-density cartridge filter, a 20-in., 5-µm spun polypropylene progressive-density cartridge filter, an activated carbon impregnated paper cartridge filter, and a high-capacity ultraviolet sterilizer. The UV module is equipped with a 22-W UV lamp. These components are mounted on a board as part of an interpretive display (Fig. 11). This system was assembled and filtration/disinfection performance was evaluated at the University of Arizona's National Science Foundation Water Quality Center (Jordan and others 2008). The filtration and disinfection performance evaluation compared heterotrophic plate count (HPC), turbidity, pH, total organic carbon (TOC), and total dissolved solids (TDS) measurement taken from the following water types: first flush, stored cistern water, and water passed through point-of-use filtration and UV disinfection units separately (Fig. 12).

Point-of-use water treatment systems similar to the one developed for this project have been demonstrated (Adams and others 1987; Wolf 1990; Pozos and others 2004; Jordan and others 2008) to be an effective and practical option for purifying water against known bacterial, viral, and protozoan pathogens. Linden and others showed effective inactivation of protozoan cysts when treating a variety of water sources with a low UV dose similar to that imparted by our UV disinfection unit (Linden and others 2001).

Perhaps the issue of most concern for potable use of harvested rainwater is maintenance and monitoring of the filtration/disinfection unit. It is not uncommon to see heterotrophic regrowth in these point-of-use devices (Adams and others 1987; Morin and others 1996). We plan to alleviate the regrowth of heterotrophic bacteria by constantly bleeding a portion of the filtered water back into the cistern to prevent filter fouling. The other option we will use as necessary is to disinfect the unit with monochloramine.

Rainwater Quality

Research has shown that the quality of roof-harvested rainwater depends on many factors. Water quality in rainwater management systems starts at the rainwater catchment surface and continues to the storage tank and on to the filtration/disinfection unit.

The roof surface material is very important. Reflective roof coatings should have a potable use rating (NSF International 2007). NSF International (www.nsf.org/) has developed a protocol that tests materials used in rainwater catchment systems. Testing involves exposing catchment system products (i.e., roofing materials, coatings, paints, liners, and gutters) to extensive accelerated outdoor weathering. Products meeting the requirements of this protocol are deemed not to impart contaminants to test waters at levels greater than those specified in the U.S. EPA's Drinking Water Regulations and Health Advisories (EPA 2006). Rainwater harvested from newly roofed buildings should be tested periodically before processing for potable use. Asphalt shingles and zinc-plated roofing systems, for example, produce undesirable residuals for some time after installation. Lead flashing should be avoided. Care should also be taken to clear the catchment surface of any debris, including litter from overhanging plantings and biological waste from birds as they are the primary depositors of pollutants in roof rainwater harvesting systems. Also, the catchment surface should be cleansed from time to time to prevent build up of particulate debris from local air pollution, including dust and residuals from automobiles and industry. Leaf litter can be managed with plant maintenance, whereas dust, air pollutants, and animal waste should be addressed by means of a first-flush system. Many devices have been developed for achieving first flush; most are viable but all require continued monitoring and maintenance. Also, the intake from the cistern to the filtration system should be six inches or more from the bottom to prevent intake of sediment. Regular tank cleansing and maintenance is also recommended.

First-Flush Devices

A number of first-flush devices were evaluated for their performance and seasonal use. In general, all of the first-flush devices tested collect a measured volume of initial roof drainage to prevent dust and debris from roof and gutters from entering the cistern. When the determined flush volume is reached, the rainwater is passively diverted to the cistern and the initial (dirty) water drains from the device's storage container.

The devices evaluated range from simple configurations of off-the-shelf PVC pipe and fittings to marketed products that are adaptations of the basic PVC pipe configurations that add plastic balls to seal the route to drain, diverting the clean water to storage.

