AN ANALYSIS OF ENTRIES IN THE U.S. DEPARTMENT OF ENERGY'S SOLAR DECATHLON 2011 WITH A FOCUS ON COST-BENEFIT ASSESSMENT OF WALL ASSEMBLIES

A Thesis
by
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Abstract

AN ANALYSIS OF THE U.S. DEPARTMENT OF ENERGY'S SOLAR DECATHLON 2011 ENTRIES WITH A FOCUS ON EACH WALL ASSEMBLY'S COST-BENEFIT ASSESSMENT

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The purpose of this study was to determine which wall assembly from the 2011 U.S. Department of Energy's Solar Decathlon proved to be the best option for widespread adoption. The wall assemblies were analyzed based on cost per square foot, clear wall R-value, and embodied energy as a means for comparison. The cost estimate calculated both material cost and associated labor cost in order to identify the most affordable assembly. Clear wall R-value was calculated based on the most common wall type used for each home and average R-value for materials. When calculating embodied energy, BTUs/sq.ft. were identified based on energy used during extraction and manufacturing only. Results were calculated for each team's wall assembly.

Acknowledgements

This venture could not have been completed without the continuous support and guidance of my thesis committee. I would like to give a special acknowledgment to Dr. James Russell, chair of the thesis committee, for his dependable assistance, his time, and invaluable knowledge, as he remained a valued mentor throughout this process. My gratitude continues to Dr. Marie Hoepfl, for her careful consideration and her detailed editorial assistance. A thank you extends to Mr. Chad Everhart, for his continuous support in all my endeavors and consistent encouragement. I would also like to thank Mr. Jason Miller, for his clear explanations and respected wisdom. Without each of their persistent support, this effort could have not taken place.

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Chapter 1

Introduction

Residential homes consume 24% of energy while commercial buildings use an additional 19%, totaling 43% of all energy consumption in the U.S. (U.S. Energy Information Administration [USEIA], 2011). Discovering innovative building materials and construction methods that help reduce energy consumption is a continuing focus of research that could aid in helping this energy problem. More specifically for the purpose of this study, it is important to analyze how various wall assemblies may be made more efficient, affordable, and environmentally conscious. The United States Department of Energy's (U.S. DOE) Solar Decathlon presents a basis for research and development of the latest building methods and materials. The Solar Decathlon event involves selection of 20 collegiate teams to design, build, and operate solar powered homes to compete biannually, where they are judged in 10 contests to determine a winner. In the 2011 competition, the U.S. DOE added an affordability contest in which a professional estimator calculated the value of the home. The purpose of the study was to evaluate how each team handled the constraints of the affordability contest, as well as energy efficiency and embodied energy. This research included an analysis of each wall assembly as a means to compare and find the optimal wall configuration. Each assembly was evaluated based on how it could benefit the builder, the homeowner, and the environment. Through the research a method for ranking each of the categories was developed to determine which wall section proved to have the most advantages. The study also provided insights about each type of wall construction as a means for comparison.

Statement of the Problem

Residential energy use accounts for 24% of the United States energy consumption, while producing twice the amount of greenhouse gas emissions as the average vehicle (USEIA, 2011). Americans pay an average of $1,900 a year on energy bills and 46% of a typical energy bill comes directly from heating and cooling a home (Energy Star, 2012) and (Lawrence Berkeley National Laboratory, 2009). Strategic changes to residential construction methods could help reduce energy use for the residential sector, while also reducing greenhouse gases, and saving homeowners thousands of dollars. Analyzing different alternatives for wall assemblies is one important way to help solve this energy problem and reduce greenhouse gases.

This study contributes information regarding thermal performance for each wall assembly constructed in the 2011 U.S. DOE's Solar Decathlon and calculates the embodied energy each material utilizes. In addition, the study establishes the cost per square foot for each wall assembly.

Reviewing the entries to the Solar Decathlon 2011 it is clear that the structures incorporate unique wall assemblies, which have not yet been studied. The results of this study provide data showing which of these wall types may prove to offer the most energy efficient, affordable, and environmentally conscious options. In addition, it contributes data to suggest which methods should not be adopted for widespread use. The conclusions of this study help supply valuable information describing which wall types are the best options for helping reduce residential energy use.

Purpose of the Study

Wall assemblies are a fundamental component of a building's construction and can make significant impacts on a building's performance. Wall assemblies may impact the environment, the builder, and the homeowner in various ways. Depending on the assembly method used to construct walls, a builder may find it easier or more difficult to install, and will identify a labor cost accordingly. Homeowners desire a wall with an affordable cost and appropriate thermal performance. Environmental concerns may include using rare or readily available materials, or avoiding use of materials, which require more energy to produce than they are offsetting. Exploring these factors to discover the ideal wall assembly is critical to enhancing building construction and performance. The purpose of this study was to clearly outline which wall assemblies constructed for the U.S. DOE's 2011 Solar Decathlon proved to be the most affordable alternatives with the least energy consumption. Analyzing each prototype allowed conclusions to be drawn about which innovative building solutions produced in the competition were the most efficient, cost effective ways to build for both the builder and the homeowner, while also analyzing the environmental impact. The research helps to establish an optimal wall assembly by evaluating options using the cost-benefit "score" developed for this study.

Research Question

This study was guided by one multi-part research question: What wall assembly construction methods emerged from the Solar Decathlon 2011 as being most promising for widespread adoption within the residential housing market, as evaluated using the following metrics:

a. Clear material cost ($\$/ft^2$)?
b. Clear labor cost, suggesting ease of installation ($\$/ft^2$)?
c. Clear wall R-value ($hft^2{}^\circ F/BTU$)?
d. Clear embodied energy (BTU/ft^2)?

Definition of Terms

British Thermal Unit (BTU): The quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit (Krigger & Dorsi, 2009, p.252).

Clear wall R-value: The measurement of thermal resistance within a wall section, including framing factors and penetrations.

R-value: Measurement of thermal resistance, or the ability to retard heat flow.

Thermal Bridging: Rapid heat conduction resulting from direct contact between very thermally conductive materials like metal and glass (Krigger & Dorsi, 2009, p. 261).

Limitations of the Study

Using data from an international competition in which standardized metrics were collected for each entry allows for a consistent set of data to review. However, with using such work, discrepancies may emerge. Using a competition with a two-year deadline, work was found incomplete in areas or not clearly detailed. Although data was verified by U.S. DOE professionals, there were still mistakes found which had not yet been identified. In the following section, descriptions are provided for these limitations.

Each set of construction documents was drawn by different groups of students from universities across the world. Because of this diversity, the detail and consistency of the documents varied from set to set. For example, Team New York's document could not be included in the research due to illegible and unclear information provided. Team New York's construction specifications on the construction documents were not presented in their project manual. The assembly utilized an insulated glass panel with integrated blinds and redirecting glass. Within this system were tightly insulated block sections. When trying to understand and find supporting documentation for Team New York's assembly, information was undiscovered.

Though a full analysis for this study was unable to be concluded, Team New York's wall assembly seems to be well insulated, expensive, and most likely would have a higher embodied energy for the heavy use of glass. Information was available for most teams but sometimes there were discrepancies between what was shown on the construction documents, in the project manual, and/or on referenced websites. Team New York was the only team not included in the research that competed in the competition.

R-values for building materials were based on an average when values were a range of numbers. The variations in cited R-values could change overall clear wall R-values but are all standard numbers for each building material. In addition to clear wall R-values, Team Tennessee used a double façade glass curtain wall. In between the two panes was an energy recovery ventilator, which harvested heat gain back to the home (U.S. DOE, 2012). For the purpose of calculating Team Tennessee's clear wall R-value fairly, the energy recovery ventilator was not included into the total R-value; however, a value was included for the air gap in between the two glass sections. The energy recovery ventilator may contribute in energy reduction in other ways, but for the purpose of this study it was not evaluated or included.

A professional cost estimator verified all cost estimates, which were provided by each team. While using a consistent resource for evaluating, some costs were either found to be missing or were included as part of a larger category, making the cost harder to identify.

Embodied energy and density of building materials figures were found using numerous resources. Without a single database available to reference embodied energy and density of materials, these amounts may be inconsistent since multiple sources were used. When determining which numbers to use, articles with more citations were referenced. In addition, the embodied energy number for fiber cement board is patent pending and has not been confirmed. For this specific material, numbers were identified based on materials used to make fiber cement board. In the instance of Team China's use of a shipping container, the associate embodied energy value for steel was used. When researching the embodied energy for shipping containers, no value was found. Therefore, the fact that shipping containers are a reusable or repurposed resource was not accredited for in the embodied energy calculation. As for the examples above, which have features that mitigate calculated rankings, an analysis was calculated without the possible contextual factors.

Chapter 2

Review of Related Literature

Current Status of Wall Construction Techniques

The history of wall construction provides an example of the evolution of understanding essential building components. One of the first types of wall assembly, Wattle and Daub, simply wove together branches and plastered them using stucco (similar to the stucco used today). Later, the invention of nails and availability of dimensional lumber led to the mass production of so-called balloon framed homes (Lstiburek, 2009). Now, there is an understanding for the need for insulation, advanced framing techniques, sealing, vapor barriers, and air barriers. Builders have made significant strides in building construction techniques, but there is still endless information to continue researching. Today, most homes are built only to satisfy building codes, but there are many assemblies that are much more advanced. The following sections describe the most simplified to the most advanced and efficient wall construction methods.

Let us begin with the most common types of wall assemblies used. This section covers typical walls offered today, ranging from commonly-used methods to more advanced techniques.

Platform framing is utilized in the majority of homes built since 1940, before balloon framing was the most common practice, and continues to be used to build many homes in the present day (Krigger & Dorsi, 2009. p. 351). This wall construction makes use of a dimensional softwood lumber (2 x 4 or a 2 x 6) framework with the vertical “sticks” or studs spaced evenly and nailed into the horizontal top and bottom frames. In most cases, the framework is filled with fiberglass or cellulose insulation, then covered with a layer of oriented strand board (OSB) sheathing (or something comparable), followed by a layer of plastic house wrap. Although this method continues to be the most common practice used, it no longer meets code in certain climate zones (Building Science Corporation, 2011, p. 1). Depending on the insulation used and the cavity size created by studs, the R-value of the wall may range from 11-21. In other words, this standard framing does not result in a good thermal envelope. This problem is exacerbated because, when determining the clear wall R-value, we must use the 25% framing factor rule. This means, to determine a clear wall R-value, you must also include the amount of framing in order to determine an accurate R-value. Typically, for common framing techniques as this, a 25% framing R-value should be included in the R-value. An example of this equation is found in Table 2. Applying the rule, a wall rated R-13 would actually have a rating of R-10. Using air permeable materials for insulation, such as fiberglass batt or sprayed cellulose, does not provide appropriate air leakage control because it allows possible air paths from interior to exterior. In spite of these concerns, use of standard framing techniques is common because its easy to build and relatively inexpensive, and materials are readily available. Overall, this framing method could be improved in all factors, including use of advanced framing techniques that would reduce the amount of lumber needed (Building Science Corporation, 2011, p. 1). In Figure 1, an example of this assembly is shown.

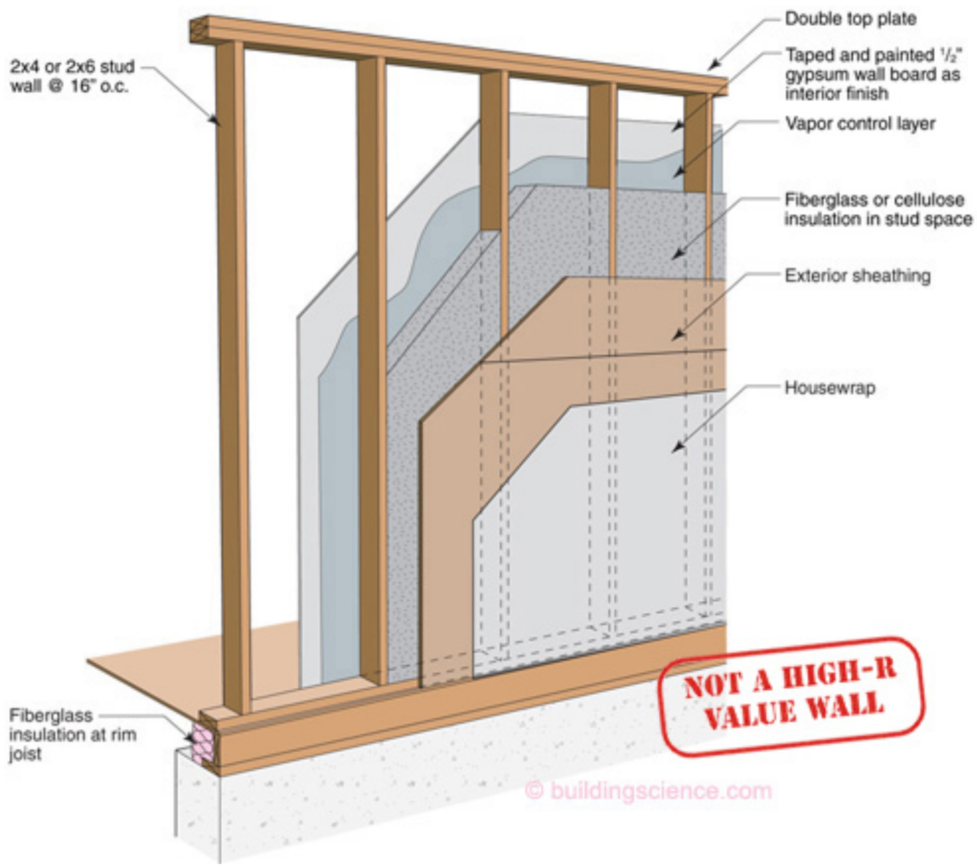


Figure 1. An image showing standard construction methods. From Building Science Corporation, 2011, p. 1.

Truss wall construction uses a 2 x 4 interior framing member and a 2 x 3 exterior framing method with a desired cavity in between. This cavity is filled with cellulose insulation and could have an R-value up to 50. If the wall were comprised of 12" of cellulose the clear wall R-value would be 36. The exterior is sheathed with a layer of OSB and housewrap. This framing method is complicated to construct because of its meticulous detailing, which may result in air leakage problems. Gussets, which hold the exterior section off the wall, must be installed, however, these are time consuming and difficult to produce. Any penetrations, such as a window, must include plywood boxes to construct in order to be structurally sound. Overall, this framing method is more time consuming to construct and more expensive because of the additional labor and materials. However, it makes for a high R-value (Building Science Corporation, 2011, p. 5). In Figure 2, an example of this assembly is shown.

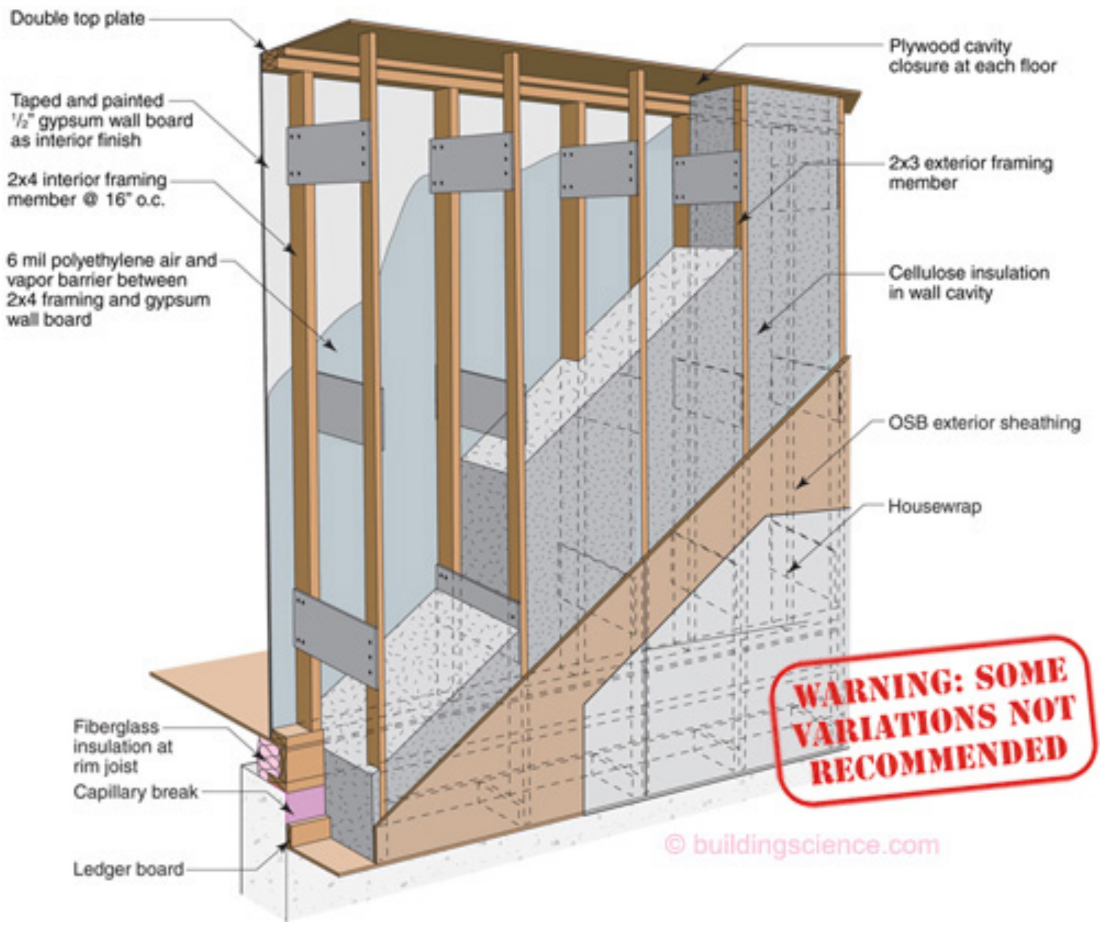


Figure 2. An image showing a truss assembly construction method. From Building Science Corporation, 2011, p. 5.

Structural Insulated Panels (SIPs) have become a popular option in construction in recent years. SIPs are prefabricated sections using two OSB boards (or something comparable) with expanded polystyrene (EPS) foam insulation fill. To complete a wall with SIPs, simply add housewrap, gypsum wallboard, and siding. Although SIPs may be customized, they typically come in a thickness of either 3.5" or 5.5", creating an R-14 or an R-22 wall. SIP wall systems reduce thermal bridging by using air-impermeable materials, but their effectiveness may vary depending on connection details. These walls are quick and easy to build by using a crane for ease of construction. However, due to the composition of SIPs, designing complicated massing may be limited. The cost of construction is higher than standard construction. Overall, the wall has an increased thermal performance, easy construction, but more expensive associated cost (Building Science Corporation, 2011, p. 6). In Figure 3, an example of SIPs construction is shown.

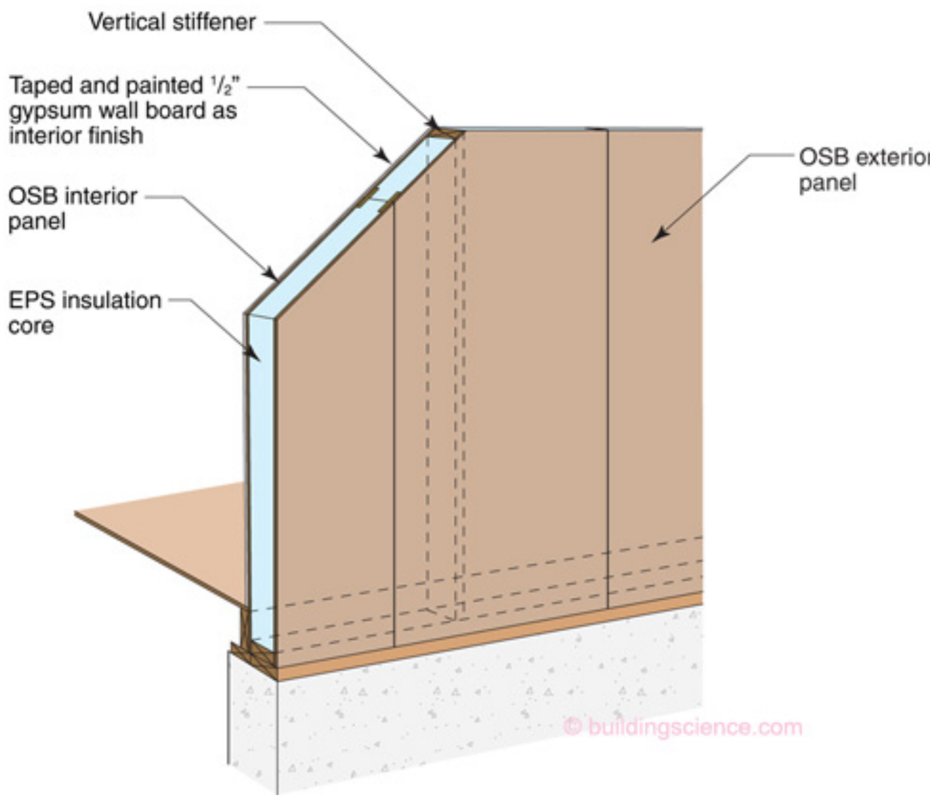


Figure 3. An image showing SIPs construction. From Building Science Corporation, 2011, p. 6.

Interior strapping wall construction uses a 2 x 3 interior horizontal strapping with fibrous insulation, then a 2 x 6 advanced framing with fiberglass or cellulose insulation. A vapor barrier is installed in between the two stud walls. The wall is finished with OSB exterior sheathing and housewrap. The typical whole wall R-value is 21.5; with thermal bridging reduced by the use of horizontal strapping. Air paths are present due to the use of air permeable materials. Construction is based on common practices but is more difficult for the builder by presenting more complicating details. Costs are higher for additional labor and framing (Building Science Corporation, 2011, p. 3). In Figure 4, an example of interior strapping wall construction is shown.

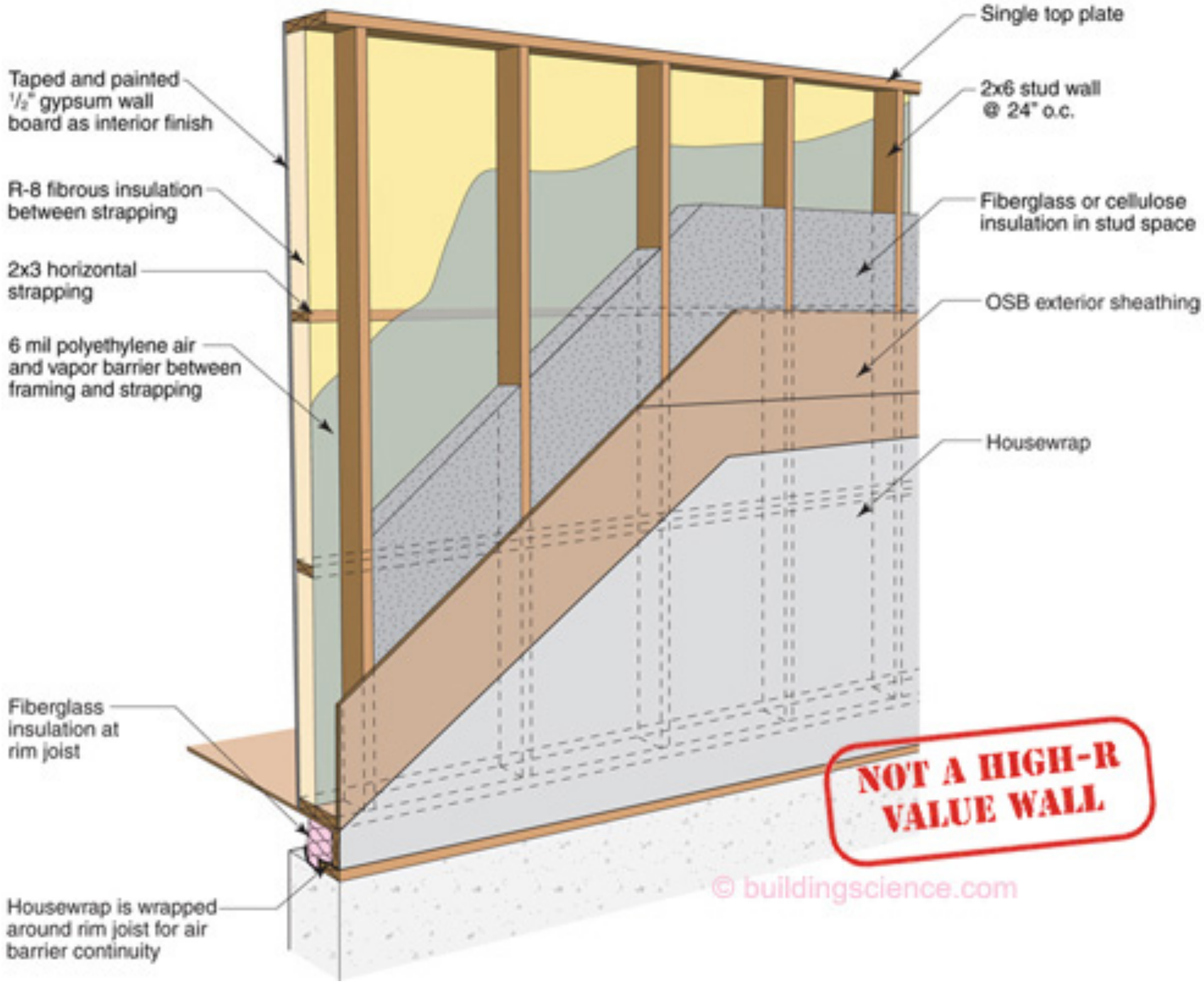


Figure 4. An image showing interior strapping wall construction. From Building Science Corporation, 2011, p. 3.

Flash-and-fill hybrid wall construction uses a 2 x 6 advanced framed wall, 24" on center (o.c.), with a single top plate. With 2" of high-density spray foam filling the cavity and additional 3.5" of fiberglass is installed on the interior face. Again, the exterior has a layer of OSB and housewrap. The R-value is 25, but decreases to 17 when totaling clear wall R-value. The high-density spray foam provides a significant increase in R-value that is lost because of thermal bridging. By using the high-density foam, air leakage is reduced, but not eliminated. The construction is consistent with common construction practices. Costs are only increased with the high-density insulation (Building Science Corporation, 2011, p. 9). In Figure 5, an example of flash and fill hybrid wall construction is shown.

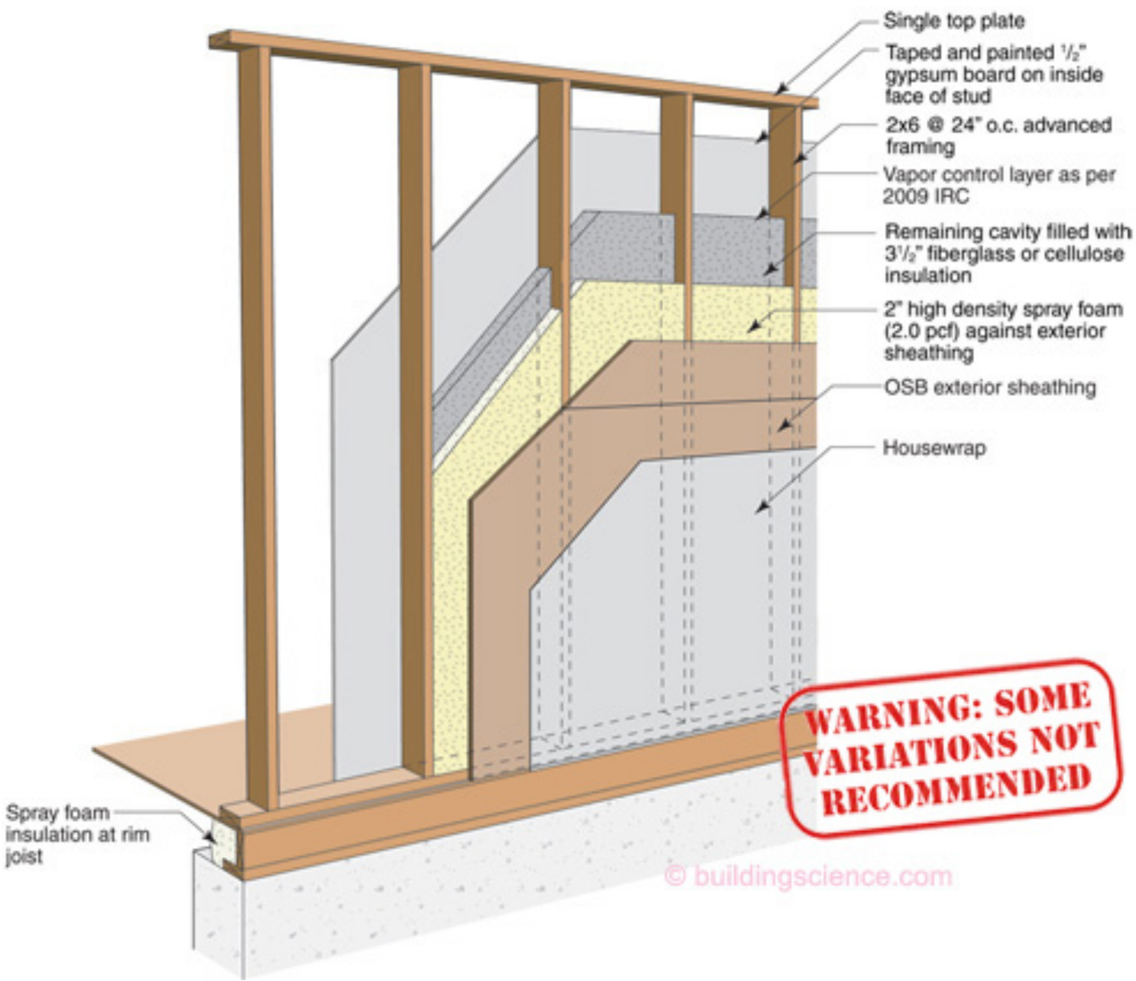


Figure 5. An image showing flash and fill hybrid wall construction. From Building Science Corporation, 2011, p. 9.

