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Article

A Sustainable Cost Benefit Assessment of Wall Assemblies from the US Department of Energy Solar Decathlon 2011

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Abstract: Residential homes consume 24% of total primary energy while commercial buildings use an additional 19%, totaling 43% of all energy consumption in the U.S. (United States Energy Information Administration [USEIA], 2011). Wall assemblies are a fundamental component of a building's construction and can make significant impacts on building performance. Wall assemblies 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 include using rare or readily available materials or avoiding use of materials which require more energy to produce than they offset. Exploring these factors to discover the ideal wall assembly is critical to enhancing building construction and performance. The purpose of this study was to identify optimal wall assemblies from the US Department of Energy Solar Decathlon 2011 using a newly developed Sustainable Cost Benefit Assessment (SCBA). The wall assemblies were analyzed using cost per square foot, clear wall R-value, and embodied energy metrics as a means for comparison. 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 reducing building energy consumption.

Keywords: wall assembly; clearwall; Solar Decathlon; R-value; cost-benefit; embodied energy; affordable.

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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. (United States 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.

1.1. 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.

1.2. 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.

1.3. 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:

Clear material cost ($\$/ft^2$)
Clear labor cost, suggesting ease of installation ($\$/ft^2$)
Clear wall R-value ($hft^2°F/BTU$)
Clear embodied energy (BTU/ft^2)

1.4. 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 and 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 and Dorsi, 2009, p. 261).

1.5. 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.

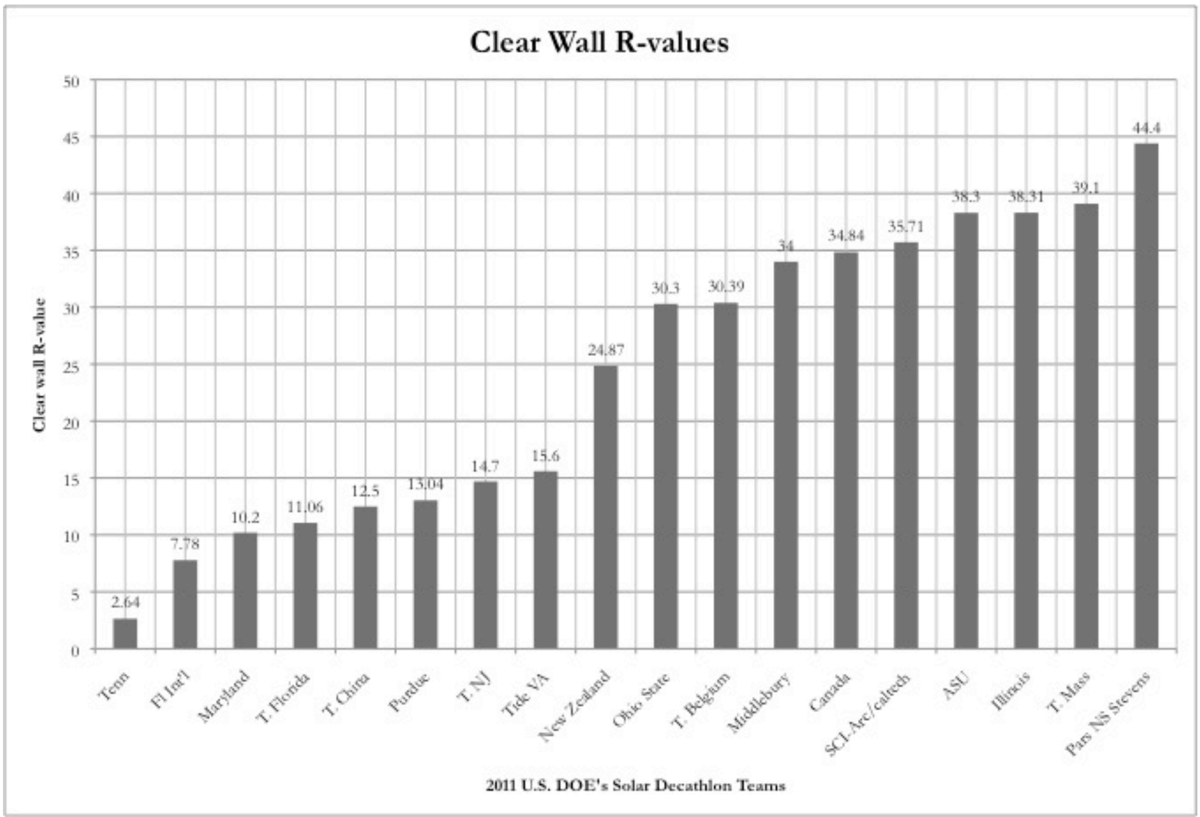
Embodied energy and density of building materials figures were found using numerous resources. Without a single database available to reference embodied energy and density of materials, these amounts may be inconsistent since multiple sources were used. When determining which numbers to use, articles 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.

2. Results and Discussion

2.1. Clear Wall R-value

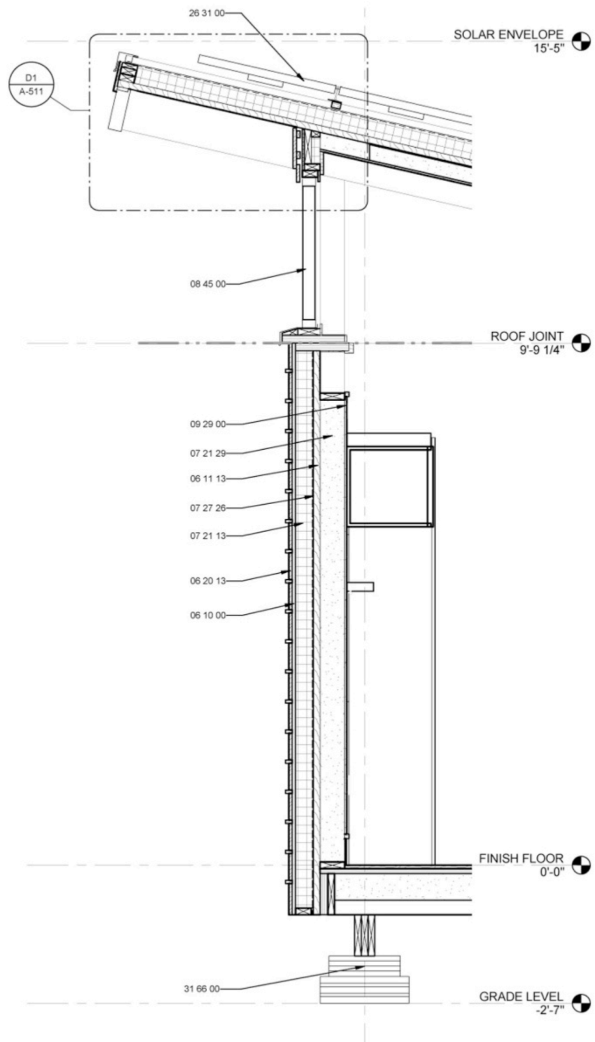
After examining and analyzing each wall configuration, a clear wall R-value was calculated for each of the 18 home entries in the 2011 U.S. DOE Solar Decathlon. There was a range of associated R-values between R-2.64 and R-44.4. For the purpose of this study, the top three highest-valued walls and three lowest-valued walls are described. In Figure 1, a graph depicting each team's calculated clear wall R-value is provided.

