Creating an Economical Solar Decathlon House

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***Abstract*— Since 2002, the U.S. Department of Energy has sponsored the Solar Decathlon competition in which collegiate teams design, build, and operate solar-powered houses that are intended to be cost-effective, energy-efficient, and attractive. The Solar Decathlon is intended to educate students and the public about the economic and environmental benefits of energy efficient, solar powered homes. Unfortunately, due to the scoring rubrics for the competition, the affordability aspect of the competition is often given only superficial consideration.**

In the 2013 the Norwich University ΔT90 house officially won first place for the Affordability Contest of the 2013 Solar Decathlon, with an estimated cost of $168,385 for a 988 square foot house ($170 per square foot), while scoring 100% for the energy balance portion of the competition.

The ΔT90 house maximizes comfort, efficiency, and spaciousness through two bedrooms, an office space, and an open living space for lounging, cooking, and gathering—offering a model for affordable and sustainable living. This paper will present design and construction details of Norwich University ΔT90 house which allowed it meet the project design objectives.

***Index Terms*—Solar Decathlon, Solar Energy, Solar Power, Solar Powered House**

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 cost-effective, energy-efficient, and attractive. The first Solar Decathlon was held in 2002; subsequent competitions took place in 2005, 2007, 2009, 2011, and 2013. The 2013 event took place at the Orange County Great Park, in Irvine California. All previous events took place in Washington D.C.

The Solar Decathlon 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.

II. HISTORIC PRECEDENT FOR AFFORDABILITY AS DESIGN CRITERIA

One of the initiating reasons for the development of the Solar Decathlon is to "demonstrate market-ready technologies that can meet the energy requirements of our activities by tapping into the sun's power." With the intent to broaden the integration and acceptance of solar power in residential applications, the Solar Decathlon has involved 112 collegiate teams and 17,000 students from the United States, Canada, and Europe. It is recognized worldwide as force for introducing and exhibiting the most creative, market-ready, residential solar applications. Over its ten-year development, the Solar Decathlon competition organizers have continually adjusted and refined the competition criteria in an effort to keep a fine balance between making the competition solely an exploratory design exercise and a pragmatic, hammer-ready houses.

Unfortunately, due to the scoring rubrics for the competition, the affordability aspect of the competition was often given only superficial consideration.[1] In the 2011 competition, the most affordable house cost $230 per square foot while the 2011 overall winner's cost exceeded $380 per square foot. In 2009, while the construction costs were tabulated for each of the entries, affordability was not a direct component of the competition.[2] Prior to 2009, affordability was not officially calculated, and houses such as the 2007 winner had self-reported cost-estimates exceeding $400,000 for an 800 square foot house ($500 per square foot).[3]

In the 2013 Solar Decathlon Competition the Norwich University ΔT90 house officially placed first in the Affordability Contest, with an estimated cost of $168,385 for a 994 square foot house (approximately $170 per square foot), while scoring 100% for the energy balance portion of the competition.[4] The Norwich ΔT90 house was named for the 90ºF difference between inside and outside temperatures that residents of Vermont experience each winter.

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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 $250,000.4

Since 2009, when cost estimates became an official component of the Solar Decathlon competition, there has been only one house, the Rice ZEROW house, that had a cost estimate that was less than the 994 square feet 2013 Norwich University ΔT90 house. However, since that house had an area of only 520 square feet, approximately one-half that of the 2013 Norwich University ΔT90 house, its $229 cost per square foot greatly exceeded the cost per square foot of the Norwich house.

III. Norwich University's Solar Decathlon Design Philosophy

While the Solar Decathlon Competition is about real estate, its focus on affordability also speaks to practical real estate. An overwhelming number of Vermonters cannot afford a house that meets the target construction costs of the 2011 Solar Decathlon's Affordability Contest, regardless of energy costs. Consequently, for the 2013 Solar Decathlon Competition the Norwich University's ΔT90 house was designed to make it affordable for a household earning 20% to 30% less than Vermont's median income level.

The 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 bio-based building envelope house is a cost-effective alternative to housing built before 1950, which often had inefficient systems and inadequate insulation. It is designed for a family of three that makes near or below the median income and is intended to be produced in high quantities. The ΔT90 house also has market appeal to 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. It maximizes comfort, efficiency, and spaciousness through two bedrooms, an office space, and an open living space for lounging, cooking, and gathering—offering a model for affordable and sustainable living.

