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When Your Best Is Not Good Enough: Building On Lessons Learned in the Solar Decathlon Competition to Create Housing that is Actually Affordable

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Abstract

After winning the most affordable house at the 2013 Department of Energy Solar Decathlon, Norwich University students are examining their design in an attempt to further reduce their costs. The information derived from the review is being applied to an interdisciplinary project to build modular "micro-houses". Similar design criteria are being applied to the micro-houses as was used to develop the Solar Decathlon structure, but with a greater emphasis on the reduction of cost. Each aspect of the Solar Decathlon structure is scrutinized for cost, constructability and energy efficiency. The Solar Decathlon structure provides the students with a known baseline in terms of material performance to make decisions where changes can be made to reduce cost, but retaining the energy efficiency that Norwich University is providing for the residents of Vermont. It is the intent that the students will commence construction of the micro houses in the fall of 2015.

Key Phrases: Cost effective; Affordability; Micro House; Solar Decathlon

I. INTRODUCTION

The U.S. Department of Energy Solar Decathlon is a competition in which collegiate teams design, build, and operate solar-powered houses that are intended to be affordable, cost-effective, energy-efficient, and attractive. Since its inception in 2002[1], this competition is intended to educate students and the public about the economic and environmental benefits of energy efficient, solar powered homes. In addition, it serves as a venue to demonstrate the comfort and affordability of homes that combine energy-efficiency with solar energy systems.

One of the initiating reasons for the development of the Solar Decathlon was to "demonstrate market-ready technologies that can meet the energy requirements of our activities by tapping into the sun's power." Competition organizers stated in the 2007 'Marketability Contest Guidelines' that, "A key goal of the Solar Decathlon is to help reduce the cost of building-integrated photovoltaic system (PV) systems. Teams build their houses for a target market of their choosing and are asked to demonstrate the potential of their houses to keep costs affordable within that market."[2]

Unfortunately, due to the scoring rubrics for the competition, the affordability aspect of the competition was often given only superficial consideration. In 2013 the houses in the competition averaged $279,000 (approximately $300 per square foot) with the winning house costing over $306,000 ($417 per square foot).

In 2013 the Norwich University ΔT90 house became the most affordable entry in the history of the Solar Decathlon Competition, by placing first in the Affordability Contest, with an estimated cost of $168,385 for a 994 square foot house (outside dimensions) with a unit cost of approximately $170 per square foot, while scoring 100% for the energy balance portion of the competition. Shown in Figure 1, the Norwich ΔT90 house was named for the 90ºF difference between inside and outside temperatures that residents of Vermont experience each winter.

Figure 1: Norwich University ΔT90 House at 2013 Solar Decathlon Competition

Although due to the scoring rubric two other schools were officially listed as tied for first place in affordability, at $234,000, one of these two houses cost 39% more than the Norwich team's house and at $248,000, the other cost 48% more than Norwich team's house. All other houses in the 2013 Solar Decathlon competition cost more than $250 per square foot.[3]

While this was the most affordable solar decathlon house in the history of the competition, based upon findings of the "2010 Housing Needs Assessment" of the Vermont's Housing and Finance Agency, at $170 per square foot, the ΔT90 House at house is beyond the reach of the majority of new households[4]. Based upon average construction costs from national survey and U.S. Bureau of Census figures, the costs for the ΔT90 House must be reduced by approximately one third in order for the house to be affordable[5].

Norwich University's Solar Decathlon Design Philosophy

While the Solar Decathlon Competition is about solar technology, its focus on affordability also speaks to practical marketability of the completed structure. An overwhelming number of Vermonter's cannot afford a house that meets the target construction costs of the 2013 Solar Decathlon's Affordability Contest, regardless of energy costs.

The ΔT90 house was designed to be low cost from the foundation up. The house was not specifically designed for the Solar Decathlon competition, but was designed for use in Vermont.