Figure 1. (a) Bar graph of 2011 Solar Decathlon teams' clear wall R-values.



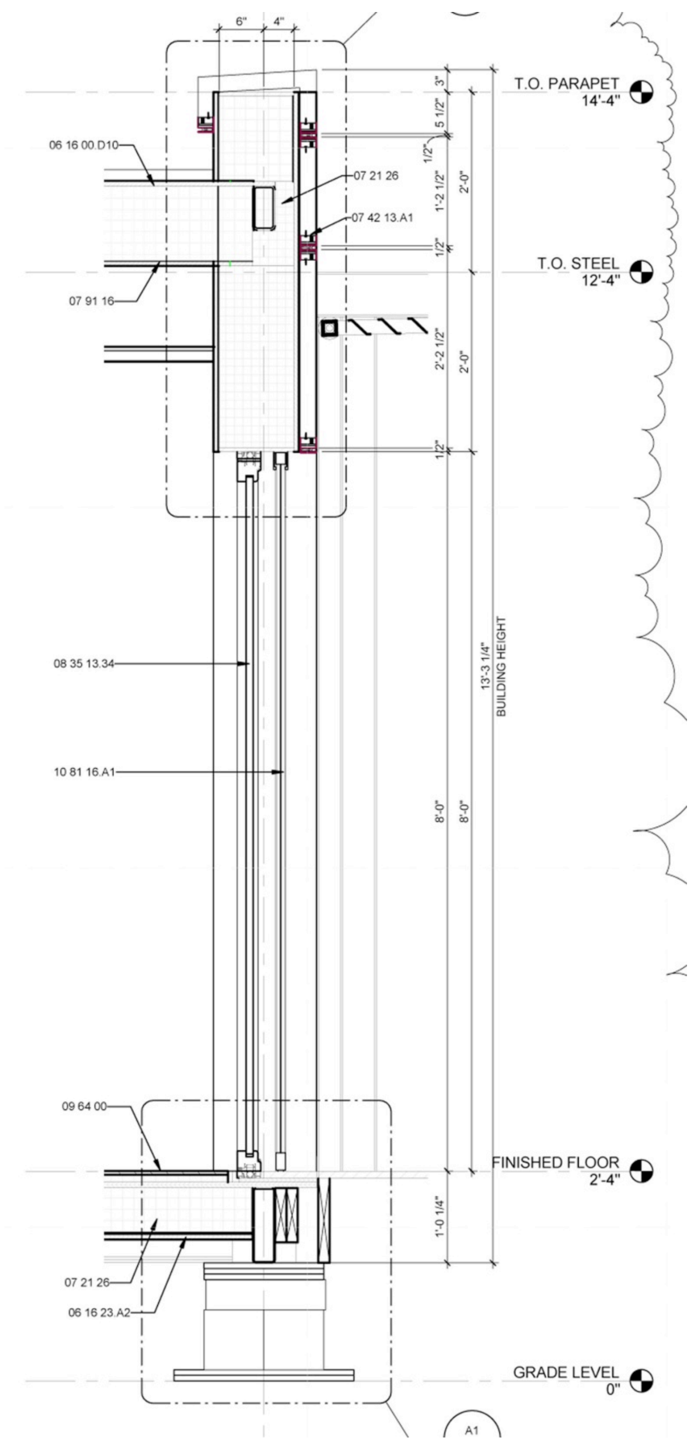
Just as it is important to discuss the best clear wall R-values, it is also important to understand what methods were not as efficient. As a note, clear wall R-values are only one method to evaluate energy efficiency. As some of these teams may have a lower clear wall R-value they may save energy use 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 2).

Figure 2. (a) Team Maryland’s wall section. From U.S. DOE, 2012.



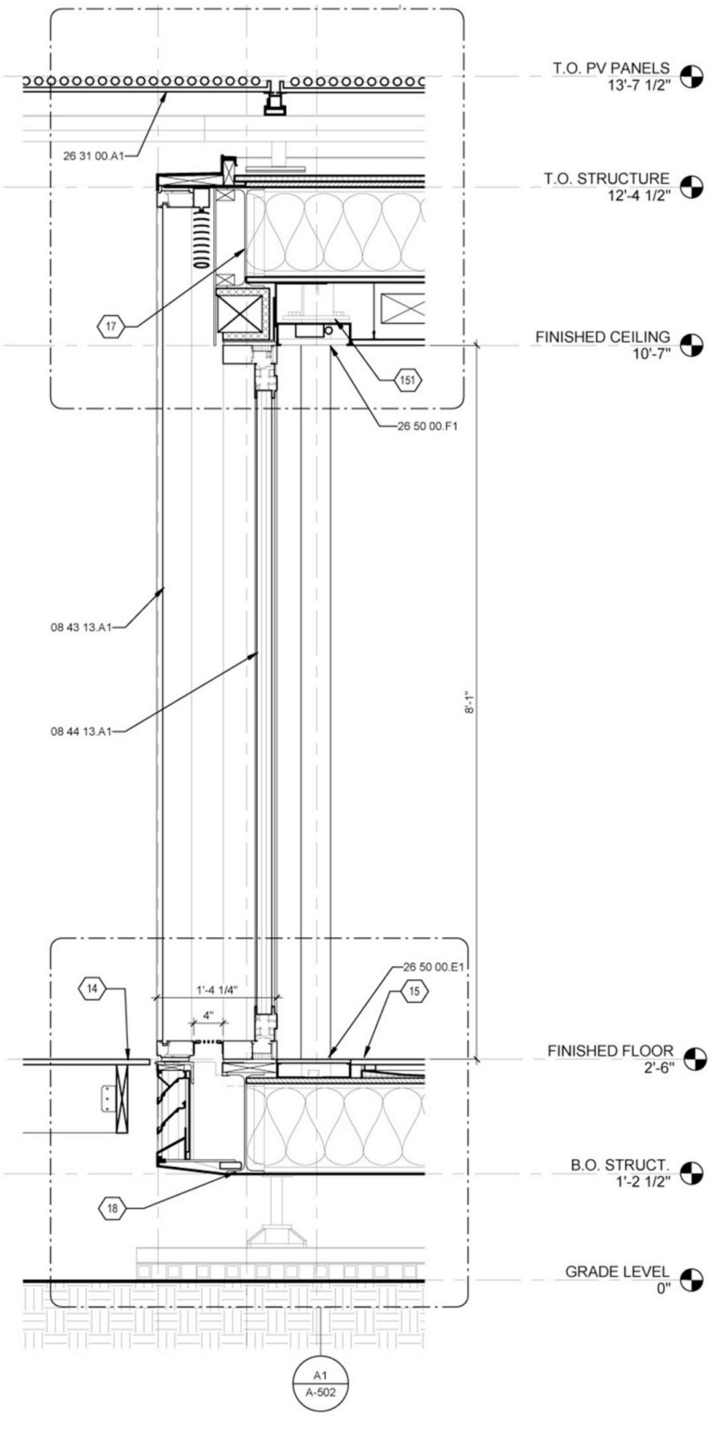
Florida International, whose house had the second-lowest rating, had a clear wall R-value of 7.78. The walls were primarily comprised of glass, with a 2’0” section of 8” spray foam. With eight feet of glass, the wall’s R-value was significantly reduced. In Figure 3, a wall section for Florida International is shown.