The structural design fulfilled these goals through effective design and engineering as well as the ability to mass produce the structure. The innovative design was achieved by determining the proper balance between the need for high technology and the practicability and affordability that is inherent to the comprehensive design.

IV. Design Considerations

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

In examining the different houses at the Solar Decathlon competition, several broad points were evaluated; HVAC/Mechanical Systems, Electrical Systems, and structure. These points selected were designated as a basis for comparing the various elements of the structures, using the Norwich entry as the baseline, being the least expensive of all the structures.

V. HVAC/Mechanical

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. This strategy ultimately resulted in reduced size, cost, and complexity of heating and cooling equipment. Use of simple, small, off-the-shelf mechanical systems was made possible simply because the primary architectural investment was placed in the building envelope. .

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. 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.

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One newly introduced product was used to meet the ventilation needs, while significantly reducing winter heat losses or summertime heat gains. The Lunos e2 heat recovery ventilation system, commonly used in the European market,

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consists of a matched pair of through-the-wall, axial ventilation fans. The matched pair of fans alternate operating direction; every 70 seconds, one fan is operational as an exhaust while the other reverses and admits ventilation air. Each fan unit has a heat recovery element that recovers 90% of the warm, or cold, air from the conditioned space during the off cycle. The systems use variable speed motors and provide continuous ventilation. Three sets were used in the following manner: a) ventilation across the kitchen/living area, b) ventilation through the two bedrooms, and c) high/low ventilation in the bathroom area. In order to meet the ASHRAE residential ventilation standards, the manufacturer modified the systems so that their highest speed air flow rate was approximately 10% higher than the European factory settings. The continuous movement of cross ventilation air assisted the distribution of conditioned air within the building envelope, while helping to control bathroom and kitchen related humidity. While the installed cost of the three-pair Lunos e2 system was generally expensive, its relatively low power consumption and some first costs were offset by the reduced size of heating and cooling equipment due to losses from high volume on demand ventilation. Ultimately, the Lunos e2 system was cost-comparable to a more conventional ducted heat recovery ventilation unit, which would have consequently lowered ceiling heights, contributed to the overall complexity of the mechanical system, and sacrificed the simplicity of building transportation and deployment.

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.

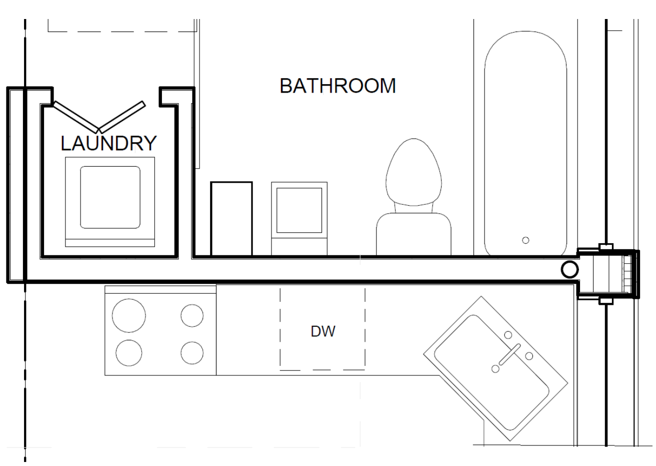

Figure 2: ΔT90 Common Systems Wall

In addition, the range, water heater, and air handler were all located on, or directly above, this systems wall. While inclusion of the electrical panel on the same wall would have further reduced some of the wiring costs, concerns about the complexity of running main electrical service through primary load-bearing members and compromising useable storage space required that the main electrical panel be placed on a separate wall in the second bedroom.

Concerns about space and safety also influenced the selection of water heating equipment. Typically, a 40 or 50 gallon tank would be specified for a small, single family home. The alternative was to specify a single on-demand water heater to provide the requisite volume and flow rate of adequately heated water. For contest purposes, 15 gallons of 115ºF water could be required during a 15 minute period every hour. To ensure adequate volume and temperature, as well as to eliminate standby losses, an instantaneous demand water heater was selected. Since our design specification was based on a Vermont location, the average cold water temperature for the state of Vermont was used to determine temperature rise. The temperature rise, combined with a conservative 1.25 GPM flow rate was used to determine the power requirements for an electrical heat source. As an added benefit, these types of units are compact and wall hung; providing the necessary capacity with a minimal space allocation requirement.

