A simple overhang over south-facing windows controls cooling-season sun while allowing for maximum solar gain during the heating season. During construction after the insulation was installed the outdoor temps hovered around zero for several weeks, but inside it never got below 60°F with no heat. This geometry provides an opportunity for the students to study solar aspects through the seasons. A common exercise is to measure the depth of sun penetration in the classroom at different times and seasons.

Passive School, ACTIVE SAVINGS

BY DAVID ELY, AIA, AND JORDAN GOLDMAN

AT THE HOLLIS MONTESSORI SCHOOL in southern New Hampshire, the school environment is a teaching tool. So, to create the best possible environment for students, it made sense to build the first Passive House certified elementary school in the U.S. It made financial sense, too. For a 10% increase in construction costs to reach certification status, the payback was only three years.

The campus is comprised of three energy-efficient buildings, the crowning jewel being the Passive House certified New Classroom Building: 11,000 ft^2 with four classrooms for primary and elementary students and teachers. The school is located in a cold climate (6,950 heating degree days, 3°F outdoor heating design temperature) on a repurposed 9.5 acre apple orchard. The site is fairly level with excellent solar access. A large portion of the orchard remains, and it is maintained by students as a business teaching model. Well water, septic, and stormwater are all managed on site. The electric utility provides all of the energy consumed; no fossil fuels are consumed on site.

Energy Efficiency

This efficient building has a measured energy use intensity (EUI) of 10.8 kBtu/ft^2·yr, compared to the ASHRAE Standard 90.1-2004 EUI of 70 kBtu/ft^2·yr for a K–12 school. That's an 85% reduction compared to other K-12 schools. The annual energy savings are on pace to pay off the roughly 10% additional construction cost within three years.

In the future, Hollis Montessori School plans to offset all of its energy consumption with photovoltaic (PV) panels, thereby achieving net zero energy performance. A 27 kW PV system would offset 100% of the 35,000 kWh/yr annual energy consumption. In comparison, a K-12 building of the same size built to ASHRAE Standard 90.1-2004 would require 175 kW of PV panels to achieve net zero energy performance.

The architecture is simple in its form to help it integrate with the fabric of small-town New England. The form also facilitates continuous insulation, air, moisture, and weather barriers. It was designed along an east-west axis to provide a south-facing roof for future PV panels, to maximize daylighting, and to capture passive solar gain through the south-facing windows. The southern roof overhang is designed to balance solar gain in winter and shading in summer.

Lighting

Lighting is controlled by daylight and occupancy sensors, using three T-8 tubes per fixture to provide three lighting levels as controlled by the daylight sensor. The occupancy sensors will shut off the fixture when the room is unoccupied. In addition to the four classrooms the building also features a conference room, staff offices, reception area, laundry, and print-room with dedicated exhaust air. Each classroom has its own kitchen.

Building Envelope

The super-insulated building envelope is the primary energy-efficiency strategy. Heating energy can comprise 50% (or more) of the overall energy profile of a building in New England, per the 2003 CBECS data. The individual components of the building envelope system include high R-values with no thermal bridging, a continuous air barrier with blower door performance testing, and triple-paned windows. The super-insulated building envelope will reduce the heating demand 90% compared to a code-compliant building, improve thermal comfort by eliminating drafts and cold surfaces, reduce the required capital expense on heating equipment, and maintain a viable indoor temperature in the event of a power outage. (The temperature in the building during winter construction, without any heat, did not drop below 60°F.)


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The Hollis Montessori School was designed to evoke a sense of place while students go about learning. This sense of place is enhanced by an environment that teaches sustainability by example. Students, teachers, faculty, parents and the community at large are inspired by the comfort and efficiency of this building.

The insulation strategy includes 12 in. type IX EPS under the slab (R-54), double stud 12 in. thick wood frame walls filled with dense pack cellulose (R-41), and parallel chord wood roof trusses filled with 20 in. dense pack cellulose and 6 in. polyisocuanurate nail-base insulation above the roof deck to warm the sheathing and prevent condensation (R-111).

All building envelope connections are thermally broken: the slab is completely thermally isolated from the exterior, the double-stud walls have separate top and bottom plates to avoid heat transmission through the framing, and the roof assembly has continuous rigid insulation over the framing. Windows are triple-glazed tilt-turn or fixed units with an overall U-value of 0.15. Similarly, doors are commercial grade aluminum frame triple glazed with an overall U-value of 0.176. Doors are equipped with a "guillotine" drop-down sill gasket for additional air sealing. All glazing has an SHGC of 0.5, which increases the passive solar gain through the windows.