Figure 3. (a) Florida International’s wall section. From U.S. DOE, 2012.



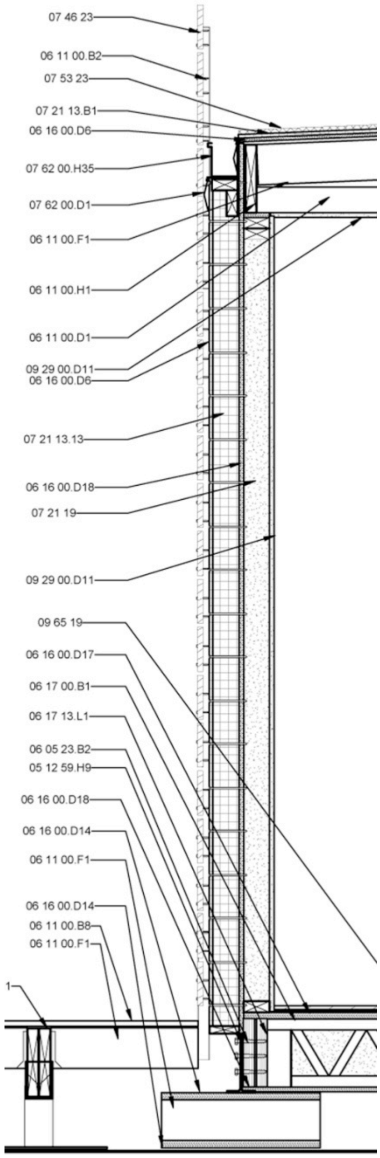
Team Tennessee ranked lowest in clear wall R-value with a R-2.64 wall assembly. This was simply due to using an all-glass façade. Team Tennessee used a double façade system, which used two glass curtain walls. The section between the two glass sections was an air gap, which was designed to harvest heat to a recovery ventilator, which then would supply the home (U.S. DOE, 2012). In Figure 4, a wall section for Team Tennessee is shown.

Figure 4. (a) Team Tennessee's wall section. From U.S. DOE, 2012.



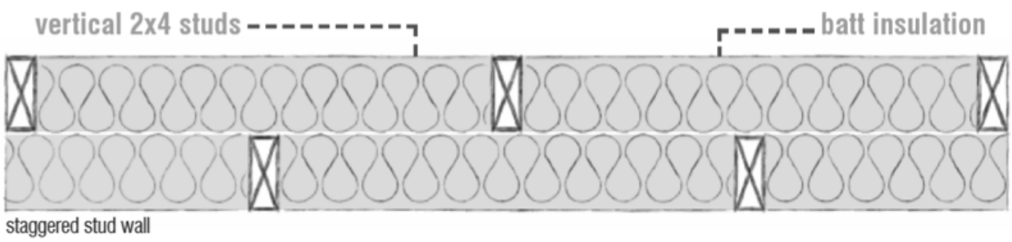
The third most-efficient wall assembly was tied between Illinois State University and Appalachian State University (ASU). Both teams designed R-38.3 wall assemblies. Illinois used common framing methods but filled the cavities with polyurethane spray foam, providing a rating of R-22 within the stud cavity alone. In addition, 4" of rigid insulation was applied to the exterior side. In Figure 5, a wall section for Team Illinois is shown.

Figure 5. (a) Team Illinois' wall section. From U.S. DOE, 2012.



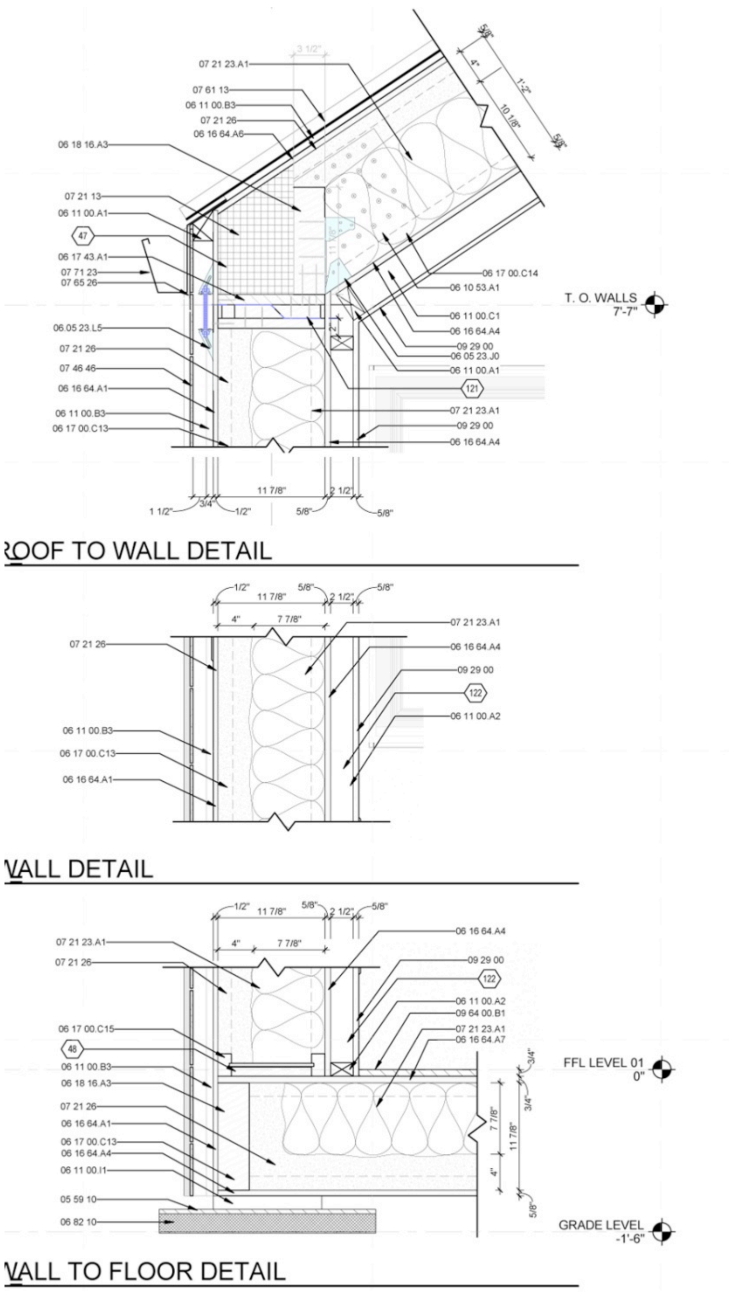
Typically, when seeking to achieve a high R-value in walls, one should not utilize fiberglass-batt insulation. However, ASU took two layers of batt insulation and incorporated them into a staggered stud framing method in order to help reduce thermal bridging. In this way, the team was able to use a low-cost insulation material and still attain a competitive R-value. Figure 6, shows a section detail of ASU's wall.