Given the equipment selections and architectural placements made, the area that would have been devoted strictly to mechanical equipment, approximately 9 ft^2, was available as a utility or storage closet. While not normally considered significant, this represented a 1% increase in useable space to the intended homeowner. And, while 9 ft^2 is indeed relatively small, it should be noted that the average footprint dedicated to mechanical equipment in Solar Decathlon 2013 houses was approximately 50 ft^2.

VI. ELECTRICAL SYSTEMS

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 three-fold. One, the Norwich ΔT90 team wanted to show the local Vermont market that with the deck stacked against it, the ΔT90 house could stay net-zero annually. 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. Again, the ΔT90 house had the smallest foot print of all the houses presented at 2013 Solar Decathlon Competition. This means the Norwich ΔT90 team was able to show that a small solar powered house could fit be integrated in tight urban lots, and be a little less critical of the relation to roof-pitch & solar orientation.

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.

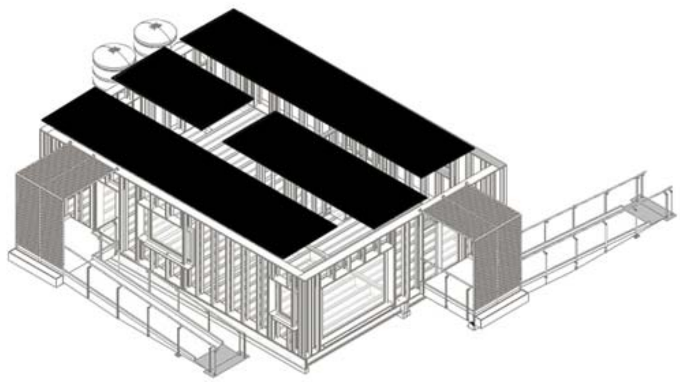

Figure 3: DT90 Roof Mounted Solar Panels (shown in black)

It should be noted that in Solar Decathlon 2013 competition, the Norwich University ΔT90 house met all energy performance requirements while having the smallest solar system of all the teams at the competition.

The thin-film photovoltaic panels also offered super reduction in weight and a streamlined profile. The entire ΔT90 building, complete with tools, safety gear, furniture, mechanical equipment, photovoltaic equipment was shipped as a complete, ready to assemble, package. The solar system, being completely building integrated, was shipped on the roof of the house, and is painfully simple to get up and running after the house modules are placed on its foundation. One the building modules are installed on the foundation, the photovoltaic system can be operable in just two hours with the help two technicians. Critical to the design criteria was to make the building come together easily at the competition, which translated into reduced labor costs.

The structure of the roof was carefully considered for the snow loads experienced in Vermont and was an opportunity to fully integrate the photovoltaic array with the rectilinear form of the ΔT90 house. The photovoltaic array, lying flat on the roof, was intentionally sized to accommodate an average of one-hundred and twenty days of annual snow coverage.

The decision to integrate a thin-film amorphous CIGS photovoltaic array on the roof was a bold move, and one that effectively removes the 'solar hardware' from the visual presence of the house. The ΔT90 house is ultra-energy efficient due to the 6kW building integrated PV Array and high performance building insulation. The occupants of the ΔT90 House will enjoy zero utility costs from heating, cooling, and household electricity thanks to energy produced by the solar array

The electrical solar panels were installed on the low sloped roof prior to shipping, with the inverter mounted on the exterior north side of the structure. This allowed the structure to be delivered intact and ready for connection. By installing the solar panels directly on the roof, there was no need for expensive racks to support the solar panels. This eliminated the need to erect the racks at the competition site, reduced the wind loads on the building structure, and resulted in the solar panels not being visible to pedestrians.

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.