In one product, the ball closes rainwater flow to flush storage tanks and includes fittings to allow slow drainage of initial (dirty) rainwater from the tank. The volume of first flush for this system is determined by the size of the tank. This first-flush device is from an Australian company (Rain Harvesting Pty, Ltd., Archerfield, Australia) and comes in a number of configurations for application flexibility. One problem we noted was with dimensional differences between PVC sizing in the United States and Australia causing problems with fitting connections.

The other product is a ball modified to take fill with water when the rain begins. The ball modifications include an adjustable, screened intake, and a drip hole for drainage. It also has an attachment loop on top and includes a spring, suspension bar, and gasket ring. It is installed into a 4-in. polyvinyl chloride pipe fitting (PVC-T) below the diversion to the rainwater storage. Its operation uses the initial roof drainage to fill the spring-suspended ball with water. As the weight of the ball increases, it drops into the gasket closing the path of water to the drain. Additional clean rainwater backs up and is diverted to the rainwater storage tank. At the end of the rainfall, the ball drains completely via a drip hole allowing the spring to raise the ball, readying the diverter for the next rain. The first-flush amount is adjusted by changing the opening to the intake screen. A problem noted with this product is that the dust/silt in the initial roof runoff causes clogging leading to device malfunction.

Other devices are available that allow detritus to pass through. They depend on surface tension to move rainwater traveling down a pipe through a fine screen to be diverted to storage. However, the cost of these devices made them unpractical for residential application.

In a cold climate like the project site, ice build-up can lead to downspout failure. Initial research indicated that such failures would be magnified in first-flush devices that were installed outdoors. To evaluate the extent and impact of such failures, two outdoor first-flush devices were installed in fall 2008. In addition, one was installed indoors. The two outdoor installations failed because of ice build-up from diurnal thaw/freeze cycles. After confirming the failure, we recommended decommissioning the rooftop rainwater harvesting systems unless the first-flush device could be located indoors. However, even the indoor application has the potential for freeze/thaw ice build-up failures in the external plumbing, either in the leaf catcher or in the pipe that carries the water to the interior.

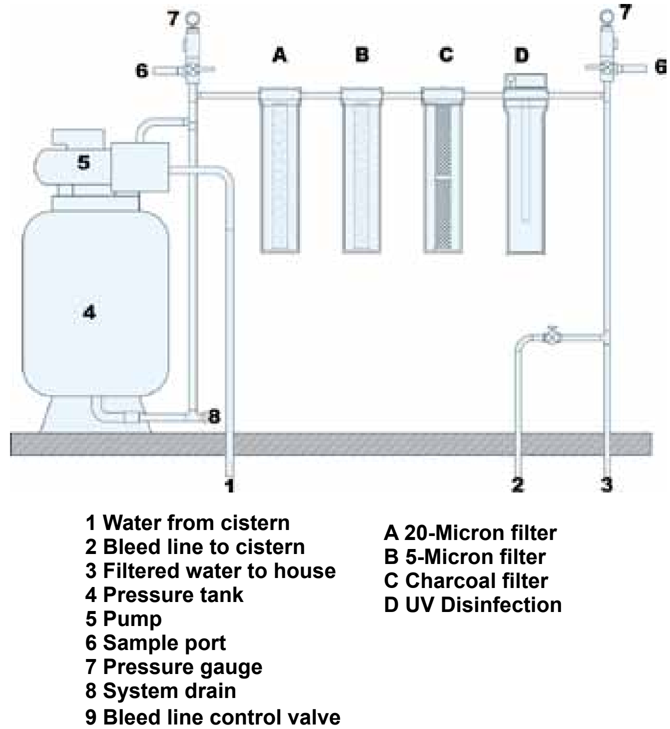

Figure 10. A schematic depicting the basic components making up the point-of-use water filtration and UV disinfection unit.