Figure 6. (a) 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 7 shows a section view of Team Massachusetts’ wall.

Figure 7. (a) 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 9 for a detail of the top and bottom plate and Figure 8 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 8. (a) Section view of Parsons and Stevens wall. From U.S. DOE, 2012.

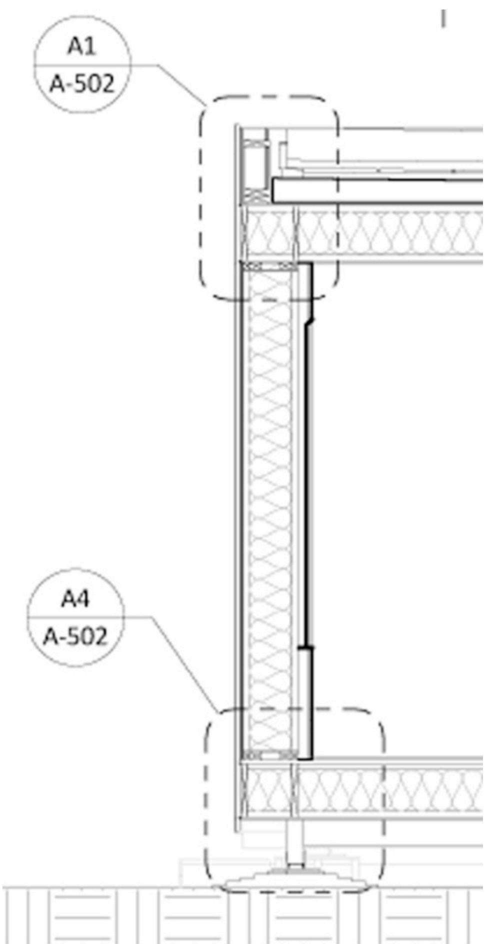
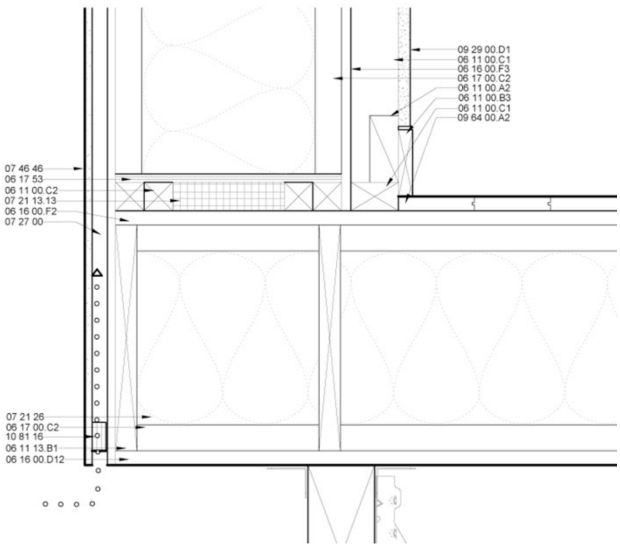


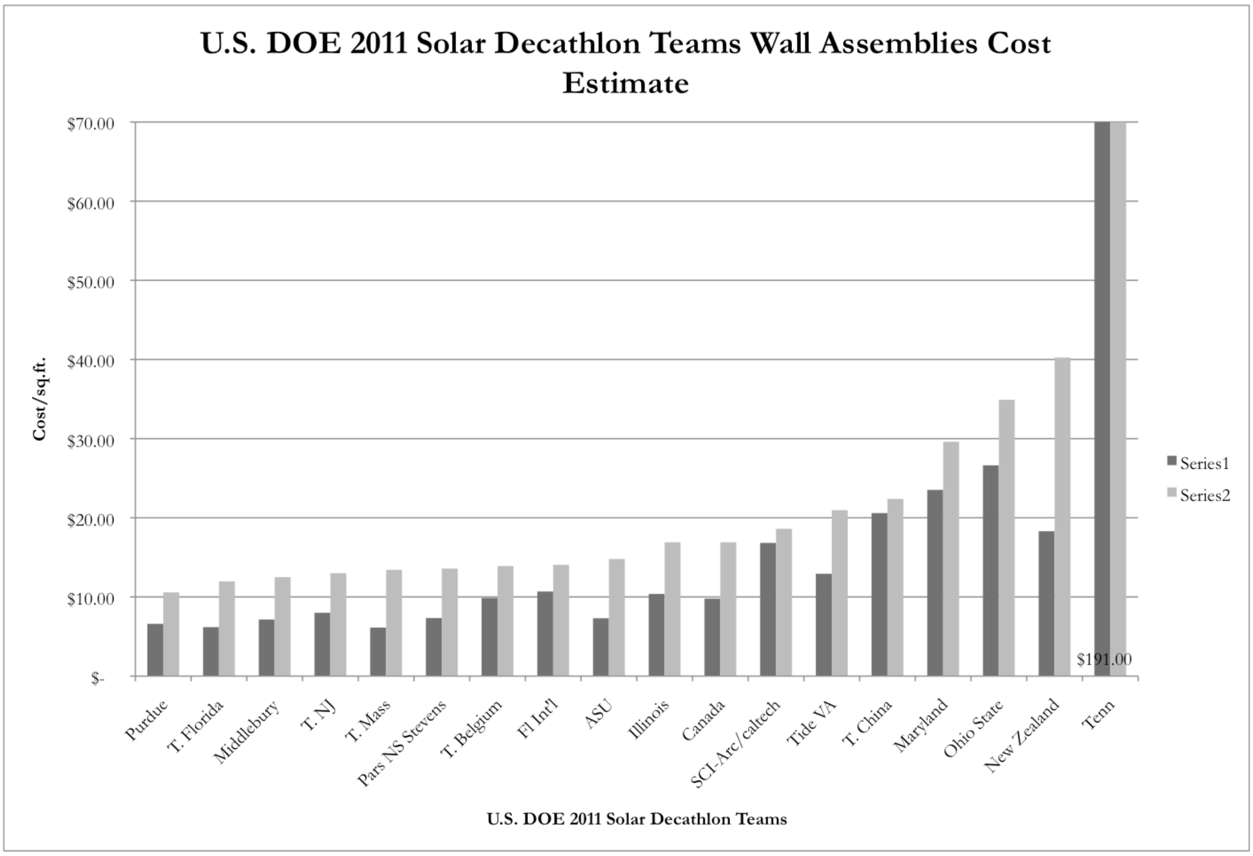
Figure 9. (a) Detail of Parsons and Stevens wall. From U.S. DOE, 2012.



