U.S. DOE Solar Decathlon 2011: A Performance Perspective

David Springer, Davis Energy Group
Blaise Stoltenberg

ABSTRACT

Nineteen college teams from the U.S., Canada, China, and Belgium had their designs accepted for the Solar Decathlon competition and built houses on the National Mall in 2011. In addition to energy performance, the competition addresses aesthetics, cost, marketability, and the ability of the teams to effectively communicate the value of their designs to the public. The perspective of this paper is provided by two of the four participants on the Engineering judging team for Solar Decathlon 2011, and focuses on the elements of the designs related to energy efficiency and overall building performance. Insights into the judging process are provided, and an alternative analysis of scoring results that focuses on energy performance is presented.

Introduction

The Solar Decathlon is a biennial competition organized by the U.S. Department of Energy that provides a venue for international teams of college students to design and construct innovative homes that approach or achieve zero net energy use. The competition provides an extraordinary opportunity for students to learn about the design of energy efficient buildings and to share their knowledge with the public.

The authors were participants on the Engineering Jury and were responsible for evaluating and scoring the engineering approaches used to make the buildings operate efficiently and sustainably. Although there are ten competition categories, this paper focuses on those characteristics of the buildings that contributed to their energy performance and highlights the innovative approaches employed by the teams. The Solar Decathlon website and other articles, for example Kaarsberg (2011), provide other perspectives on the 2011 event.

Background

The Solar Decathlon was initiated in 2002 and all subsequent competitions have been held on the National Mall in Washington, DC. For the first time, the 2013 event will take place in another location, Irvine, California. The event provides an opportunity for education and engagement through a free ten day public exhibition, as well as a six day workshop for builders and related industry. The competition typically hosts twenty teams from the U.S. and abroad. To date, five Solar Decathlons with 92 participating teams have taken place. DOE notes that "a critical long-range outcome of the Solar Decathlon is the development and demonstration of cost-effective solar-powered homes." As organizers point out, it is a team event in which the diversity of abilities comes from the composition of the team rather than a single individual (NREL 2011). The value of the event from a communications perspective is to increase awareness of the existence, viability, and benefit of demonstrated technologies by the general public, home consumers, and the building industry. By increasing awareness, the intent is to have these technologies more widely demanded by consumers and subsequently adopted throughout the building industry (Hicks 2007).

The event is typically staged over 24 days, following a schedule such as shown in Figure 1. This schedule demands extreme focus and dedication on the part of all participants, but particularly the college teams who have only eight days to build homes that are fully functional and livable. Each team is responsible for the transport of its house, the house's contents, and all necessary tools and equipment; for procuring all necessary equipment, tools, and supplies; for team transportation, accommodations, lodging, and food; and for covering all necessary costs. Except for an award from DOE, teams are required to support their projects using college resources and donations from manufacturers and material and equipment suppliers.

Figure 1. 2011 Solar Decathlon Schedule

Rules in Brief

Team Selection

Proposals from team applicants must demonstrate that teams and supporting institutions have the expertise and resources to conduct a successful project. Applications are scored on technical innovation and design, fundraising and team support, organization and planning, conceptual design, and curriculum integration by judges from NREL, AIA, USGBC, and ASHRAE. Approximately 50 applications were submitted for the 2011 event.

Rules of Engagement

The organizers provide a very detailed rulebook that governs such topics as building square footage, lot size, ground penetration restrictions, water management, vegetation, grid connections, late design changes, as well as how the teams must be organized. Teams are required to appoint officers to fill roles such as Project Engineer, Construction Manager, Health & Safety Officer, etc. College faculty members can only act in an advisory role, leaving it to the students to identify sponsors and other financial resources, develop and implement designs, arrange shipping, and complete on-site construction (DOE 2011).

