The Dynamic Double Façade: An Integrated Approach to High Performance Building Envelopes

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ABSTRACT: The LivingLight house, an entrant in the 2011 Department of Energy Solar Decathlon, incorporates an innovative dynamic double façade system. This paper details key features of the façade system including aesthetic integration of technical components, natural and electric illumination, design of shading devices, and use of the façade cavity to harness solar-thermal energy.

KEYWORDS: Smart Façade, Double Façade, PV Technology, Automated Building Control Systems.

INTRODUCTION

This paper details key features of the integrated façade system developed for the LivingLight house. The house, one of twenty entries in the 2011 Department of Energy Solar Decathlon, resulted from a collaborative effort between students and faculty of Architecture, Mechanical Engineering, Electrical engineering, Graphic Design, Landscape Architecture, Interior Design, and Business. In addition to meeting the contest criteria of achieving a zero-net energy balance through the use of solar-electric power, the LivingLight house proposes an innovative double façade system to passively harness solar-thermal energy. Although integrated into a small house for the competition, the façade system lends itself well to commercial and residential applications in both retrofit and new construction. The façade resolves the multiple aims of its diverse design team and proposes a new aesthetic expression for an emerging building technology.

Concept

Through a series of multidisciplinary charette sessions early in the project, the team developed a set of six principles to focus design decisions (Figure1):

Figure 1 six key design principles

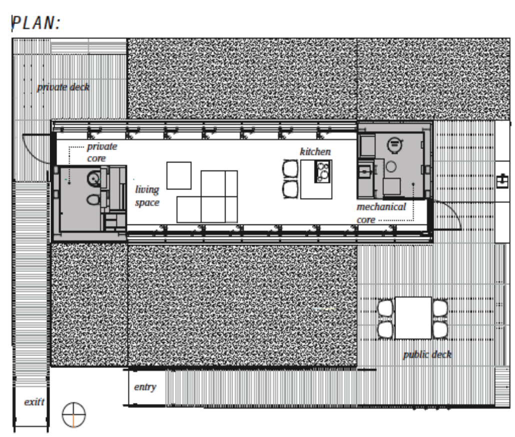

Figure 2 Floor Plan Living Light House

Two dense cores pushed to the perimeter of the space leave the living area free, opening it up to exterior views and maximizing daylighting capabilities (Figure2). These two cores organize the daily routines of life.

The public core contains most kitchen appliances and is near the mixed-use island accommodating dining and food preparation. The millwork of the public core can be entirely closed to hide its function while the island extends to accommodate from two to eight people. The opposite core contains the more private elements of the bed and bath. The adjacent entertainment center acts as a footboard and defines the space of the bed when in use and folds out to become a desk when the pull-down bed is stored. The proportions of the home are strictly limited by our transportation method, which dictates the maximum dimensions in height, length, and width. These tight restrictions however allow us to create a single, airtight volume.

The design of the LivingLight house owes equally to the precedents of the Cantilever Barn of Southern Appalachia and Mies van der Rohe's Farnsworth house. The simple formal and climatic strategies of vernacular architecture inspired the use of passive energy systems while the elegance of the modern glass box lead to the development of an energy efficient transparent façade (Figure 3).

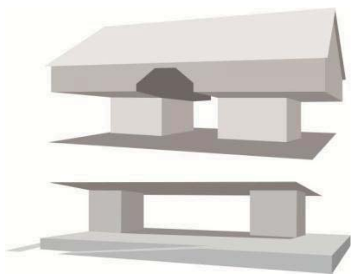

Figure 3 Shown on top, a diagram of the Cantilever barn and on the bottom, the LivingLight house
The Illustration shows the transformative approach of using the vernacular forms of the Cantilever Barn as a strategy to organize space in the LivingLight house. Support spaces are arranged as two dense cubes of program framing the open living space in between.

The Living Light house makes extensive use of glass for transparency, daylighting, and spatial connection to the surrounding environment. A dynamic double façade system, made up of interior high-performance insulated glazed units and a single-pane exterior, is implemented along the majority of the north and south facades.
These facades become the stage upon which the building comes to life. Sandwiched within the façade cavity is a motorized horizontal blind system that blocks sunlight and heat before it reaches the conditioned space. The blind system is programmed to provide proper lighting and shading throughout the year as well as provide privacy when desired. The cavity within the system is integral to the mechanical system of the home as a means to thermally buffer incoming fresh air and to moderate heat gain and loss.

1.0 Aesthetics and Experience

In the LivingLight house the ubiquitous glass façade is re-imagined as a transparent wrapper that simultaneously resolves dissimilar interior and exterior design criteria. From the exterior the outer layer of the façade appears taught, flat, and monolithic. Depending on time of day its appearance varies from reflective to transparent, becoming a glowing lantern at night.

Figure 4 Exterior view of the south Facade of the LivingLight house from the public deck. The glazing appears dark and reflective, contributing to the reading of the glass house as monolithic and private. Cylindrical photovoltaic modules extend over the glazing to provide shade.