The keys to the Minimalist Design Approach were:

(1) Simplify design
(2) Use passive vs. active systems
(3) Reduce systems to minimum required
(4) Eliminate space wasting mechanical room
(5) Avoid expensive equipment
(6) Reduce operational complexity

The ΔT90 house is the second structure designed and constructed by Norwich University students. The first structure experimented with 2x6 wall construction and spray foam insulation. Spray foam was also applied to the roof and floor systems. This method created a high level of VOC's and it was decided that the ΔT90 house would have no to low VOC's. To determine the best design for the ΔT90 house different systems were modeled and evaluated for the cost and efficiency of operation. This balance was achieved in the accepted design and was proofed during the competition as the ΔT90 structure was awarded the most cost efficient to construct while also taking full points for energy usage.

The original ΔT90 house is attuned not only to the climactic demands of the Northeast but also to the financial demands of the population that lives there. The ΔT90 house was designed for a family of three that makes near or below the median income or retirees who are looking for a structure that is easy to maintain, affordable, does not require a computer to operate and does not have large monthly utility costs. The house maximizes comfort, efficiency, and spaciousness through two bedrooms, an office space, and an open living space for lounging, cooking, and gathering.

While some aspects of the overall design fulfilled these economic goals, other aspects proved to be cost prohibitive. Based upon the cost estimates prepared for the Solar Decathlon Competition by Faithful+Gould[6], the HVAC/Mechanical/Plumbing Systems/Electrical systems of the Norwich ΔT90 house were essentially cost effective, while the structural framing, insulation, and windows were less economical.

In HVAC and mechanical systems, there are always compromises between first costs and high performance. On the Norwich ΔT90 house, long-term performance was the main criterion. Toward this end, the ΔT90 mechanical system integration began with the building envelope itself. By radically slowing heat loss through high-performance building envelope insulation and passive heat-gain strategy, primary annual heating demand could be reduced significantly. The use of simple, small, off-the-shelf mechanical systems was made possible simply because the primary investment placed in the building envelope, thus keeping the PV system to a minimum. While this strategy ultimately resulted in reduced size, cost, and complexity of heating and cooling equipment, some of the decisions unnecessarily increased the cost of the structural system.

The heating and cooling system was a ceiling-mounted, ducted mini-split heat pump system with almost zero duct length. Air distribution was accomplished by the use of partially open transoms above the bedroom entry doors, combined with the open concept living, dining and kitchen space. As a space saving measure, the interior unit was located at the ceiling of the laundry room. While heat pumps typically do not perform well in extremely cold climates, such as Vermont, the heating load was sufficiently low so that the electric heat strips would be more than adequate to supply heat during the rare occasions when the heat pump became ineffective.

An operational skylight, combined with an abundance of high-R-value tilt and turn windows, provided significant ventilation and passive cooling capability. The windows and skylight, couple with seasonally tuned shutters, also provided a significant amount of natural lighting throughout the day.

The plumbing and electrical system costs were minimized by the use of a common systems wall, shown on Figure 2. All plumbing supply, waste and vent piping, along with the majority of the high current electrical equipment, was confined to a single 13 foot wall section. The bathroom, including stacked washer/dryer combination, backed up to the kitchen sink and dishwasher. While this consolidation effort reduced first-time costs, it also reduced long-term costs by cutting stand-by losses in transferring hot water from the heat-source to the delivery point. In addition, the range, water heater, and air handler units were all located on this systems wall.

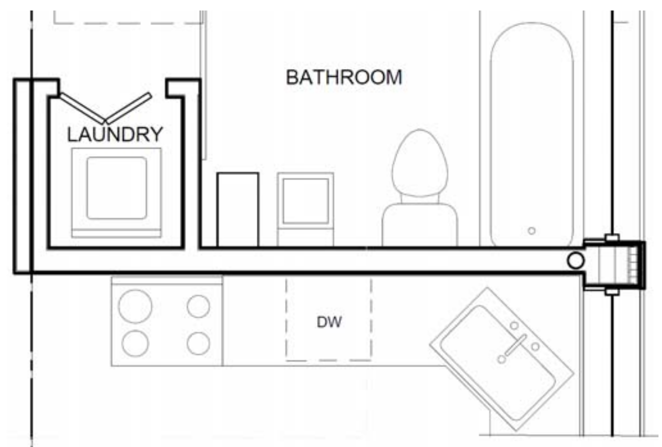


Figure 2: ΔT90 Common Systems Wall[7]