A continuous air barrier was meticulously designed, with particular care given to transitions between different assemblies. The wall and roof sheathing comprise the primary air barrier system; all seams were taped. The under-slab vapor barrier wraps over the top of the foundation wall and is taped to the wall sheathing, eliminating air leakage at the perimeter sill plate. The taped sheathing wraps around the eaves and rakes to maintain continuity between the wall and roof sheathing. Window and door frames were taped to the exterior sheathing and expanding foam tape fills the rough opening cavities of each window and door.

All penetrations, including those under-slab, were diligently sealed to the air barrier. Air sealing was measured by blower door testing multiple times throughout the project. The building achieved an airtightness of 0.26 air changes per hour (ach) at 50 Pa, 50% better than the Passive House requirement (0.6 ach at 50 Pa) and almost 90% better than the building code requirement (3.0 ach at 50 Pa).

The framing crew and other subcontractors deserve enormous credit for the measured air-tightness. Before construction started, the project goals were clarified, the construction details reviewed, and the team was instructed on best practices to achieve the stringent requirements. Despite the fact

BUILDING AT A GLANCE

Name Hollis Montessori School

Location Hollis, N.H.

Miles from nearest major city
5 miles west of Nashua, N.H.

Owner Hollis Montessori School

Principal Use Elementary and Pre-school

Employees/Occupants 112

Expected (Design) Occupancy 112
Percent Occupied 100%

Gross Square Footage 11,000
Conditioned Space 11,000

Distinctions/Awards
Passive House Certified

Total Cost $2,000,000
Cost per Square Foot $181.82

Substantial Completion/Occupancy
April 1, 2013

BUILDING ENVELOPE

Roof
Type Shingle w/ 6 in. polyisocyanruate nail base and dense pack cellulose insulation.
Overall R-value 111

Walls
Type 12 in. thick double stud w/dense pack cellulose insulation
Overall R-value 41
Glazing Percentage 14%

Basement/Foundation
Slab Edge Insulation R-value 20
Basement Wall Insulation R-value N/A
Basement Floor R-value N/A
Under-Slab Insulation R-value 54

Windows
Effective U-factor for Assembly 0.15
Solar Heat Gain Coefficient (SHGC) 0.325
Visual Transmittance 0.71

Location
Latitude 42.7 N°
Orientation N/S long sides

ENERGY AT A GLANCE

Annual Energy Use Intensity (EUI) (Site) (kBtu/ft²)	10.80
Electricity (Grid Purchase)	10.80
Annual Net Energy Use Intensity	10.8 kBtu/ft²
Annual Source (Primary) Energy	33.912 kBtu/ft²
Annual Energy Cost Index (ECI)	$0.59/ft²
Savings vs. Standard 90.1-2004 Design Building	84%
Heating Degree Days (Base 65°F)	6,950
Annual Hours Occupied	1,800

WATER AT A GLANCE

Annual Water Use Water meter not installed.

KEY SUSTAINABLE FEATURES

Water Conservation Waterless urinals, 1.2 GPF toilets, low flow faucets and shower.

Daylighting All classrooms have large south-facing windows.

Individual Controls Daylight, occupancy and vacancy sensors for all lighting.

Carbon Reduction Strategies Extremely low energy use for heating and lighting. South-facing roof is solar panel ready.

Other Major Sustainable Features
Passive House Certified. Natural materials include wool carpets, zero VOC finishes, linoleum flooring, dedicated exhaust from print room, CO_2 sensor controlled HRV's, daylight, occupancy and vacancy sensor lighting controls.

BUILDING TEAM

Building Owner/Representative
Hollis Montessori School

Architect Windy Hill Associates, David Ely, AIA

Construction Manager Windy Hill Associates/ TMD Construction Services, LLC

Mechanical Designer ZeroEnergy Design, Jordan Goldman

Electrical Engineer Reno Engineering and Light Design, Vic Reno, P.E.