Offset frame wall construction uses a 2 x 6 interior framed wall, 24" o.c., with a fiberglass or cellulose infill. A 2 x 3 wall is then cantilevered off and filled with 4.5" of high-density spray foam. A substrate is placed in between the two walls. This wall creates an R-value of 47 and an R-37 clear wall. Air leakage is controlled well with having the high-density spray foam on the exterior. Construction methods are easy to train with clear details shown. There is a significant cost increase with the amount of high-density spray foam, but it does make for a tight envelope (Building Science Corporation, 2011, p. 11). In Figure 6, an example of offset frame wall construction is shown.

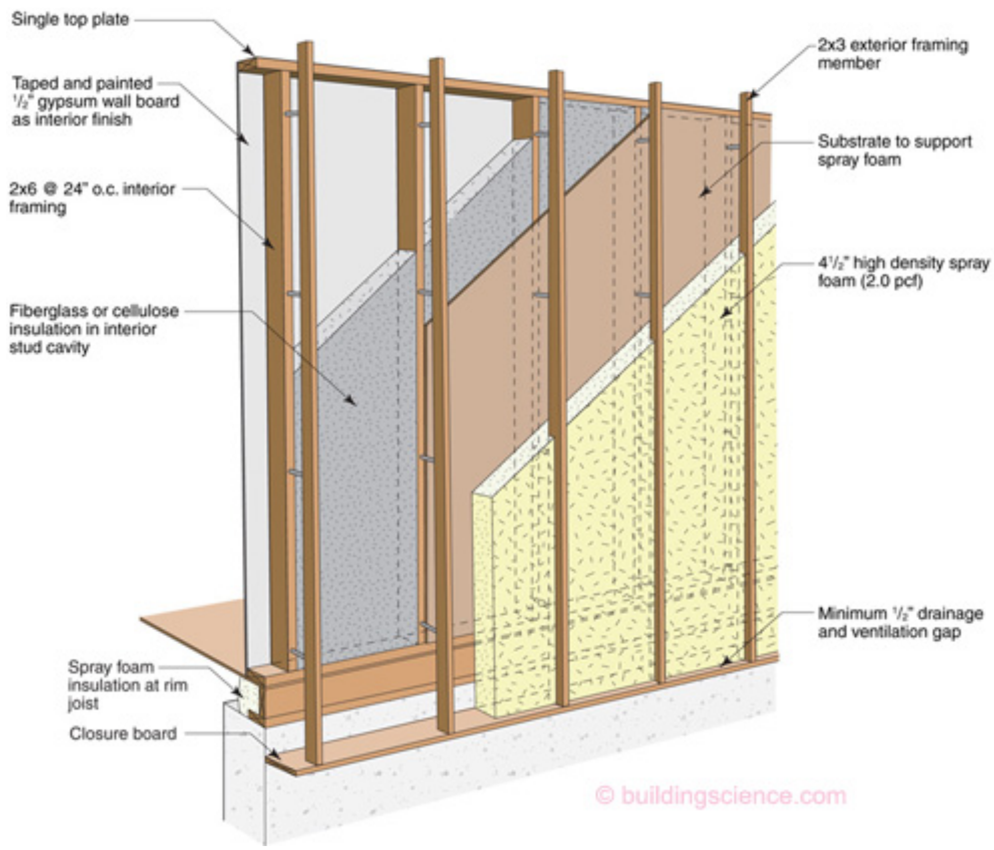


Figure 6. An image showing offset frame wall construction. From Building Science Corporation, 2011, p. 11.

Insulated Concrete Forms (ICFs) consist of an EPS inner and outer face (sometimes cement wood fiber) and filled with cast-in-place concrete. The thickness of EPS and concrete varies to specifications and higher R-value options are beginning to be available. By using a 9" ICF form with 5" of EPS, an R-20 wall is constructed with few thermal bridges. The concrete forms a good air barrier in the wall. Construction has been proven to be easy but should be researched prior, to prevent complications. The general cost varies, but is more than standard construction (Building Science Corporation, 2011, p. 7). In Figure 7, an example of ICFs wall construction is shown.

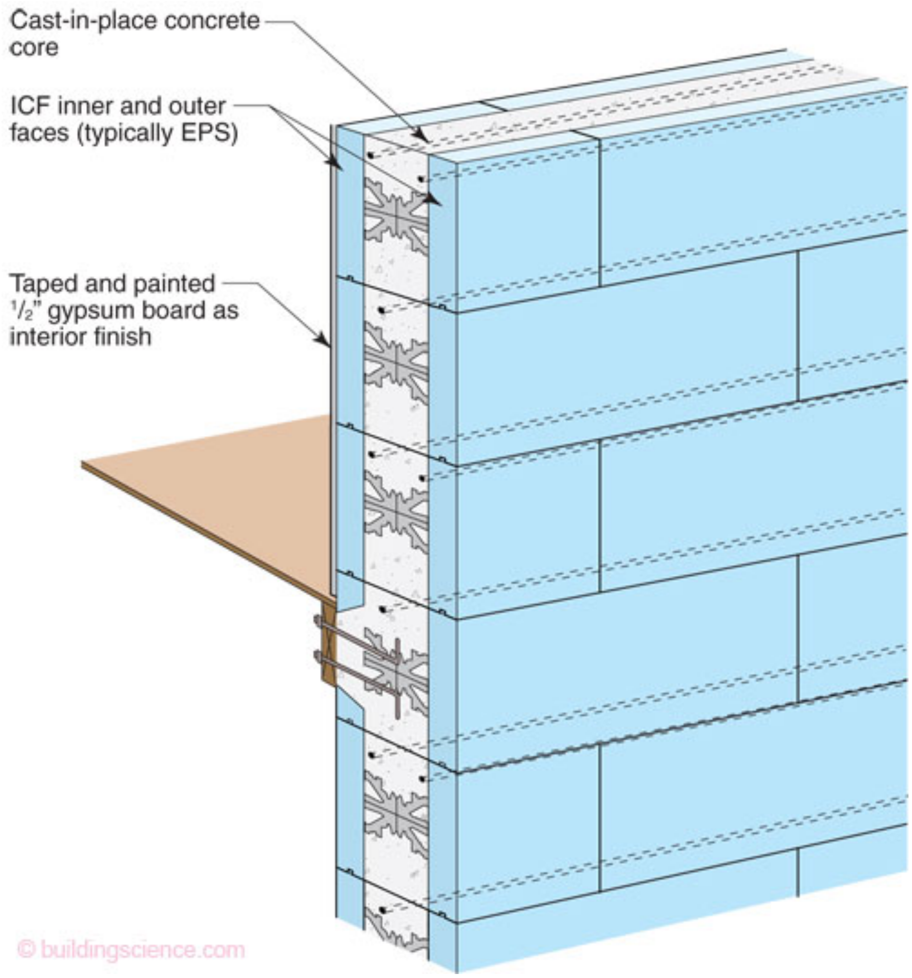


Figure 7. An image showing ICFs construction. From Building Science Corporation, 2011, p. 7.

Double stud with spray foam wall construction uses a 2 x 3 interior wall with cellulose insulation and staggering 2 x 4 exterior wall with 2" high-density spray foam insulation and cellulose. Fiberboard or DensGlass sheathing and housewrap finish the exterior surface. This wall creates a R-40 assembly. Although thermal bridges are greatly decreased by staggering the studs, the rim joist accounts for some losses bringing the whole wall R-value to R-33. The spray foam greatly reduces air leakage. Construction is more complicated when detailing and requires more lumber. Costs are increased due to labor and materials (Building Science Corporation, 2011, p. 4). In Figure 8, an example of double stud wall construction is shown.

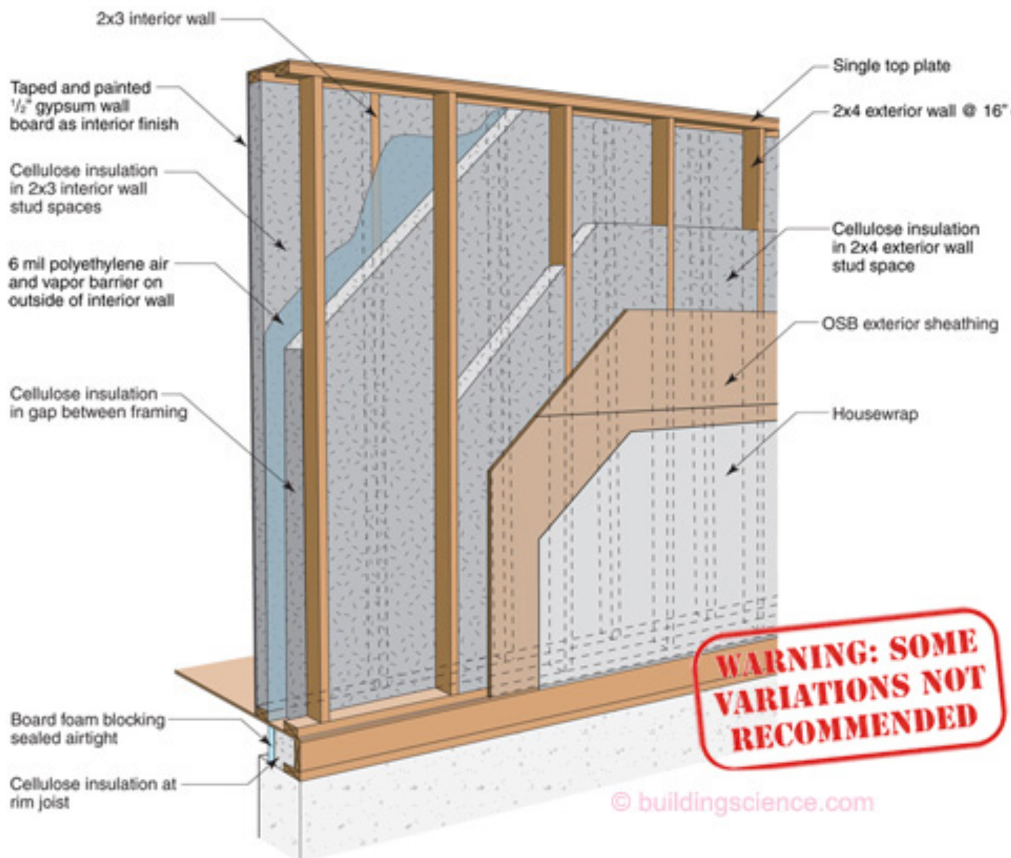


Figure 8. An image showing double stud wall construction. From Building Science Corporation, 2011, p. 4.

A 2 x 6 advanced framed wall, spaces studs at 24" o.c., with fiberglass or cellulose insulation. Between 1" to 4" of XPS exterior sheathing with tape joints wrap the exterior. An R-34 assembly would be a generous whole wall R-value. The exterior EPS creates an air impermeable face, and with taping and sealing, the wall creates a well-sealed assembly. Framing details for penetrations are slightly more difficult to traditional framing, so cladding may need strapping if sheathing is more than 1". The advanced framing methods decrease cost in lumber, and the sheathing may require more initial cost, but it does reduce energy cost later (Building Science Corporation, 2011, p. 2). In Figure 9, an example of 2 x 6 advanced framed wall construction is shown.

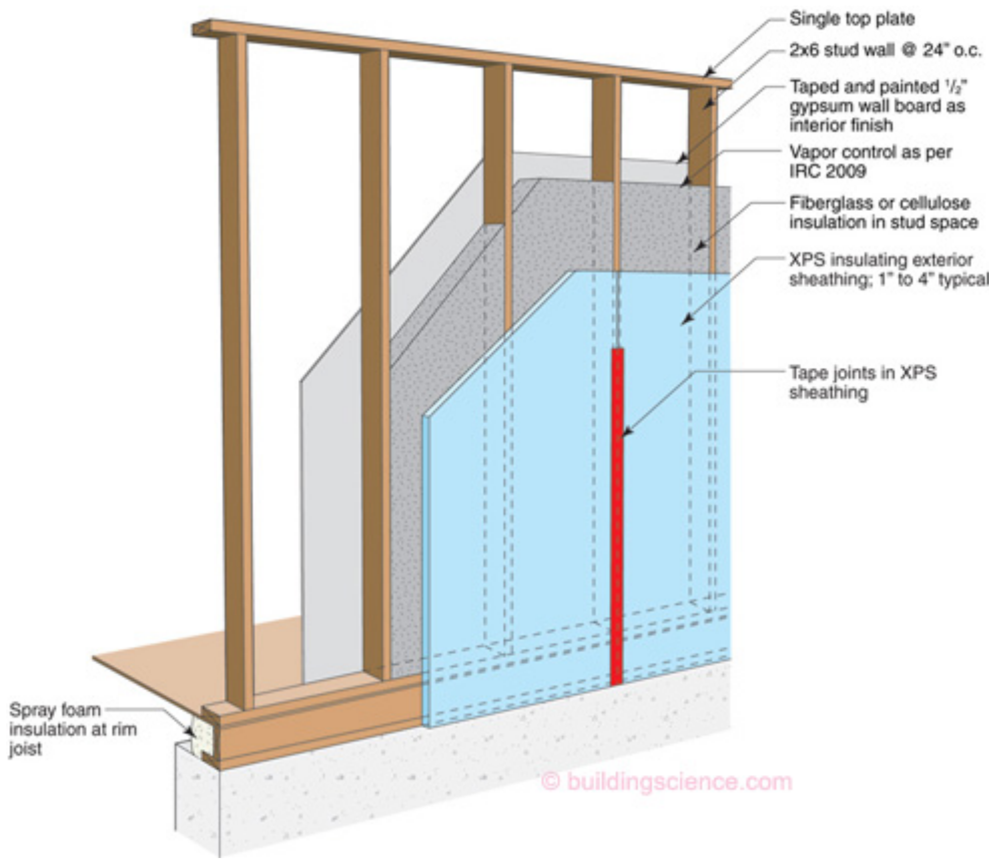


Figure 9. An image showing 2 x 6 advanced framed wall construction. From Building Science Corporation, 2011, p. 2.

Spray foam wall construction uses 2 x 6 framing at 24" o.c. and advanced framing techniques. Cavities are filled with spray foam and the exterior is clad with OSB and housewrap. Because of significant thermal bridging, a high-density insulated wall of R-30 is reduced to R-20. Construction uses common practices and the spray foam insulation is easily adopted. Increases in cost due to spray foam appear to be worth reduced energy loss (Building Science Corporation, 2011, p. 8). In Figure 10, an example of spray foam wall construction is shown.

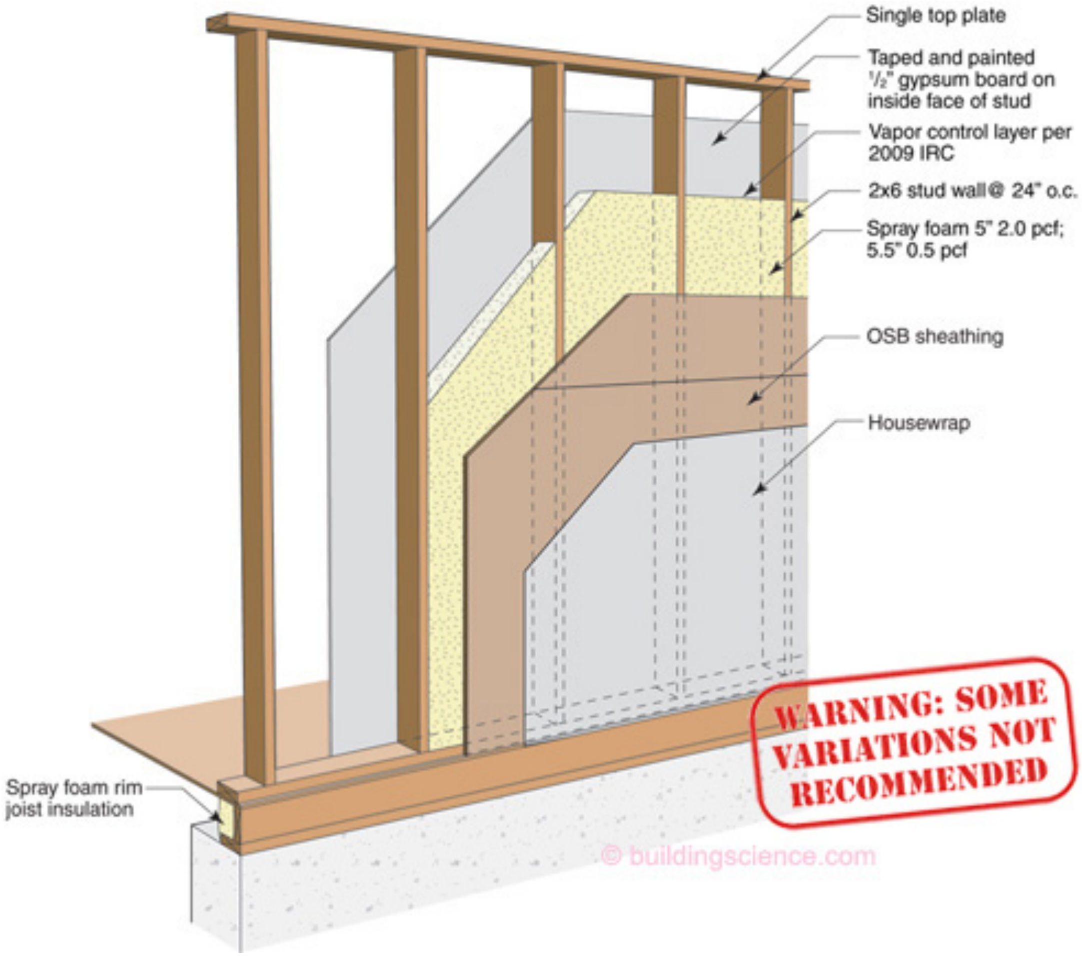


Figure 10. An image showing spray foam framed wall construction. From Building Science Corporation, 2011, p. 8.

Exterior Insulation Finish Systems (EIFS) walls use a 2 x 6 interior wall, 24" o.c., filled with fiberglass or cellulose insulation. The shell is clad first with a layer of exterior sheathing, then a liquid applied drainage plane, then 3" to 6" of EPS, and finished with stucco. The whole wall R-value is 30 with 4" of EPS insulation. Minor changes are required for framing and insulation. The EIPS finish requires a skilled trade to install. There is an increased cost associated with the EIPS finish, but it creates a durable, energy efficient assembly (Building Science Corporation, 2011, p. 12). In Figure 11, an example of EIFs wall construction is shown.

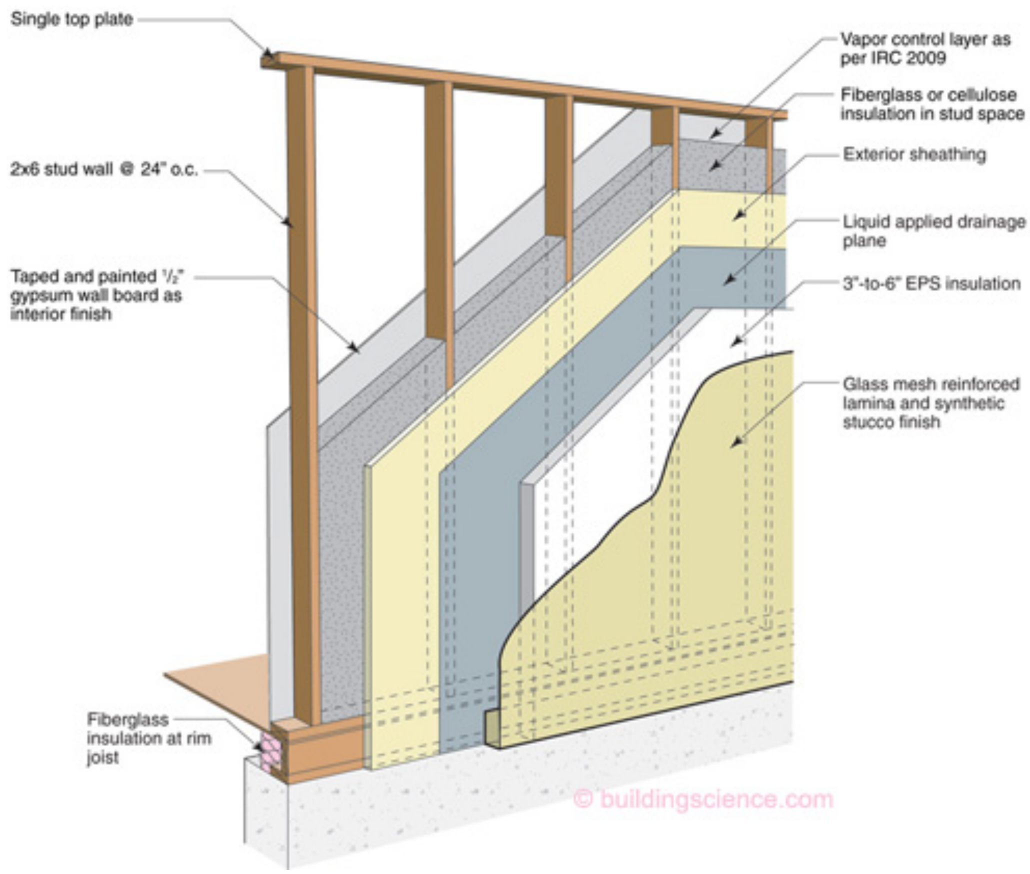


Figure 11. An image showing EIFs wall construction. From Building Science Corporation, 2011, p. 12.

Green Building Certification Programs

A large number of so-called green building certification programs exist in the United States and worldwide. Some are state-level programs and others are recognized nationally. Three of the more prominent programs in current use in the U.S. are described here. There are many other programs available in addition to the ones identified below.

Leadership in Energy and Environmental Design (LEED)

There are many green building certification programs, but the most commonly used and one of the most widely recognized certifications is the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program. LEED is an internationally recognized rating system for green building in both residential and commercial construction. LEED certification entails meeting standards concerned with the building process as well as with the completed building's performance. LEED certification standards are organized into the following categories (U.S. Green Building Council, 2011):

- Sustainable Site
- Water Efficiency
- Energy & Atmosphere
- Materials & Resources
- Home Environmental Air Quality
- Locations & Linkages
- Awareness & Education
- Innovation in Design

The Energy and Atmosphere section includes those criteria that best relate to what is required of the building envelope. Before a building is credited points, there are a few prerequisites that must be approved. Prerequisite one focuses on fundamental commissioning of a building's energy systems. The intent is to lower energy use by verifying that all energy-related systems are installed and calibrated to perform as the design intended. The second prerequisite focuses on minimum energy performance. This may be accomplished by using energy modeling software and calculating energy savings or complying with the measures identified in the Advanced Buildings Core Performance Guide developed by the New Buildings Institute (U.S. Green Building Council, 2009, p.33-34). The last prerequisite focuses on fundamental refrigerant management of cooling systems to reduce ozone depletion (U.S. Green Building Council, 2011).

The LEED credit that provides the most possible points (up to 19 points) is the section that focuses on optimizing energy performance. It creates a point structure that gives credits for any additional energy savings beyond the mandated prerequisite percentages. The percentages range from 8%-48% energy savings in existing and new buildings. These energy savings can be increased with strategic wall construction methods. Optimizing energy performance is the one section in the LEED rating system that acknowledges and credits a tight building envelope.

There are also credits relating to indoor air quality performance, which can only be accomplished by using wall assemblies with appropriate vapor and air control. In addition, there are credits for using low VOC-emitting paints and coatings. A review of LEED's energy performance section shows that the program does not specifically recognize any one wall assembly that would be strategic (U.S. Green Building Council, 2011).

Passive House

Passive House is an organization that is setting the most ambitious standard for energy efficiency in homes (Passive House Institute US, 2011). With the use of passive solar design, solar energy, a tight building envelope, and efficient equipment, this organization aims to substantially reduce energy consumption in buildings. Buildings that meet Passive House standards can achieve a 60-70% energy savings in addition to 90% savings in space heating (Passive House Institute US, 2011). Moreover, these savings are calculated before the integration of solar technologies. The general requirements to be rated a Passive House are (Passive House Institute US, 2011):

- Airtight building shell ≤ 0.6 air changes per hour (ACH) @ 50 pascals of pressure, measured by blower-door test
- Annual heat requirement ≤ 15 kWh/m2/year (4.75 kBtu/sf/yr)
- Primary Energy ≤ 120 kWh/m2/year (38.1 kBtu/sf/yr)

Passive House recommendations stipulate the following design specifications:

- Window u-value ≤ 0.8 W/m2/K
- Ventilation system with heat recovery with ≥ 75%, efficiency with low electric consumption @ 0.45 Wh/m3
- Thermal Bridge Free Construction ≤ 0.01 W/mK

The Passive House Institute does not share details about its standard for wall assemblies without attending the organization's training workshops. However, Passive House has shared two case studies for public review. The so-called "New American Four Square" is a 4,120 square foot home in Bethesda, MD (climate zone four). For the wall construction of this home, 8” thick structural insulated panels (SIPs) with 1.5” expanded polystyrene (EPS) were used. Housewrap was applied over the exterior, along with 1” furring and fiber cement siding, bringing the whole wall R-value rating to a 36 (Passive House Alliance US, 2011a).

The second case study is the “New O’Neill Passive House Retrofit” in Sonoma, CA. This home has 2,357 square feet and is located in climate zone two. Its walls are comprised of 2x6 studs added to the existing 2x4 studs, and both layers are filled with sprayed-on, dense pack fiberglass. The exterior is sheathed with EPS (a rainscreen) and siding to create a R-31 wall assembly (Passive House Alliance US, 2011b).

ENERGY STAR Homes

The U.S. Environmental Protection Agency (USEPA) has expanded its Energy Star efficiency program to buildings via its ENERGY STAR Homes program, which sets guidelines for new and existing homes. ENERGY STAR homes are 20-30% more efficient than standard homes (U.S. Environmental Protection Agency [USEPA], 2012a). The criteria for ENERGY STAR certification are broken down into five categories which include: effective insulation systems, high-performance windows, tight construction and ducts, efficient heating and cooling equipment, and ENERGY STAR qualified lighting and appliances (U.S. Environmental Protection Agency, 2012b). Certification through ENERGY STAR requires inspection by an approved Home Energy (HERS) rater who has undergone ENERGY STAR training and earned the HERS rater license. Within the ENERGY STAR program, walls have insulation requirements and insulation installation requirements, as well as air barrier and air sealing requirements. Builders typical use SIPs, ICFs, double-wall framing, and advanced framing techniques in order to achieve the criteria specified (U.S. Environmental Protection Agency, 2012b).

Building the Perfect Wall

Many building science experts have their own solution for a perfect wall assembly. For example, Joseph Lstiburek wrote an article in May of 2007 titled *The Perfect Wall*. In this article, he writes about three ideal wall types for different applications: institutional, commercial, and residential. For each wall type, Lstiburek (2007, p 1) describes the layers in the wall, "presented in order of importance:

- A rain control layer
- An air control layer
- A vapor control layer
- A thermal control layer"

In explaining this order, Lstiburek notes that an air control layer is unnecessary if the rain can get through. A vapor control layer is unnecessary if the air is not controlled, and a thermal control layer is unnecessary if vapor is not controlled (Lstiburek, 2007, p 1). Using this knowledge, a better understanding of Lstiburek's "perfect wall" may be seen in Figure 12.

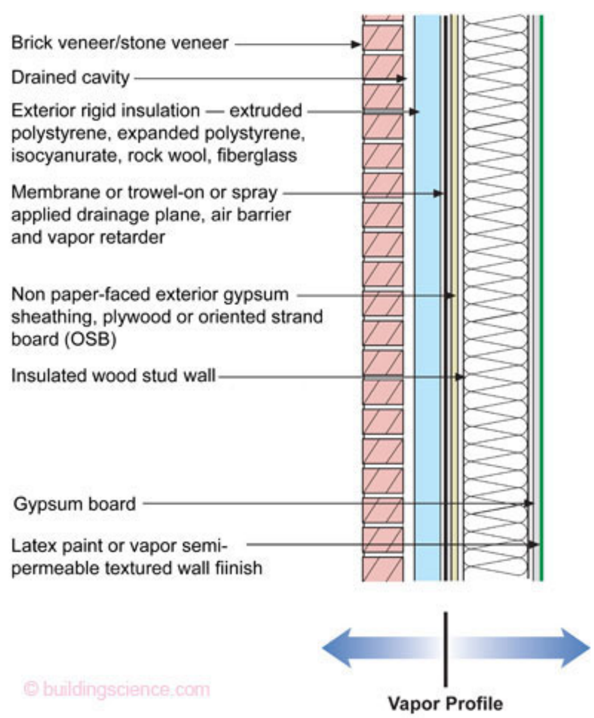


Figure 12. The Perfect Wall. Adapted from Lstiburek, J. W. (2007). The perfect wall. ASHRAE Journal: Building Sciences, 3.

In retrospect, there is no “perfect wall” for every situation and climate. Each construction project will have unique opportunities for designing the best wall for a specific job. This decision should consider whether the climate is damp or dry, or hot or cold. Consideration should also extend to seasonal weather, where changes may be drastic or stay consistent throughout the year.. In addition, local resources will vary depending on location and will provide different alternatives for construction materials. Although there are guidelines for designing better walls, there will never be one wall that fits all circumstances perfectly. We may, however, find wall assemblies that work best for certain zones, and aim to make those the most optimal wall configurations.

The U.S. Department of Energy Solar Decathlon Competition

A Brief History of the Solar Decathlon

The U.S. Department of Energy’s (U.S. DOE) Solar Decathlon began in 2002. The Solar Decathlon is a competitive event designed to bring together teams from around the world to design, build, and operate a solar power home. Each team must transport their home to the competition site where they are judged in 10 contests to determine a winner (U.S. DOE, 2012).