Given the equipment selections and architectural placements made, the approximately 9 square feet are that would have been devoted strictly to mechanical equipment room was available as a utility or storage closet. This compares favorably with the average footprint of approximately 50 square feet that was dedicated to mechanical equipment in the typical Solar Decathlon 2013 houses.

The solar electric system chosen for the ΔT90 house was a thin-film amorphous CIGS (copper indium gallium selenide) system offered by Solopower, Inc. As shown in Figure 3, the panels are mounted directly to the flat roof. The SoloPower CIGS system offered the maximum wattage per-square-foot available in thin film technology. The reasoning behind choosing a thin-film photovoltaic system was four-fold. One, the Norwich ΔT90 team wanted to show the local Vermont market that with their cold climate, the ΔT90 house could stay net-zero on an annual basis. While mounting the photovoltaic panels to the flat roof did slightly reduce the possible annual kWH produced, it also allowed the team to show that the overall footprint of the house could be quite small and reduced the structural cost associated with supports for the solar panels. Lastly, the structure is grid tied to eliminate the need for storage batteries. The batteries not only consume space and cost, but also they require maintenance to ensure their life span and safety to the structures inhabitants. Being grid tied and that the structure produces adequate amount of electricity over the period of the year, the owner, in essence, uses the existing power grid as a storage device. The excess power produced is sold to the power company and then repurchased during times that the PV panels are not at their peak production.

The 5.84 KW photovoltaic system was sized to accommodate the panels being under snow for 120 days annually. This reduced the estimated annual kWh production from approximately 5800 kWh to only 4900 kWh, the intent to show that ΔT90 could, under worst-case-scenario conditions still meet net-zero annual criteria was successful. The Norwich ΔT90 team could then begin to show, in its home market how, under optimum conditions (photovoltaic panels mounted at optimum angle) how energy production could become net-positive. Again, because the primary architectural investment was placed in the building envelope the overall primary energy demand could be reduced, which led to an overall reduction in the size and cost of the photovoltaic system required to meet net-zero criteria.

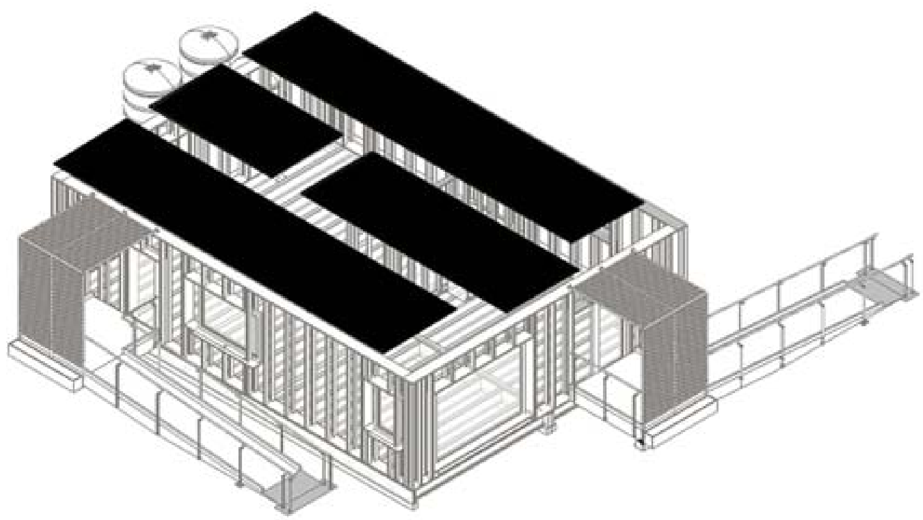


Figure 3: ΔT90 Roof Mounted Solar Panels (shown in black)[7]

At the 2013 Solar Decathlon Competition, the Norwich University ΔT90 house had the smallest solar system present. While one team had a slightly smaller photovoltaic system at 5.4kW, their overall solar system also included a 1.7kW solar thermal system.