2.2. Cost Estimates

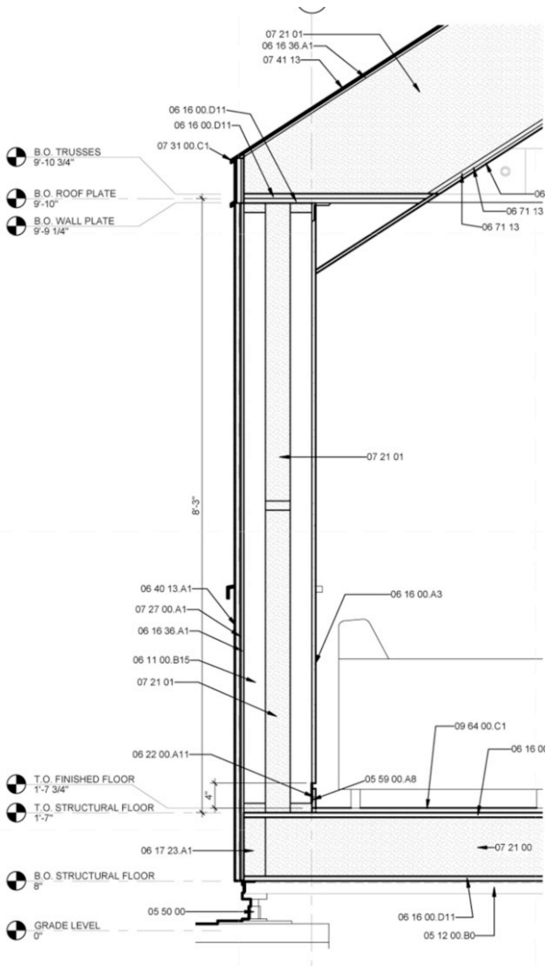
The cost for each wall assembly was estimated using a quantity take-off based on cost per square foot. Within this method, each wall had an associated material cost and an additional labor cost. The ranking of each team was based on the sum of material and labor costs. A chart with each team's material and labor costs is provided in Figure 10. Descriptions of the most and least affordable wall assembly estimates are described.

Figure 10. (a) Bar graph of final cost estimates for each wall assembly. **(a)** 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 11, a section view of Team Middlebury's wall is provided.

Figure 11. (a) 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.

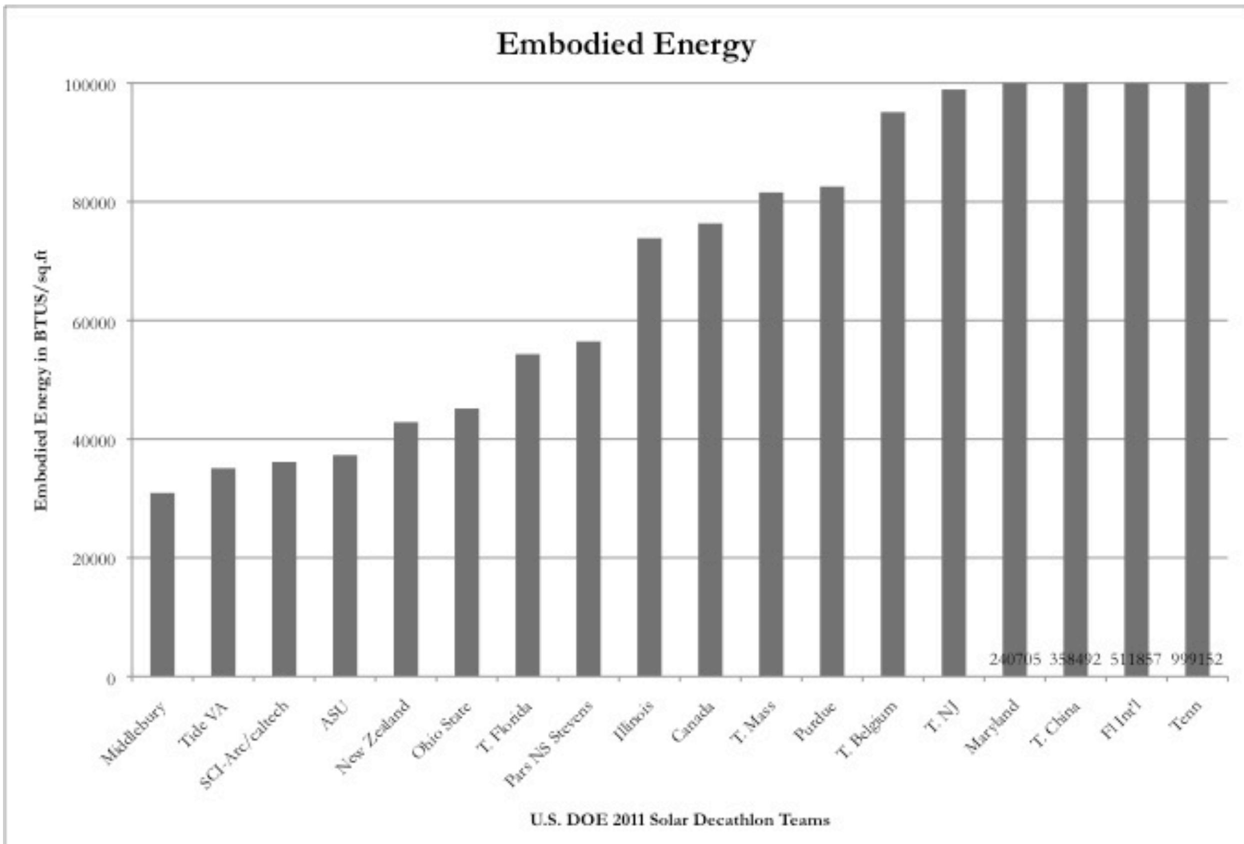
Team New Zealand had the third-highest cost estimate with a total cost of $40.25/sq.ft. This cost was due to a custom wood wall panel system that was student fabricated for the exterior cladding. The custom cladding alone accounted for $25.00 of the total $40.25/sq.ft. Without the integration of a custom 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.

2.3. 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 12 shows a graph depicting each team's overall performance in embodied energy.

Figure 12. (a) 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.

3. Experimental Section

3.1. 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.

3.2. 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.

3.3. 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.

3.4. 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.

3.5. 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 13 and Figure 14).

Figure 13. (a) Example plan for finding clear wall R-value.

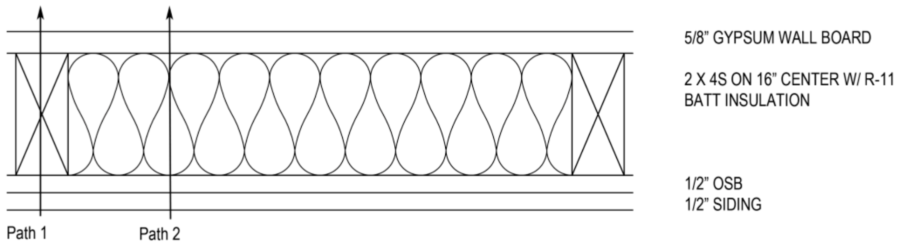
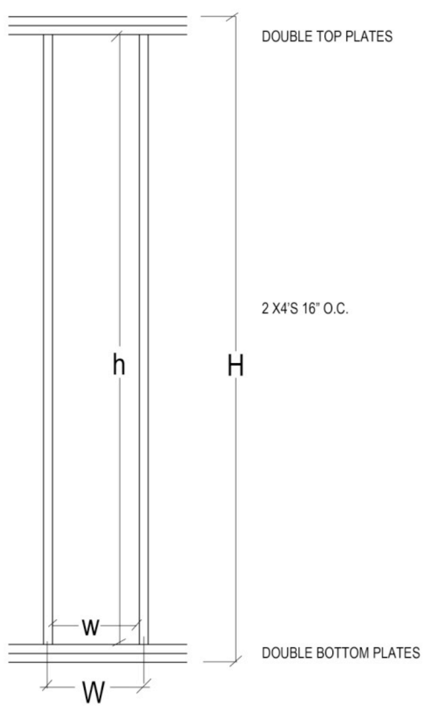


Figure 14. (a) Example section for finding clear wall R-value.