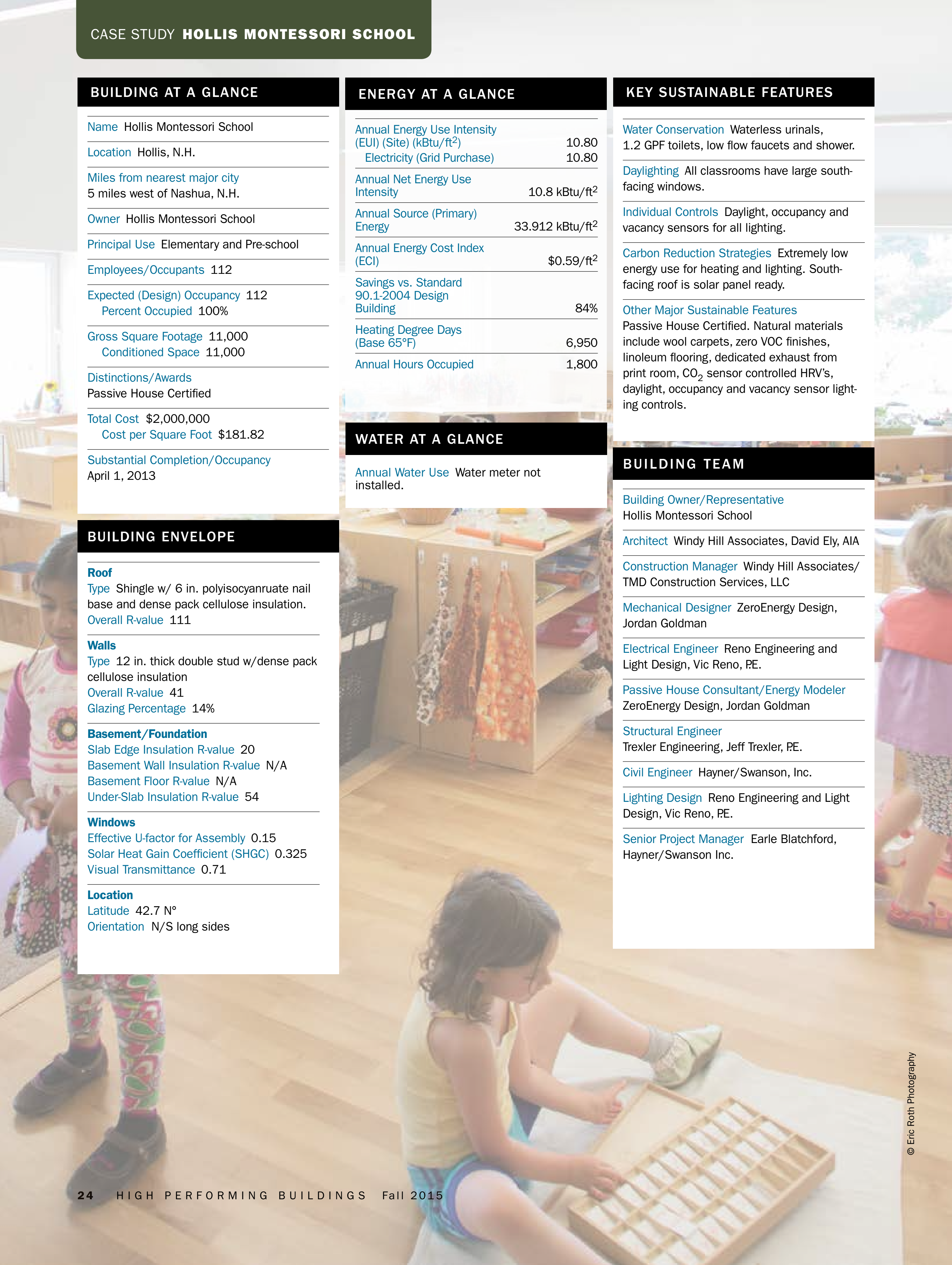
Passive House Consultant/Energy Modeler
ZeroEnergy Design, Jordan Goldman

Structural Engineer
Trexler Engineering, Jeff Trexler, P.E.

Civil Engineer Hayner/Swanson, Inc.

Lighting Design Reno Engineering and Light Design, Vic Reno, P.E.

Senior Project Manager Earle Blatchford, Hayner/Swanson Inc.