Categories, Contests, and Judging

The Solar Decathlon has ten competition contests, listed below:

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

Scores are developed either by jury decision or by a combination of jury scores and measured results. Each juried contest has its own specific judging criteria. For example, the Engineering Jury is tasked to include Functionality, Efficiency, Innovation, Reliability, and Documentation criteria in their scoring rubric. Information available to the Engineering jury to aid in assessing and scoring the projects included a video on the homes' engineering features, design drawings, specifications, and observations made during tours. This was the first year that Affordability was included as a separate contest.

Energy loads are standardized by requiring all houses to be operated as indicated in Table 1. All of the houses are monitored in detail by a team provided by NREL. Monitoring results are used to develop scoring for the Comfort Zone, Hot Water, Appliances, and Energy Balance contests. Since this information is not available until after the Engineering contest is completed, Engineering jurors must make qualitative assessments of how well systems will perform.

Table 1. Engineering Related Contests and Criteria

Contest Name	Criteria
Comfort	Indoor Temperature 71 – 76°F, TH 60% or lower or lower
Water Heating	Draw 15 gal. of water over 10 minutes at 110°F average, 16 times
Refrigerator	Maintain temperature at 34 to 40°F
Freezer	Maintain temperature at -20 to 5°F
Clothes Washer	Run 8 loads of 6 bath towels
Dishwasher	Run 5 loads of 6 place settings
Lighting	Indoor & outdoor lights on fully at night
Hosted Events	Two dinner parties of eight guests and one "Theater Night"

Overview of the 2011 Solar Decathlon

Participating Teams, Winners, and Losers

Of the 20 invited schools, 19 successfully completed the required submissions and constructed houses on the Mall (see Table 2 for listing). After three earlier tries, the University of Maryland won the overall competition with their "WaterShed" house. The first and second runners up were Purdue and the New Zealand team, respectively. In the opinion of the authors there were no losers. All of the teams appeared to be totally invested and clearly learned a great deal from their own efforts and what was shared by other teams, and all contributed to the overall energy and excitement surrounding the event. Some of the most innovative designs did not perform well, probably as a result of the continually cloudy and rainy conditions under which the Decathlon was conducted.

Event Statistics

DOE reported the following statistics on attendance and public outreach:

- 1,200 online articles
- 250 print articles
- 357,000 house visits
- 5,000 tours by middle school students and teachers
- VIP coverage from Capitol Hill members and staff

Scoring

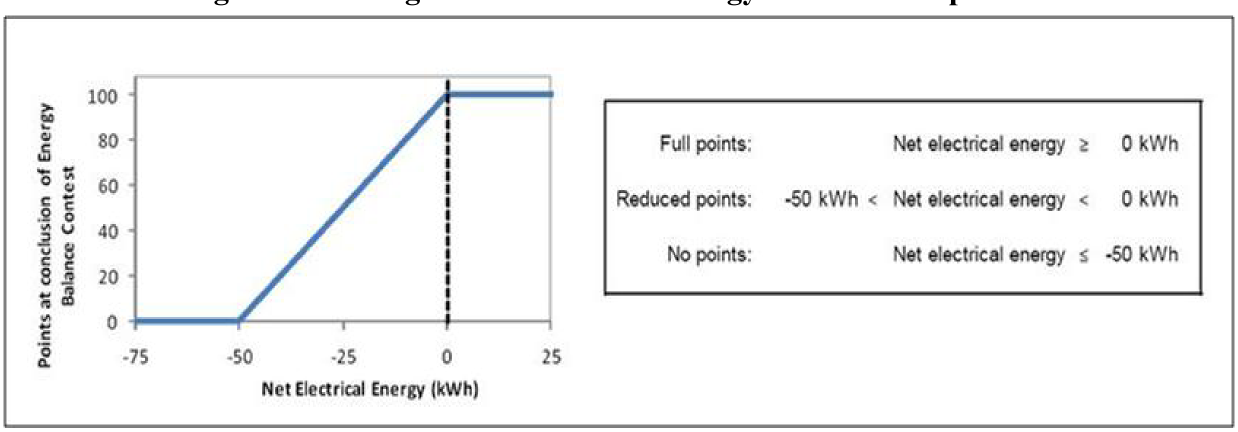
Results

Final scoring and ranking for the teams in categories related to energy performance, as well as the overall results, are listed in Table 2. Scores for other categories are available on the Solar Decathlon website.