Discussion

Residential photovoltaic systems are becoming more affordable through incentives, improved technology, and acceptance. Energy efficiency in building envelope design is recognized as an essential part of the sustainable energy equation. Together they provide the opportunity for moving closer to net-zero energy at the residential scale. Advances in building energy modeling and cost reductions in photovoltaics are helping to move these technologies into the mainstream. Yet, many remain skeptical or do not understand how these work together. This project is accessible to the public and is designed to help bridge the gap between research and application.

Rainwater harvesting and use has even older roots in the traditions of the region. But its acceptance as a viable water resource is diminished by the availability of water from municipal utilities. This project is designed to showcase how technology can bridge the gap between the traditional use of rainwater and a contemporary source for residential water needs whether for irrigation, non-potable household uses, and even potable use through careful development and management of the filtration/disinfection system.

Finally, climate change and unforeseen consequences in early fire management policies has placed challenges to our perception of how we manage forest resources. A shift in forest management strategy has created a new resource in woody biomass from the slash and small-diameter logs that

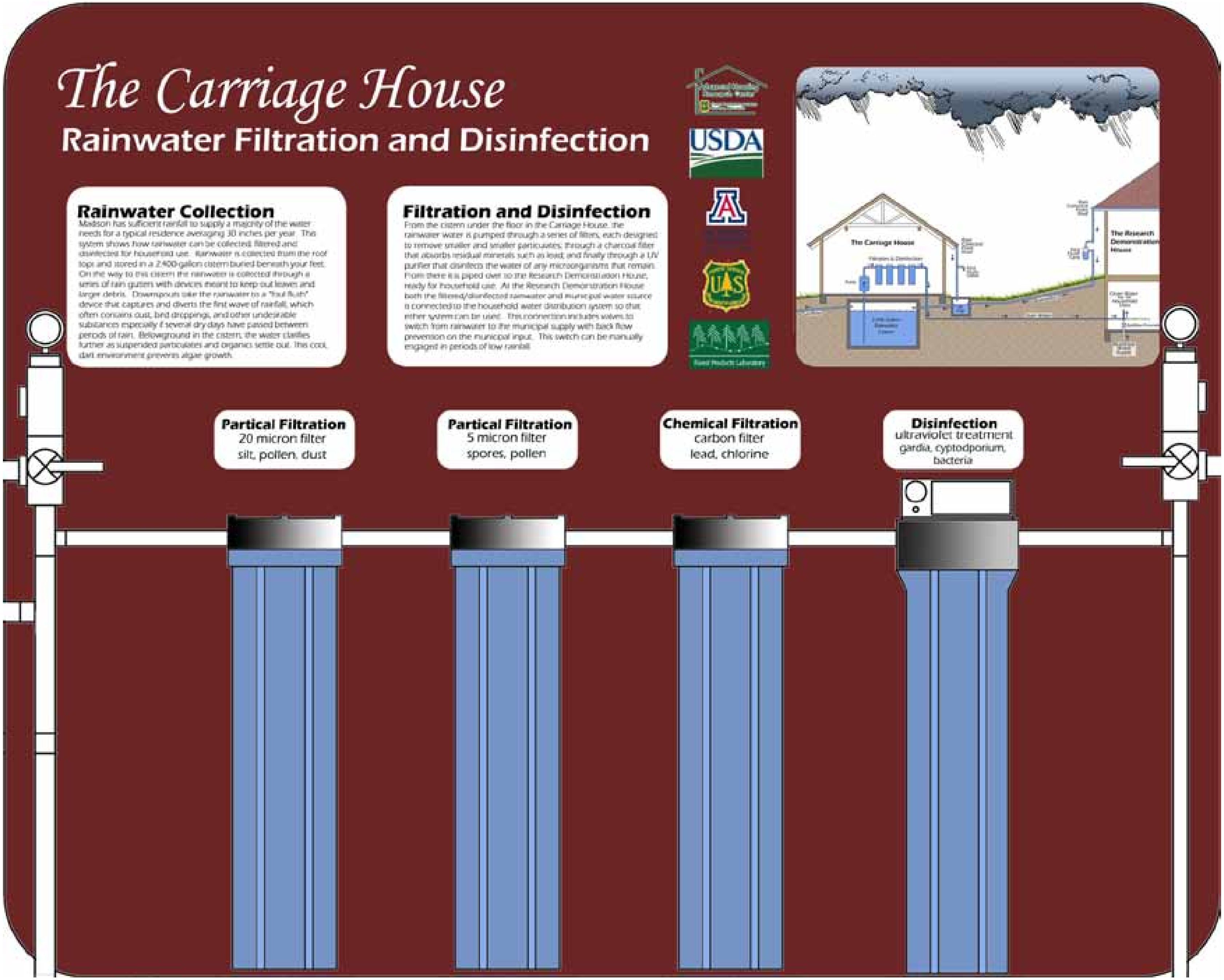

Figure 11. Graphic illustration of the rainwater filtration/ disinfection systems with interpretive materials and illustrations.

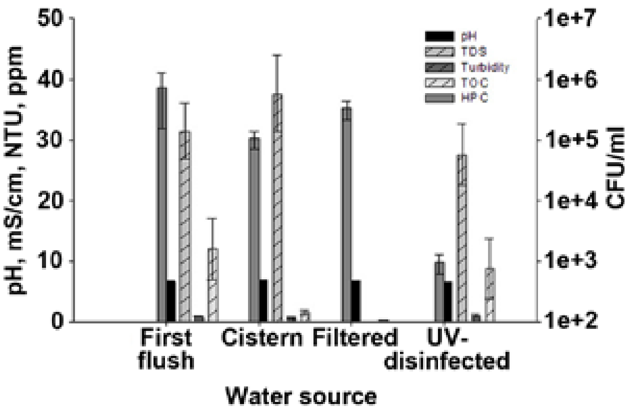

Figure 12. A comparison of HPC, turbidity, pH, TOC, and TDS measurement taken from the following water types: first flush, stored cistern water, and water passed through point-of-use filtration and UV disinfection unit separately.

may be processed into useful forest products. The slash can be used in new technology like the BioMax® for heat and energy production, and the products from small-diameter logs should be developed and integrated into the building industry instead of being land filled.

Showing how these systems work and can be effectively integrated through collaborative design, engineering, and technology development is an essential part of this effort. The Research Demonstration House at FPL will help interpret this idea.