After a successful first competition, the U.S. DOE decided to host another competition in 2005; since that time, the Solar Decathlon has become a biannual event. In the past, the Solar Decathlon was held on the main expanse of the National Mall in Washington D.C. However, for the 2011 competition, the site was moved to West Potomac Park on the National Mall. The contests have changed slightly over the years, advancing the competition into a competitive and prominently recognized event (U.S. DOE, 2012).

Judged Contests in the Solar Decathlon 2011

The homes that were accepted to compete in the Solar Decathlon 2011 were judged in 10 contests, each worth 100 points, for a total of up to 1,000 points. The 10 contests included (U.S. DOE, 2011):

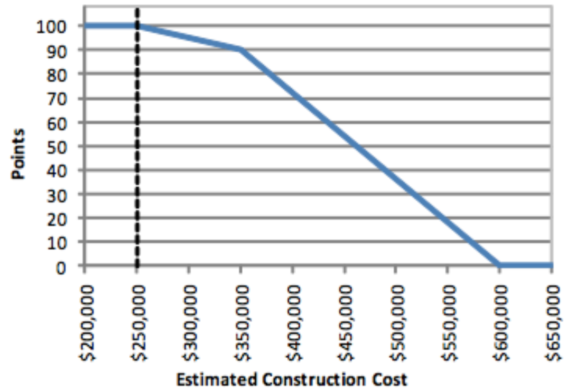
1. Architecture	6. Comfort Zone
2. Engineering	7. Hot Water
3. Market Appeal	8. Appliances
4. Communications	9. Home Entertainment
5. Affordability	10. Energy Balance

In discussing the contests, it may be best to organize them according to whether they were juried or measured contests. That is, five of the contests were decided based on the rankings of expert judges; the remaining five were based on calculated or empirical data collected from each home during the competition on the National Mall. The architecture contest was judged by three architects who evaluated the construction drawings, specifications, the architecture video walkthrough, and the final home design and concept. The engineering contest was also judged by selected professional engineers through the drawings, specifications, engineering audiovisual presentation, and the completed home's engineered system design. In addition, a jury reviewed the energy analysis results. Juries evaluated the marketability of each home, basing points on the construction documents, the audiovisual sales presentation, and the final home design review. The communications contest was also juried, and evaluated how well teams communicated and educated the public through public exhibit tours, signage, their website, a video walkthrough, and a handout. All of these juried contests were subjective in nature, allowing the judges to have a significant input on the final score results (U.S. DOE, 2011).

The measured contests were strictly monitored. Comfort zone measured the relative humidity and temperature of the home. The temperature should have been between 71°F- 76°F

(22°C-24°C) and the relative humidity should have been below 60% for the duration of the competition. Hot water draws were taken 16 times over the contest week. The draws were allotted 10 minutes and the water was expected to have an average temperature of 110° F (43° C). Appliances were measured throughout contest week, each time with a different measured task to perform. The refrigerator and freezer were tested to prove that stable temperatures were maintained. The washing machine and dryer had to successfully complete eight loads of laundry and dry the laundry back to the original weight. The dishwasher had to complete five loads. Together, these tasks comprised the entire 100 points for the appliance contest criteria. The home entertainment contest was based on a mix of juried and measured events. Lighting was measured every night based on the performance of all exterior and interior lights, turned on to their full levels. Cooking was measured on four events based on the ability to vaporize five pounds of water in less than two hours. Home electronics events mandated operating a TV and a computer during listed hours. The juried components included hosting two dinner parties and one movie night for your "neighbors," and letting the other teams judge the performance. The energy balance contests measured the home's ability to produce as many kWh as were consumed over the contest week, with the goal of achieving net zero performance, or no net energy draws from the electrical grid (U.S. DOE, 2011).

The affordability contest was added to the competition in 2011, an important addition considering that the purpose of the competition is to design a home that is net zero but still reasonably affordable. Each team had to develop a cost estimate based on the finished home as it sat on the National Mall for the estimator to review. Full points were given for any home built at or under $250,000. Anything above that target cost was given points based on a sliding scale down, shown below in Figure 13 (U.S. DOE, 2011).



Full Points:		Cost	≤	$250,000
Reduced Points (shallow):	$250,000 <	Cost	≤	$350,000
Reduced Points (steep):	$350,000 <	Cost	<	$600,000
No Points:		Cost	≥	$600,000

Figure 13. Scoring function for the affordability contest. From U.S. DOE, 2011.

The 2011 Solar Decathlon Entries

To select teams for the 2011 competition, the U.S. DOE had each prospective entrant submit a proposal including project budget, architectural concept, logistics, and overall project timeline. In making its decision about competitors for the 2011 competition, the U.S. DOE decided to require an additional submission before narrowing the field down to 20 teams. For the second-round submission each team had to build a scale model of the home and a tri-fold board for display. The selected teams would have their work displayed at the National Building Museum in Washington D.C. (U.S. DOE, 2012). The 20 teams selected were the following, listed in alphabetical order (an additional description of each entry, taken from the DOE website, can be found in Appendix A):

- Appalachian State University
- Florida International University
- Middlebury College
- New Zealand: Victoria University of Wellington
- The Ohio State University
- Parsons The New School for Design and Stevens Institute of Technology
- Purdue University
- The Southern California Institute of Architecture and California Institute of Technology
- Team Belgium: Ghent University
- Team Canada: University of Calgary
- Team China: Tongji University

- Team Florida: The University of South Florida, Florida State University, The University of Central Florida, and The University of Florida
- Team Massachusetts: Massachusetts College of Art and Design and the University of Massachusetts at Lowell
- Team New Jersey: Rutgers - The State University of New Jersey and New Jersey Institute of Technology
- Team New York: The City College of New York
- Tidewater Virginia: Old Dominion University and Hampton University
- University of Hawaii
- University of Illinois at Urbana-Champaign
- University of Maryland
- The University of Tennessee

Construction Estimating

Construction estimating is an important function of the building process whereby itemized material and labor costs are calculated for an overall cost of building a given structure. Multiple techniques can be used for calculating construction costs. In this section, three common methods are explained. Each style considers its own set of factors, which may cause variations in the final number from estimator to estimator. This variation is described as "reasonable cost." Reasonable cost accounts for price variation in materials and labor for every individual project (R.S. Means Company, Inc., 2009, p.xix). The phrase "takeoff" is derived from taking information off the construction documents and specifications and identifying quantities and prices (R.S. Means Company, Inc., 2009, p.xix). Accurate cost accounting requires an estimator with great knowledge and experience to develop a thorough and complete estimate.

Square Foot-Basis Takeoffs

Square foot or cubic foot takeoffs are the initial cost estimates completed early on in a project. Typically these are completed when planning is completed and the total square footage is known. These estimates are only accurate to between -20% to +30%, since construction details are in progress (R.S. Means Company, Inc., 2009, p.xxi).

Assembly Takeoffs

The assembly estimate is used during the early stages of a construction project. When a full quantity takeoff is too detailed to complete early on, the assembly take-off estimate is ideal in order to define budgets. Assembly takeoffs also allow builders to make changes to materials and construction without making any time-intensive changes to the estimate. By having the assemblies divided by section, changes can be calculated quickly and easily. Although this process works well during the early stages, it is not appropriate for the final estimate, where all details need to be known. The assembly estimate is typically between -10% to +20% accurate (R.S. Means Company, Inc., 2009, p.xx). The assembly estimate is broken into seven sections identified by a building's construction components, as follows (R.S. Means Company, Inc., 2009, p.xxi):

- Substructure
- Shell
- Interiors
- Services
- Equipment and Furnishings
- Special Construction
- Building Site Work

These divisions also have subdivisions where more detailed criteria are outlined. The same materials may be accounted for in multiple sections due to the method of structure.

Quantity Takeoffs

Quantity takeoffs are the most detailed measures of estimating. These are completed when all aspects of design and construction are known. First, the estimator must understand the plans and specifications entirely to know what to take off. Once understanding the plans, measurements from each item used need to be accurate dimensions identified from drawings. The dimensions may be found using a building information model (BIM), CAD drawing, or architectural scale. The estimator then takes the known quantities and records them into a spreadsheet, labeling each reference drawing to avoid mistakes (Ding, 2010, p. 29).

Understanding cost estimating is imperative to this research in order to determine an accurate cost evaluation of each home. With many methods available, finding the best takeoff method was important to research. In addition, to best understand the provided cost estimates of each home, it was necessary to have a basis for understanding the fundamentals of estimating.

Environmental Impacts

As a result of a growing world population and expanding industrialization, natural resources and available energy have been exploited to unsustainable levels. It is imperative to look at the value of what is being produced and justify whether its impact is worth its cost. Although various metrics can be included in an analysis of environmental impact, for the purpose of this study, embodied energy was examined as a means to compare materials used to build walls to create the least impact on the environment.

Embodied Energy

Embodied energy is an approach used to measure the energy it takes to develop, process, manufacture, and transport a product (Randolph & Masters, 2008, p. 167). Table 1 shows a typical building material's embodied energy.

Table 1

Samples of Embodied Energy Numbers in MJ/kg and BTUs Per Pound

Building materials		Embodied Energy		Weight	
Material	**Product type**	**MJ/kg**	**BTU"s/lb.**	**lb/sqft**	**lb/cuft**
	batts	30.3	13029		1
	dense pack				1.75
Fiberglass	rigid board				4
	batts	16.1	6923		2.75
	loose fill				2
Mineral Wool	rigid board				4.5
	loose fill	3.3	1419		1.85
	NU-wool		750		1.6
	dense pack			4	4
	recycled blown	1.7	750		3.35
Cellulose	spray on	1.7	731		3.3
Vermiculite	loose fill				3.5
Polyisocyanurate	rigid board				1.8
	hi-density	101.5	43645		2.25
Polyurethane spray	low-density				0.5
	rigid board expanded/ EPS	117	50310		1.45
polystyrene	rigid extruded/XPS/blueboard	117	50310		1.8
Soy based	spray on				
Concrete	precast	2	860		145
	1/4"	15	6450	0.71	
	1/2"	15	6450	1.42	
	5/8"	15	6450	1.77	
Plywood	3/4"	15	6450	2.13	
	1/2"	6.1	2623	2.5	52.8
GWB	5/8"		2623	2.75	
	7/16"	15	6450	1.7	
OSB	1/2"		6450	1.55	37.2
Alcoa metal panels	aluminum composite material			1.49	
aluminum		227	97610		169
steel		34.8	14964		492
Glass		15.9	6837	8	161
	one gallon covers: in sq ft	93.3	40119		10
Paint	350				
Fiberglass Reinforced plastic		92.2	39646		112
Lumber					
1 x 3		2.5	1075		0.47
2 x 2		2.5	1075	0.55	lb/linear
2 x 4 12 oc		2.5	1075	1.2	1.22
2 x 4		2.5	1075		2
2 x 6		2.5	1075		2.64
2 x 8		2.5	1075		3.37
2 x 10		2.5	1075		4.1
2 x 12		2.5	1075		2.98
4 x 4		2.5	1075		7.35
6 x 6		2.5	1075		10.03
6 x 8		2.5	1075		
Timber	kiln dried, dressed	2.5	1075		
Polycarbonate panels		112.9	48547		0.553
kiln dried cedar		2.5	1075		23
Polyester Membrane	(as HDPE)		7710		24
thermo treated poplar	use kiln dried		1075		
wood stain		50	21500		
polyethelene (LDPE)		130	55900		61
polypropylene		95.4	41022		
corrugated metal	*use sheet metal	199	537300		1.156
nordic I-joist	break down into components (2x2 and osb)		1075	0.55	
Fiber cement Siding	(Magnesium Oxide wallboard)	3.9	1677		74.9
shipping container	use numbers for steel				8,750
Inside air film					
Outside air film					
Wallpaper		36.4	15652	0.017	

Note. Associated values were adapted from Krigger, J., & Dorsi, C. (2009). *Residential energy.* (5 ed., p. 316). Helena MT: Saturn Resource Management, Inc. and Alcorn, J. A., & Baird, G. (1996). *Use of hybrid energy analysis method for evaluating the embodied energy of building materials.* (Master's thesis, Victoria University of Wellington, Wellington, New Zealand).

Chapter 3

Research Methods

The purpose of this study was to analyze the wall assembly techniques used by entrants in the Solar Decathlon 2011 competition to determine which assemblies were superior in terms of energy effectiveness, cost, and environmental impact. All data was sourced from the U.S. DOE's Solar Decathlon 2011, which provided a consistent set of measures to use in this research. Each Solar Decathlon team had complete sets of construction documents, cost estimates, and project manuals available for use in this data analysis. Using the following methodology, the research was conducted.

Methods and procedures may best be understood in two stages. The first stage focused on identifying and characterizing the methods to be used in the analysis. The second stage focused on analyzing each assembly using the metrics identified. Each home was carefully analyzed and characterized by the nature of its wall assembly. This allowed for a thorough understanding of each construction method. After reviewing and understanding each wall assembly, information was gathered on that wall's cost of materials, cost of labor, clear wall R-value, and embodied energy in BTUs /sq.ft.

Sample

The homes that were analyzed in this sample include 18 of the 20 homes that competed in the U.S. Department of Energy's Solar Decathlon in 2011. Twenty teams were accepted into the competition, but only 19 actually built their homes on site (Team Hawaii withdrew prior to the competition). Of the remaining homes, 18 had legible, detailed drawings available that allowed them to be included in this study (Team New York's construction drawings were not usable for this analysis).

These homes were all designed to be energy efficient, net zero, affordable homes. Given the criteria of the competition, each was also designed with economic constraints in mind. These 18 homes were appropriate candidates to compare because they were designed and built using the same guidelines. Each team focused on affordability and energy efficiency when making design decisions. Additionally, the homes all had complete "as-built" construction documents to use for data collection and review. Teams were required to produce full estimates, which were reviewed and approved by a professional estimator. Having 18 original homes with construction estimates already approved by a professional estimator and complete construction documents, theses samples seemed like ideal candidates to study affordable and energy efficient materials and construction methods.

Data Collection Procedures

Multiple documents provided by the 2011 U.S. DOE's Solar Decathlon were used for data collection. All cost estimates were transferred into Microsoft Excel. For additional information required, references were sourced from construction documents, project manuals, team websites, and project photos. Data collection included using each of these resources for the most precise data to review.

Data Analysis Procedures

Construction documents provided the basis for research. Once determining the type of wall section, a clear wall R-value was calculated based on the dimensions of and materials used in the assembly. Also, using the construction documents and the project manual, embodied energy was calculated. The data from each estimate was broken down to calculate the cost per square foot of each home's wall assembly. Once the totals were identified, bar graphs provided a clear tool for comparing each wall assembly's performance.

Before analyzing R-values, embodied energy, and cost per square foot, a defined wall section needed to be selected from each of the 18 homes. Each wall was chosen based on the following guidelines. First, it needed to be the tallest wall section in the home (unless the home contained a second floor with no livable area); second, it was the most common wall type represented in a given home; and third, it comprised the section from center to center of a stud cavity or an equivalent section. The wall section analyzed included the area from the bottom plate to the top of the wall. When a clerestory window or other continuous feature was part of a section, that feature was also included in the analysis.

Clear Wall R-value

Once each wall assembly was selected for review, the first analysis verified the clear wall R-value. Each section was carefully examined to determine the exact materials and the dimensions of those materials. Typically, a clear wall R-value may be determined using two paths. The first path includes examining the insulated section of a cavity. The second path accounts for the path through the stud section of a cavity. By finding the percentage of each of these paths, a clear wall R-value may be calculated. Refer to Figure 3 for an example plan for finding the clear wall R-value, Figure 4 for an example section view, and Table 2 for the example equation.

Take a typical 2 x 4 wall on 16" centers with a double top and bottom plate and R-11 batt insulation for example. Assuming a 9' wall height, 5/8" gypsum wallboard on the interior walls, and ½" OSB sheathing and siding on the exterior are shown below (Figure 14 and Figure 15).

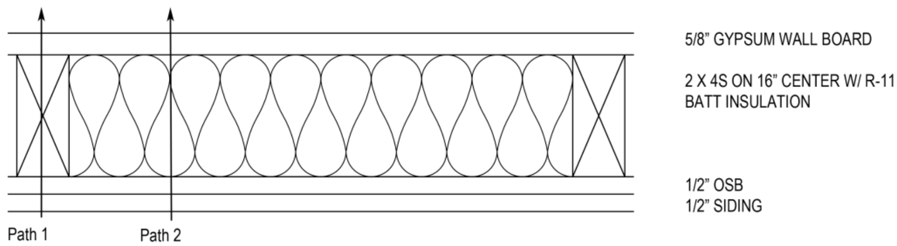


Figure 14. Example plan for finding clear wall R-value.

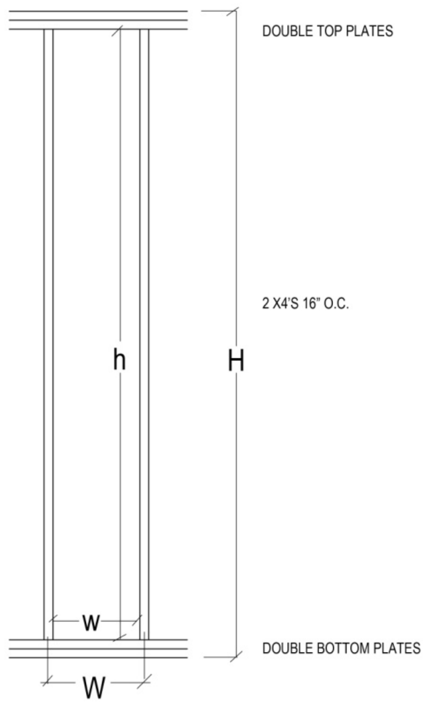


Figure 15. An example of a section for finding clear wall R-value.

Where w=14.5", W=16", h= 8'6", and H= 9'0" for Figure 15. The following formula determines the percent of both insulation and framing using the metrics above:

(w x h) ÷ (W x H)= (14.5 x 102) ÷ (16 x 108)= 1479/1728= 85.6% insulation, 14.4% framing

In Table 2, an example of the method to the equation may be found.

Table 2

Sample of Finding Clear Wall R-value Referring to the Wall Section in Figure 3 and 4.

	Path 1 (framing)	Path 2 (insulation)
Inside Air Film	.68	.68
Drywall	.56	.56
Insulation/framing	3.5	11
OSB	.62	.62
Outside Air Film	.17	.17
∑ of R	5.53	13.03
∑ of U	=(1÷5.53)= .1808	=(1÷13.03)= .0767
Multiply by area percentages	=.1808 x .144	=.0767 x .856
	=.0260	=.0656
Add U-values	=.0260+.0656= .0923	
∑ of both U	.0916	
Clear Wall R-value	=(1÷ .0916) = **10.91**	

Note. When determining paths, begin adding R-values, then convert to U-value when multiplying by percent of insulation or framing.

All associated R-values were compiled from multiple resources including: Krigger, and Dorsi, 2009; Singh, Dev, Hasan and Tiwari , 2011; and Colorado Energy, 2001. When R-values were defined within a range of numbers, a mean was used to determine a constant value for each equation.

Embodied Energy

Embodied energy may be assessed by calculating the total primary energy starting from beginning of production to either completion of manufacturing, on-site installation, or the total energy used throughout the material’s lifetime. This may include extraction, manufacturing, and transportation. These energy calculations are more commonly explained as “Cradle-to-Gate,” “Cradle-to-Site,” and “Cradle-to-Grave,” but may also be referred to as initial embodied energy or recurring embodied energy (GreenSpec, 2012). Cradle-to-site includes not only the energy it takes to produce the material, but any energy used getting the material to the construction site.

Cradle-to-grave includes any energy consumed from the beginning of a material's life through disposal (including energy used for maintenance, transportation, equipment used, etc.). Cradle-to-gate includes the energy it takes to produce the material up until it leaves the factory gate. Because these values require complex calculations and specific data to configure, engineers have developed standard numbers for cradle-to-gate calculations (GreenSpec, 2012). For this study, cradle-to-gate standards were used for the greatest accuracy and consistency, as information about the other factors were unknown.

In order to determine the embodied energy of each building material, the weight of the material must be calculated. Taking the cubic feet of each material and multiplying by the pounds per cubic foot can yield the weight in pounds. After the weight is calculated, one multiplies by the Btu/lb. This number is the total embodied energy for that entire wall section. Once these totals are calculated for each component used, the totals are added and then divided by the area for a basis of comparison to calculate the BTUs/sq.ft.. For an example, readers can refer to Table 3.

All numbers used for embodied energy and weight of building materials were compiled from the following sources: Edmund A. Allen Lumber Company, 2010; The Engineering Toolbox, 2012; Krigger and Dorsi, 2009; Nordic Engineered Wood, 2009; University of Bath, 2006; Wilson, 2012.

Table 3

Example Table for Calculating Embodied Energy in BTUs/ft²

Embodied Energy	Interior finish	Int. sheathing	Int. paint	Framing	Insulation	Vapor Retarder	Sheathing	HardiePlank, HZ5	Stain	
	1/2" GWB	7/16" OSB	Gypsom Flat	SIPS	EPS	Building paper	7/16" OSB	fiber cement board	2 coats	
cubic in	864	756		1302	5460		756	1296		
cubic ft	0.5000	0.437500		20.2 linear ft	3.159722222	0.02394	0.4375000	0.75		
lbs	26.4	20.349	1.026	40.4	4.581597222	0.003219499	20.349	56.175	0.684	**Total Btu's**
Btu	69247.2	131251.05	41162.094	43430	462906.2569	179.9699716	131251.05	94205.48	14706	988339.10
Btu/ft2									**Btus/ft2**	82568.01

Wall Dimensions	1'4 x 9'
Area	11.97

Cost Estimates

All estimates were calculated using the cost estimates used for the U.S. Department of Energy's Solar Decathlon 2011. These numbers were verified by a professional cost estimator and may be used as a consistent basis for comparison. Totals for each wall assembly were calculated using quantity takeoffs based on a cost per square foot for the best means for comparison. Totals include material cost separately, and also labor cost with material cost. The total for both material and labor cost together can determine the buildability of each wall system. In Table 4, an example of Ohio State's estimate is shown, taken from the final cost estimate provided by the team, and only including the components within the wall assembly.

Table 4

Example of the Cost Estimate for Team Ohio State's Wall Assembly

Spec Section	Brief Description	Detailed Description	Qty	Unit	Material Cost	Labor Cost	TOTALS
060000 Wood, Plastic, Composites							
	Partitions	Wood framing, partitions, standard & better lumber, 2" x 6" studs, 16" O.C., 10' high,	240	L.F.	$ 4.79	$ 8.70	$ 13.49
	Wood - Sheathing - plywood Total	Sheathing, plywood on walls, CDX, 1/2" thick	4162	S.F.	$ 0.46	$ 0.70	$ 1.16
	ZIP WALL, Wall Sheathing: 1/2 inch thick OSB, 48 x 96 inch sized sheets, Walls, floors, ceiling	*Sheathing, plywood on walls, CDX, 1/2" thick*	*2600*	*S.F.*	*$ 0.46*	*$ 0.70*	*$ 1.16*
070000 Thermal and Moisture Protection							
	Owens Corning Energy Complete, R 21 fiberglass insulation, Mineral-Fiber-Blanket Insulation:	Typical Fiberglass Batt Insulation , Floors, Walls and Ceilings, kraft faced fiberglass	900	S.F.	$ 1.05	$ 0.30	$ 1.35
72100	Owens Corning Foamular, 1/2 inch rigid insulation, Extruded-Polystyrene Board Insulation:	Foam board insulation, polystyrene, expanded, 2" thick, R8	1750	S.F.	$ 0.64	$ 0.78	$ 1.42
	Perforated Exterior polycarbonate Panel w/operable & sliding sections - Aluminum edging	Polycarb Corrugated Square Wave Panel, 8' Wht Corrugated Panel	400	SF	$ 23.25	$ 4.00	$ 27.25
090000 Finishes							
	Typical Interior Paint	Paints & Coatings, walls & ceilings, interior, concrete, drywall or plaster, zero voc latex, 3 coats, smooth finish, roller	2728	S.F.	$ 0.21	$ 0.52	$ 0.73
	Glass-Mat, Water-Resistant Gypsum Backing Board:, G-P Gypsum; Dens-Shield Tile Guard.	Gypsum wallboard, on walls, standard, w/compound skim coat (level 5 finish), 5/8" thick	2728	S.F.	$ 0.40	$ 1.01	$ 1.41

Note. Adapted from U.S. Department of Energy. (2012, January 26). *U.S. Department of Energy Solar Decathlon*. Retrieved from http://www.solardecathlon.gov/

Chapter 4

Findings and Conclusions

Clear Wall R-Value

After examining and analyzing each wall configuration, a clear wall R-value was calculated for each of the 18 home entries in the 2011 U.S. DOE Solar Decathlon. There was a range of associated R-values between R-2.64 and R-44.4. For the purpose of this study, the top three highest-valued walls and three lowest-valued walls are described. In Figure 16, a graph depicting each team's calculated clear wall R-value is provided.

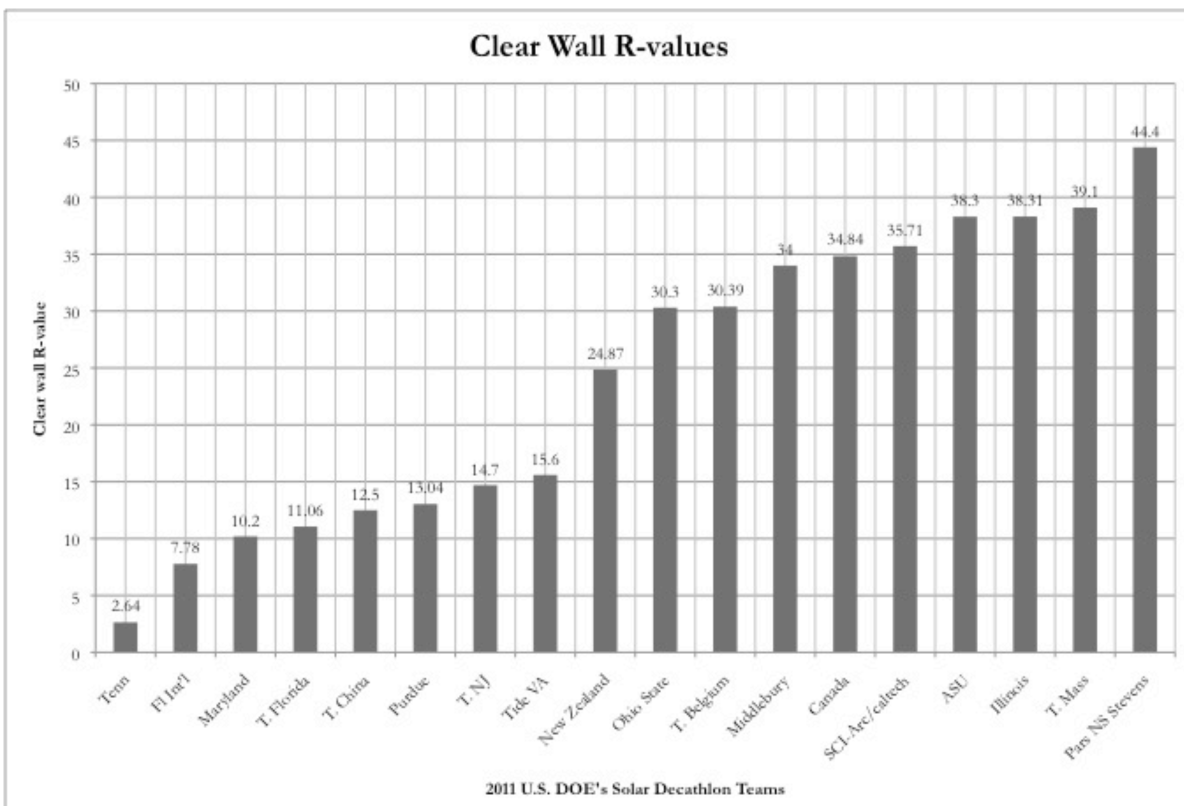


Figure 16. Bar graph of 2011 Solar Decathlon teams' clear wall R-values.

Just as it is important to discuss the best clear wall R-values, it is also important to understand what methods were not as efficient. As a note, clear wall R-values are only one method to evaluate energy efficiency. As some of these teams may have a lower clear wall R-value they may save energy use with integration of day lighting, structural details, or innovative materials and construction methods. For the purpose of this study, the third-lowest ranking team was Team Maryland, with a clear wall R-value of 10.2. This was unexpected, because Team Maryland used a thick wall assembly and 4" of EXS on the exterior. However, Team Maryland used "heavy stick" framing (the load bearing structure is comprised of triple 2 x 6 stud packs 4' o.c., which allows for fewer thermal breaks), which contributed to a lower R-value (University of Maryland, 2011). In addition, they had a 9.5" section that was only insulated on the exterior. Lastly, Team Maryland included a 3'3" fiberglass clerestory window. Although Team Maryland's wall assembly seemed to be an energy-efficient method, its clear wall R-value was greatly impacted by inclusion of the clerestory for architectural detail (see Figure 17).