Energy Balance scores are based on the ability of the houses to produce as much electricity as they consume on a net basis over the weekly competition period as shown in Figure 2. Given the cloudy weather conditions and demanding competition requirements it is remarkable that seven of the teams achieved a net zero (or better) energy balance.

If the results are viewed strictly from the perspective of how well the houses and systems performed to provide comfort and hot water and minimize energy use, the ranking would be different than the overall results. Giving equal weight to Energy Balance, Comfort Zone, and Water Heating categories would put New Zealand on top followed by Purdue, Tennessee, and the overall winning team, Maryland.

Figure 2. Scoring Function for the Energy Balance Competition



Source: U.S. Department of Energy Solar Decathlon Rules, 2011

Table 2. Selected 2011 Scoring Results

Team	Engineering		Energy Balance		Comfort Zone		Water Heating		Overall	
	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking
Maryland	89.85	4	100.00	1	73.19	14	100	1	951.15	1
Purdue	88.84	6	100.00	1	91.82	5	99.75	3	931.39	2
New Zealand	92.55	1	100.00	1	98.65	1	100	1	919.06	3
Middlebury College	83.02	11	83.23	4	81.63	7	97.375	5	914.81	4
Ohio State	89.38	5	88.59	3	56.4	19	100	1	903.94	5
SCI-Arc/Caltech	90.47	2	100.00	1	61.83	17	100	1	899.49	6
Illinois	73.05	16	100.00	1	72.66	15	98.25	4	875.72	7
Tennessee	89.94	3	100.00	1	88.2	6	100	1	859.13	8
Team Massachusetts	84.34	9	96.16	2	64.6	16	96.375	6	856.35	9
Team Canada	83.09	10	56.01	5	77.9	11	99.5	2	836.42	10
Florida Int'l	71.50	17	100.00	1	78.72	10	86	9	833.16	11
Appalachian State	80.78	13	36.58	6	80.34	9	100	1	832.50	12
Parsons NS Stevens	86.45	8	35.17	7	81.07	8	100	1	828.82	13
Tidewater Virginia	64.30	19	0.00	9	96.14	3	93.75	7	774.91	14
Team China	87.42	7	3.59	8	74.63	13	93.75	7	765.47	15
Team Belgium	73.55	15	0.00	9	77.35	12	89.688	8	709.84	16
Team New York	81.65	12	0.00	9	61.35	18	62.5	11	677.36	17
New Jersey	78.30	14	0.00	9	92.88	4	85.688	10	669.35	18
Team Florida	65.95	18	0.00	9	98.53	2	0	12	619.01	19