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Natural materials, daylight, and healthy air quality are essential to the **Montessori teaching environment.**

Clockwise from top left Classrooms are organized into several curriculum areas: language arts, mathematics and geometry, everyday living skills, sensory awareness exercises and puzzles, geography, history, science, art, music, and movement.

Students learn hands-on. Fresh air, natural materials and daylight add to the experience. Triple glazed tilt-turn windows are often opened in the tilt position for fresh air and to allow continued use of the wide window sills for plants and other items.

Age-appropriate components are found throughout the school. Students move freely within the rooms, selecting work that captures their interest, rather than passively participating in lessons and projects selected by the teachers.

We know that young children are full and complete individuals in their own right. They deserve to be treated with the full and sincere respect that we would extend to their parents. Respect breeds respect and creates an atmosphere within which learning is facilitated.

The Primary (or "Children's House") classroom environment is carefully designed to meet the needs of children between the ages of 2½ and 6. The teacher acts as a nurturing guide and facilitator. Once they have been introduced to the activities and materials, children enjoy choosing their own work.

Montessori education differs from public schools so the architecture must respond to the individual's learning needs. Students sometimes gather as a group, but are typically scattered around the classroom working alone or in small groups. It may take a moment to spot the teacher working with one or two students at a time, giving a new lesson or quietly observing. The atmosphere is remarkably peaceful as students concentrate on their tasks.

that no one on the construction team had prior experience with the Passive House standard, they took an immense interest in the building's performance, which fostered a sense of accountability and pride. On-the-job training for a thermally excellent building became a normal part of construction administration and everybody benefited from the experience. At the end of the process they all had a much greater respect and understanding for what was initially mysterious.

Heating and Cooling

Given the exceptionally well insulated and air-sealed building envelope, the heating and cooling systems are smaller and simpler than they would be ordinarily. Mini-split air-source heat pumps (ASHPs), without any backup heat source, provide 100% of the building's heating and cooling needs. This might seem a strange choice in a cold climate; however, they are incredibly well-suited for the Hollis Montessori school. The installed systems are rated down to –13°F, well below the design temperature.

The relatively small heat output of a mini-split ASHP pairs well with the greatly reduced peak heat demand of the Passive House certified school. The school requires less than 4 Btu/h·ft^2 at peak conditions, about 90% less than a code complaint school of the same size. Each of the four classrooms has its own mini-split system which pairs an outdoor heat pump unit with a wall-mounted indoor unit.

The super-insulated envelope and triple-paned windows make point-source heating viable and allow for the elimination of a ducted distribution system. The R-10 glazing maintains a warm interior surface temperature and eliminates the need to supply heat at the windows. The entry, circulation areas, and offices are served by a single ducted indoor mini-split unit combined with its corresponding outdoor unit. The ducted unit was selected, in this case, to provide a heat supply in each of several separate rooms.

A ground-source heat pump (GSHP) was not selected due to its high installation cost for drilling, piping, and distribution systems. Given the extremely small heating requirement, the increase in efficiency from an ASHP to a GSHP (COP 2.5 and COP 3.5, respectively) could not offset the higher first costs.

Heat recovery ventilators (HRVs) (84% sensible efficiency, 0.4 W/cfm) distribute fresh air to the classrooms and offices and exhaust stale air from the kitchenettes and bathrooms. Each HRV is controlled by a CO_2 sensor as part of a demand-controlled ventilation system; the interior CO_2 concentration acts as a proxy for occupancy. When

Table 1 ENERGY COMPARISON TO CODE MINIMUMS (2009 IECC)

Element	Code	Hollis Montessori School
Slab	R-15 for 24 in. Below	R-54 Continuous
Walls	R-13 + R-3.8 ci	R-41
Roof	R-20 ci	R-111 (R-30 ci)
Windows	U-0.35	U-0.15
Window Air Leakage	0.3 cfm/ft^2	0.03 cfm/ft^2
Door Air Leakage	1 cfm/ft^2	0.03 cfm/ft^2