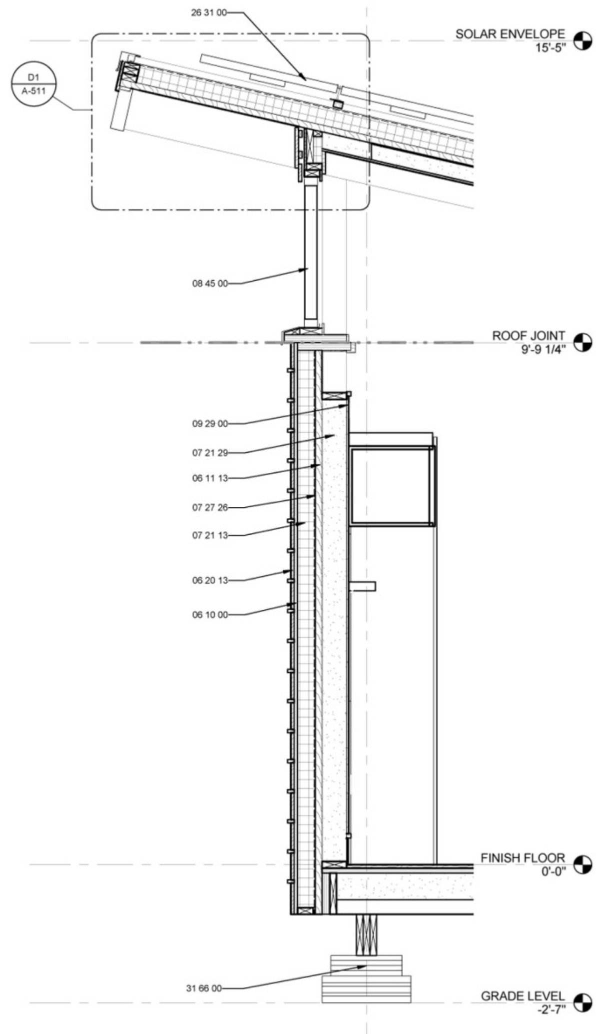


Figure 17. Team Maryland's wall section. From U.S. DOE, 2012.

Florida International, whose house had the second-lowest rating, had a clear wall R-value of 7.78. The walls were primarily comprised of glass, with a 2'0" section of 8" spray foam. With eight feet of glass, the wall's R-value was significantly reduced. In Figure 18, a wall section for Florida International is shown.

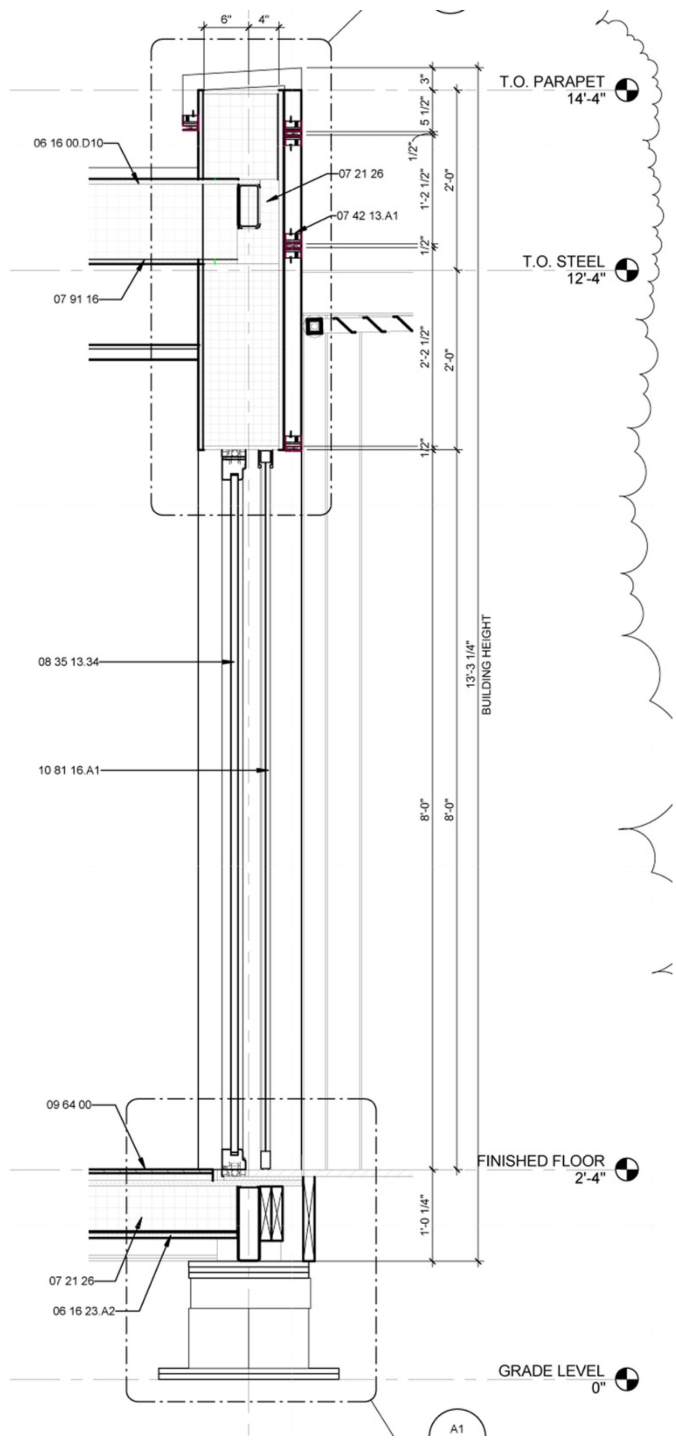


Figure 18. Florida International's wall section. From U.S. DOE, 2012.

Team Tennessee ranked lowest in clear wall R-value with a R-2.64 wall assembly. This was simply due to using an all-glass façade. Team Tennessee used a double façade system, which used two glass curtain walls. The section between the two glass sections was an air gap, which was designed to harvest heat to a recovery ventilator, which then would supply the home (U.S. DOE, 2012). In Figure 19, a wall section for Team Tennessee is shown.

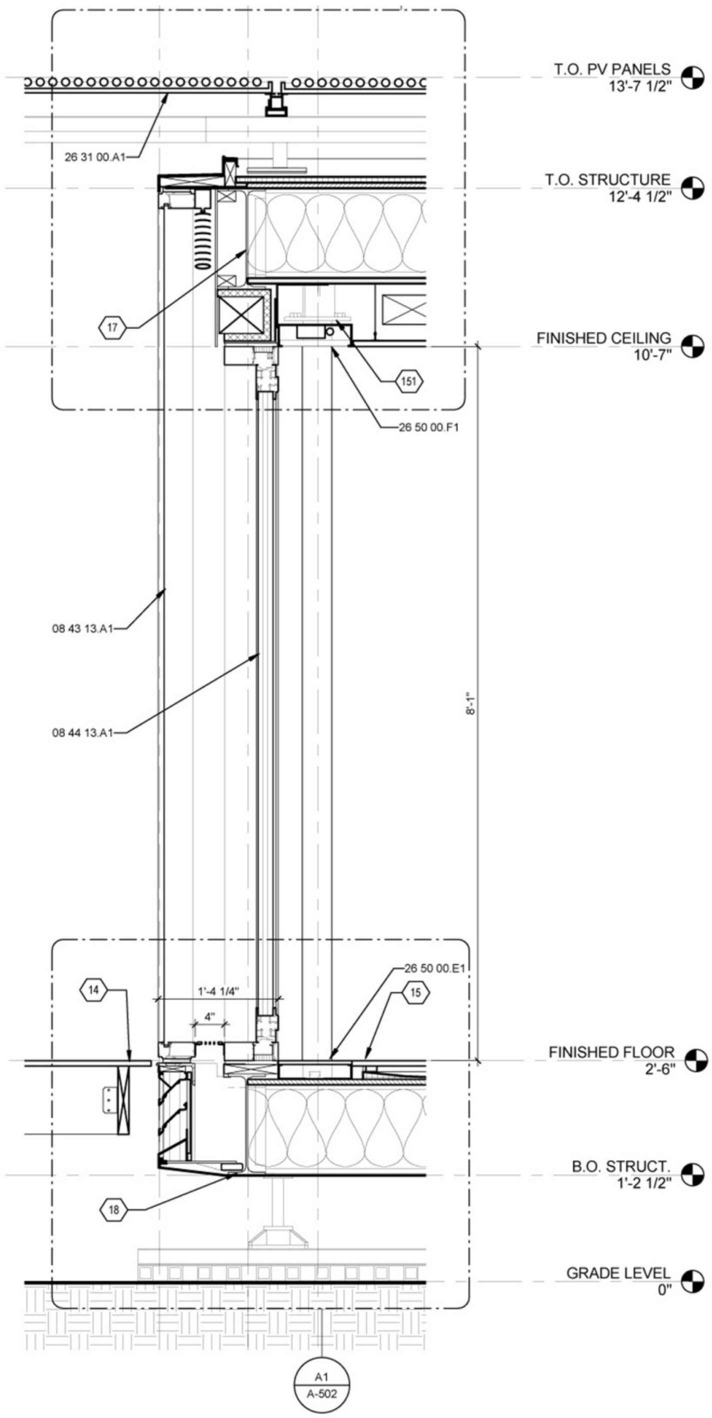


Figure 19. Team Tennessee's wall section. From U.S. DOE, 2012.

The third most-efficient wall assembly was tied between Illinois State University and Appalachian State University (ASU). Both teams designed R-38.3 wall assemblies. Illinois used common framing methods but filled the cavities with polyurethane spray foam, providing a rating of R-22 within the stud cavity alone. In addition, 4” of rigid insulation was applied to the exterior side. In Figure 20, a wall section for Team Illinois is shown.

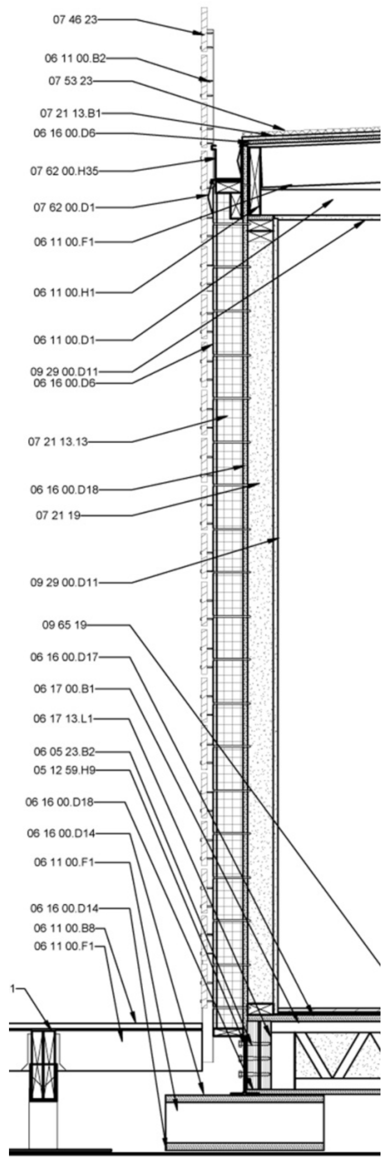


Figure 20. Team Illinois wall section. From U.S. DOE, 2012.

Typically, when seeking to achieve a high R-value in walls, one should not utilize fiberglass-batt insulation. However, ASU took two layers of batt insulation and incorporated them into a staggered stud framing method in order to help reduce thermal bridging. In this way, the team was able to use a low-cost insulation material and still attain a competitive R-value. Figure 21, shows a section detail of ASU's wall.

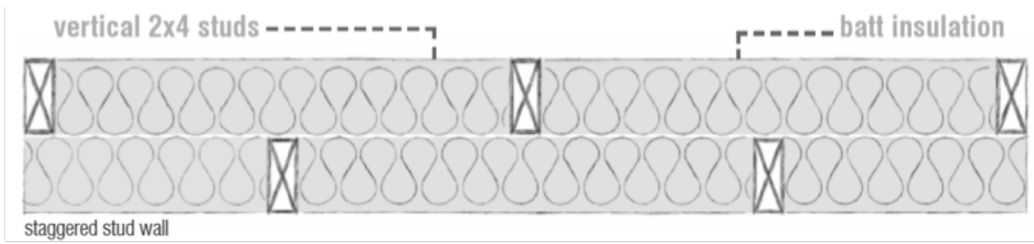


Figure 21. Detail of Appalachian State University's staggered stud framing section.

Team Massachusetts constructed a wall valued at R-39.1. This number was achieved by using almost 8" of blown fiberglass insulation with 4" of spray foam. By taking advantage of a thick wall assembly, Team Massachusetts created a tight, efficient envelope. Figure 22 shows a section view of Team Massachusetts' wall.

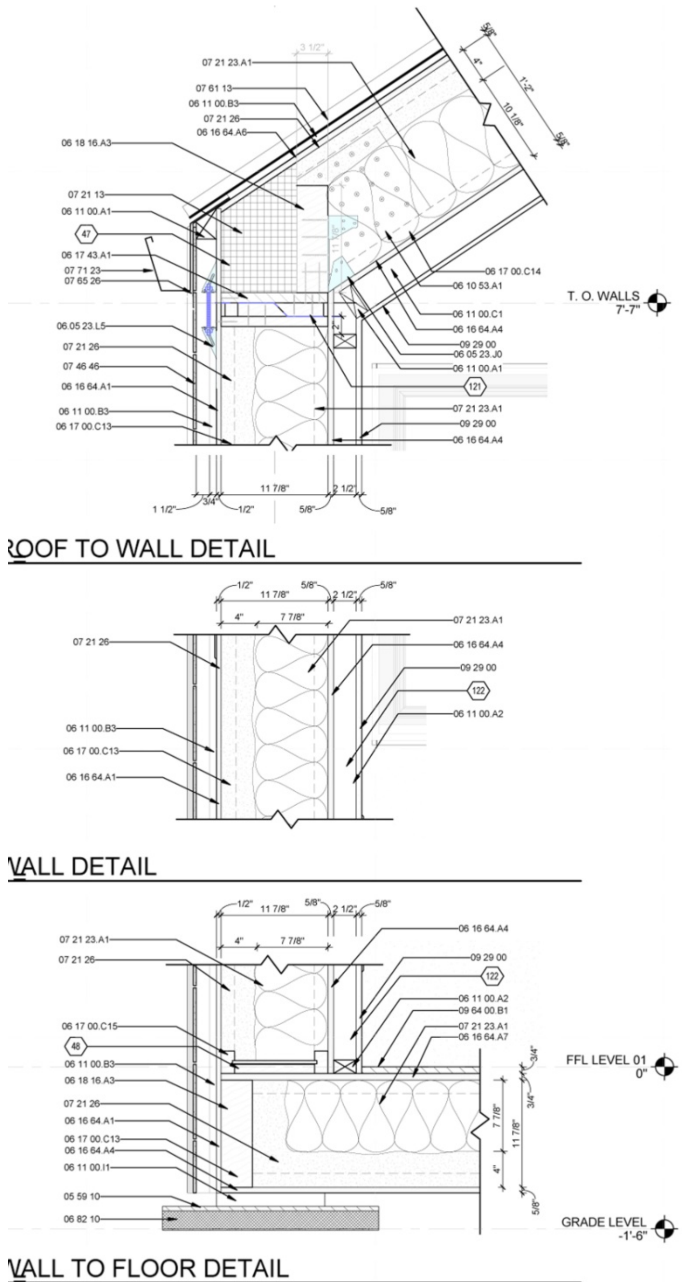


Figure 22. Team Massachusetts wall section. From U.S. DOE, 2012.

Team Parsons the New School for Design and Stevens Institute of Technology took first place by producing a R-44.4 wall. Although Parsons and Stevens utilized a 12" wood I-joist to create a thick insulated wall, they also incorporated some unique details. Different to many 2 x 4 top and bottom plates, this wall assembly was detailed more carefully. Using 2 x 2's allowed for 6" of rigid insulation to be integrated into the top and bottom plates, reducing thermal bridging. Refer to Figure 24 for a detail of the top and bottom plate and Figure 23 for a section view. Parsons' attention to detail and careful construction considerations contributed to its taking first place in the clear wall R-values.

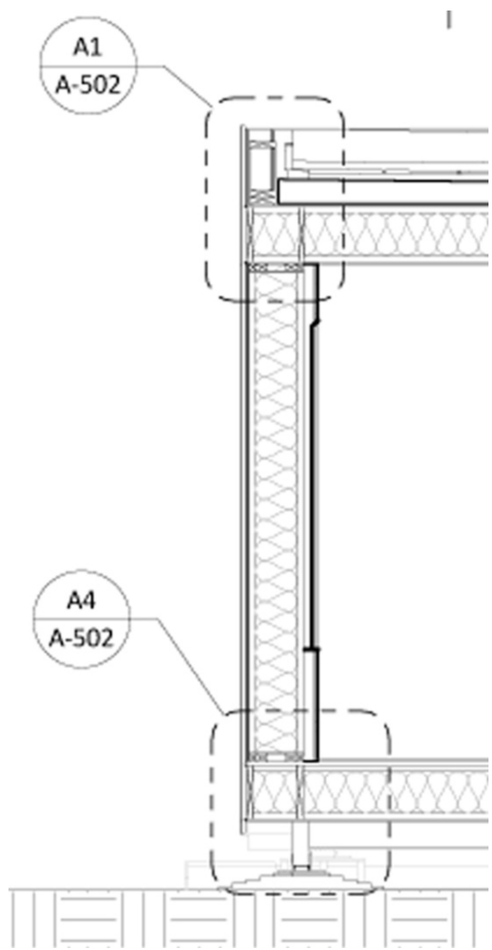


Figure 23. Section view of Parsons and Stevens wall. From U.S. DOE, 2012.

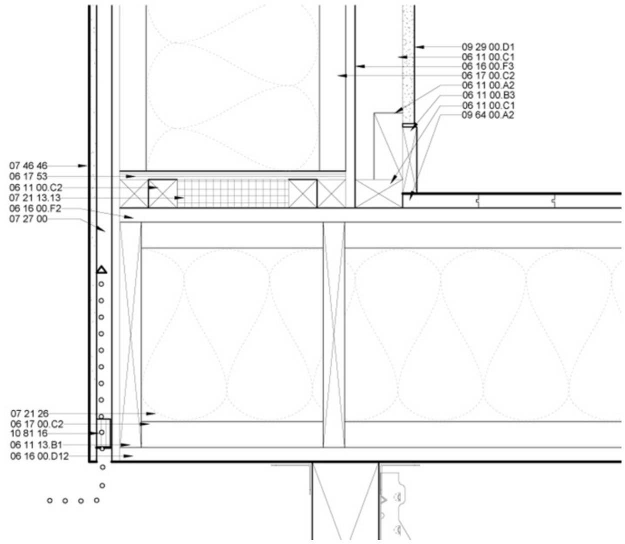


Figure 24. Detail of the Parsons and Stevens wall. From U.S. DOE, 2012.

Cost Estimates

The cost for each wall assembly was estimated using a quantity take-off based on cost per square foot. Within this method, each wall had an associated material cost and an additional labor cost. The ranking of each team was based on the sum of material and labor costs. A chart with each team's material and labor costs is provided in Figure 25. Descriptions of the most and least affordable wall assembly estimates are described.

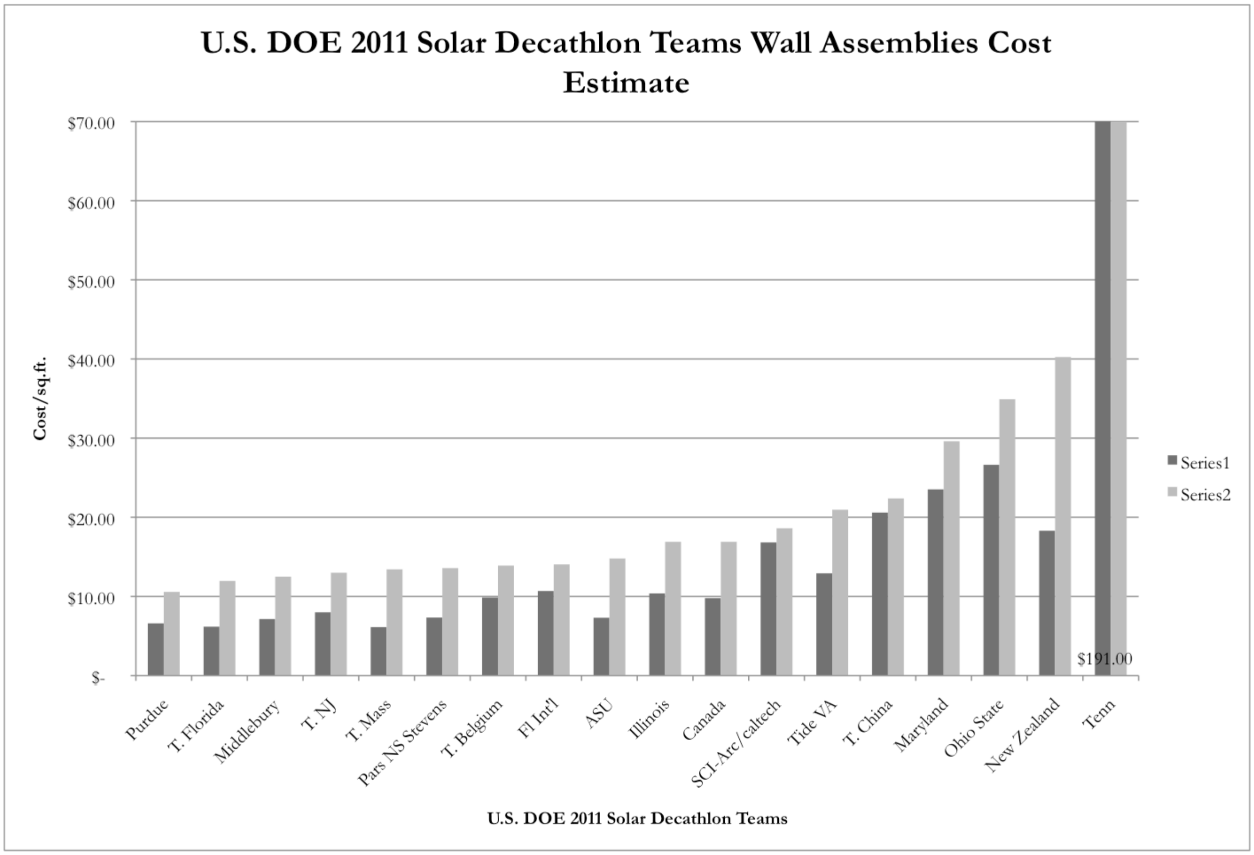


Figure 25. Bar graph of final cost estimates for each wall assembly.
Note: Series 1 is material cost and Series 2 is material cost and labor cost totaled.

With a total cost of $12.50 per square foot, Team Middlebury ranked third in the most affordable wall assembly. By using recycled cellulose, unique framing methods, and traditional materials, Middlebury designed an affordable and well-insulated wall (R-34). Although Middlebury's framing was unique, it was still simple and helped reduce thermal bridging. By using two layers of 2 x 4 studs on 12" centers, with a 4.5" gap in between that was filled with cellulose, they achieved an affordable option for wall assemblies. In Figure 26, a section view of Team Middlebury's wall is provided.

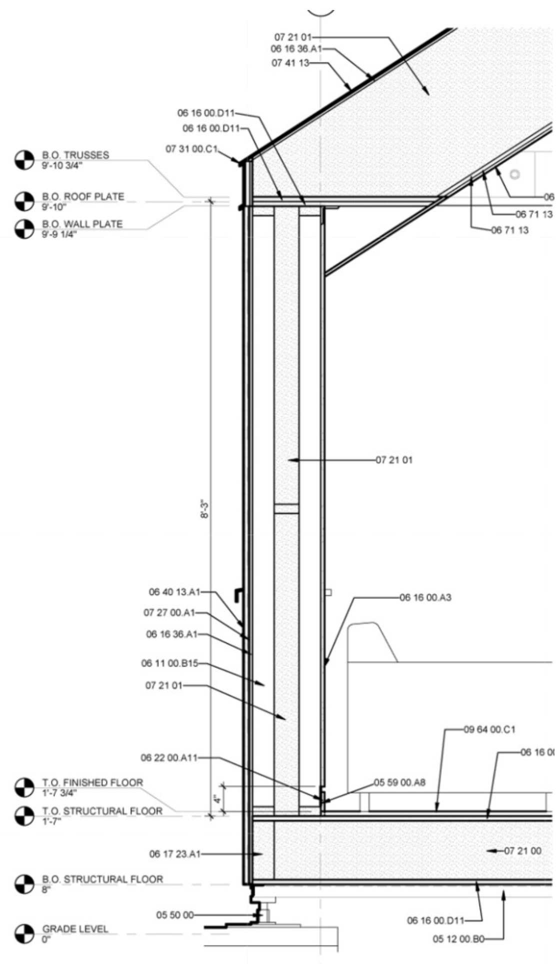


Figure 26. A section view of Team Middlebury's wall assembly. From U.S. DOE, 2012.

Team Florida created a wall assembly for $11.96/sq.ft, making it the second least-costly wall. With one of the simplest assemblies, Team Florida created an easily-constructed wall with common materials and standard construction methods. Team Florida used 2 x 4's on 16" centers with R-11 batt insulation. They clad the exterior with ½" OSB and ¾" furring strips. Although this wall assembly was not original, it still proved to be an affordable method.

Purdue ranked first, for the most affordable wall assembly at $10.58 a square foot. Using SIP panels with 3-5/8" EPS insulation, Purdue was able to build a low-cost wall assembly. SIPs are not always the lowest cost option, but in comparison to the other teams' methods, Purdue ranked first place. This was due to sticking with one method, SIPs, which are easy to install, keeping labor cost at a minimum. This strategy produced an affordable, efficient, wall.

Team New Zealand had the third-highest cost estimate with a total cost of $40.25/sq.ft. This cost was due to a custom wood wall panel system that was student fabricated for the exterior cladding. The custom cladding alone accounted for $25.00 of the total $40.25/sq.ft. Without the integration of a custom siding, Team New Zealand would have had a much more affordable wall assembly. Ohio State had a similar associated cost due to siding, with the use of polycarbonate panels, which cost $27.25/sq.ft. With a total cost of $34.91, Ohio State placed second to last rank.

Team Tennessee proved to have a significantly higher cost at $191.00/sq.ft. This was an all-inclusive cost, including framing for the Kawneer architectural aluminum curtain wall system. This curtain wall proves to be inefficient and expensive in comparison to the other wall assemblies.

Embodied Energy

Embodied energy was calculated based on the entire wall assembly and then was divided by the square footage to provide a consistent measurement for comparison. Results uncovered a wide range of numbers, from 18,414 to 98,925 BTUs/sq.ft. This variation resulted from using materials such as glass, metal, and other materials that require abundant energy to produce. For instance, Tennessee's glass wall façade had an embodied energy count of 98,925.97 BTUs/sq.ft. due to the fact that the only materials used were glass and steel. However, the majority of the teams managed to design wall assemblies with embodied energy use of less than 10,000 BTUs/sq.ft. Figure 27 shows a graph depicting each team's overall performance in embodied energy.

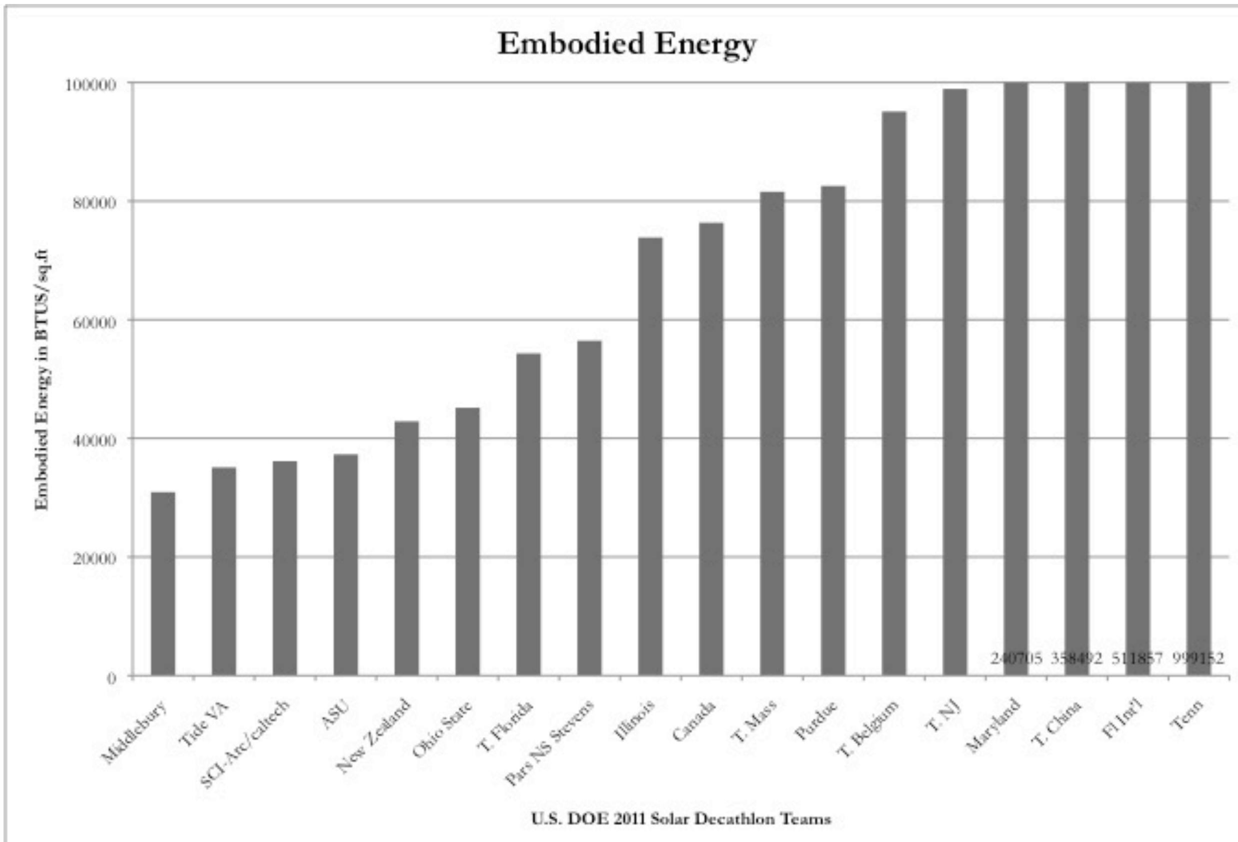


Figure 27. Bar graph of total embodied energy for each wall assembly.