One trade-off was made concerning operating costs compared to initial costs; after comparing energy costs to initial costs, it was decided to rely solely on photovoltaic panels for the solar power. A vacuum tube hot water collector system, utilizing heat pipes as the primary heat collector, could have been matched with a 40 gallon storage tank to supply all of the domestic hot water, and possibly augment the space heating needs of the structure deployed in Vermont. However, the first costs were approximately three times the costs associated with the selected electric demand water heater, and some source of space heating would still be required. In addition, to meet the cooling and humidity criteria, even if deployed in Vermont, some air conditioning equipment, and the attendant photovoltaic power capacity, was going to be required; effectively eliminating any substantial photovoltaic panel savings that might have been realized if the vacuum tube collector system was used. The tank, pumps, valves, and fittings also would occupy a significant amount of space that was preferably used for living or domestic storage.

The following areas were considered for potential cost reductions:

(1) Wall and Floor framing
(2) Insulation
(3) Windows
(4) Roof

Original ΔT90 Building Structure

In keeping with the concept of mass production of the structure, the initial design was used modular construction, with the dimensions of the structure limited by shipping constraints for Solar Decathlon Competition. In order to minimize shipping costs, the house was designed using only two modules, each limited to 14 feet width. In order to meet interstate shipping height requirements, while providing 9 feet interior ceiling heights, the structure was designed with a low sloped roof. The structure for the original ΔT90 house was completed by Huntington Homes of East Montpelier, Vermont, a modular home builder. They delivered the structure in two modules, which were rough framed, wired, and plumbed. The two modules were insulated and had interior dry-wall. Students finished out the flooring, interior paint, designed and constructed several light fixtures, set the appliances, cabinets, doors, windows, trim and exterior siding. Specialty contractors were required by the state to complete the HVAC systems, solar panels, plumbing and electrical.

Research Question

Given the excellent performance of the ΔT90 house at the 2013 Solar Decathlon, is it feasible to maintain the original concepts and reduce the production cost? This question is evaluated by examining the various systems in the ΔT90 house by applying different materials to preserve the designed efficiency in comparison to the reduction of the cost.

II. EVALUATION

Wall Framing

As shown in Figure 4, the original ΔT90 house utilized advanced double stud wall framing in order to take advantage of its three key benefits: less material waste, simpler and quicker construction processes, and improved insulation performance. By aligning the window and door openings with the framing members there is an insulation gain with a reduction in thermal bridging throughout the wall envelope. The roof joists, floor joists, and wall studs are vertically in line at 24 inches on center, which creates a simple, yet direct load path to distribute the roof live loads and dead loads uniformly to the ground. The roof construction is more than sufficient to support the average snow load of 60 pounds per square foot (psf) typically found in Vermont. Unfortunately, the economies of using this framing were partially lost by the use of 9 foot interior ceilings. This non-standard interior height resulted in significant waste lumber.