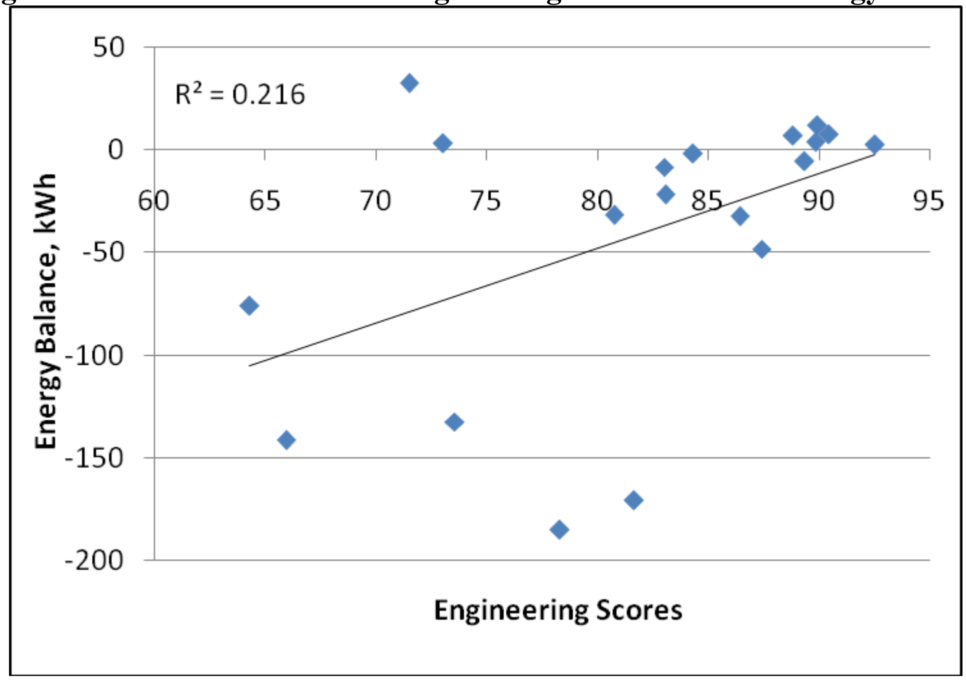
Source: www.solardecathlon.org

Analysis of Energy-Related Scores

An analysis of the data from this competition can be useful in planning future Solar Decathlons, can help guide future competitors, and can also be instructional to homebuilders and policymakers who have their eye on the net zero energy goal. One question that interested the authors is, how well can the performance of a building be judged from a qualitative review of the designs and the houses as built? Figure 3 suggests the judges opinions were headed in the right direction, but there were some surprises. The 20 minutes allocated for each tour was not sufficient to accurately predict the energy balance rankings. Also, higher scores assigned for thorough documentation and quality of presentations did not count towards the energy balance results, yet teams deserve credit for displaying excellence in these areas.

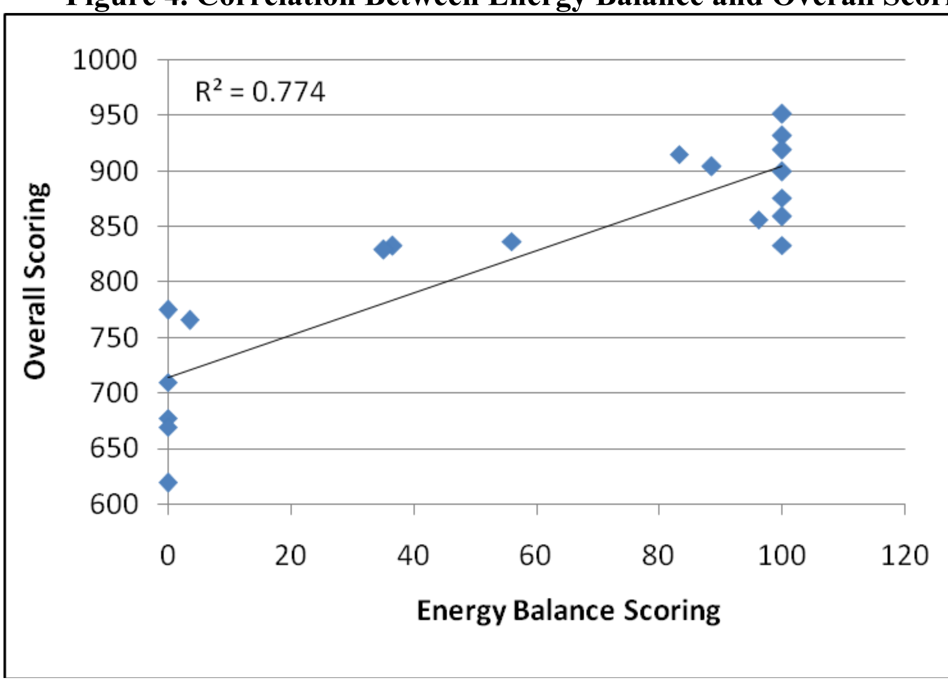
Given that there are many contests that are not related to the energy performance of the buildings, it is interesting to observe how much the Energy Balance scores might have influenced the overall results. Figure 4 shows that those that did well in the Energy Balance category also excelled in the overall ranking. Since the top three teams had energy balance scores of 100, it could almost be concluded that projects require a high energy balance score to be in the running for the overall competition.