Sci-Arch Caltech ranked third lowest in embodied energy with 36,152.61 BTUs/sq.ft. This was accomplished by using alternative methods for construction. For example, Sci-Arc did not finish the interior with gypsum wallboard but rather left the framing exposed. In addition, the siding was a lightweight vinyl-coated polyester membrane. When calculating the membrane's embodied energy, it was compared to high-density polyethylene (HDPE) for the closest comparison. Although HDPE does not have low embodied energy, HDPE's weight helps contribute to a lower overall quantity. Each of these factors helped Sci-Arc rank third in embodied energy.

Team Middlebury obtained the lowest embodied energy, using only 30,935.38 BTUs/sq.ft. The main contributing factor was the use of blown recycled cellulose. Recycled cellulose requires 750 BTUs per pound, as opposed to other insulations, which use between 1,400 and 50,000 BTUs/lb. This one contributing factor made a significant difference in Middlebury's embodied energy totals. Tidewater Virginia ranked second using 35,103.65 BTUs/sq.ft. Although Tidewater did not use as much cellulose, (only 1" with an additional 4.5" batt insulation), using cellulose kept their overall embodied energy lower. Teams whose wall assemblies had the highest embodied energy were those that made use of glass and aluminum. For example, Florida International required 511,857.26 BTUs/sq.ft and Team Tennessee required 999,152.08 BTUs/sq.ft. Both homes had glass facades. Team China's use of a shipping container as the primary structure of the home resulted in an embodied energy use of 358,492.13 BTUs/sq.ft. Although shipping containers are considered a repurposed material, they do have a high-embodied energy because of the metal required to make them.

Discussion and Conclusions

After analyzing multiple features of the wall assemblies used by entrants in the 2011 Solar Decathlon, including R-value, embodied energy, and cost per sq.ft., many walls were found to have significant relative benefits. But which wall assembly proved to be the optimal wall for adoption? By ranking each category and then computing the ranks, a "perfect" wall was chosen. Through these research findings, Team Middlebury proved to have the ideal wall design among the samples reviewed. In Figure 28, each team's completed rankings are displayed in a bar graph. Associated rankings were based on descending or ascending order, depending on ultimate goal for each. Note that the lowest cumulative total represents the most favorable ranking on each of the metrics analyzed.

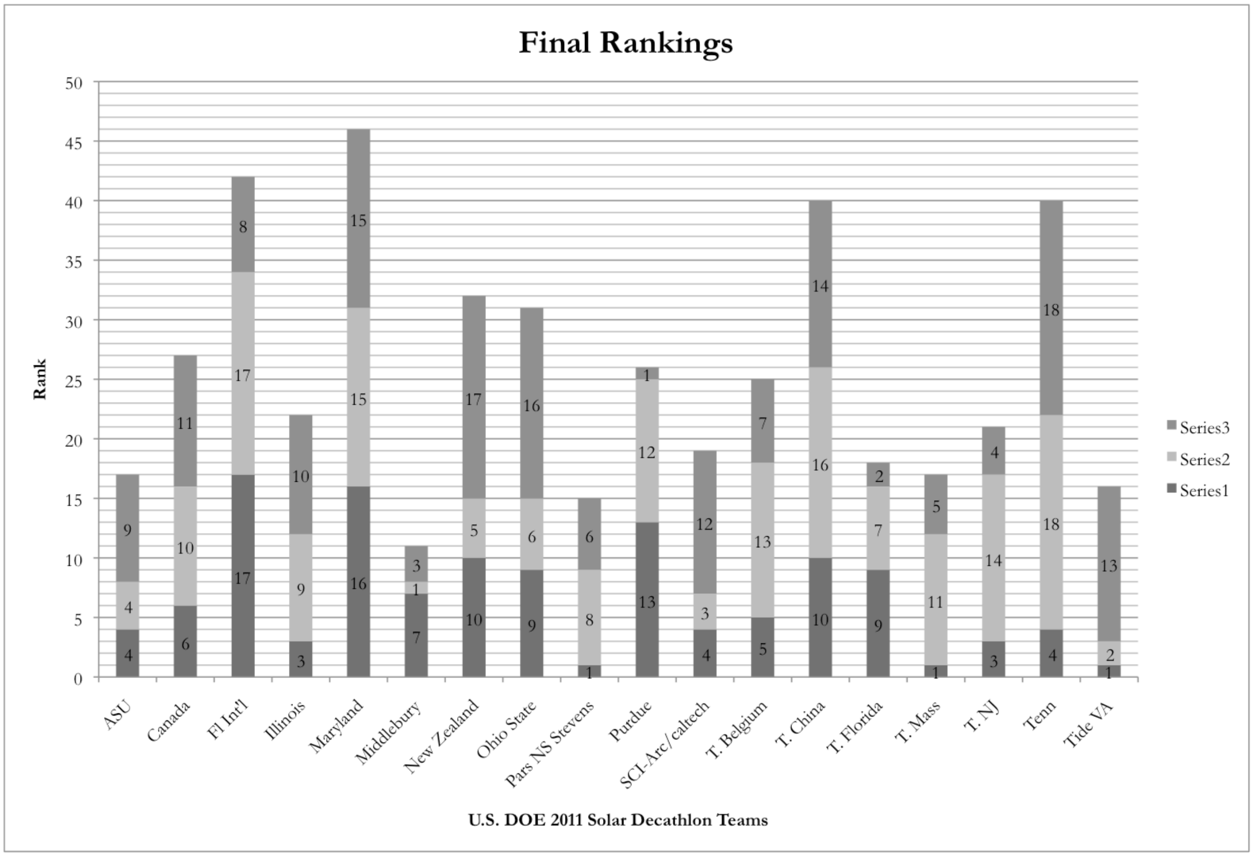


Figure 28. Bar graph of each team's completed ranking. Series 1 represents the clear wall R-value ranking, Series 2 represents the embodied energy ranking, and Series 3 represents the total cost ranking.

Team China had the third least cost-effective wall assembly. The use of a shipping container resulted in a higher associated cost and embodied energy. With a thinner SIP panel the clear wall R-value also ranked among the lower R-values. Team Maryland was the second lowest ranking team due to its low R-value that resulted from the use of heavy stick framing and clerestory windows. The integration of these clerestories also contributed to a higher embodied energy. The cost estimate also proved to be higher for expensive spray foam insulation, clerestory windows, and thermo-treated siding. As noted in the previous data, Team Tennessee proved to be the least cost-effective wall assembly, for the expensive, high embodied energy glass façade that made for a very low clear wall R-value.

Team Middlebury designed a strategic wall assembly that performed well in each category analyzed in this study. The team constructed a thermally strong wall with a clear wall R-value of 34 using 11.5” of blown recycled insulation. The blown recycled insulation also contributed to having a significantly lower embodied energy. Team Middlebury reached these goals while maintaining a cost of $12.50 per square foot. By taking the simple idea of a stud wall and expanding on it to provide enough insulation, Team Middlebury pioneered a new concept. This idea, taking common and affordable methods and enhancing them to become more efficient and environmentally friendly, is one solution to reducing a residential home’s energy impact.

Another method for analyzing these results is to see the R-value per embodied energy. In Figure 29, you can see how the previous relationships between embodied energy and R-value compare. As would be expected, the wall assemblies with particularly high-embodied energy show how much is required to achieve only R-1 of the assembly. These were found to be the teams that used glass or steel as a primary material within their wall assemblies. This diagram shows how much greater an environmental impact these materials make. In reference to the lower embodied energy, many of the teams were able to maintain a sufficiently low embodied energy per R-value.

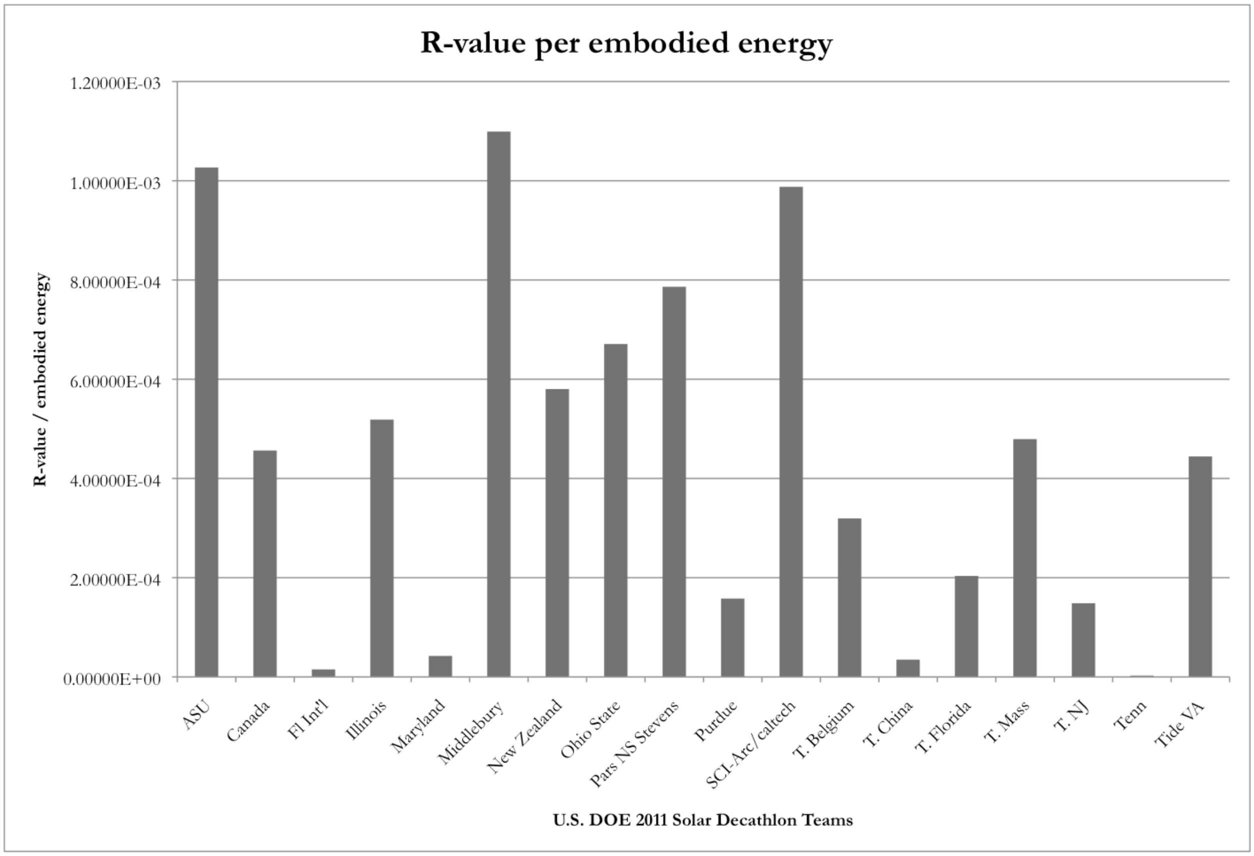


Figure 29. Bar graph depicting the embodied energy for the R-value.

Another interesting way to review this information is to calculate the R-value accomplished per dollar spent. This is just another means of showing the most affordable method with the highest R-value. Figure 30, shows a bar graph of each team's R-value per dollar spent.

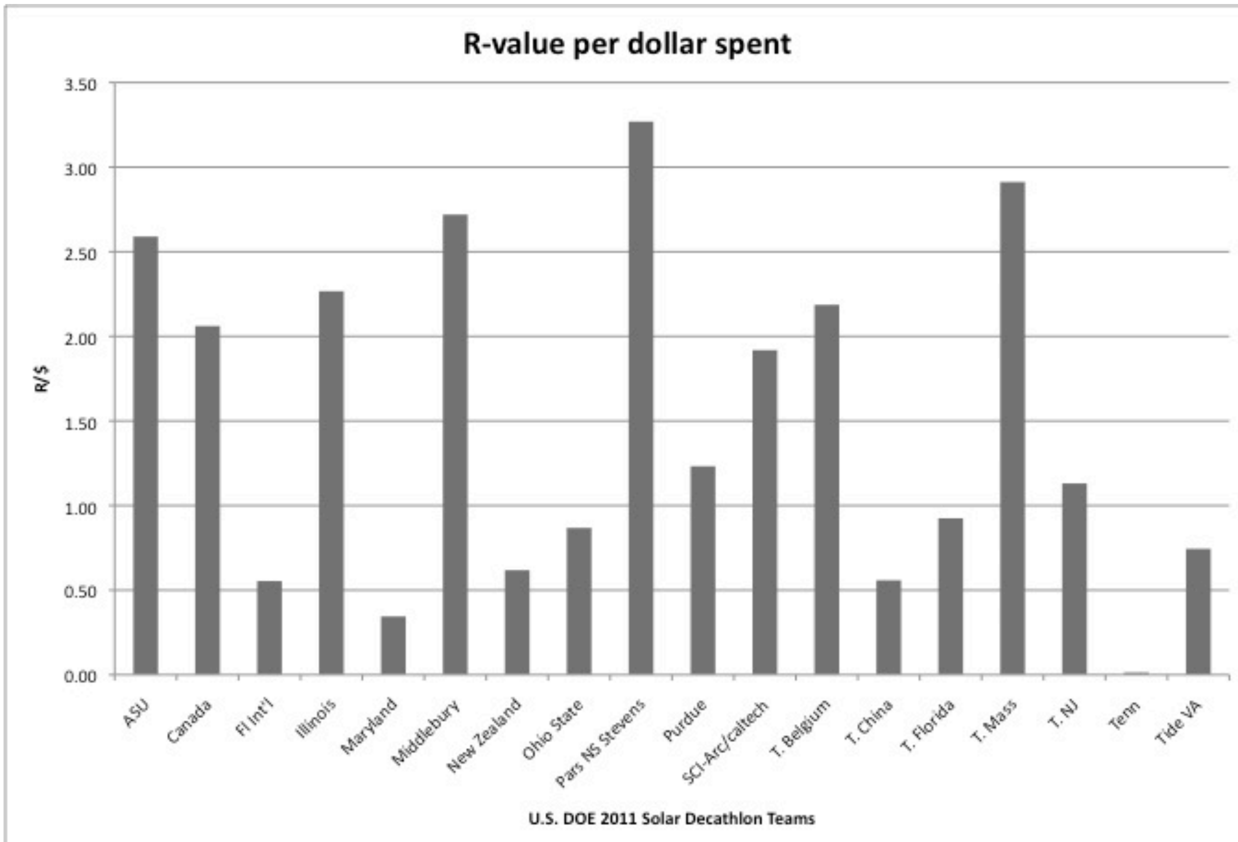


Figure 30. Bar graph showing the R-value for the dollar.

By taking the information found in Figure 29 and Figure 30, we can evaluate how each team's R-value contributed in an overall comparison. Figure 31, shows a graph normalizing each series to calculate the most optimal wall assembly based on their R-value related to embodied energy and cost. For example, taking the teams R-value per the dollar and dividing it by the maximum value across the board calculated the normalized R-value per dollar. By normalizing each set we can evaluate the differences more accurately. This method was used to find the R-value for the dollar normalized, the R-value per embodied energy normalized, and the clear wall R-value normalized. The data was then combined to determine the most optimal wall assembly based on the R-value.

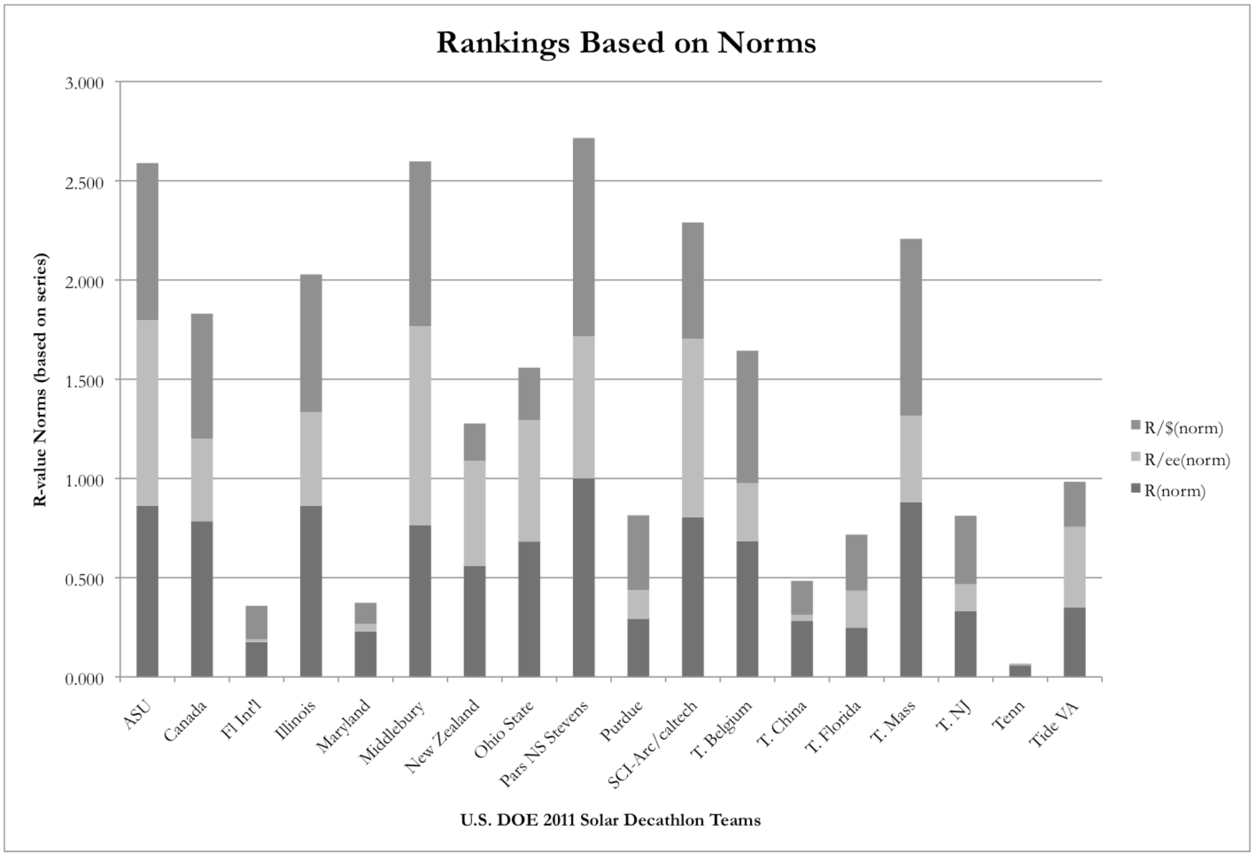


Figure 31. Bar graph of each teams normalized R-value associated to the series listed.

With the data in Figure 31, Parsons and Stevens proved to have the most optimal wall in relation to R-value, embodied energy, and cost when normalized. Team Middlebury and Appalachian State University were close behind.

The U.S. DOE determined scores for each team's performance in the 10 contests. In Figure 32, a bar graph shows the difference in each team's ranking in the normalized ranking, the Solar Decathlon competition ranking, and the research ranking. Based on the data illustrated by this graph, it is apparent that the scores assigned by the U.S. DOE were significantly different than the results of this study. Many of the teams that competed well in the Solar Decathlon did not prove to have cost-effective wall designs as measured by their clear wall R-value, embodied energy, and affordability.

With these discrepancies between scoring, it may be implied that the U.S. Solar Decathlon does not judge as distinctively on building performance. Although the contests encourage the teams to design energy efficient homes, the contests do not inquire basic whole building performance. In addition, the homes are only monitored for a short period. The competition does not allow for actual analysis of how a building may perform over time. With that said, the competition also neglects the climate for which these homes were designed to target. This all alludes to designing for a specific climate zone and monitoring it within that zone over time, to be able to calculate the most efficient building performance. This competition's contests do not allow for this to be a part of the judging criteria.

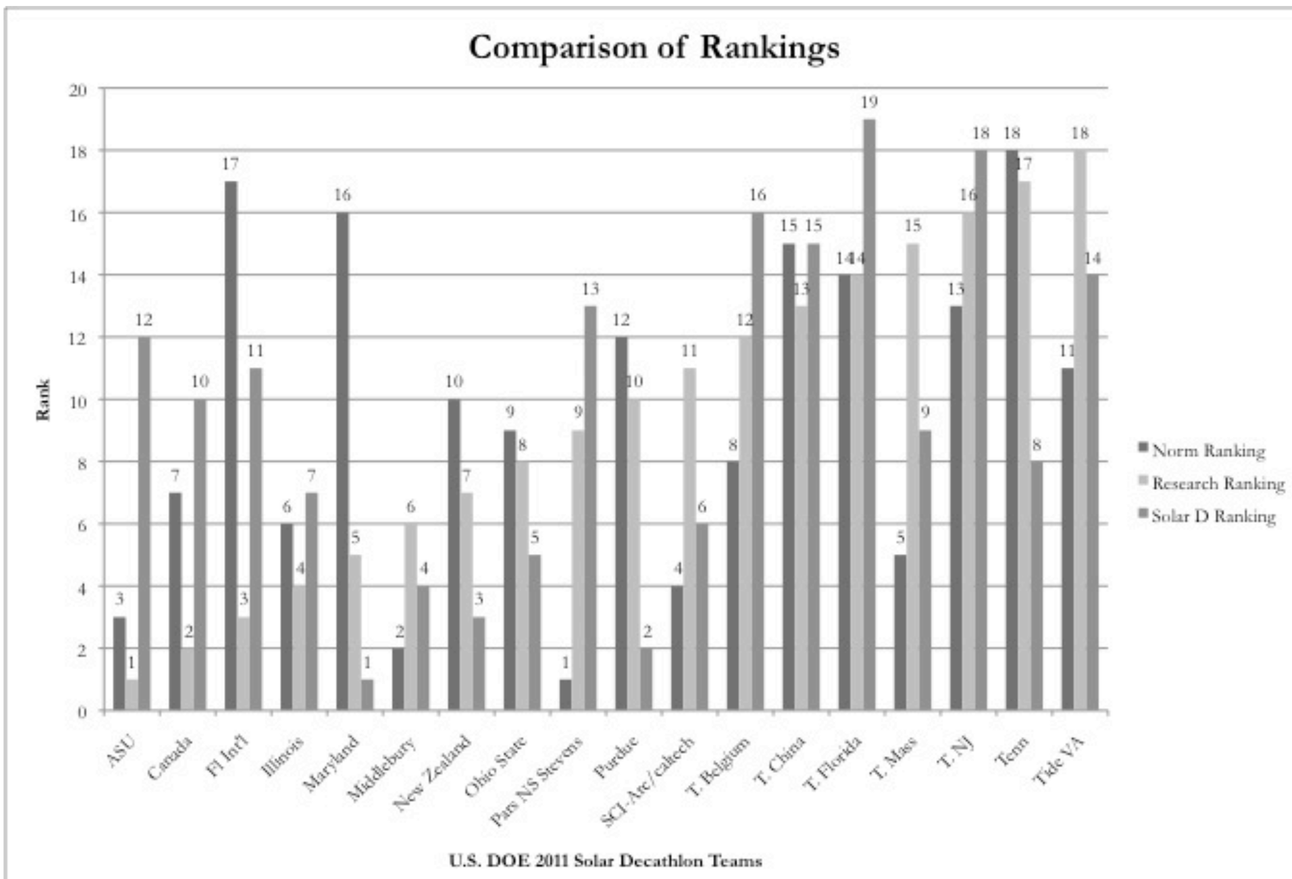


Figure 32. Bar graph of each teams completed ranking in the normalized rank, the U.S. DOE Solar Decathlon, and the research ranking. Data for Solar Decathlon Ranking was adapted from U.S. DOE. (2012, January 26). U.S. Department of Energy's Solar Decathlon. Retrieved from http://www.solardecathlon.gov/.

Suggestions for Further Research

This research only begins to review options for wall construction assemblies. With endless opportunities for design come endless opportunities for research. However, taking just a few ideas from this paper would be a good start.

For example, Parsons and Stevens designed a very detailed top and bottom plate that made a significant impact in their home's R-value. What are alternative methods to top and bottom plates that, like Parsons and Stevens, do not create a thermal bridge? How can walls be designed to be both affordable and airtight? There are multiple ways these small details may be approached, but they still need to be designed and studied.

On a larger scale, there are many opportunities for different wall configurations. Only 18 walls were studied in this research, which is only a start. Continuing research on other prototypes and existing standards should be analyzed. Although Team Middlebury proved to be the best overall wall assembly in this study, there are other walls that could be designed more efficiently. Can some of these ideas be combined to construct a more optimal wall? Are there better techniques to building SIPs with more consideration to the environment? What results could be gathered by taking Parsons and Stevens' plate detail, and combining it with a simple, yet thicker, wall assembly like Middlebury's? Is Sci-Arc Caltech's exterior envelope practical for other applications? The questions are endless and this study provided only a foundation for analyzing future wall assembly opportunities.

In addition to the discussion above, further conversation on the methods of evaluation for the U.S. Solar Decathlon would only benefit the competition. Is the competition considering a whole building approach to energy efficiency or only looking at specifics of technology? How would the homes compete if they were actually studied under the climate zones in which they were designed for, and for longer durations of time? This would give us accurate insight to the buildings performance. And during this period of analysis, what are the actual savings over time, both energy savings and financial savings? If the U.S. DOE's Solar Decathlon wants to remain the leader in competitions for the most efficient, affordable, solar powered homes, what considerations need to be changed? The U.S. DOE's Solar Decathlon has created a great foundation for recognizing and encouraging net-zero homes, however the contest requirements need to continue to push the envelope and advocate a better approach to whole building design and construction.

As buildings continue to be constructed each day, it is necessary to develop tight and efficient building envelopes that are still affordable. The optimal wall for widespread adoption is still not known, but there are many facets to investigate. As research of wall types continues, considerations to the environment, energy, homeowners and builders must be adopted in order to continue and further efficient building models.

References

Alcorn, J. A., & Baird, G. (1996). *Use of hybrid energy analysis method for evaluating the embodied energy of building materials*. New Zealand: Center for Building Performance and Research, Victoria University of Wellington.

Building Science Corporation. (2011). *High R-value wall assemblies*. Retrieved from http://www.buildingscience.com/resources/high-r-value

Burnham, R. (1998). *Housing ourselves: Creating affordable, sustainable shelter*. W. Lochner (Ed.). New York, NY: McGraw-Hill Companies, Inc.

Canadian Architect. (2008). *Measures of sustainability*. Retrieved from http://www.canadianarchitect.com/asf/perspectives_sustainibility/measures_of_sustainablity/measures_of_sustainablity_embodied.htm

Carson, J. (1989). *Weights of building materials, agricultural commodities, and floor loads for buildings*. Retrieved from http://pubs.cas.psu.edu/freepubs/pdfs/H20.pdf

Colorado Energy. (2001, November 11). *R-value table*. Retrieved from http://www.coloradoenergy.org/procorner/stuff/r-values.htm

Ding, A. (2010). *Dewalt construction estimating complete handbook*. Clifton Park, NY: Delmar Cengage Learning.

Energy Star. (2012). *Residential new construction: An overview of energy use and energy efficiency opportunities*. Retrieved from http://www.energystar.gov/ia/business/challenge/learn_more/ResidentialNewConstruction.pdf

Edmund A. Allen Lumber Company. (2010). *Why western red cedar*? Retrieved from http://www.edmundallen.com/WhyCedar.asp

GreenSpec. (2012). *About materials, embodied energy*. Retrieved from http://www.greenspec.co.uk/embodied-energy.php

Krigger, J, & Dorsi, C. (2009). *Residential Energy—Cost Savings and Comfort for Existing Buildings* (5th ed.). Helena, MT: Saturn Resource Management, Inc.

Lawrence Berkeley National Laboratory. (2009). *Typical House memo and spreadsheet*. Retrieved from http://www.epa.gov/statelocalclimate/documents/pdf/energy_efficiency_new_and_existing_homes.pdf

Lstiburek, J. W. (2009, June). The evolution of walls. *ASHRAE Journal: Building Sciences*, 4, 81-85.

Lstiburek, J. W. (2007, May). The perfect wall. *ASHRAE Journal: Building Sciences*, 3, 74-78.

Nordic Engineered Wood. (2009, April). *Nordic joist*. Retrieved from http://nordicewp.com/literatures/N-U202_925__1125_NI-40x_Apr_2009.pdf

Passive House Alliance US. (2011a). *The new American four square: Case study 1*. Retrieved from http://www.phalliance.com/media/BAhbBlsHOgZmIkIyMDExLzEyLzI2LzA5XzAzXzIxXzEyM19DYXNlX1N0dWR5XzFfQW1lcmljYW5fRm91cl9TcXVhcmUucGRm

Passive House Alliance US. (2011b). *The New O'Neill Passive House Retrofit: Case study 2*. Retrieved from http://www.phalliance.com/media/BAhbBlsHOgZmIkcyMDEyLzAxLzA0LzExXzA2XzMyXzc3N19DYXNlX1N0dWR5XzJfT19OZWlsbF9SZXNfUmV0cm9maXRGSU5BTC5wZGY

Passive House Institute US. (2011). *What is a passive house?* Retrieved from http://www.passivehouse.us/passiveHouse/PassiveHouseInfo.html

Randolph, J., & Masters, G. M. (2008). *Energy for sustainability: Technology, planning, and policy*. Washington, D.C.: Island Press.

R.S. Means Company, Inc. (2009). *R.S. means estimating handbook*. (3 ed., p. 935). Kingston, MA: Construction Publishers and Consultants.

Singh, R., Dev, R., Hasan, M., & Tiwari, G. (2011). Comparative energy and exergy analysis of various passive solar distillation systems. In *World renewable energy congress 2011-Swedan* (pp. 3929-3936). Linkoping, Swedan: Retrieved from http://www.ep.liu.se/ecp/057/vol14/034/ecp57vol14_034.pdf

Sirmans, G. S., & Macpherson, D. A. (2003). The state of affordable housing. *Journal of Real Estate Literature, 11*(2), 133-155.