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 1, an example of the method to the equation may be found.

Table 1. Sample of finding clear wall R-value referring to the wall section in Figure _ and _. (*Note*. When determining paths, begin adding R-values, then convert to U-value when multiplying by percent of insulation or framing).

	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**	

All associated R-values were compiled from multiple resources including: Krigger, & Dorsi, 2009, Singh, Dev, Hasan & 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.

3.6. 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 2.

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 & Dorsi, 2009; Nordic Engineered Wood, 2009; University of Bath, 2006; Wilson, 2012).

Table 2. Example Table for Calculating Embodied Energy in BTUs/ft^2

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

3.7. 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 3, 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 3. Example of the cost estimate for Team Ohio State's wall assembly (*Note.* Adapted from U.S. Department of Energy. (2012, January 26). *U.S. Department of Energy Solar Decathlon*. Retrieved from http://www.solardecathlon.gov/).

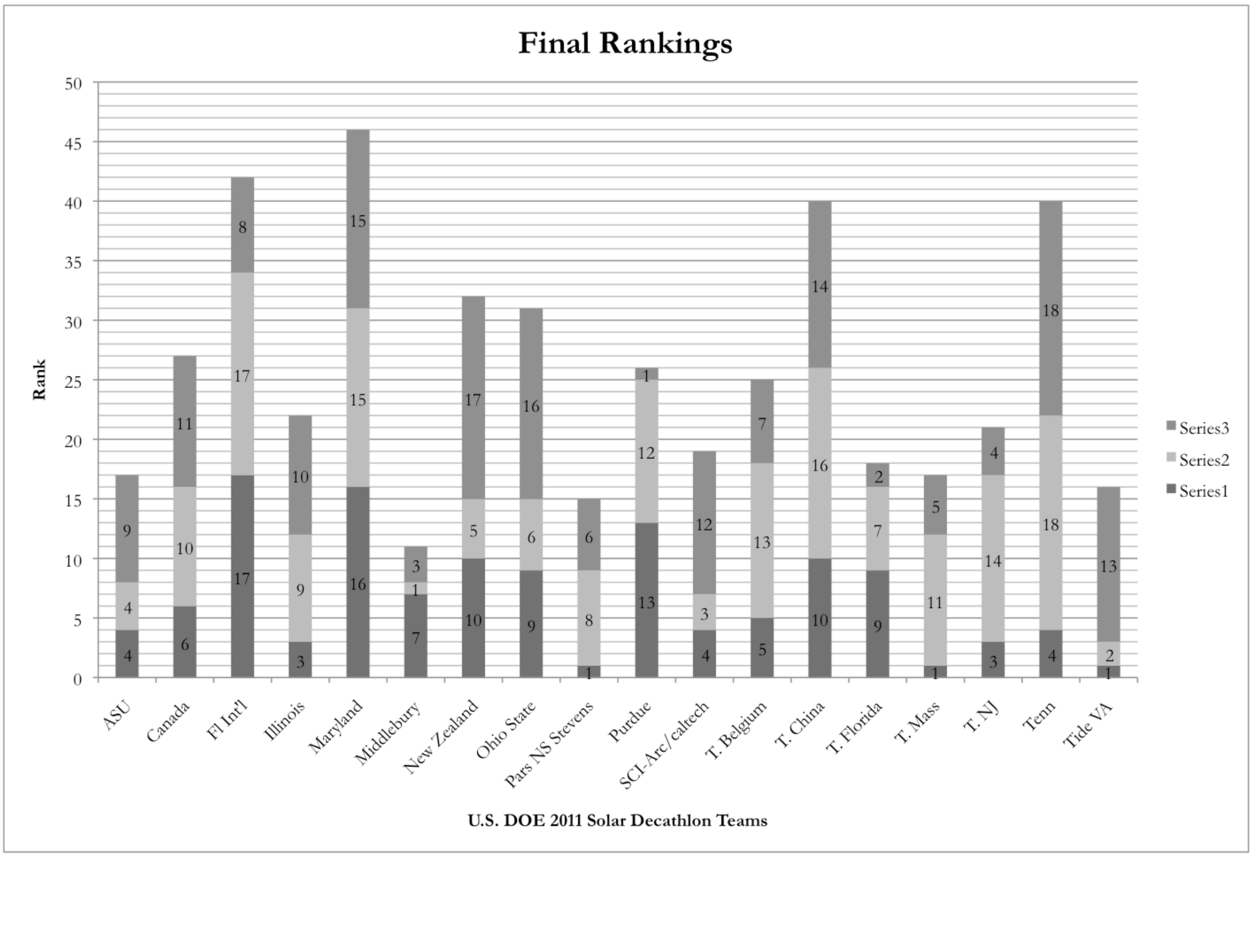
Spec Section	Brief Description	Detailed Description	Qty	Unit	Material Cost	Labor Cost	TOTALS
060000 Wood, Plastic, Composites							
	Partitions	Wood framing, partitions, standard & better lumber, 2" x 6" studs, 16" O.C., 10' high,	240	L.F.	$ 4.79	$ 8.70	$ 13.49
	Wood - Sheathing - plywood Total	Sheathing, 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

4. Conclusions

4.1. Discussions and Conclusion

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 15, 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 15. (a) Bar graph of each team's completed ranking. **(b)** Series 1 represents the clear wall R-value ranking, Series 2 represents the embodied energy ranking, and Series 3 represents the total cost ranking.