VII. Structural Design Considerations

The comparative analysis of the structures commences with the foundation. As shown in Figure 4, the Norwich ΔT90 house utilized a simple system for the temporary foundation, both in Vermont during preliminary construction and during the competition. A simple system of 6x6 blocks attached to plywood bases functioned efficiently and at a minimal cost. The system was attached to the tarmac using a single 1" diameter A36 steel rod specified as 36" long, but due to site restrictions some were cut shorter after approval of the competition administrators. Note that while the use of the 1" diameter rods was mandated by the competition rules, structural calculations showed that this rod was not necessary to meet the seismic and wind forces specified in the either the competition building code or the California building code. Wooden shims of varying thicknesses were added to bring the top of the 6x6 blocks to the proper elevation, and to allow for the slope of the tarmac at the competition site.

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The Norwich University team selected this simple temporary foundation for use at the Solar Decathlon Competition, considering factors such as material cost, labor requirements, installation, disassembly, and disposal.

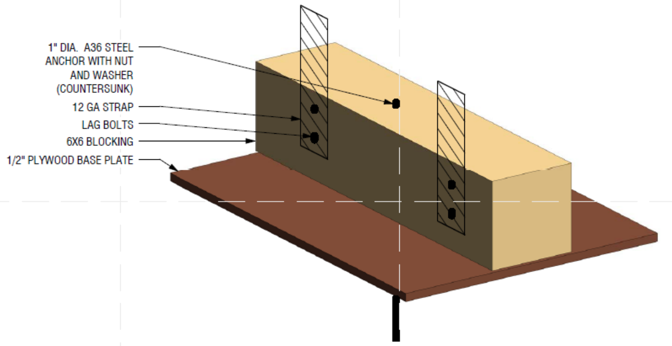

Figure 4: ΔT90 Foundation Detail (Competition)

VIII. Modular Building Structure

In keeping with the concept of mass replication of the structure, the initial construction 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, but not flooring, interior paint, light fixtures, plumbing fixtures, appliances, cabinets, doors, windows, trim, exterior siding, HVAC systems, or solar panels.

As shown in Figure 5, the ΔT90 house utilizes 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.

The walls, floors, and low slope roof are nominally 12” thick. As shown in Figure 68, the exterior walls utilized 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. The Norwich design did not use any foam insulation; the environmentally friendly dense pack cellulose insulation was used instead. The exterior was sheathed using 7/16” plywood covered with 2" of mineral wool board insulation on the exterior covered with a layer of house wrap. The house wrap and the mineral wool board also provide hydrophobic protection to the exterior envelope. The exterior cedar siding was attached to the walls via 3/4” batten strips.

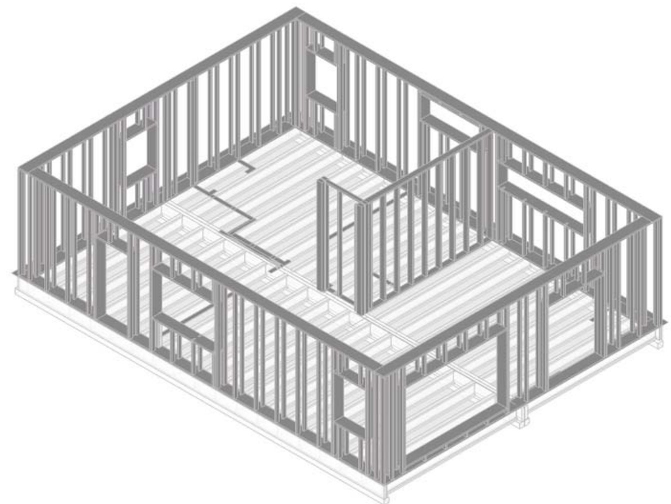

Figure 5: ΔT90 Framing Scheme[5]

Also shown in Figure 6, the floor was of 2x12 construction, with 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.

Finally, as shown in Figure 8, the 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” TPO membrane. Conventional timber framing was used throughout the ΔT90 house.

IX. On-Site Construction

The Norwich team shipped our entire project (tools, safety gear, furniture, ramps, decks, porches, everything) inside the two modules that made up the ΔT90 house. As shown in Figure 710, the ΔT90 house required only two modules to be placed on a simple temporary foundation. The house installation required only a crane for only a few hours. The solar electric systems were shipped attached to the roof of the house, and were simple to get up and running after the house modules were installed. At the competition, the ΔT90 house was completely operational before some teams had finished using their cranes to unloading all their materials.