Straube, J., & Smegal, J. (2009). Building america special research project: High-r walls case study analysis. *Building Science*, 66. Retrieved from http://www.buildingscience.com/documents/reports/rr-0903-building-america-special-research-project-high-r-walls

The Engineering Toolbox. (2010). *Gauge and weight chart*. Retrieved from http://www.engineeringtoolbox.com/gauge-sheet-d_915.html

University of Bath, Department of Mechanical Engineering. (2006). *Inventory of carbon and energy report*. Retrieved from www.bath.ac.uk/mech-eng/research/sert/

University of Maryland. (2011). *Structure. Watershed at the University of Maryland*. Retrieved from http://2011.solarteam.org/design/architecture/structure

U.S. Department of Energy. (2012). *U.S. Department of Energy Solar Decathlon*. Retrieved from http://www.solardecathlon.gov/

U.S. Department of Energy. (2011). *U.S. Department of Energy's Solar Decathlon rules*. Retrieved from http://www.solardecathlon.gov/pdfs/2011_rules.pdf

U.S. Energy Information Agency. (2011). *Use of energy in the United States*. Retrieved from http://www.eia.gov/energyexplained/index.cfm?page=us_energy_use

U.S. Environmental Protection Agency. (2012a). *Certified new homes*. Retrieved from http://www.energystar.gov/index.cfm?c=new_homes.hm_index

U.S. Environmental Protection Agency. (2012b). *How new homes earn the ENERGY STAR*. Retrieved from http://www.energystar.gov/index.cfm?c=new_homes.nh_verification_process

U.S. Green Building Council. (2009). *Green building, design, and construction with global alternative compliance paths*. Retrieved from https://www.usgbc.org/ShowFile.aspx?

U.S. Green Building Council. (2011). *LEED rating system*. Retrieved from http://www.usgbc.org/

Victoria University of Wellington. (2007). *Embodied energy coefficients*. Retrieved from http://www.victoria.ac.nz/cbpr/documents/pdfs/ee-coefficients.pdf

Wilson, J. (2012, March). Green exteriors, upgrading for lower energy costs. *New England Condominum*. Retrieved from http://newenglandcondo.com/articles/489/1/Green-Exteriors/Page1.html

Appendix A

Solar Decathlon 2011 Entrant Descriptions

Appalachian State University was inspired by traditional Appalachian settlements for its U.S. Department of Energy Solar Decathlon 2011 entry. Solar Homestead is composed of multiple buildings that form a self-sufficient ensemble. Six outbuilding modules connect to form the Great Porch, an outdoor living space protected by an 8.2-kW trellis of bifacial solar cells. Inside, the 833-ft^2 (77-m^2) house features two bedrooms, a day-lit bathroom, energy-efficient appliances, and a versatile living and dining area. The Solar Homestead also includes an independent 120-ft^2 (11-m^2) Flex Space that can be used as a home office, art studio, or guest quarters.

TRTL, Canada's entry for the U.S. Department of Energy Solar Decathlon 2011, is a unique response to the culture of Treaty 7 Native Peoples in Southern Alberta. Inspired by the tipi, the house's rounded form, east-facing entrance, and south-facing windows relate to the sun as a traditional source of energy and life. The two-bedroom, open-concept design is flexible and includes ample space for storage, recreation, and communal gatherings for meals.

Florida International University's U.S. Department of Energy Solar Decathlon 2011 entry, the perFORM[D]ance House, responds to its environment, its inhabitants, and its use. Its open pavilion design links the interior with the exterior through a layered façade and integrated landscape, and operable louver panels open to extend the interior space and expand the livable space to the exterior. The ever-changing configuration is driven by environmental conditions, resulting in an interactive performance that showcases sustainable strategies and technologies.

For the U.S. Department of Energy Solar Decathlon 2011, the University of Illinois at Urbana-Champaign returns with Re_home, a rapid-response solution for a family affected by natural disaster. The solar-powered Re_ home uses a rapid deployment strategy to offer an immediate and sustainable solution for a family left without a home. By combining good design, smart planning, and low-cost solutions, the Re_ home responds to the physical and emotional needs of impacted families while bringing environmentally aware living to the forefront of a community-led recovery effort.

Inspired by the Chesapeake Bay ecosystem, the University of Maryland returns to the U.S. Department of Energy Solar Decathlon 2011 with WaterShed—an entry that proposes solutions to water and energy shortages. The house is a model of how the built environment can help preserve watersheds everywhere by managing storm water onsite, filtering pollutants from greywater, and minimizing water use. The photovoltaic and solar thermal arrays, effectiveness of the building envelope, and efficiency of the mechanical systems make WaterShed less thirsty for fossil fuels than standard homes.

Self-Reliance, Middlebury College's U.S. Department of Energy Solar Decathlon 2011 entry, is a two-bedroom, ultra-efficient, 990-ft^2 house designed for a family of four. It features a green wall for growing plants, open family living space, and healthy building materials. Its traditional gable, or peaked roof, is a familiar form that holds a 7.2-kW photovoltaic array.

First Light, Victoria University of Wellington's U.S. Department of Energy Solar Decathlon 2011 entry, is inspired by the traditional New Zealand holiday home—the "Kiwi bach." First Light's design reflects a relaxed lifestyle in which socializing and connecting with the outdoors are central to living. At the heart of the design is a glazed central section that functions as a bridge between exterior and interior. A cedar canopy supports the solar array, which produces hot water and generates energy to power the house.

The Ohio State University's U.S. Department of Energy Solar Decathlon entry, enCORE, presents a family-friendly solution for residential needs while addressing the world's growing energy problem. enCORE features living spaces arranged around a central core that contains the house's mechanical and plumbing systems. The flexible, interconnected design gives this 930-ft^2 (86-m^2) solar-powered house the same functionality and livability of projects much larger in size and budget.

Parsons the New School for Design and Stevens Institute of Technology are developing a solar-powered house for the U.S. Department of Energy Solar Decathlon in partnership with Habitat for Humanity of Washington, D.C., and the D.C. Department of Housing and Community Development. The house minimizes energy demand by optimizing the building envelope, using a highly efficient micro-mechanical system, and incorporating strategic lighting and daylighting.

The INhome, Purdue University's U.S. Department of Energy Solar Decathlon 2011 entry, offers a realistic and balanced vision for ultra-efficient housing. The INhome—short for Indiana home—is an innovative, yet practical, house that meets the needs of a typical Midwestern consumer in today's cost-competitive residential market.

CHIP is a real-life application of green design in the modern world created by the Southern California Institute of Architecture and California Institute of Technology for the U.S. Department of Energy Solar Decathlon 2011. CHIP offers a solution to the challenges of home ownership and energy consumption. While appearing to be a house of the future, this "prototype to product" is ready to be injected into the Los Angeles landscape after it returns from Washington, D.C.

Team Belgium aimed for simplicity with E-Cube, its entry for the U.S. Department of Energy Solar Decathlon 2011. This approach resulted in a design that is stripped of its nonessential components and finishes, leaving its structure and façade exposed to the interior.

The ultra-efficient house is conceived as an affordable building kit that can be assembled in days rather than months.

Team China's U.S. Department of Energy Solar Decathlon 2011 entry, Y Container, combines six recycled shipping containers into a succinct, Y-shaped solar house. Y Container is easy to transport, assemble, and expand—providing the freedom to live anywhere with low costs and clean energy. It is a living house that can contain the energy, water, and plants required for an individual to enjoy an independent and natural lifestyle.

Team Florida's U.S. Department of Energy Solar Decathlon 2011 entry, FLeX House, is a prefabricated prototype that combines the wisdom of Florida residential design with modern technology. The house opens up to take advantage of passive cooling during mild months and closes down to take advantage of the highly efficient mechanical systems during months of temperature extremes. This hybrid open-and-closed building type is conducive to a healthy indoor/outdoor Florida lifestyle.

Team Massachusetts designed the New England-inspired 4D Home for the U.S. Department of Energy Solar Decathlon 2011. This solar-powered prototype is an affordable, ultra-efficient house that can adapt to a family's changing needs. The team hopes the 4D Home will serve as a precedent for home builders and designers creating sustainable homes in New England.

Team New Jersey's entry for the U.S. Department of Energy Solar Decathlon 2011, ENJOY House, suggests a new way of approaching high-performance, energy-efficient residential design. Cutting-edge fabrication techniques meet the age-old technology of concrete in its intelligent design. The roof's inverted-hip shape is calibrated for optimal solar energy and rainwater collection, contributing to an architecture informed by performance criteria.

Team New York's Solar Roofpod, designed for the U.S. Department of Energy Solar

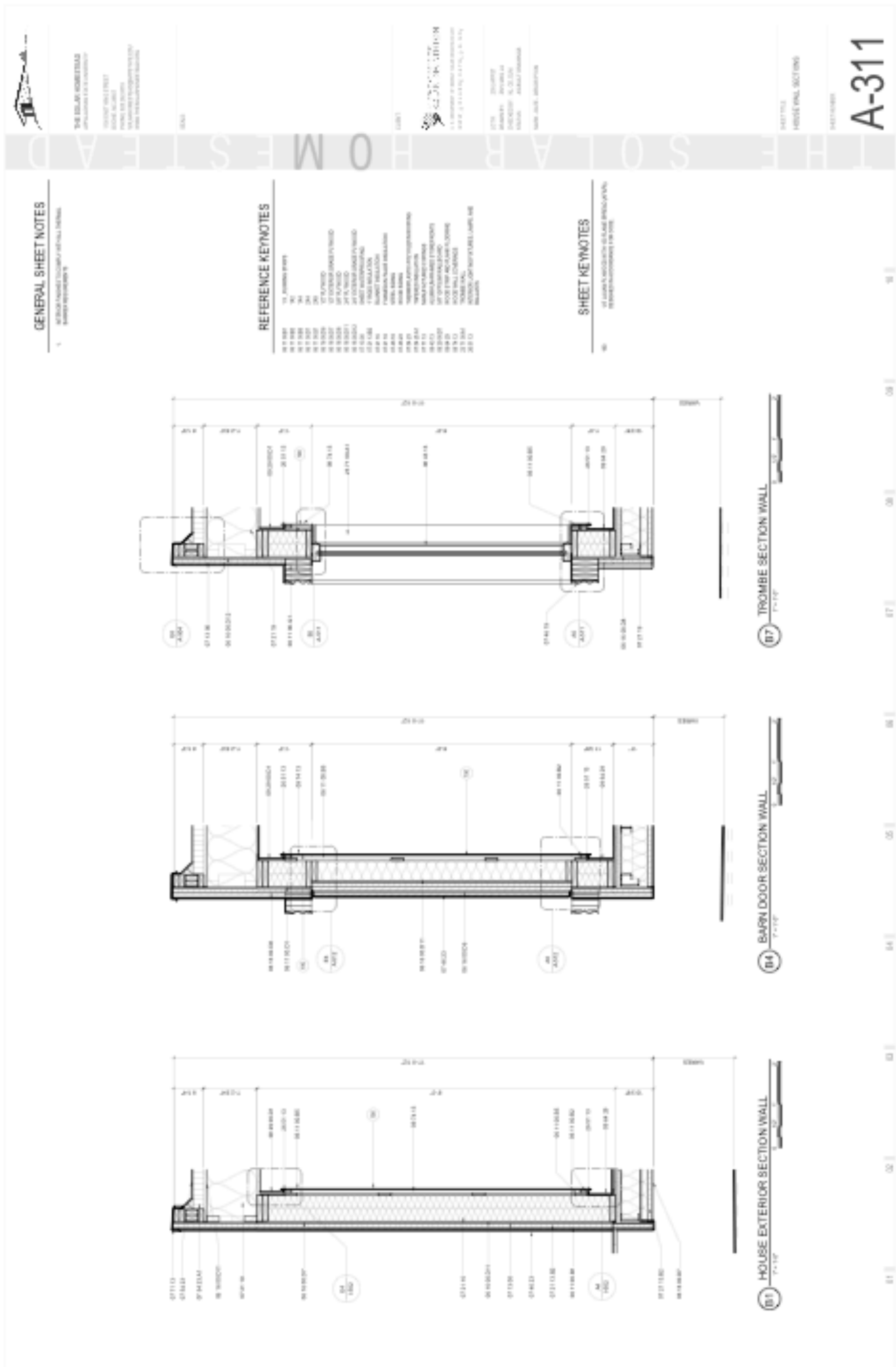
Decathlon 2011, responds to the fact that urban rooftops are largely under-used. Intended for existing mid-rise buildings, the house enables eco-conscious city dwellers to live lightly by producing solar power, cultivating roof gardens, and retaining and recycling storm water.

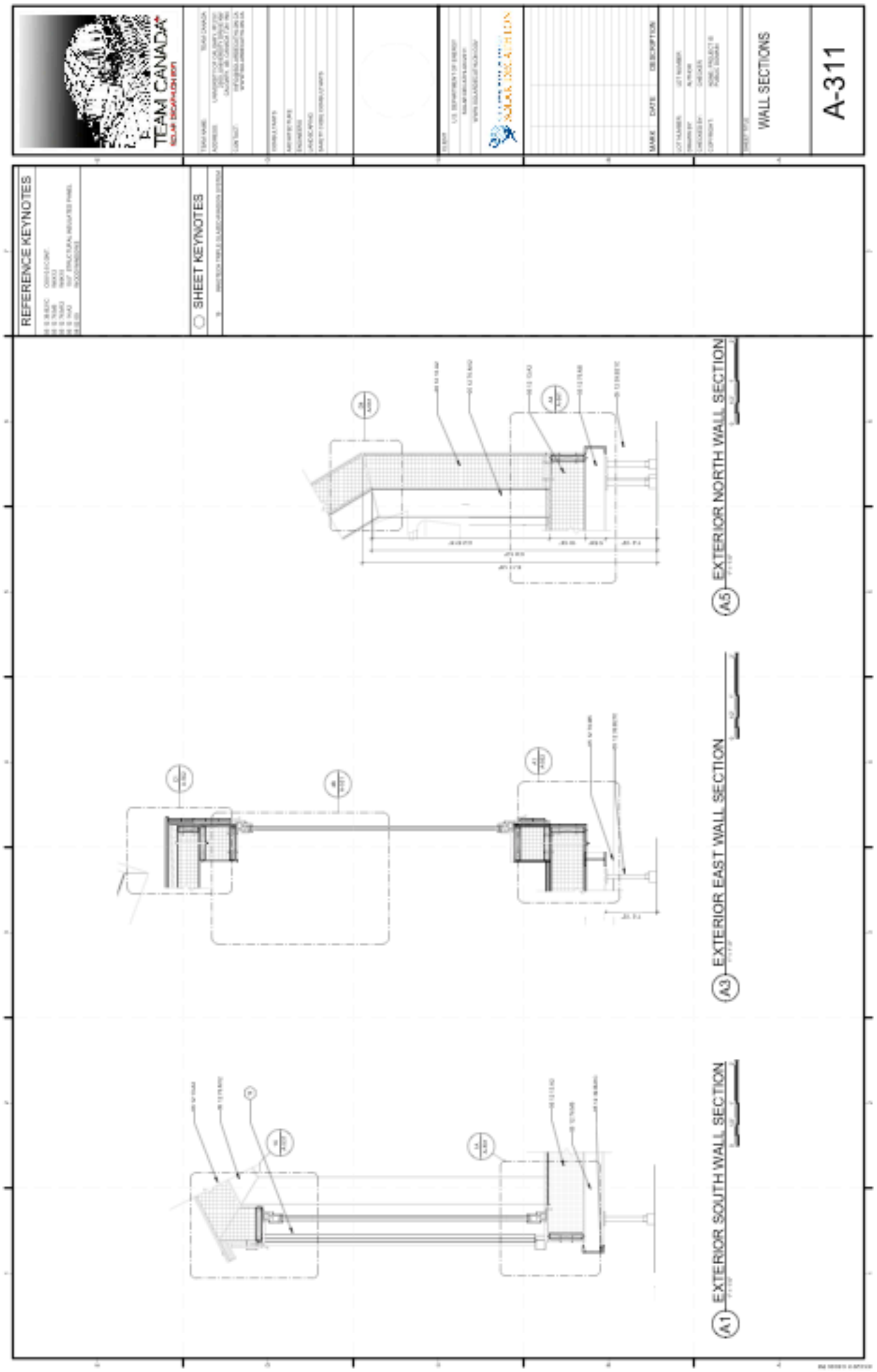
The University of Tennessee's Living Light, designed for the U.S. Department of Energy Solar Decathlon 2011, incorporates the knowledge of Tennesseans past and present. Although the forms and spaces of Living Light were inspired by the cantilever barns of southern Appalachia, the systems in the dynamic façade and integrated roof array are scalable and tunable to a range of climates and applications.

Tidewater Virginia's Unit 6 Unplugged, designed for the U.S. Department of Energy Solar Decathlon 2011, is a modular house that blends seamlessly into a historic center-city neighborhood. Unit 6 is conceived of as part of a larger, six-unit multifamily building. By sharing infrastructure costs between units of the building, this energy-efficient house is made more affordable. (U.S. DOE, 2012).

Appendix B

U.S. DOE's Solar Decathlon 2011 Entrant Construction Document Reference




TEAM CANADA
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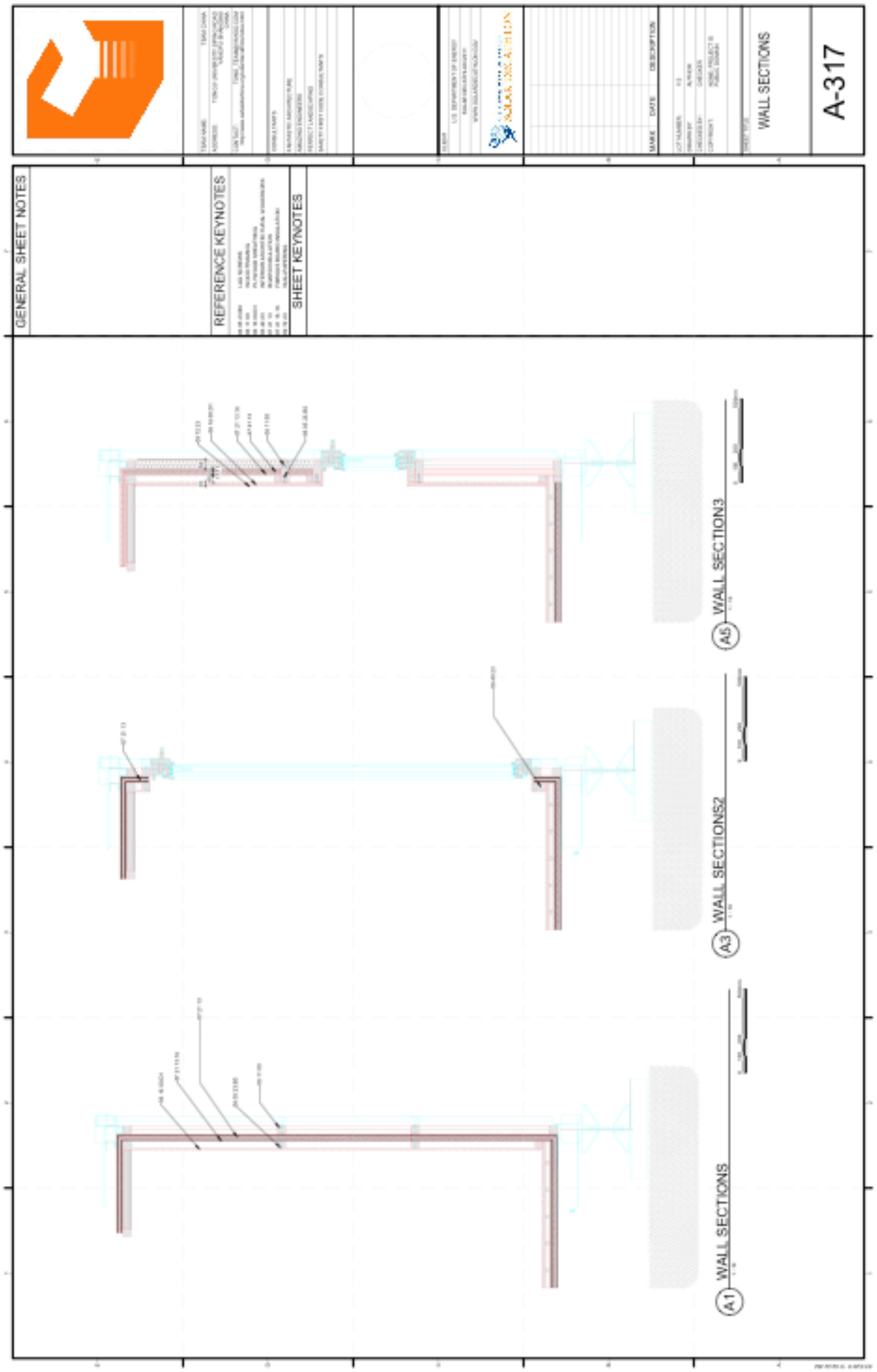
A3 EXTERIOR EAST WALL SECTION
A1 EXTERIOR SOUTH WALL SECTION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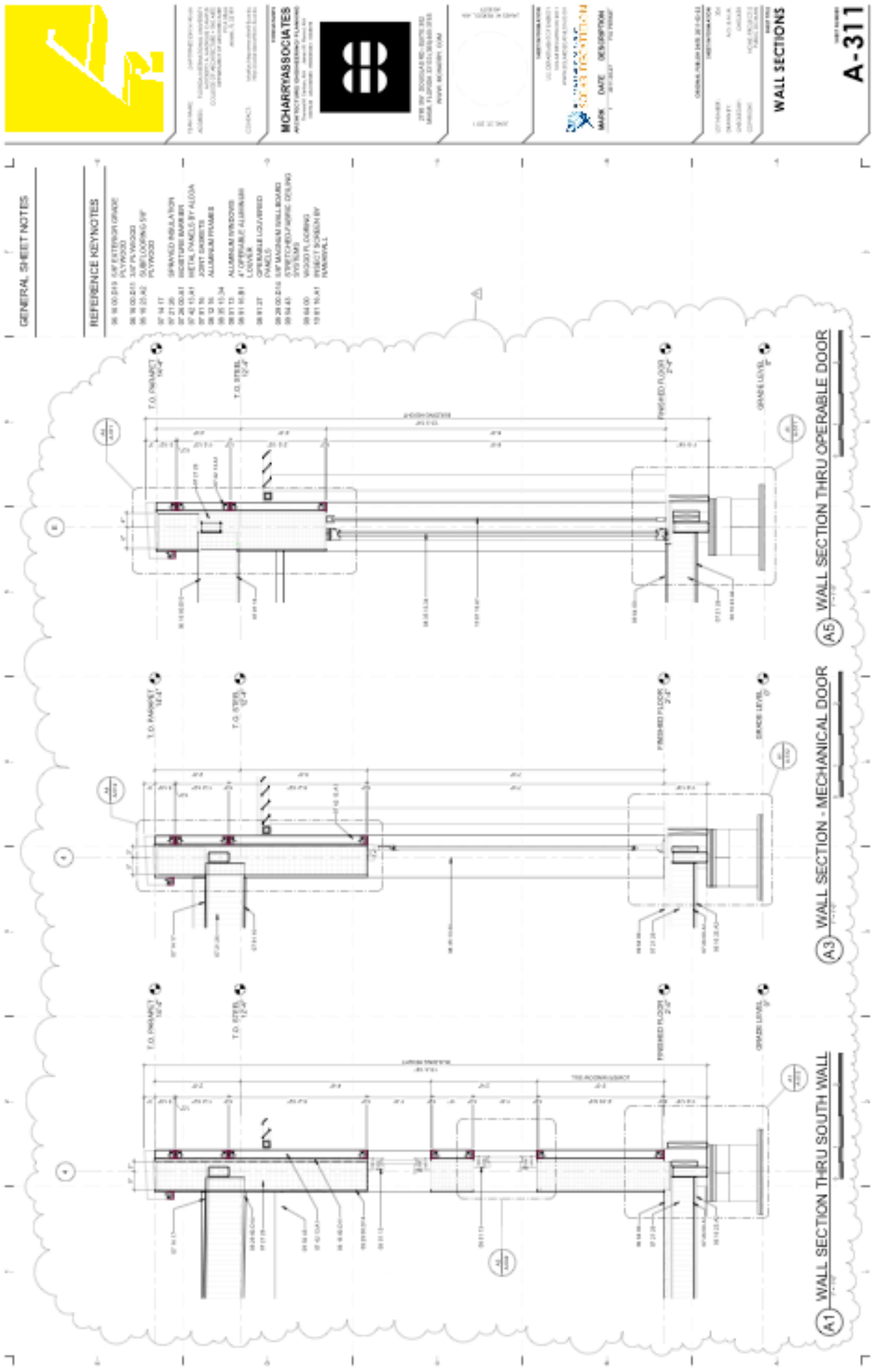
A-317
A1 WALL SECTIONS
A3 WALL SECTIONS2
A5 WALL SECTION3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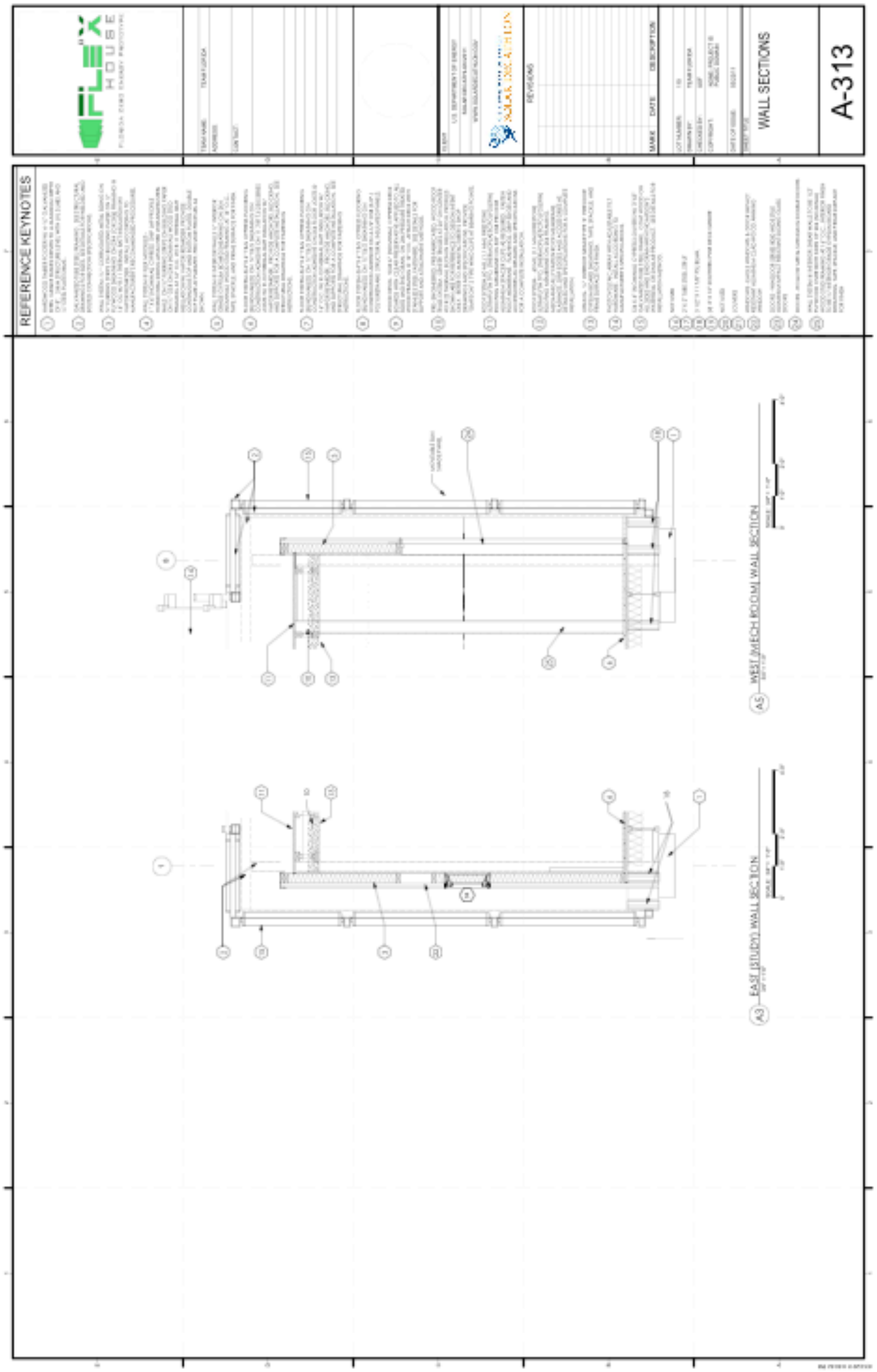
A1 WALL SECTION THRU SOUTH WALL
A3 WALL SECTION - MECHANICAL DOOR
A5 WALL SECTION THRU OPERABLE DOOR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WEST (MECH ROOM) WALL SECTION
REVISIONS
WALL SECTIONS
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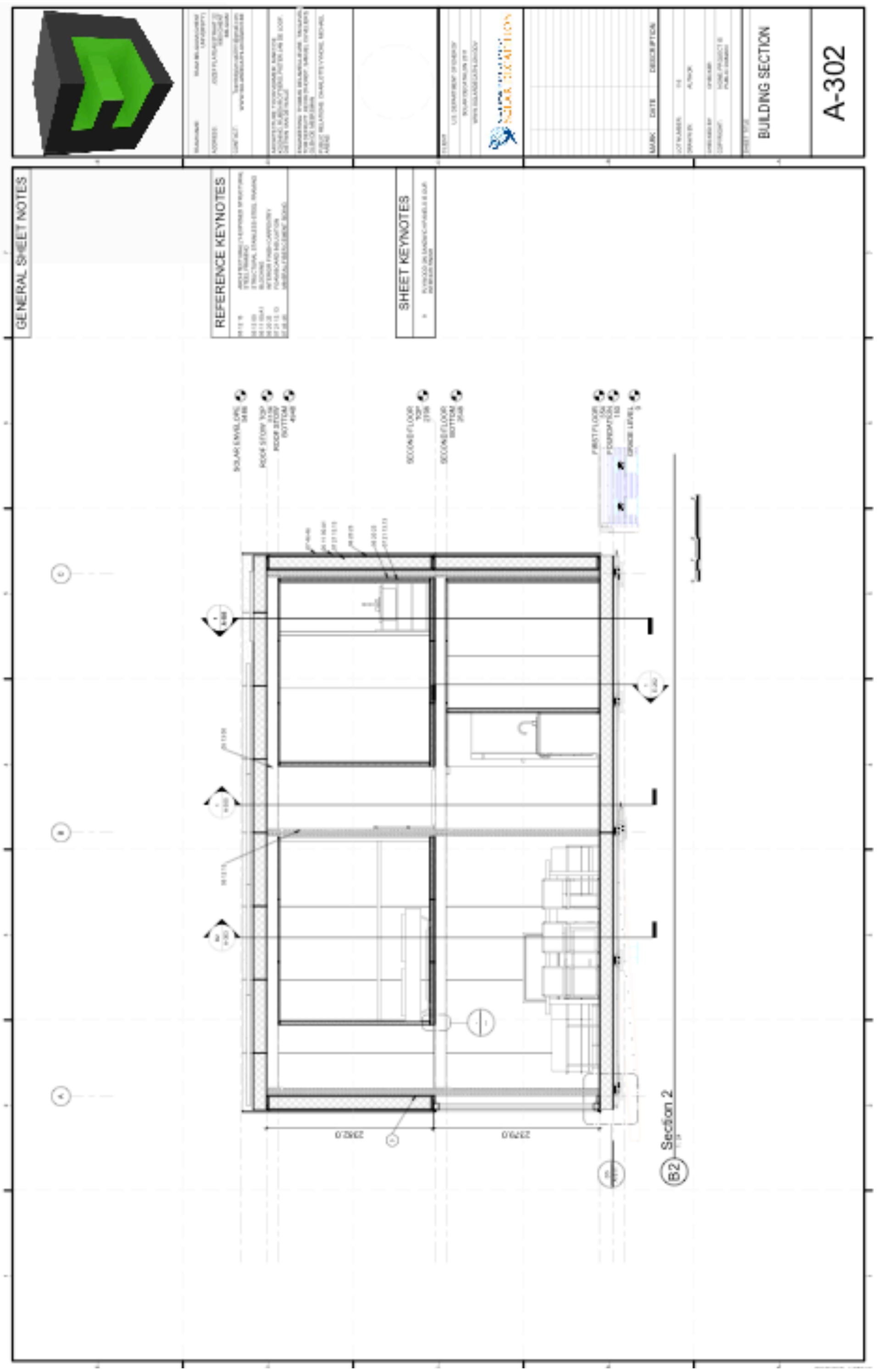
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Section 2
B2
BUILDING SECTION
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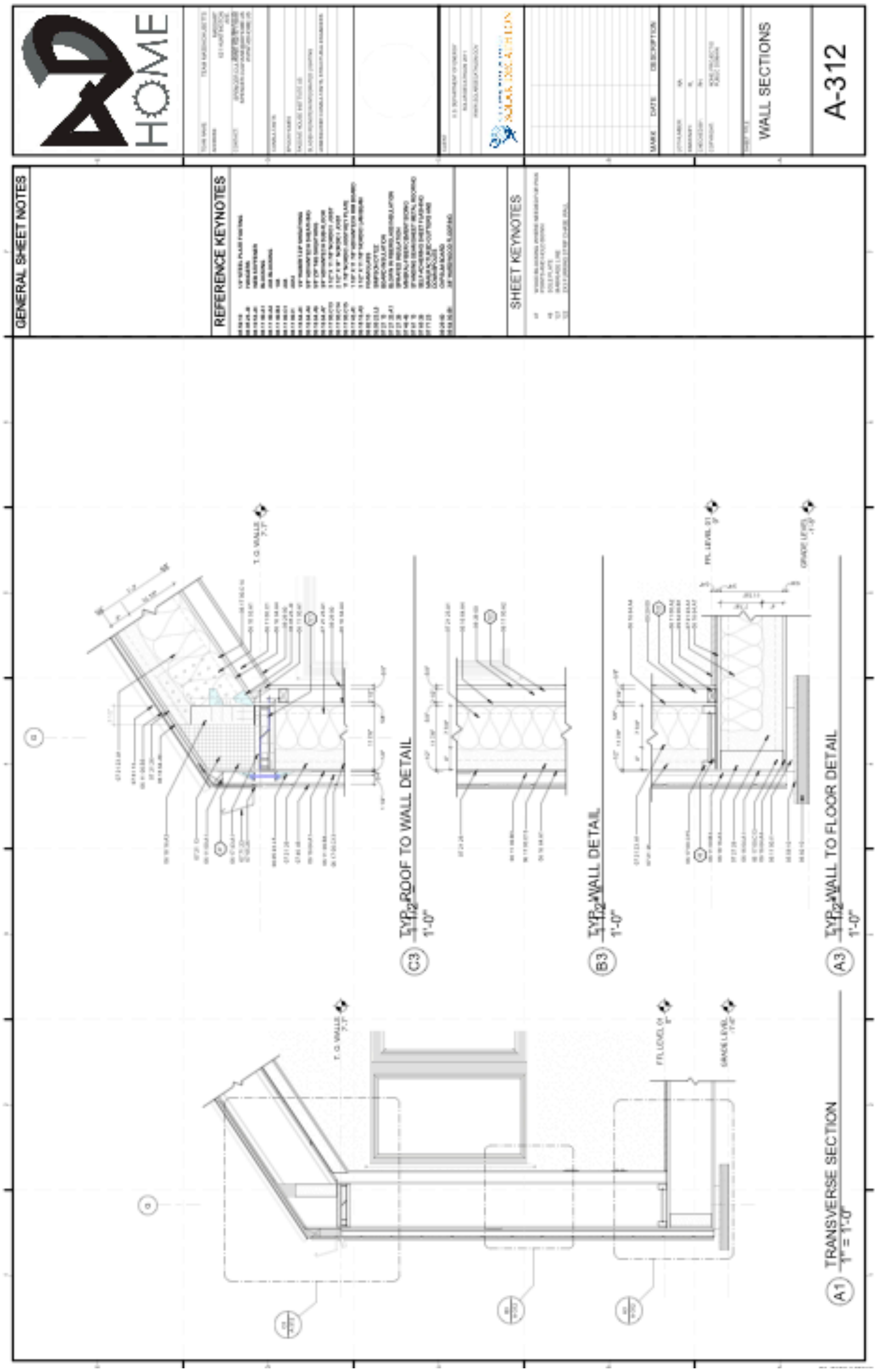
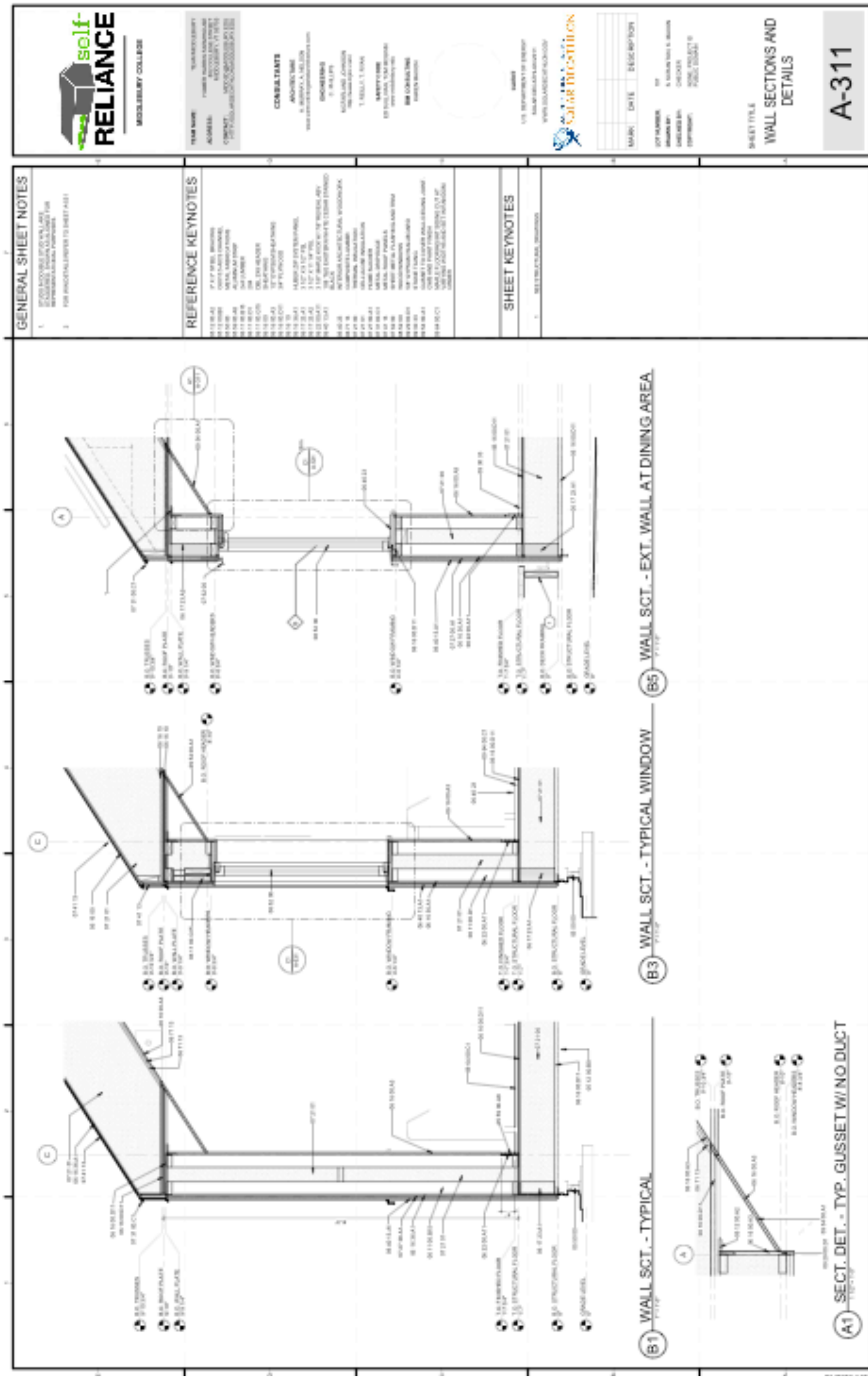