Figure 1 ANNUAL ENERGY CONSUMPTION

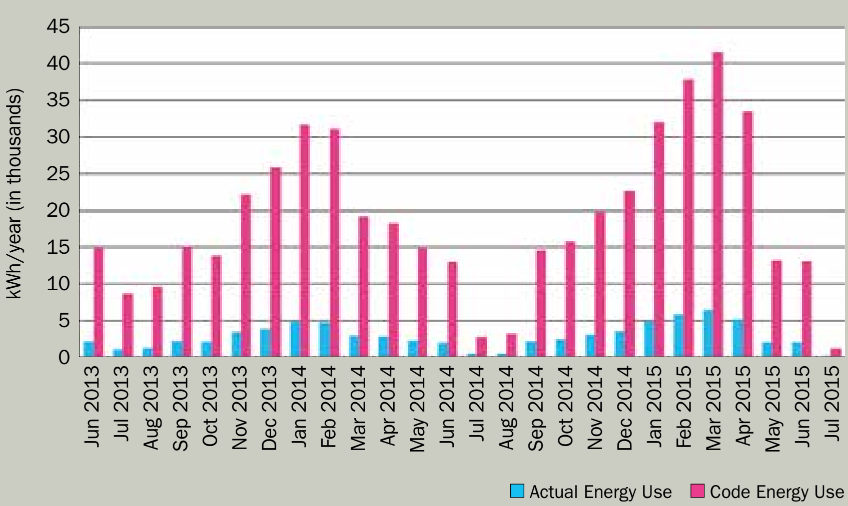
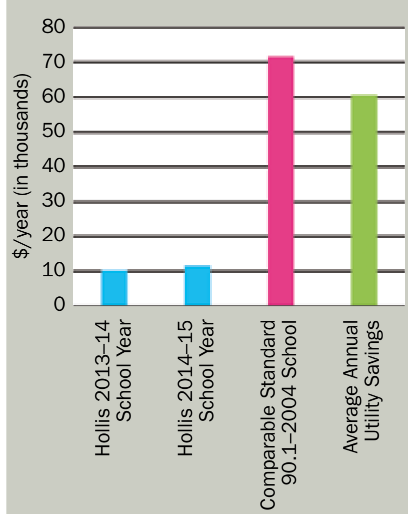


Figure 2 UTILITY COSTS & SAVINGS



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Clockwise from above Mechanical equipment is not hidden, rather it is displayed so students can learn how energy is used. The compressors for the air-source heat pumps are on racks to keep them above the snow. Mechanical rooms are not necessary for this type of equipment.

Each of the four classrooms has its own mini-split system that pairs an outdoor heat pump unit with a wall-mounted indoor unit. The super-insulated envelope and triple-paned windows make point-source heating viable and allow for the elimination of a ducted distribution system.

One classroom includes an exposed fabric duct as a learning opportunity. Seen here on the ceiling with air holes, the duct visibly inflates when the heat recovery ventilator (HRV) is energized. This enables the students to see the air being distributed and understand how the system changes with fluctuations in occupancy. The volume of fresh air from the HRV and duct is controlled in part by CO_2 sensors.

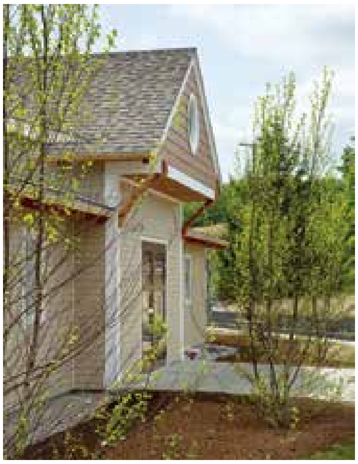
Mechanical equipment is visible in many locations offering learning opportunities to students. Point-of-use water heaters eliminate the need for large volumes of stand-by hot water thus using energy only on demand.

Heat recovery ventilators provide fresh air and are operated automatically by CO_2 sensors in each classroom.

The R-10 triple glazed tilt-turn windows and triple glazed entrances with thermally broken aluminum frames and drop-down sill gaskets were used throughout the building. Passive solar gain through the windows make this building extremely resilient in the cold New England climate. This rural area can be susceptible to power outages; however, even without electricity the temperature in this building rarely drops below 60°F in the winter.

Mini-split air-source heat pumps, without any backup heat source, provide 100% of the building's heating and cooling needs. The relatively small heat output of a mini-split ASHP pairs well with the greatly reduced peak heat demand of the Passive House certified school. The school requires less than 4 Btu/h·ft^2 at peak conditions, about 90% less than a code-compliant school of the same size.

Architectural details enrich the energy-efficient campus.



In the future, Hollis Montessori School plans to **offset all of its energy consumption** with photovoltaic (PV) panels.