Figure 3. Correlation Between Engineering Scores and Net Energy Balance



Source: National Renewable Energy Laboratory Data

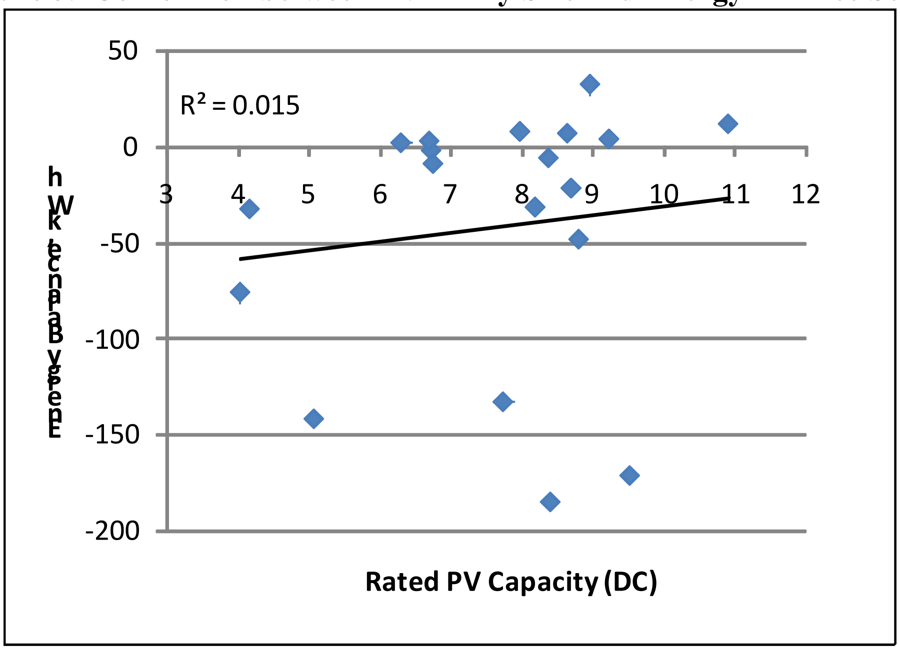
Figure 4. Correlation Between Energy Balance and Overall Scoring



Source: National Renewable Energy Laboratory Data

It would seem that higher Energy Balance scores can be obtained by brute force by maximizing the size of the PV array, it is of interest to see whether there was a correlation between the size of the arrays and Energy Balance scores. Figure 5 plots the correlation between PV array size and Net Energy Balance. Given the low coefficient of determination, other factors played a much more significant role in the net energy balance outcomes. Advocates of applying energy efficiency before on-site generation will be pleased to learn that energy efficiency can trump large PV arrays. The winning Maryland team had the 3rd largest array, and second-ranked Purdue had the 7th largest. New Zealand placed third overall and scored 100 with one of the smallest arrays (6.3 kW_{DC}).

Figure 5. Correlation between PV Array Size and Energy Balance Score



Source: National Renewable Energy Laboratory Data

Climate and Transportation Challenges

Many of the teams were challenged to design buildings tuned to their home climates, but that also compete well under the cloudy Washington, DC skies and humid environment. Several, including the Canadian, California, Belgium, and New Zealand houses were designing for quite different climates. The Canadian house would not have needed air conditioning in its home climate, but it was required to maintain the requisite indoor conditions in the Washington climate. Both Team China and Team Belgium used very creative methods to construct houses that would survive their journey across the sea. Belgium used an "erector set" approach, while China built their house out of shipping containers. Dealing with the practicalities of transportation probably diverted resources away from features that would have helped the teams achieve higher scores. Such are the limitations of an international competition that is staged in one location. A team of Chinese delegates were very closely observing the process in preparation for holding a similar competition on their own soil.