HOME
GENERAL SHEET NOTES
REFERENCE KEYNOTES
SHEET KEYNOTES
WALL SECTIONS
A-312
C3 TYP. ROOF TO WALL DETAIL
1 1/2" = 1'-0"
B3 TYP. WALL DETAIL
1 1/2" = 1'-0"
A3 TYP. WALL TO FLOOR DETAIL
1 1/2" = 1'-0"
A1 TRANSVERSE SECTION
1" = 1'-0"
T.O. WALLS
FFL LEVEL 01
GRADE LEVEL



self-
RELIANCE
MIDDLEBURY COLLEGE
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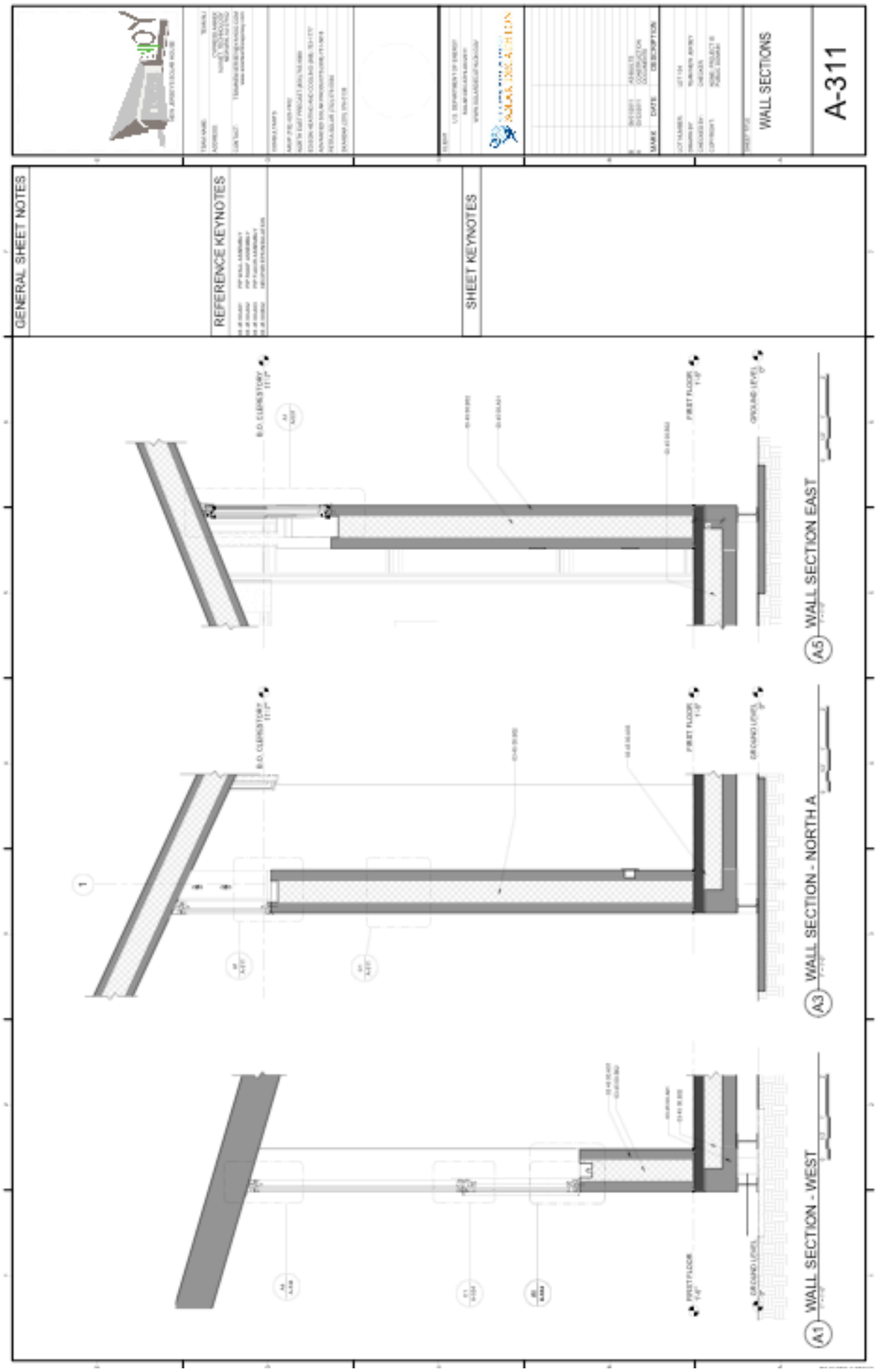
WALL SCT. - EXT. WALL AT DINING AREA
WALL SCT. - TYPICAL WINDOW
WALL SCT. - TYPICAL
SECT. DET. - TYP. GUSSET W/ NO DUCT
WALL SECTIONS AND DETAILS
A-311



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FIRST FLOOR
GROUND LEVEL
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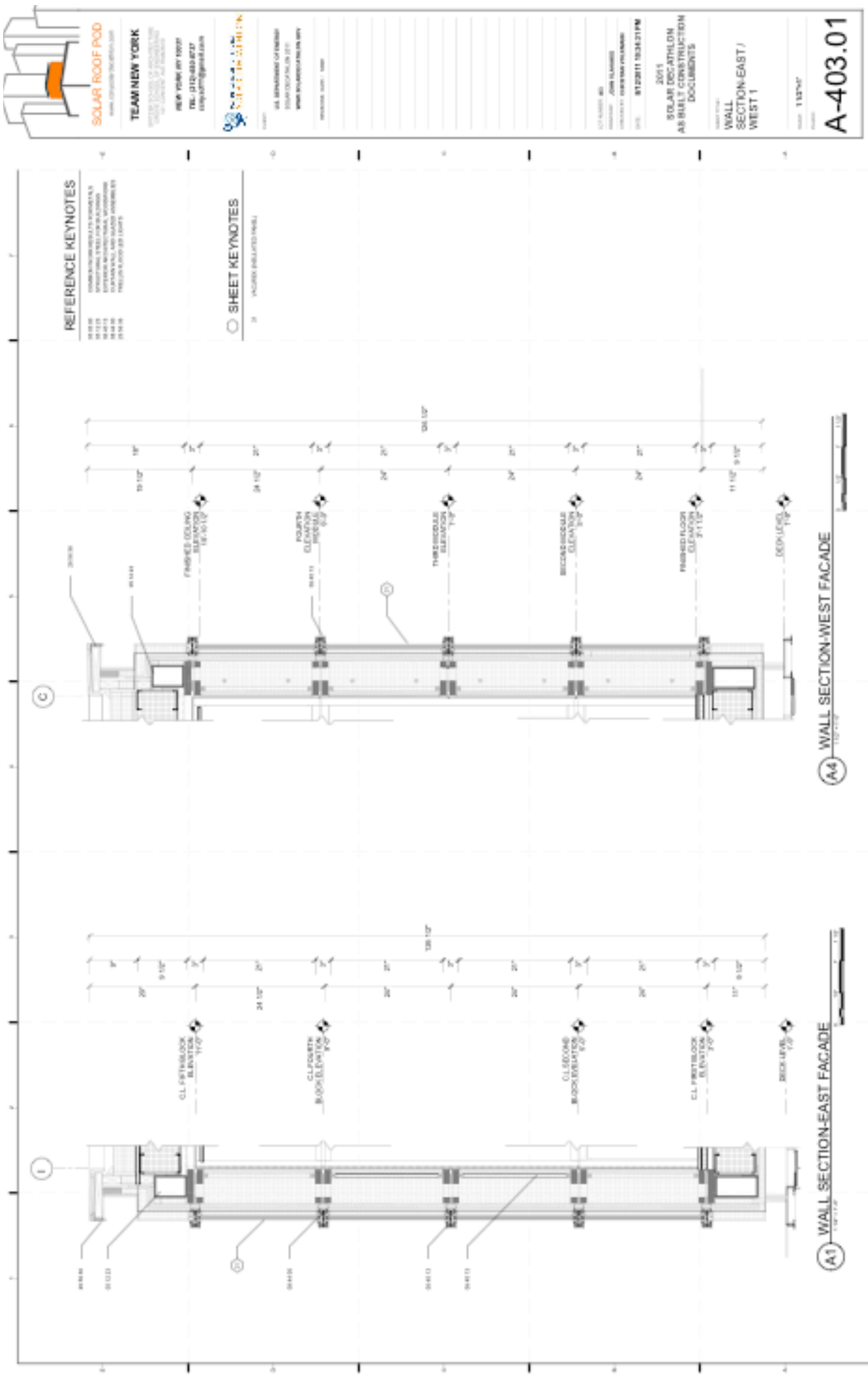
A3 WALL SECTION - NORTH A
A5 WALL SECTION EAST


SOLAR ROOF POD
TEAM NEW YORK
2011
SOLAR DECATHLON
AS BUILT CONSTRUCTION
DOCUMENTS
WALL
SECTION-EAST /
WEST 1
A-403.01
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SHEET KEYNOTES
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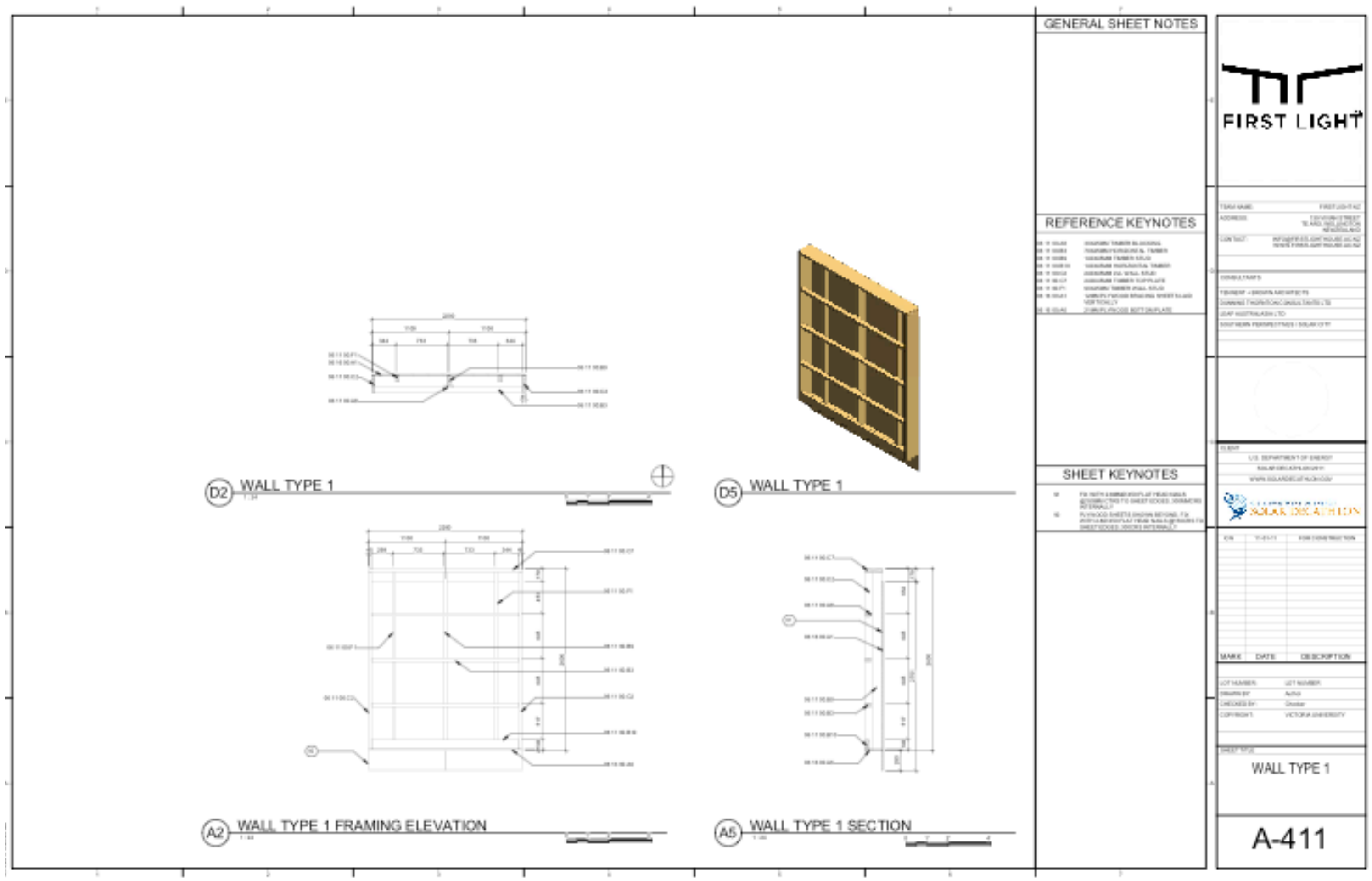
A1 WALL SECTION-EAST FACADE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SHEET KEYNOTES
FIRST LIGHT
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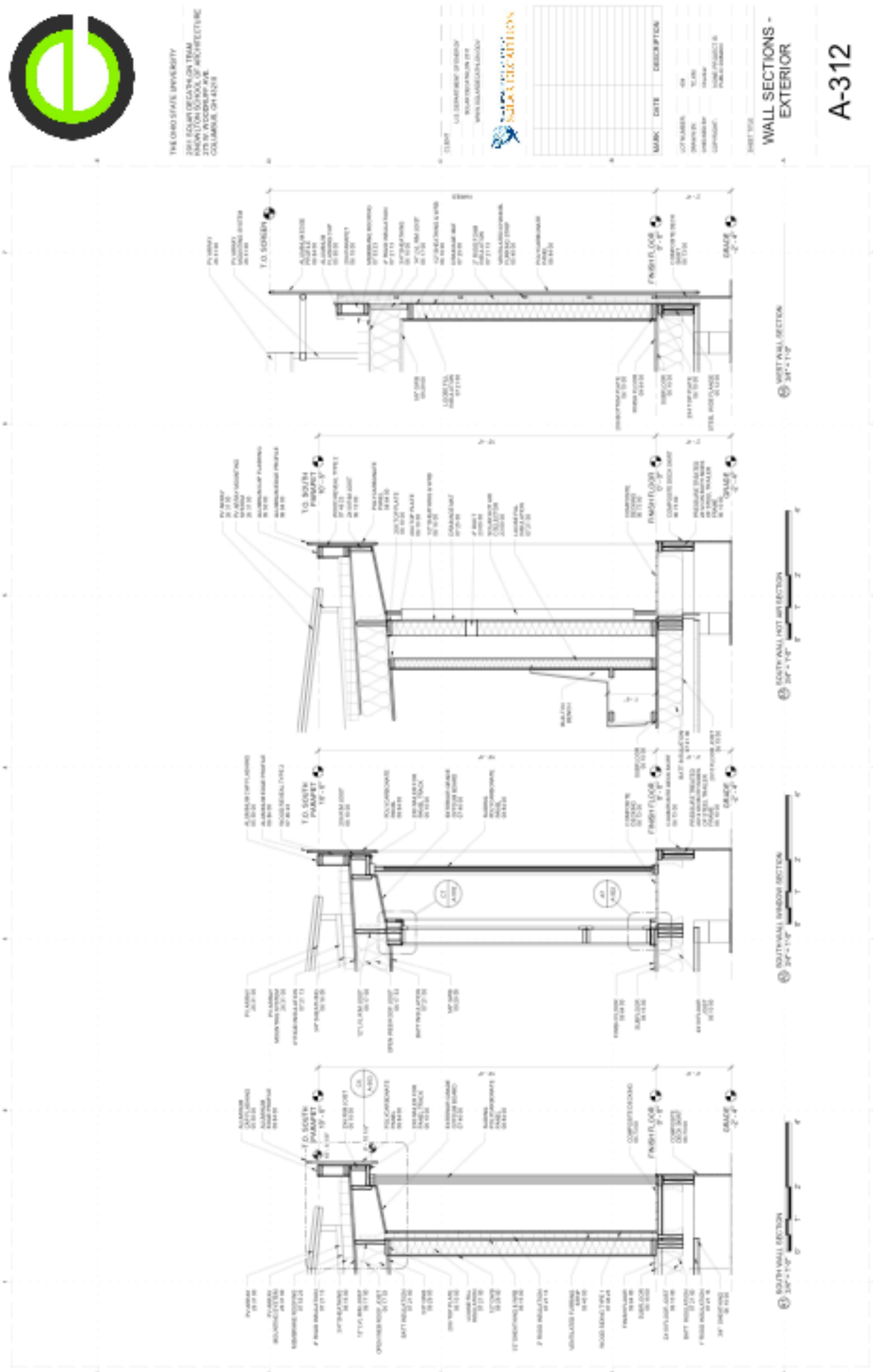
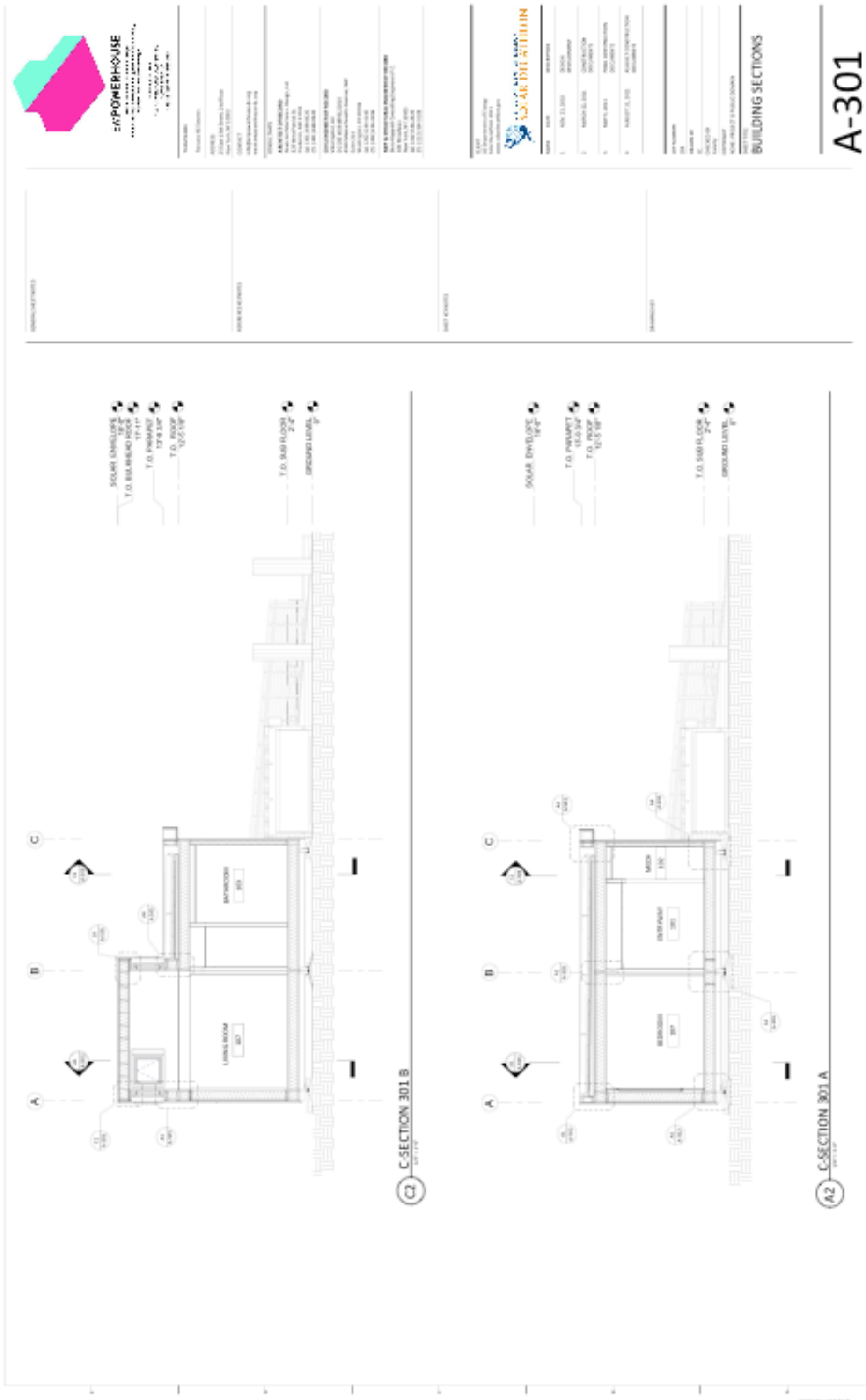
D5 WALL TYPE 1
A2 WALL TYPE 1 FRAMING ELEVATION
A5 WALL TYPE 1 SECTION
MARK
DATE
DESCRIPTION
WALL TYPE 1
A-411