Conclusion

This project has shown that the integration of building systems with renewable energy and rainwater harvesting systems can achieve net-zero energy on an annual basis for electric requirements including air conditioning. The total energy requirement including heating may be further reduced through the incorporation of waste heat recovery from the BioMax® system. The national goal of 50% reduction in municipal water use can be met by conservation and through the use of rainwater for non-potable demands for an average family of three. This research has shown that with adequate collection area, storage, and filtration/disinfection to potable standards, the water needs for an average family in cold climates can be met through the use of rainwater. However, current water infrastructure safety requirements do not allow other water sources to be connected to the municipal systems because of concerns for the maintenance of water quality. Rainwater harvesting systems developed for potable use must be continually monitored to assure water quality and safety.

This project validates that (1) the grid-interconnected combination of the BioMax® wood-pellet energy system (5-kW generator with battery storage and inverter capable of 10 kW with solar energy via photovoltaics (3.7 kW) can provide all of the power needs for a residential unit in a cold climate; (2) rainwater can be stored (2,500-gallon cistern) and reliably filtered and disinfected for potable use; (3) systems for renewable energy and water are safe, reliable, and provide water security that is not dependent on community infrastructure; and (4) these technologies are available and work well in cold climates like Wisconsin.

As the interest in sustainability increases and technologies such as those shown and evaluated in the project become more available, affordable, and acceptable, the payback periods for such fully integrated sustainable systems will become shorter. More importantly, the impact of this project is expected to be in demonstrating the possibilities and potentials for the development of sustainable energy and water in a residence in the cold winter conditions of the upper Midwest.

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