Highlights Related to Energy Performance of the 2011 Projects

Several teams had stand-out designs that displayed great innovation in their approach to controlling building energy loads and handling them with mechanical systems. It is useful to look at these innovations and how they may have contributed to the performance of the outstanding homes.

Architectural/Structural Innovations

Nearly all of the houses employed highly insulated enclosures using SIP's or advanced framing with wall R-values exceeding 40 in most cases. Many used triple pane windows to improve thermal performance. Some competitors also included thermal mass in their structures. China used a combination of rigid foam and phase change materials (PCM's) to cover their steel shipping containers. Incredibly, Rutgers erected a structure composed of concrete panels with EPS foam sandwiched in the middle. They claimed their house weighed more than all of the others in the competition combined. With the mild and nearly constant temperature conditions during the evaluation period and the high occupant loads, the high performance wall systems and houses that utilized thermal storage were not given a proper test.

The most visually unique project was the Southern California Institute of Architecture & CalTech entry pictured in Figure 6. The usually shaped structure was insulated on the exterior using a vinyl-covered quilt of recycled denim, thus eliminating penetration of insulation by structural members.

Figure 6. The Southern California Institute of Architecture & CalTech Team House

Photo Credit: David Springer

Innovative Systems

Most teams incorporated one or more innovative design features that set them apart from the other competitors. Many used custom home automation controls that operated building systems and displayed electric use of various loads, PV production, and indoor and outdoor conditions. Some of the more notable innovations included:

- **New Zealand**: An indoor drying cabinet incorporating racks made of piping for hanging towels and clothes, heated by the solar water heater and hydronic heating system.

- **University of South Florida**: A liquid desiccant dehumidifier that circulates a calcium chloride solution over a "waterfall".

- **Virginia**: A south facing sunspace with PCM under floor tiles, and automatically controlled windows that connect the space with the house.

- **Purdue**: An attractive "biowall" that purifies indoor air.

- **Tennessee**: A double glass façade on the north and south with blinds in between the glass, and a circulation system that moves air from the inner window space to where heating or cooling is needed.

- **Parsons**: A condensing dryer that receives waste heat from the heat pump water heater.

- **Appalachian**: A PCM (bees wax) thermal storage tank for heat collected from roof mounted thermal collectors instead of a typical hot water tank. Trombe wall with louvers containing PCM material.

- **Florida International**: Shade structures that can be rotated downward to become hurricane shutters for windows.

- **Maryland**: A liquid desiccant "waterfall" dehumidifier that circulates a lithium chloride solution that is regenerated with solar thermal energy.

- **SCIA/CalTech**: Custom constructed desuperheater heat recovery from the mini-split heat pum for water heating, X-Box lighting controls, single button to shut off lighting and plug loads.

- **Ohio State: A** desiccant wheel that was regenerated with heat from a solar air collector.

- **New York**: Solar thermal system coupled to PCM storage which supplies an adsorption chiller and the domestic hot water system.

The City College of New York's mechanical system was certainly the most bold attempt at providing efficient heating and cooling. Unfortunately, the weather did not cooperate making it necessary for them to use electric resistance to melt the paraffin used for phase change storage.

Features of the Best Performing Designs

To identify the top performing designs from an energy perspective, "energy scores" were tabulated by giving equal weight to Energy Balance, Comfort Zone, and Water Heating judging categories. This approach accounts for the energy consumed to provide comfort and hot water, as well as the PV and solar thermal energy produced to offset energy use. Table 3 lists the top five performers (with energy scores in parenthesis), and correlates the design features used by each of the houses. Given more extreme weather conditions and sunshine, the results of this contest may have been completely different.