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Passive House Certification

Passive House is a voluntary international building standard composed of several strict performance requirements for new building construction: annual heating demand, annual cooling demand, total primary (source) energy demand, and building airtightness. The resulting performance represents a roughly 90% reduction in heating and cooling energy usage and up to a 75% reduction in primary energy usage compared to building code. These measures are intended to aggressively meet the climate change crisis by reducing carbon emissions while making a comfortable, healthy and affordable built environment.

The Passive House Standard for new buildings addresses energy usage and building airtightness:

Space Heating Energy Demand
4.75 kBtu/ft^2·yr

Space Cooling Energy Demand
4.75 kBtu/ft^2·yr

Primary Energy Demand
38.0 kBtu/ft^2·yr

Airtight Enclosure
Allowable limit of 0.6 air changes per hour at 50 Pa pressure (ach50) that is verified with an onsite blower door test (pressurized and depressurized).

Lessons Learned

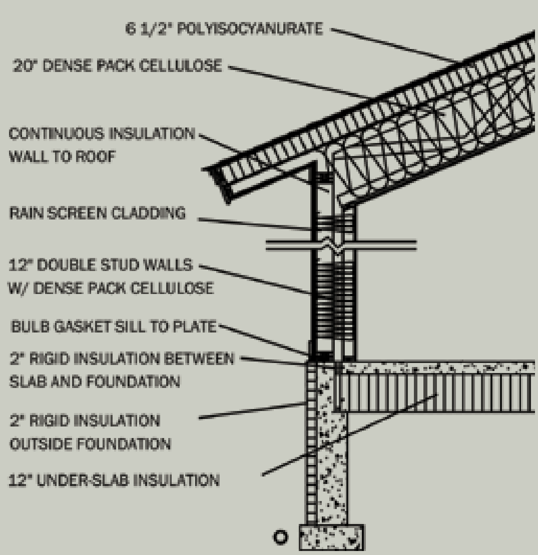
- ☐ Automatic lighting controls were problematic; commissioning should have been required in the initial contract documents, not an add-on with extra cost associated.
- ☐ The contracts with subcontractors should have included a requirement for air-sealing their own penetrations.
- ☐ The designers specified energy monitoring from the beginning, but for the next project, they intend to break it down more granularly, circuit-by-circuit, and have a post-construction review program to identify problem areas.
- ☐ If the insulation under the slab is more than 4 in. thick it should be staggered in two layers to mitigate cupping and improve the ease of installation.

the room is occupied, the CO_2 sensor energizes the HRV into high speed. Once the CO_2 concentration has fallen below its defined threshold of 700 ppm, the HRV reverts to its lowest speed. One classroom includes an exposed fabric duct that visibly inflates when the HRV is energized. This provides a learning opportunity; the students can see the air being distributed and understand how the system changes with fluctuations in occupancy.

Another learning opportunity comes from the building-wide energy monitoring system. Students use measurements to understand how much energy is being used per classroom, how their behavior affects consumption, and even compete against the other classrooms to minimize consumption.

The building is currently not used during summer vacation. As such, the mechanical systems are dormant except the small amount of dehumidification necessary to keep the hardwood finishes from warping, meaning that almost no summertime air conditioning is required.

Figure 3 INSULATION STRATEGY TO AVOID THERMAL BRIDGING



Insulation is continuous from under slab to wall to roof. The double-stud wall covers the slab-edge insulation. The parallel chord roof has top chord bearing allowing the interior non load-bearing stud to be attached to the end of the bottom chord of the roof truss forming a continuous insulation cavity. The rigid insulation on the roof keeps the dew point above the roof deck thus avoiding a cold surface where condensation could occur in winter.

Conclusion

Having a Passive House certified school, makes a big impact on the budget. It only takes $5,000 to $6,000 annually to operate a 11,000 ft^2 building with 112 people (includes heating, cooling, lighting, hot water and plug loads), which is a large enough savings that it has an effect on the whole organization. Another impact is the ease of running the building. Other than cleaning the filters a few times a year, not much adjustment is needed. And, finally, the large amounts of daylighting and comfortable environment contributes to a sense of wellness for the occupants. ●

ABOUT THE AUTHORS

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Jordan Goldman is the engineering principal for ZeroEnergy Design in Boston.