The Norwich team designed the Norwich ΔT90 so that there was no finish work done on site, that all fixtures and appliances were installed before shipping, and the only electrical and plumbing connections were required on-site.

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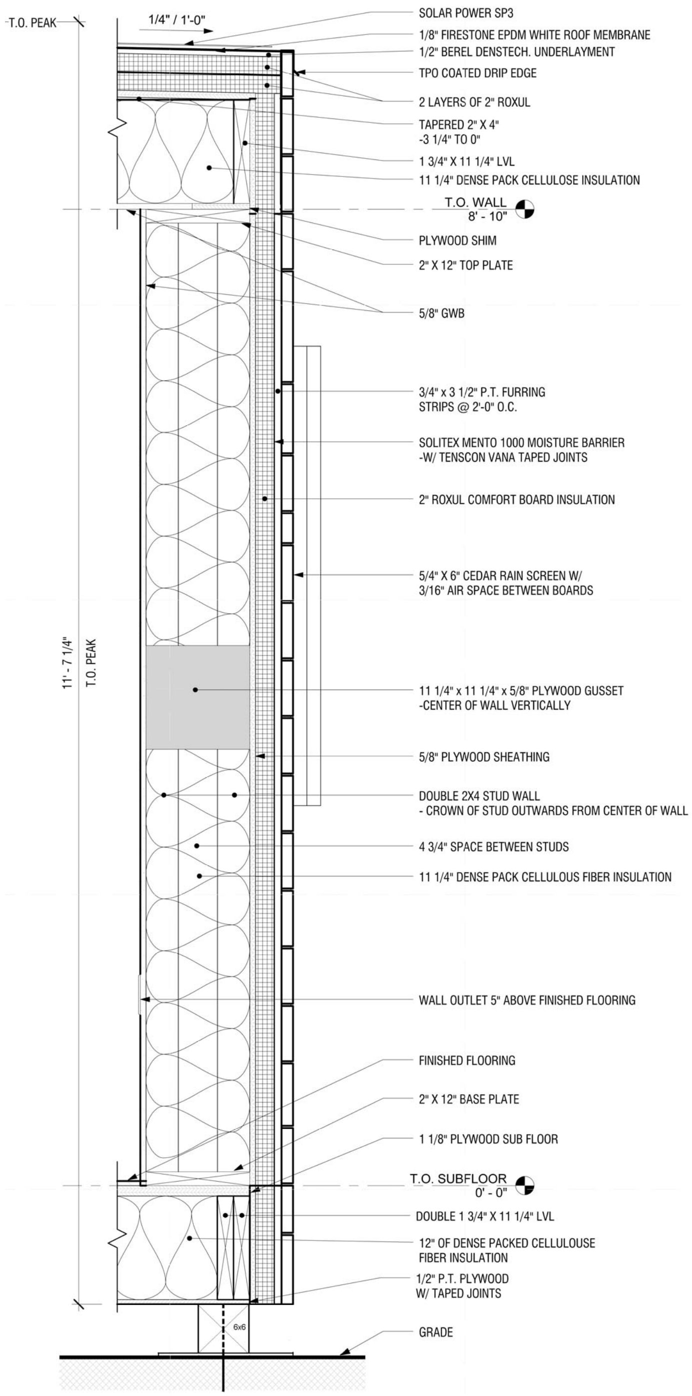

Figure 6: ΔT90 Wall Section[5]

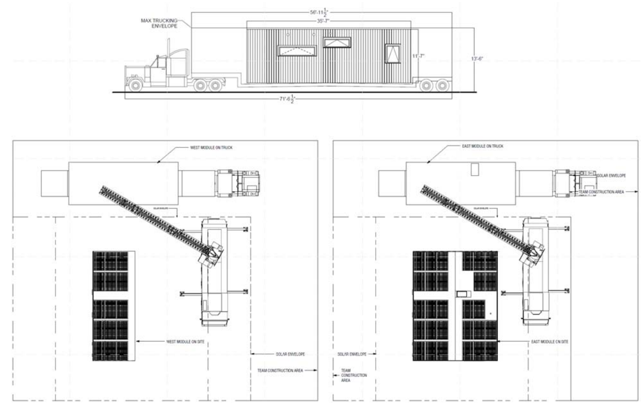

Figure 7: ΔT90 Building Module Installation Sequence[5]