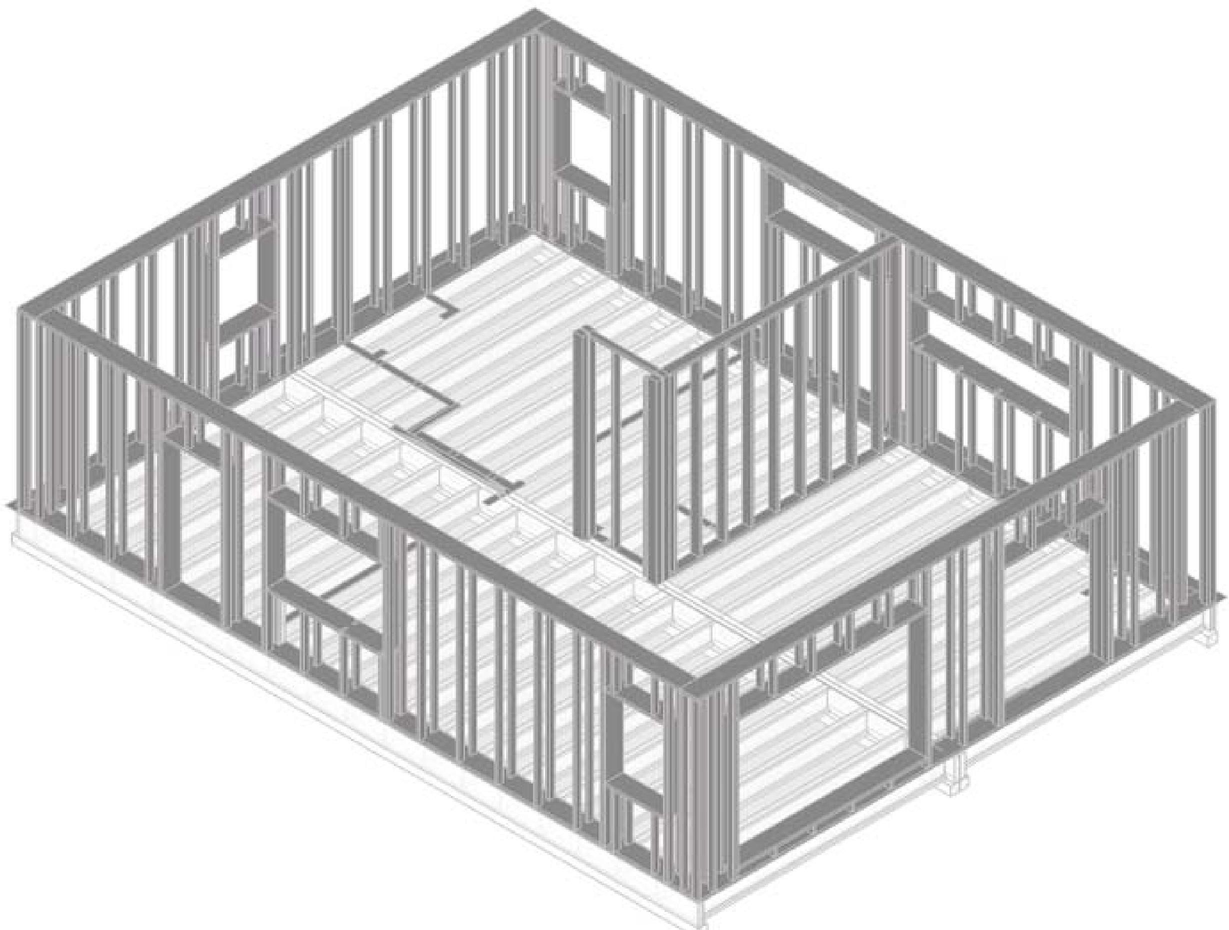
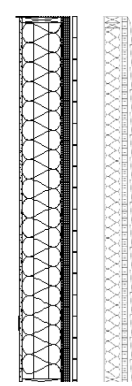


Figure 4: Original ΔT90 Framing Scheme[7]

As shown in Figure 5 (A) the original design utilized exterior walls with 2x12 plates with double 2x4 studs (one the interior and one on the exterior) to reduce the thermal bridging potential. The walls were insulated with nearly 12” of dense pack cellulose insulation with an additional 2" of mineral wool board insulation on the exterior. The exterior cedar siding was attached to the walls via 3/4” batten strips.

However, for this design the walls, floors, and flat roof were over 14” thick. While this construction results in a wall system that has greater than R-50 insulation, this high insulation value come at the cost of both greater material use and a reduction in usable interior space. In addition, the mineral board insulation provided minimal additional insulation, while greatly increasing the transportation weight of the structure.