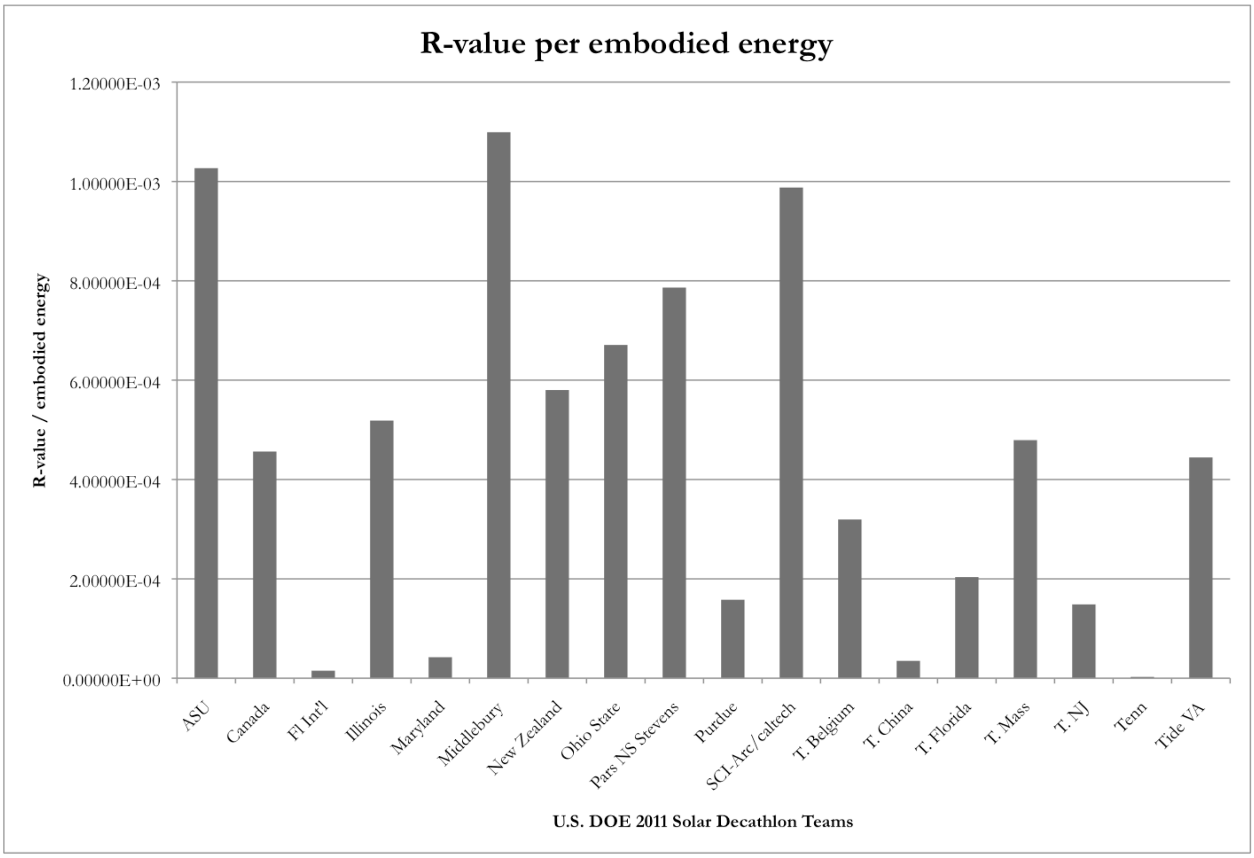


Team China had the third least cost-effective wall assembly. The use of a shipping container resulted in a higher associated cost and embodied energy. With a thinner SIP panel the clear wall R-value also ranked among the lower R-values. Team Maryland was the second lowest ranking team due to its low 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.

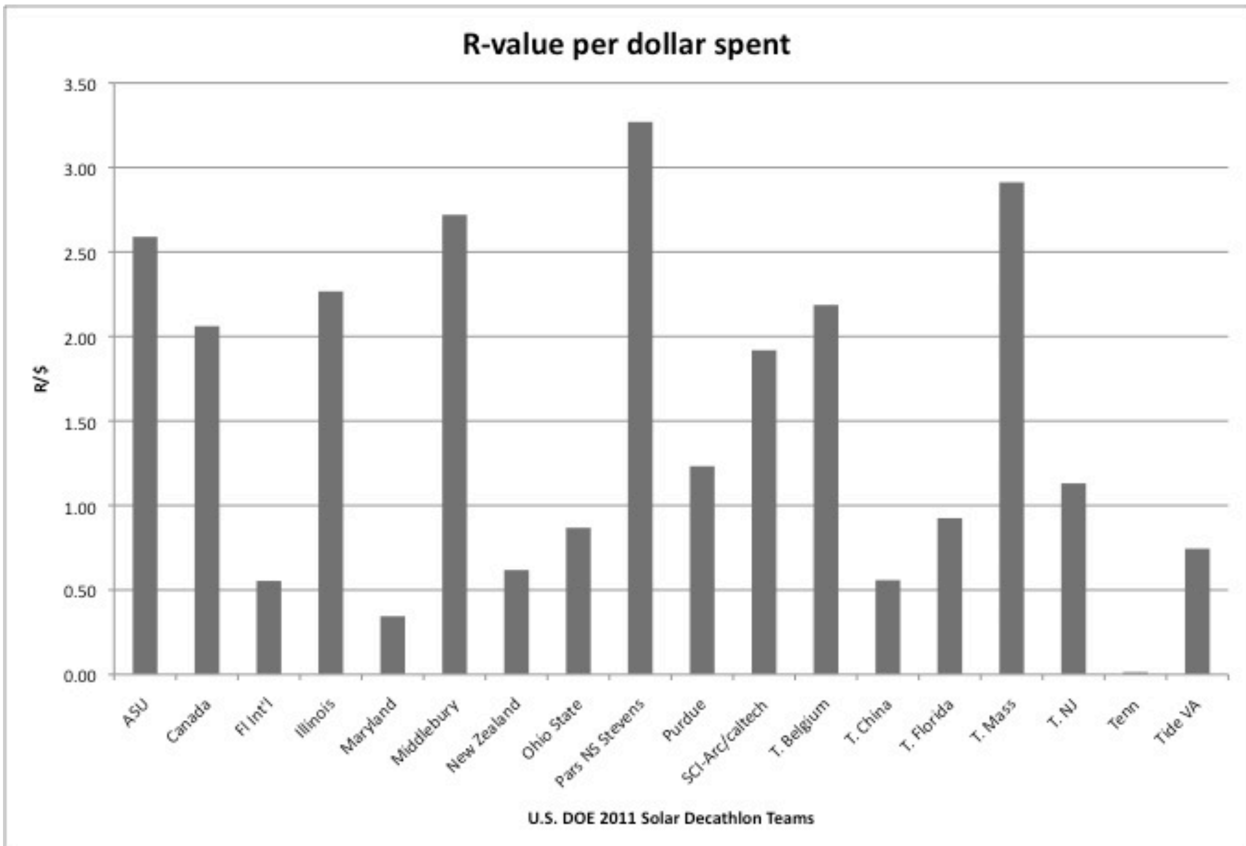
Another method for analyzing these results is to see the R-value per embodied energy. In Figure 16, you can see how the previous relationships between embodied energy and R-value compare. As would be expected, the wall assemblies with particularly high-embodied energy show how much is required to achieve 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 16. **(a)** Bar graph depicting the embodied energy for the R-value.