WALL SECTIONS - EXTERIOR
A-312


POWERHOUSE
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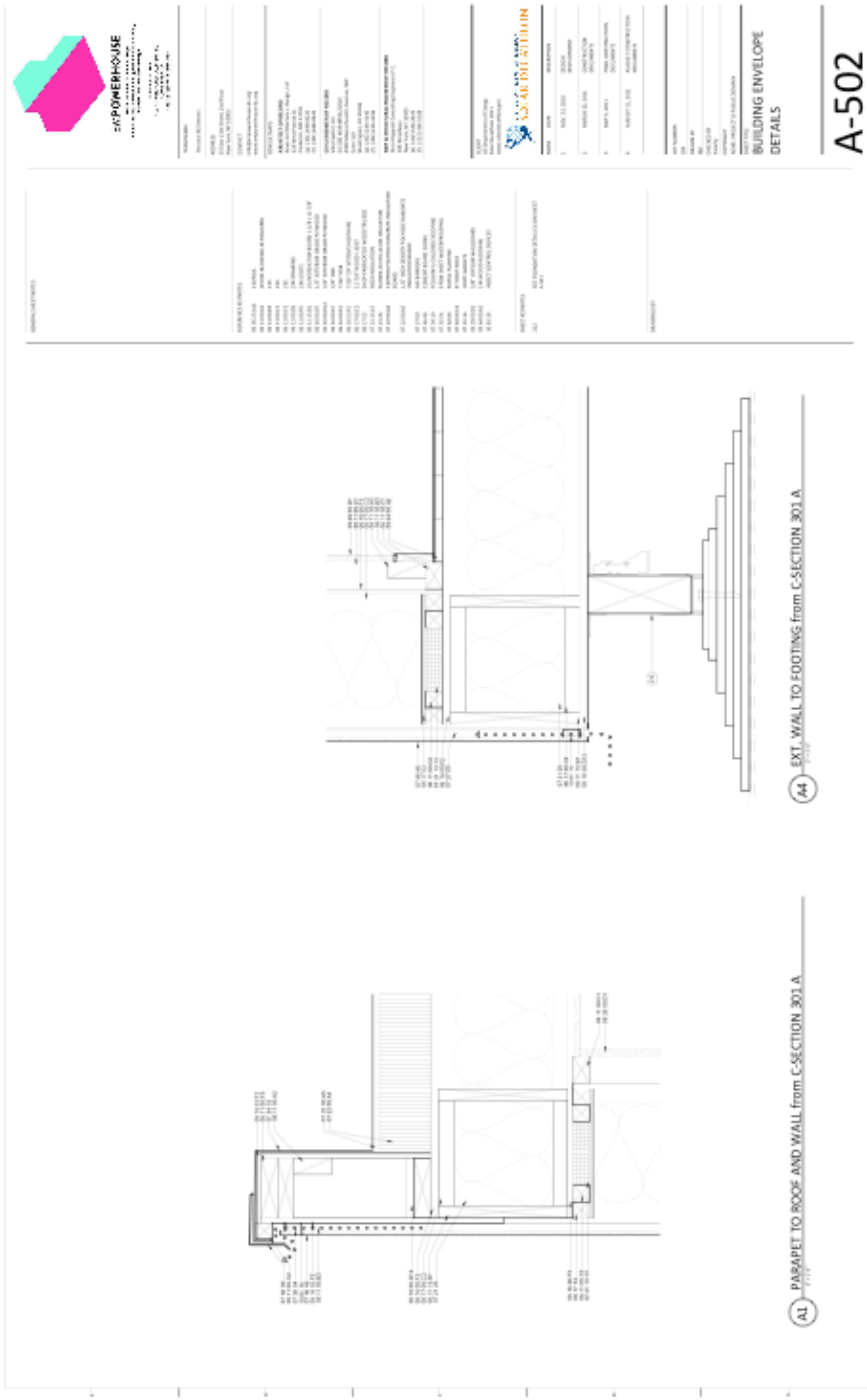
C-SECTION 301 B
C-SECTION 301 A
LIVING ROOM
BATHROOM
BEDROOM
ENTRYWAY
MECH
SOLAR ENVELOPE
T.O. PARAPET
T.O. ROOF
T.O. SUB FLOOR
GROUND LEVEL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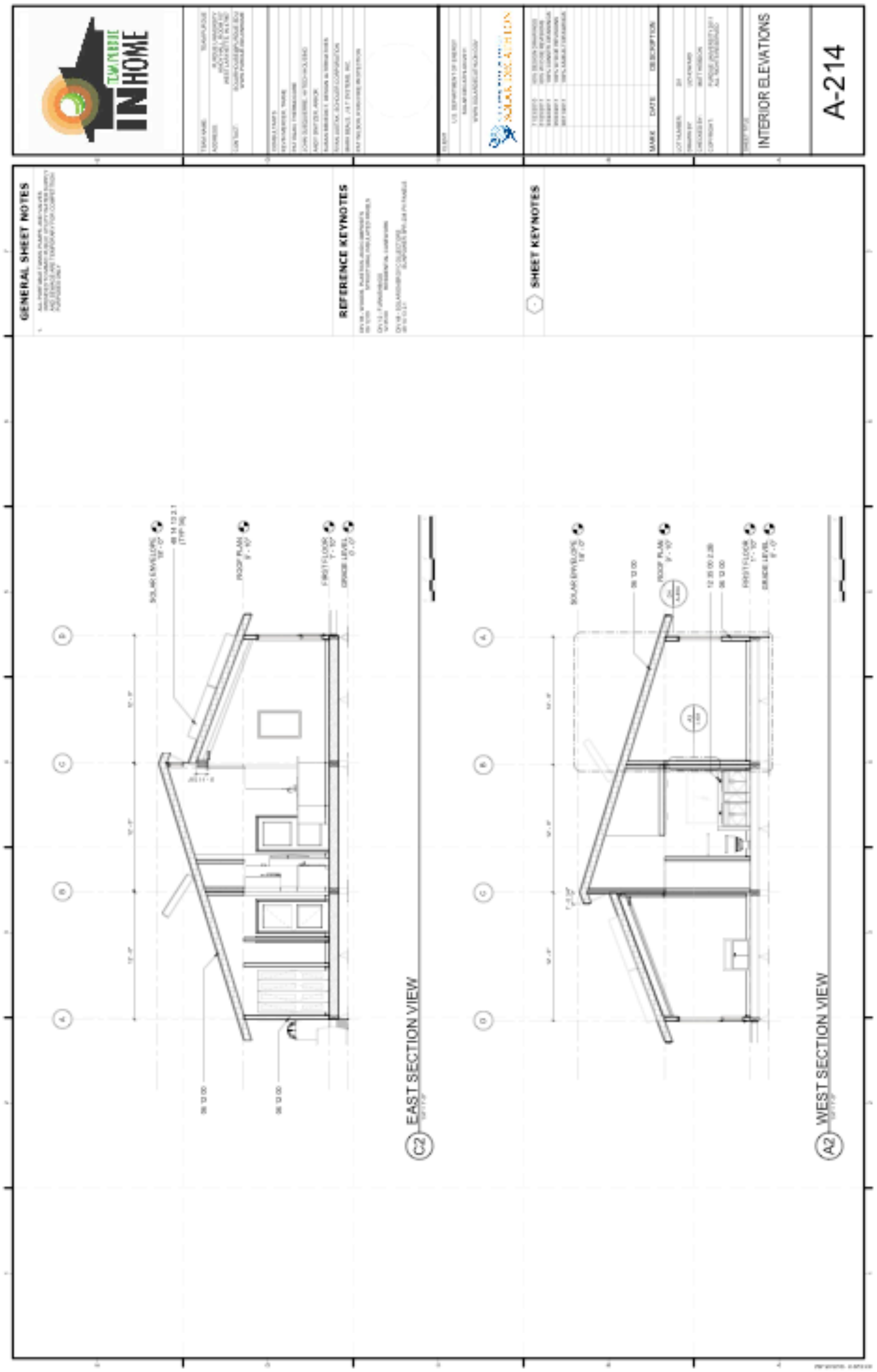
A4 EXT. WALL TO FOOTING from C-SECTION 301 A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SHEET KEYNOTES
SOLAR ENVELOPE
ROOF PLAN
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GRADE LEVEL
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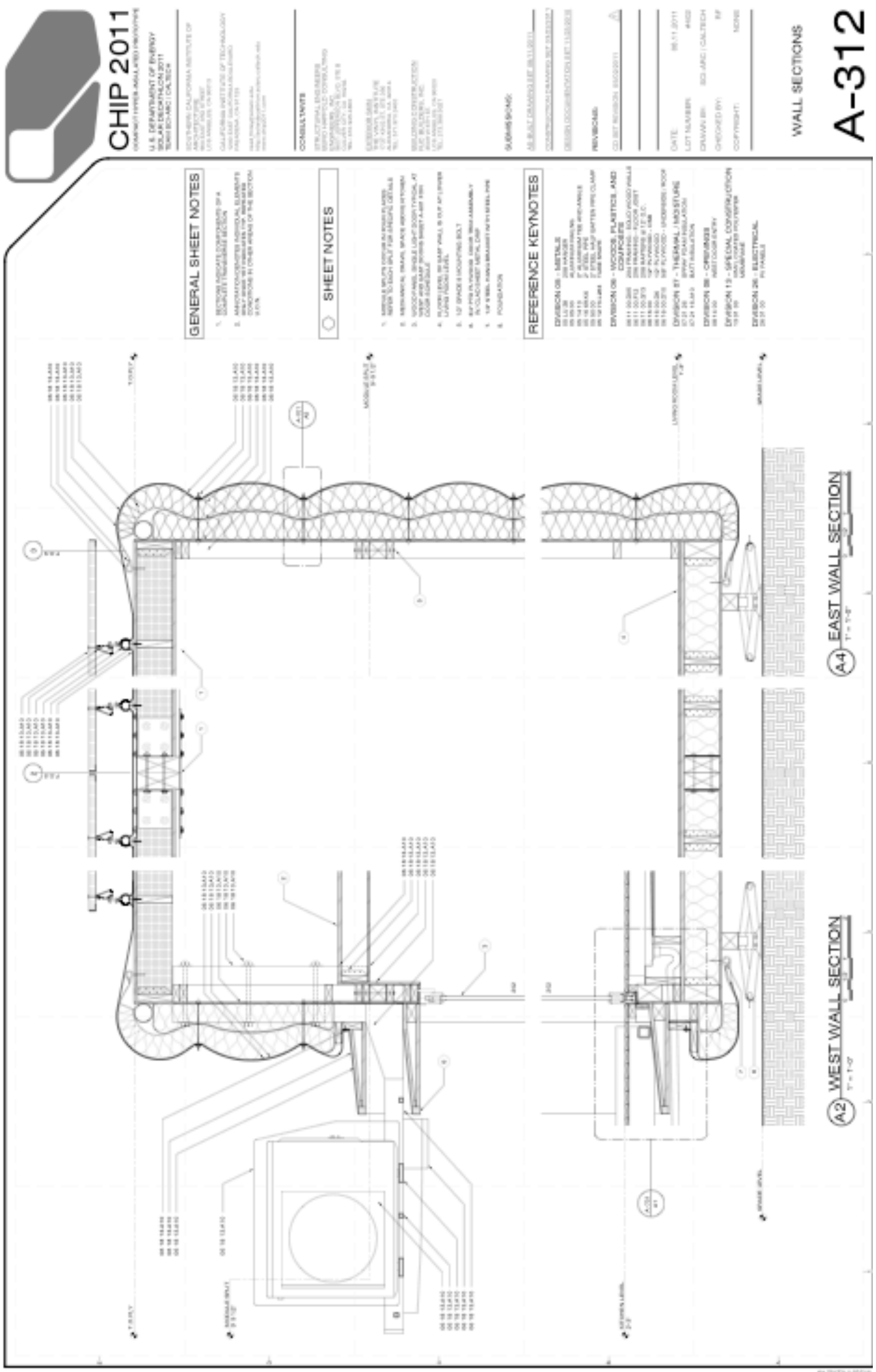
WEST SECTION VIEW
TEAM PURDUE
INHOME
MARK
DATE
DESCRIPTION
INTERIOR ELEVATIONS
A-214



CHIP 2011
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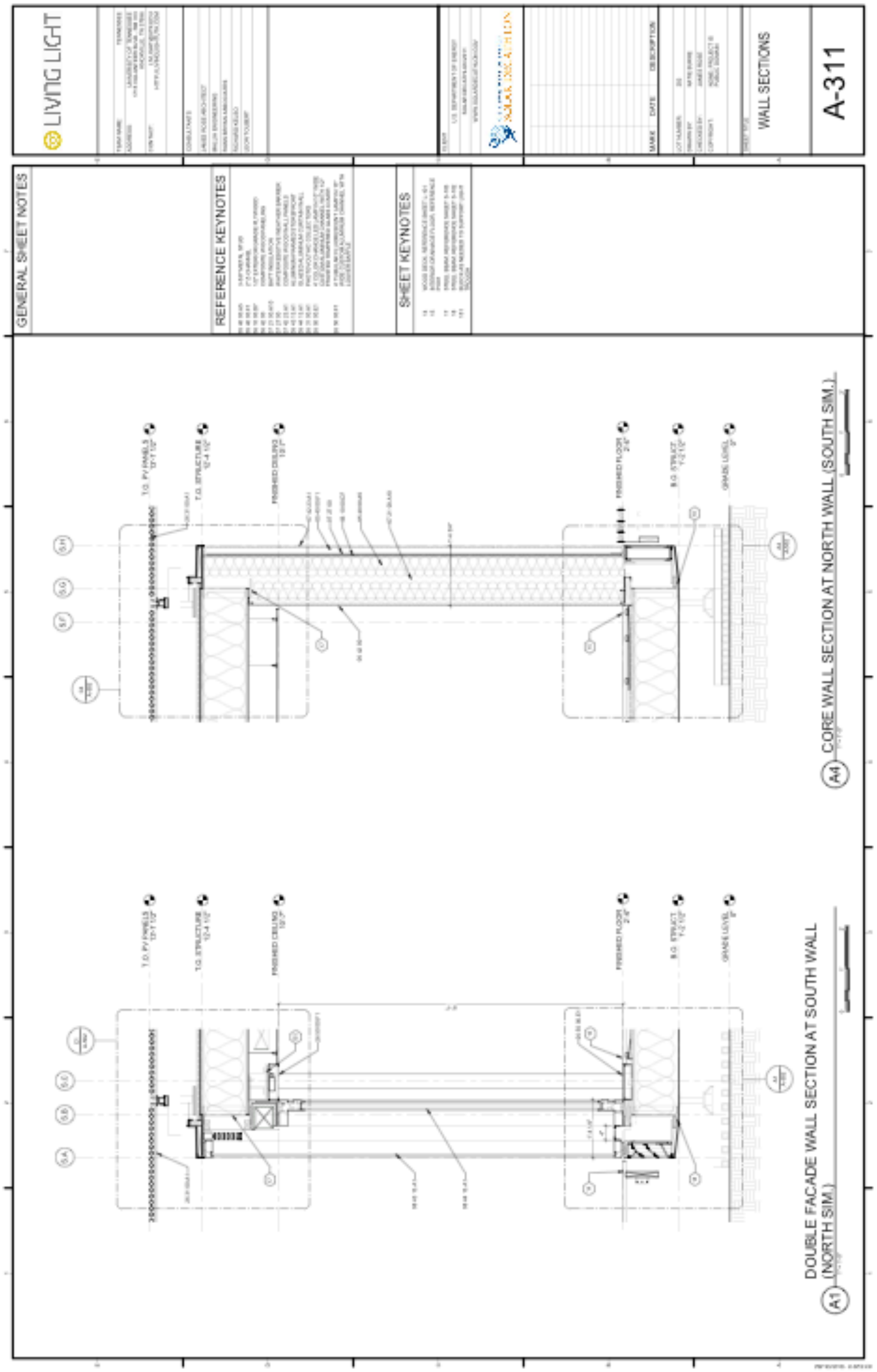
A4 EAST WALL SECTION
WALL SECTIONS
A-312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SHEET KEYNOTES
WALL SECTIONS
A-311
T.O. PV PANELS
T.O. STRUCTURE
FINISHED CEILING
FINISHED FLOOR
B.O. STRUCT.
GRADE LEVEL
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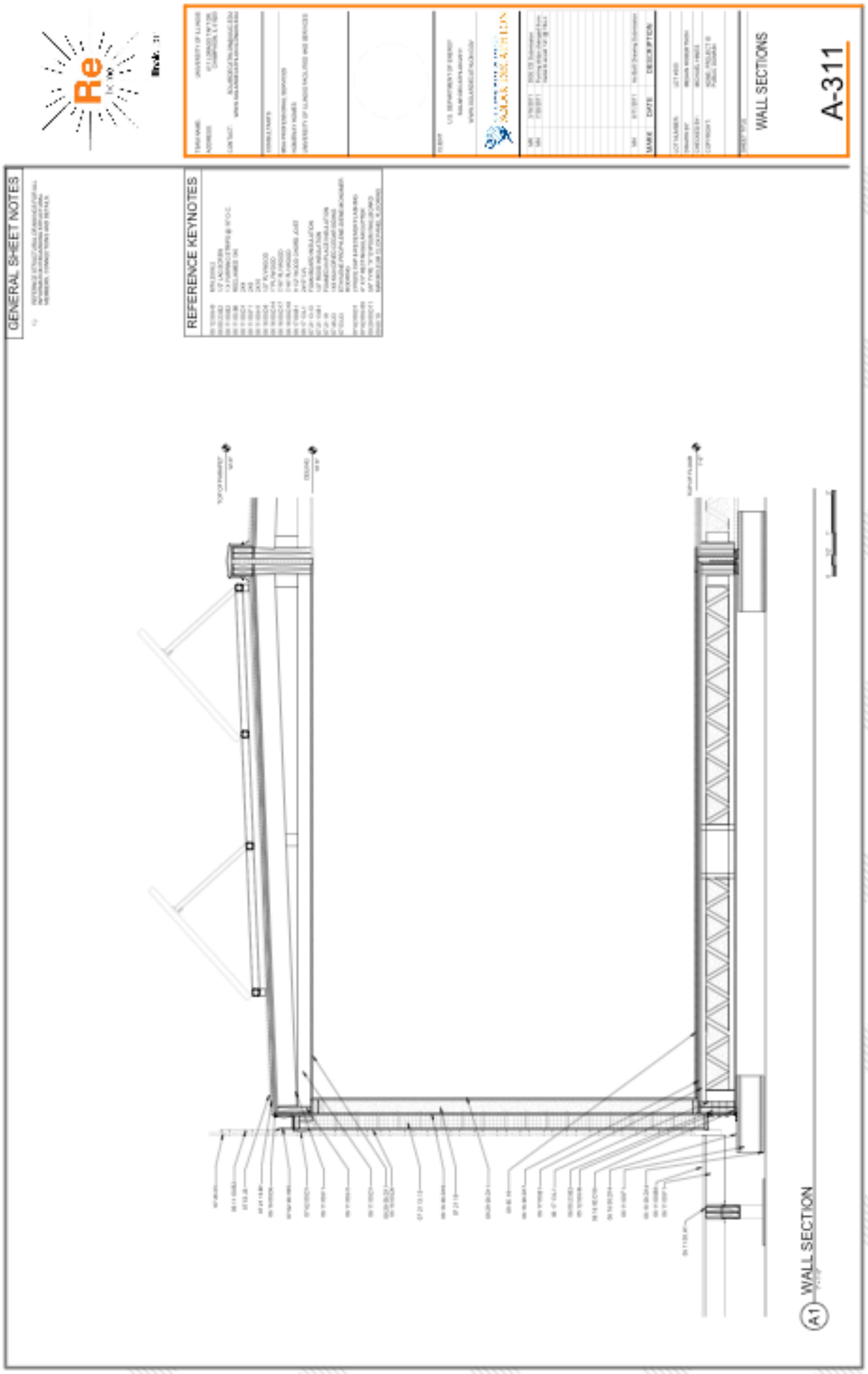
A1 DOUBLE FACADE WALL SECTION AT SOUTH WALL (NORTH SIM.)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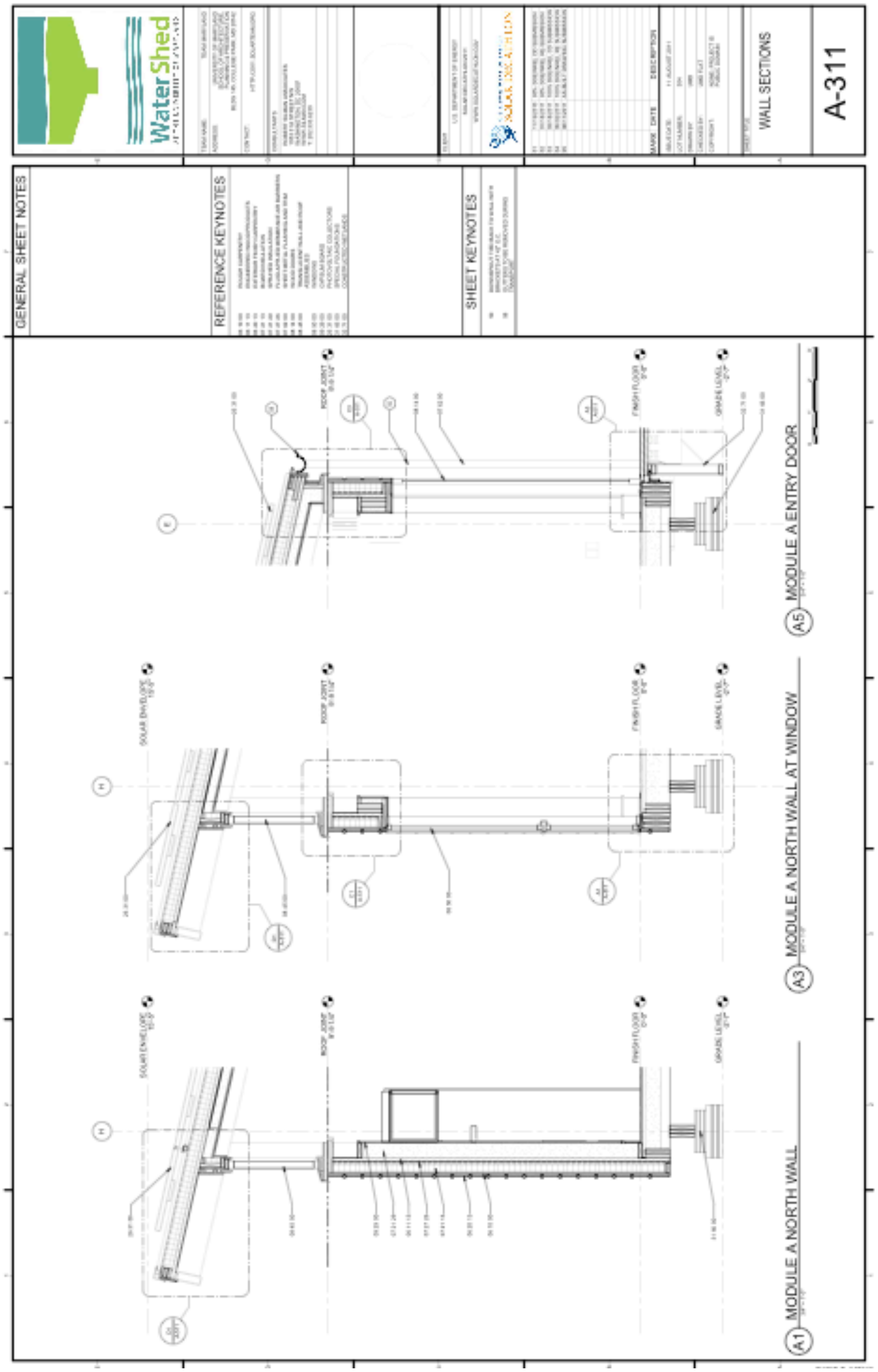
WALL SECTIONS
A-311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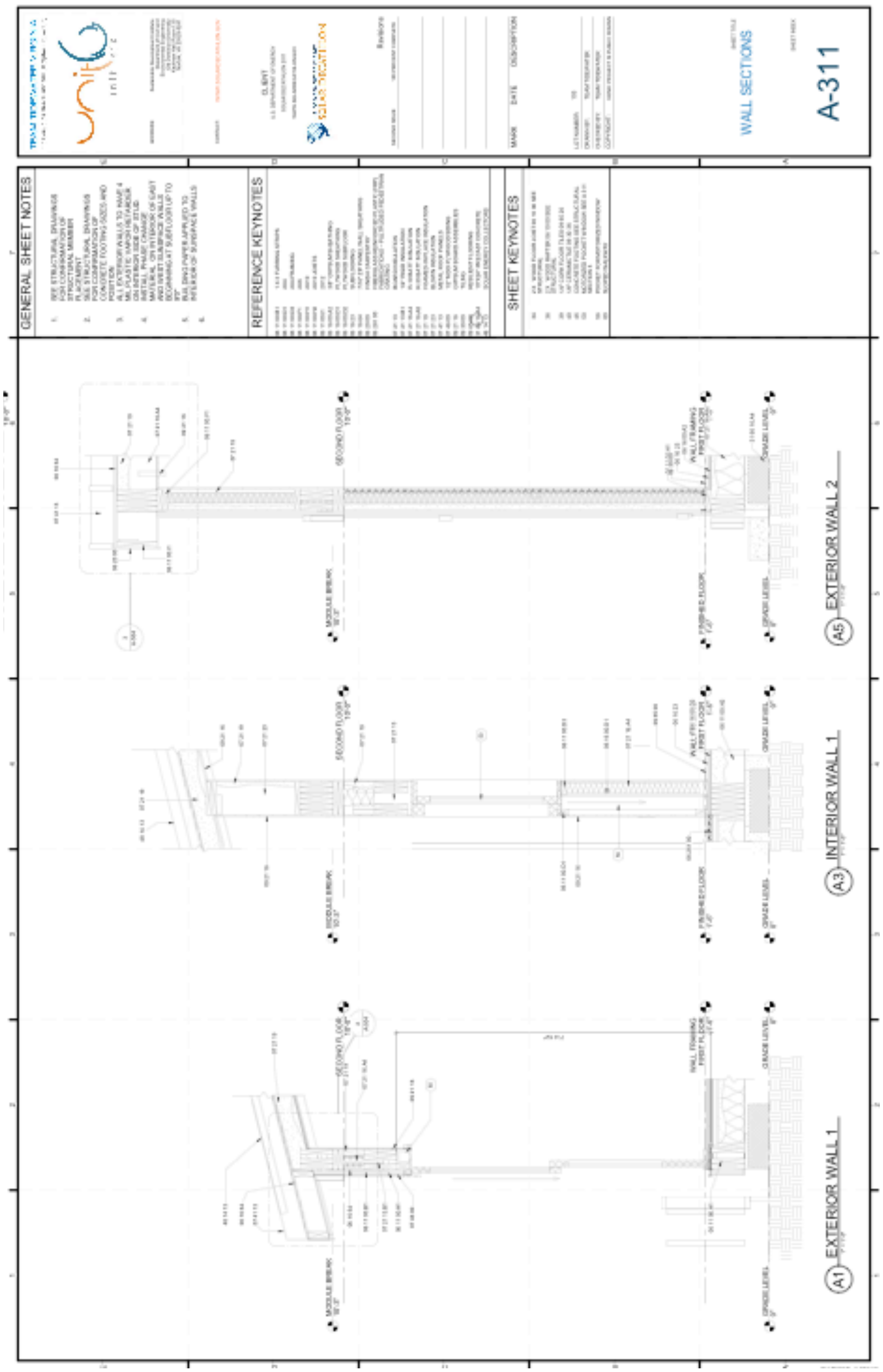
MODULE A NORTH WALL AT WINDOW
MODULE A NORTH WALL
A5
A3
A1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SHEET KEYNOTES
WALL SECTIONS
A-311
A1 EXTERIOR WALL 1
A3 INTERIOR WALL 1
A5 EXTERIOR WALL 2

Biographical Sketch

Chelsea Lauren Royall was born to Mrs. Joy Klingler Royall and Mr. Robert Benjamin Royall in Greensboro, North Carolina. She graduated from Southeast Guilford High School in Greensboro, North Carolina in May of 2006. She attended Appalachian State University for her undergraduate degree in Interior Design and graduated in May of 2010 from the Department of Technology and Environmental Design. That summer of 2010 she decided to continue her education at Appalachian State University and work towards a Master of Science in Technology with a concentration in Building Science, which she earned in December of 2012. Her future plans include designing better buildings, by using strategic construction methods and energy efficient guidelines.

Chelsea was on the Dean's and Chancellor's Lists multiple times in undergraduate and graduate school career. She worked as the Design Director for Appalachian State University's entry in the U.S. Department of Energy's Solar Decathlon 2011.