A B

Figure 5: Original and Proposed Wall Section[7]

In the proposed replacement, Figure 5 (B), the walls would be a hybrid constructed with 2x6's on 24 inch spacing, with fiberglass insulation, and a continuous exterior layer of 2 inch thick rigid foam insulation. The continuous exterior insulation eliminates the thermal bridging of the 2x6 studs. This system provides R-20+ range of insulation. Alternately, the walls could be constructed with 2x4's and 4 inches of exterior rigid foam insulation, providing greater than R-30+ insulation. Compared to original ΔT90 framing scheme, either of these alternatives is approximately six inches thinner, providing an increase of 60 sq.ft. of living space with no change to the outside dimensions. Elimination of the double framing and the exterior mineral wool insulation saves approximately $12 per square foot for a savings of $11,928.

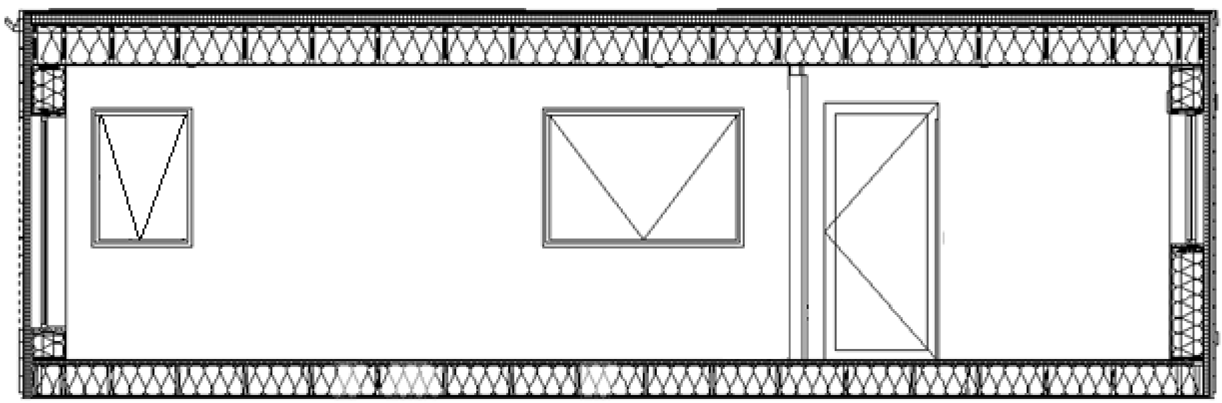


Figure 6: Original ΔT90 House, Longitudinal Section[7]

Floor Framing:

Also shown in the longitudinal section, Figure 6, the floor was constructed with 2x12 framing members, 1-1/8" Tongue & Groove OSB on the upper surface, and 1/2" pressure treated plywood on the lower surface. The floor was insulated with dense pack cellulose insulation between the 2x12 floor joists. The 2x12's were not selected based upon strength requirements, but were selected to provide the desired thickness of dense pack insulation. The 1/2" plywood was installed on the lower surface to ease handing at the Solar Decathlon Competition site, where the building would be installed, then later shipped to a final destination.

In the revised design, the 2x12' would be replaced with 2x10's, the plywood on the lower surface eliminated, and the dense pack insulation replaced with fiberglass insulation. The fiberglass insulation provides the floor with R-40 insulation meeting all State of Vermont and Energy Star recommendations. This change saves approximately $2 per square foot. This is a savings of $1,988.

Finally, as shown in Figure 6, the original flat roof system also utilized 2x12 construction, with 3/4" plywood sheathing on tapered framing to provide the low slope necessary for roof drainage. The roof was topped with 4" of mineral wool board and the voids between 2x12 roof joists filled with dense pack cellulose insulation. The roof was covered with a 1/8" thermoplastic polyolefin (TPO) membrane.