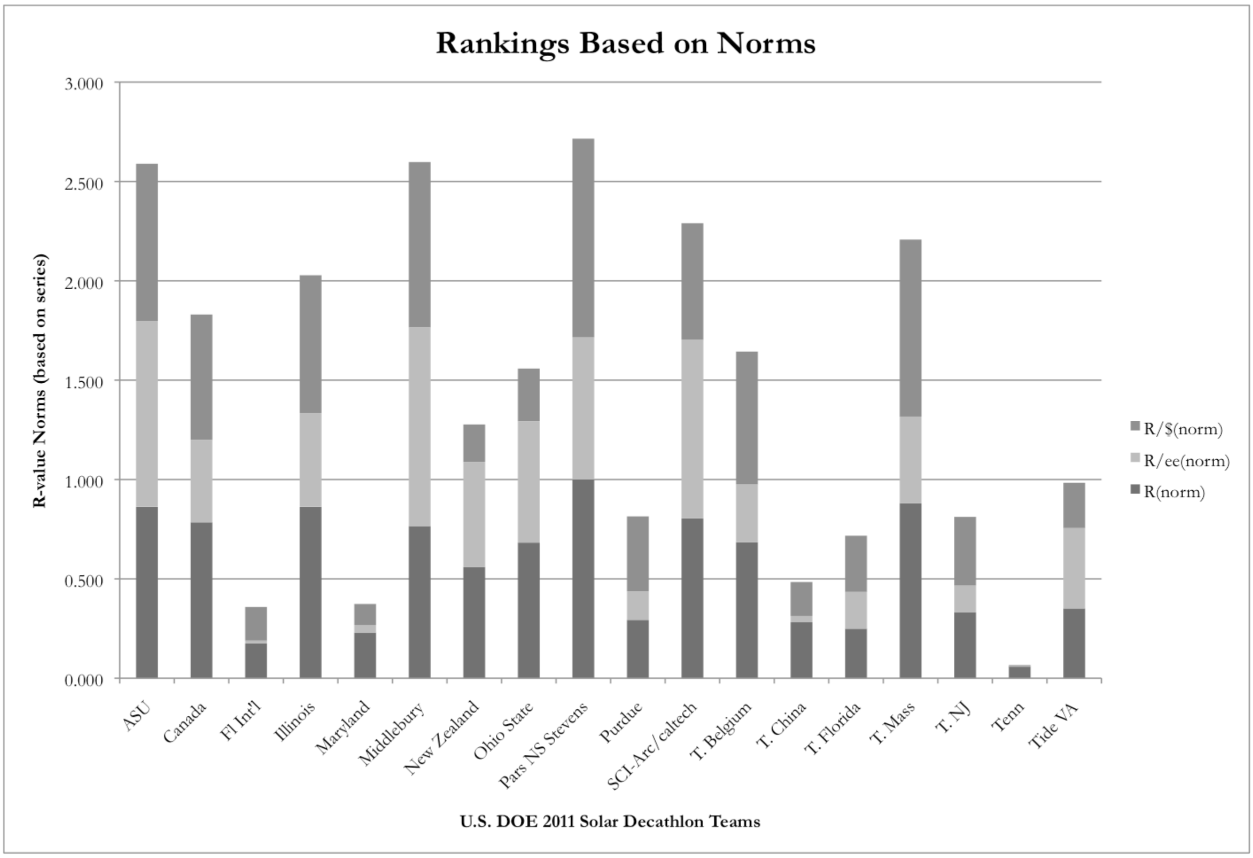
Another interesting way to review this information is to calculate the R-value accomplished per dollar spent. This is just another means of showing the most affordable method with the highest R-value. Figure 17, shows a bar graph of each team's R-value per dollar spent.

Figure 17. (a) Bar graph showing the R-value for the dollar.



By taking the information found in Figure 16 and Figure 17, we can evaluate how each team's R-value contributed in an overall comparison. Figure 18, 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 18. (a) Bar graph of each teams normalized R-value associated to the series listed.



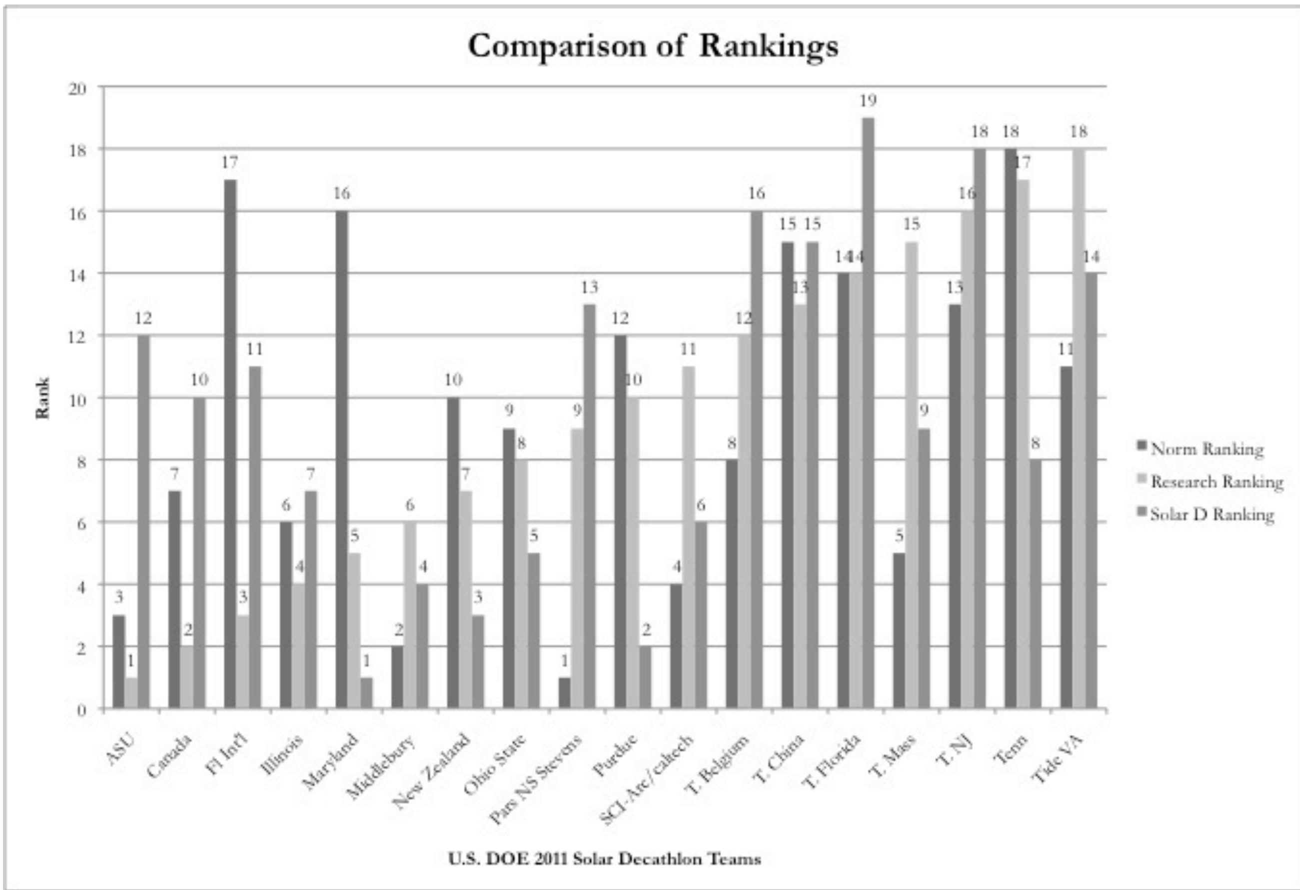
With the data in Figure 18, Parsons and Stevens proved to have the most optimal wall in relation to R-value, embodied energy, and cost when normalized. Team Middlebury and Appalachian State University were close behind.

The U.S. DOE determined scores for each team's performance in the 10 contests. In Figure 19, 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 19. (a) Bar graph of each teams completed ranking in the normalized rank, the U.S. DOE Solar Decathlon, and the research ranking. **(b)** 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/.



4.2. 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 research on the U.S. Solar Decathlon should be researched. 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.

Conflict of Interest

The authors declare no conflict of interest.

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