X. SUMMARY

The simplicity of the design and construction of the Norwich ΔT90 house fulfilled the mission to create a cost effective, reliable, simple and replicable structure. The design of the structure is open to all of varying economic limits. The design is architecturally pleasing as well as well engineered for efficiency. This structure is available to anyone on a commercial basis and is adaptable to differing climate conditions. The structure was specifically designed for the harsh winters of Vermont, but the same insulation qualities that the structure contains to retain heat in the winter will also assist in retaining cool air in warmer climates. This structure can be placed on differing foundation systems for permanent installation. The original goal to produce a cost effective design also lead to an overall pleasing, efficient structure.

The use of the modular systems was cost effective and allowed for reduction in the duration for the on-site construction. There were no mechanically moving parts to the structure (i.e. the wall systems did not retract, the entire structure did not move on rails, etc.). None of the mechanical or electrical controls required the use of computers. The cost and functionality of the computer based control systems were not found to be cost effective, and they were not found to add to the efficiency of operation of the structure.

The Norwich entry did not require a separate mechanical room. This utilized the floor space with greater efficiency and the reduction of systems reduced the initial costs and maintenance costs. This is directly tied to the mission of the design and to maintain the overall floor space within the maximum requirement of less than 1000 square feet.

XI. CONCLUSIONS

In the 2013 the Norwich University ΔT90 house officially placed first for the Affordability Contest of the 2013 Solar Decathlon, with an estimated cost of $168,385 for a 994 square foot house (approximately $170 per square foot), while

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scoring 100% for the energy balance portion of the competition. As shown in Figure 8, all other houses at the 2013 Solar Decathlon Competition were considerably more expensive than the Norwich University ΔT90 house.

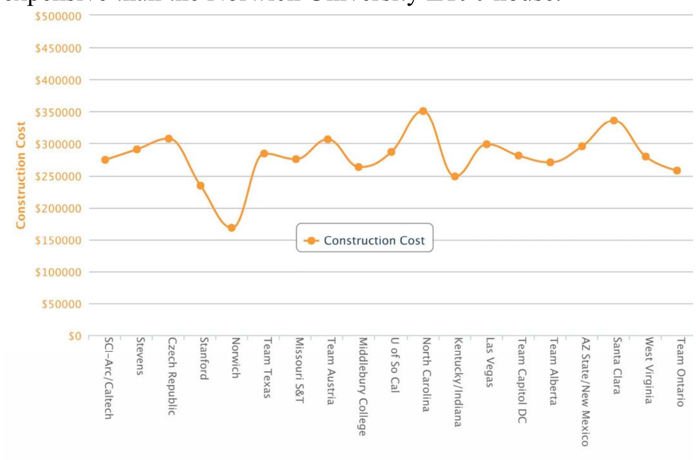

Figure 8: 2013 Solar Decathlon - Construction Cost Data[4]

The Norwich University team set a goal before design began to accomplish a high performance home that is affordable to a household earning 20% below median income in Vermont. The 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 bio-based building envelope house is a cost-effective alternative to housing built before 1950, which often had inefficient systems and inadequate insulation. It is designed for a family of three that makes near or below the median income and is intended to be produced in high quantities. It maximizes comfort, efficiency, and spaciousness through two bedrooms, an office space, and an open living space for lounging, cooking, and gathering—offering a model for affordable and sustainable living.

Design and Construction details were critically important in attaining the team's cost goals for the house. This paper presented design and construction details of Norwich University ΔT90 house, and compared them to design and construction details of the other houses at the Solar Decathlon Competition. The Norwich University ΔT90 house was the most economical house in the history of the Solar Decathlon Competition.

At the conclusion of the 2013 Solar Decathlon Competition awards ceremony, the Norwich University ΔT90 team was presented with the Bryon Stafford Award of Distinction for being "honest, caring, humble, intelligent, fair, reliable, steadfast, and genuine." The award is a tribute to Byron Stafford, who served as the event's site operations manager from the first Solar Decathlon in 2002 until his death in 2013.

After the completion of the 2013 Solar Decathlon Competition, the ΔT90 house was transported to Frank Lloyd Wright's The Westcott House for use as an education center

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