In the original design, in order to achieve the designed R-53 insulation value for the roof, 2x12's were used for the framing members. Replacing the flat roof with a 3:12 pitched roof reduces the structure cost while providing insulation with a larger R-value for the roofing system (R-60). The house can still be easily transported, since the roof is folded down for shipping, and the dense-pack insulation used in the original design is replaced with blown-in insulation, and the plastic membrane roof replaced with conventional built-up roofing. Huntington Homes estimated that simply changing the roof would save $8000, or approximately $8per square foot. Placing the solar panels on one side of the sloped roof reduces the area available for the solar panels, but increases the overall panel efficiency, since the solar panels have a better orientation towards the sun.

Exterior Design Changes

Several design changes to the exterior of the house have been proposed to reduce the cost of the structure. Figure 7 shows the original ΔT90 house was designed with a custom 70 square foot quadruple-pane picture window on the South facing elevation. This custom window was difficult to procure and install. In addition, during the Solar Decathlon competition, the window had to be specially protected during shipping. Finally, constructability issues arose from the skylight and the plastic membrane on the flat roof.

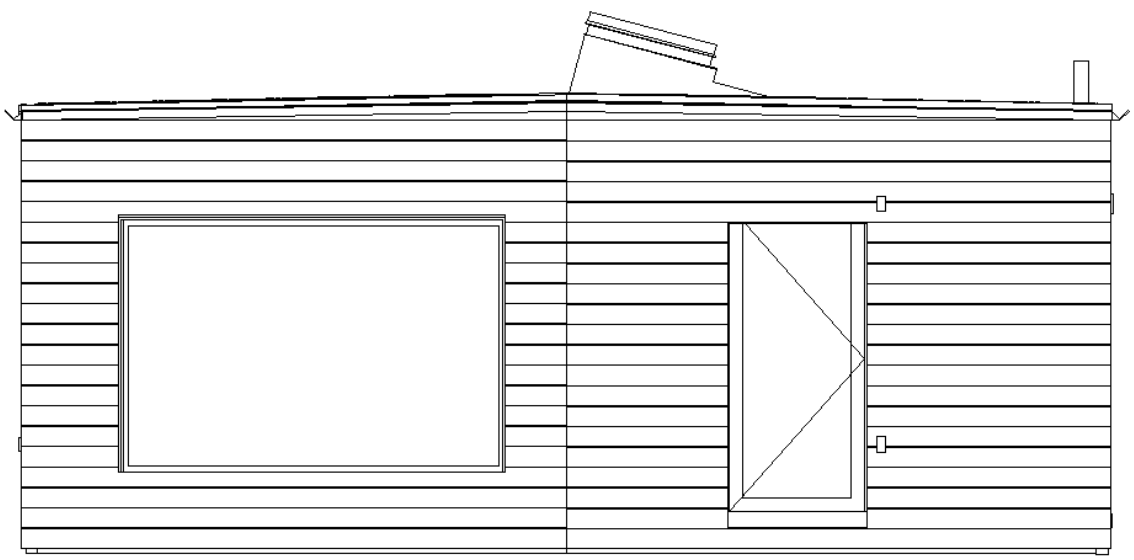


Figure 7: South Elevation: Original ΔT90 House[7]