All houses had exemplary building enclosures. The Tennessee team incorporated a window system to actively capture and reject heat. Except for Illinois and New York, mechanical systems in all houses were kept simple by using mini-split heat pumps and ERV's. All teams except Maryland installed heat pump water heaters. Both New Zealand and Maryland incorporated solar water heaters with evacuated tube collectors. Except perhaps for Tennessee's window system and SCI/CalTech's desuperheater for water heating, it is unlikely that the innovations that were incorporated contributed significantly to energy performance.

Table 3. Design Features of the Top Five Energy Performers

Team	Enclosure	Mechanical	PV kW	Other
New Zealand (99.6)	R33 walls, R37 roof, R31 floor, triple pane windows, U-0.16	Ducted mini-split heat pump, ERV, heat pump water heater, solar water heater with evacuated tube collectors	6.3	2" topping slab for mass, hydronic clothes drying cabinet
Purdue (97.2)	R26 walls (SIP), R56 roof, triple low-e windows with high SHGC on south	Ducted mini-split heat pump, ERV, heat pump water heater, dehumidifier	8.6	"Biowall" with water supplied from dehumidifier
Tennessee (96.0)	R30 (?) enclosure. Triple inner & single outer windows with 12" airspace and blinds in between	Mini-split with two heads and RH control, ERV, heat pump water heater	10.9	In summer ERV draws outdoor air through north window space and exhausts to outdoors through south window space. Operation reverses in winter. Blinds controlled automatically.

Team	Enclosure	Mechanical	PV kW	Other
Maryland (91.0)	R48 walls, R51 roof, double windows (U-0.22 to 0.30, SHGC-0.14 to 0.32)	Mini-split heat pump with two heads, ERV with solar reheat coil, solar water heating with evacuated tube collectors	9.2	Liquid desiccant dehumidifier in two locations
Illinois (90.3)	R45 walls, R60 roof, triple pane heat mirror windows	"CERV" integrated heat pump with indoor compressor, ducted supply, ERV, heat pump water heater	6.7	Stand-alone conventional dehumidifier

Source: Engineering Panel Observations and NREL Data

Summary

The Solar Decathlon is a very well managed and coordinated event with well-defined rules, judging procedures, and scoring rubric. It is unfortunate that judges have so little time to spend with the houses, but compromises must be made to prevent the event from lasting longer and further taxing DOE and NREL staff, competing teams, and other participants. Despite the dilution of building performance scoring by contests that do not directly impact energy use or production, performance was a key factor in the winning teams' strategies. More extreme weather conditions likely to be experienced at other venues will result in a wider spread of energy performance than seen in Washington DC. Studying results of the 2011 Solar Decathlon will provide useful guidance to future competitors.

If the 2011 Solar Decathlon is any indication, this event serves as a superb training ground for students who will become the next generation of architects, engineers, planners, policy makers and communicators who will have the skills and knowledge to meet the national challenge of reducing dependence on foreign energy sources. The participating students demonstrated their ability to assemble buildings that are as good as or better than anything being built by professional builders today. The creativity and energy with which the students produced and presented their zero net energy designs under unfavorable circumstances and difficult schedules, all while meeting other educational and personal obligations, was widely evident and gives one hope for the future.

References

[DOE] U.S. Department of Energy. 2011. *Solar Decathlon Rules*. Updated August 25, 2011. http://www.solardecathlon.gov/pdfs/2011_rules.pdf Washington, D.C. U.S Department of Energy, Office of Energy Efficiency and Renewable Energy.

Hicks, D. 2007. "Changing Behaviors: Market Transformation Web Sites as Online Narrative." In *2007 Summer Study Proceedings, American Council for an Energy Efficient Economy*. Washington, D.C.

Kaarsberg, T. 2012. "The Incredible, Affordable Solar Decathlon 2011". In *Home Energy*. March/April 2012. Berkeley, CA.

[NREL] National Renewable Energy Laboratory. 2011. "Solar Decathlon 2013: Request for Proposals." Golden, Colorado.