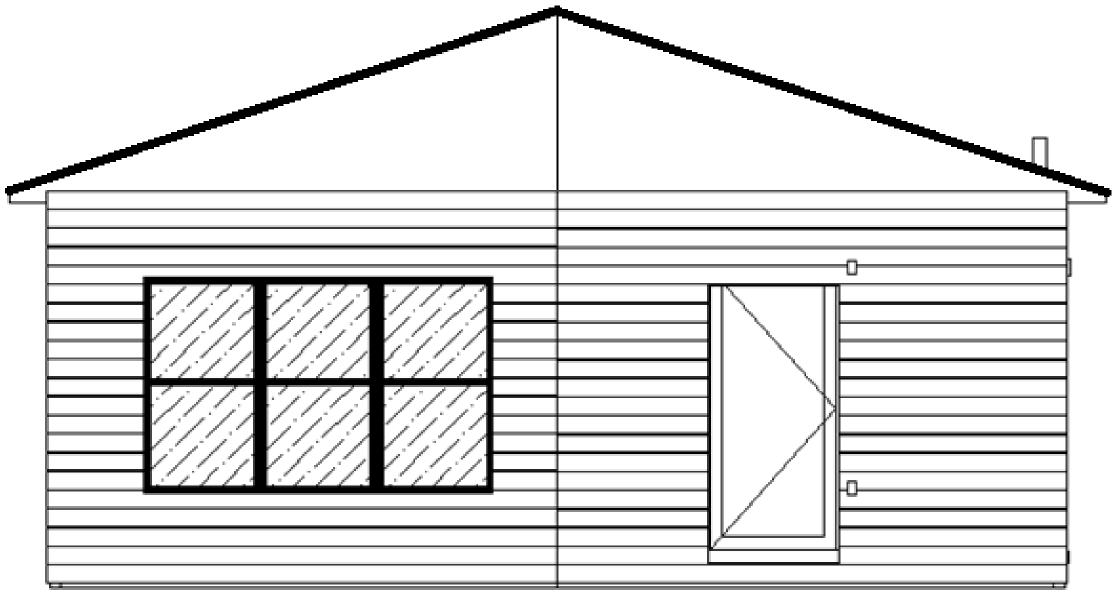


Figure 8: Revised South Elevation

Figure 8 shows the revised South Elevation the 70 square foot quadruple-pane picture window has been replaced with three standard sized triple-pane double-hung windows. Using tracked cellular blinds, the R-value of the replacement windows is greater than the R-value of the windows used in the original design. The total glass area of these three windows is 64 square feet. Note that due to ADA requirements, the windows are placed such that the sills are slightly higher on the wall than in the original. If all the custom quadruple-paned windows in the original design were replaced with standard dimension triple-paned windows, then the cost of windows would be less than one half of the cost of the windows in the original design, resulting in a savings of approximately $11 per square foot, a $10,934 cost savings.[5]

III. Results

In examining the different systems incorporated in the construction of the ΔT90 house in each case the cost has been reduced and the energy efficiency maintained. With the few changes there is a cost savings of $ 32,850. This is a reduction in cost of $33 per square foot. This indicates to the students the various areas that value engineering is applied. They will gain further knowledge as they move forward in constructing the micro houses. The results of the research present to the students the necessity of examining alternative construction practices.

IV. Conclusion

This paper shows how teams of students from the University's Architecture, Engineering, and Construction Management programs are using lessons from the Solar Decathlon Competition to develop a regionally derived, solar powered, affordable housing model. Toward these ends, the student teams are working to design a series of modular micro-houses (approximately 200 square feet each) that can stand alone or be combined to create a larger, cohesive structure (similar to how a New England 1/2 Cape was first constructed, then as the family grew, the house was enlarged into a 3/4 Cape or a Full Cape, etc.) Additional room modules could be added to the house over time. The students have discovered an alternative method of assembling the structure at a lower cost and keeping the required efficiency required for homes in Vermont. The reduction in cost and application of different materials will continue to evolve as the students further examine the micro houses and explore alternative construction techniques and

The core micro-house module is designed to contain basic amenities, such as kitchen and bathrooms. Two walls of the core module are designed so that additional room modules can be readily attached. These "add-in" modules can be designed to be more flexible and less expensive to manufacture than the core module, and can vary depending on the needs of the occupant. This project will serve to demonstrate how houses could be constructed in stages from micro-houses, with the micro-houses being combined, over time, to create a larger house. The design teams will explore non-conventional structural framing for the micro-houses and optimize the mechanical and electrical integration process by designing standardized, modular systems. The project teams will also integrate the photovoltaic systems into the building structure, considering innovations such as the use of DC current to eliminate the DC to AC conversion.

The student teams will construct the first core micro-house module during 2015. Lessons from the construction of the first module will be incorporated into the construction of subsequent modules. The student built structure involves several disciplines and is related to courses for direct application. The research has involved value engineering, reassessment of energy efficiency, new designs are being produced, systems and structural analysis and estimating and scheduling of the project.

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