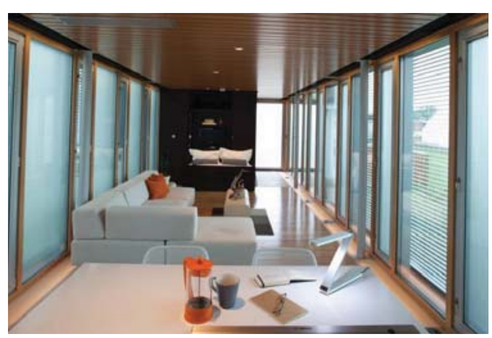

Figure 5 Interior view of the open, loft-like, living space. Alternating translucent and transparent glass panels help provide privacy to the public front and more extensive views to the private back. The large expanse of glass also allows the house to be naturally lit during the daytime.

By contrast, the interior layer of the façade has expressed oak-clad mullions defining a rhythm of transparent, translucent, and operable glazed panels. The wood mullions lend warmth and scale to the residential interior and harmonize with the other wood surfaces. From the earliest stages of design, the intent has been to incorporate technological systems at an aesthetic level. Lighting, ventilation, and shading are all given an integrated architectural expression in the façade. Given the constraints of a relatively small area and high-energy efficiency, the LivingLight house celebrates the luxuries of transparency, natural illumination, and abundant space.

2.0 Solar Photovoltaic System, Mechanical Systems, Home Automation System

The integrated roof-top array not only supplies two times the amount of energy to power the home, but it also shades the home's south facade. The 10.9-kW array employs a cylindrical module, so that direct, reflected, and diffused sunlight is captured across a 360° photovoltaic (PV) surface while maintaining a low profile (Figure 6).

The home is optimized to be controlled by a home automation system while providing the user with vital information about the house so they are able to make educated decisions about their energy usage. Lighting and operation of blinds located in the air space of the double facade are also controlled through the automation system (Figure7).

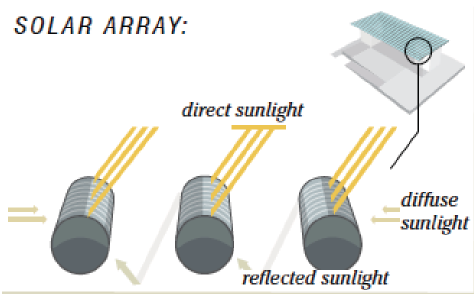

Figure 6 Diagram - Sylindra PV system

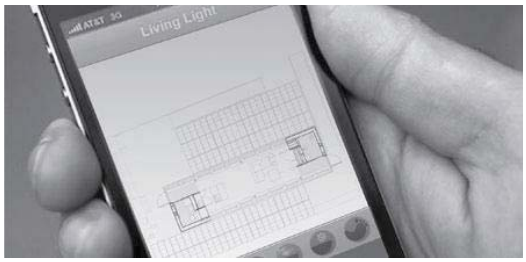

Figure 7 Home Automation System Interface

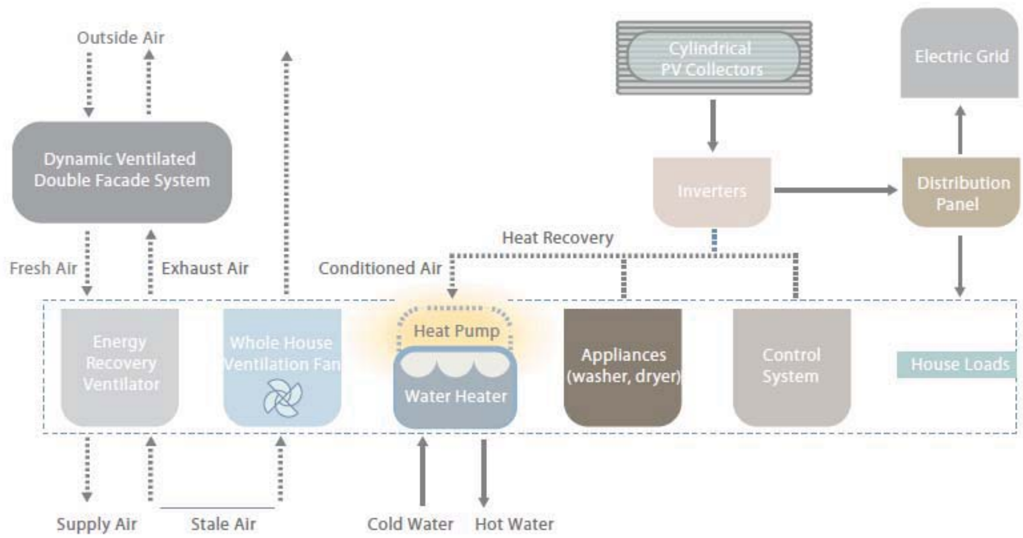

Figure 7 The mechanical room centralizes all of the mechanical, electrical, and plumbing systems.

3.0 Illumination

Control of both of natural and artificial light is incorporated into the facades. Daylight is controlled through motorized 2" Somfy blinds mounted between the inner and outer layers of both long facades. These blinds may be adjusted directly by the occupant through the mobile touch pad interface, programmed to follow a schedule, or set to maintain a preset illumination level. The blinds are divided into five-foot units on the module of the exterior layer of the façade and can be controlled simultaneously or in groups. In order that both natural and artificial light come from the outside walls, electric light sources are built into a strip at the floor and ceiling just inside the inner façade.

Figure 8 The lighting can be easily adjusted to pre-set 'moods' from the home automation system. The dinner party mood is illustrated in the interior view to the left. The LED lighting strips help create a unique and memorable ambiance.

Figure 9 LED lights arranged in strips embedded in the floor vary in color and intensity. All light coves and luminaires change colors from a "warm" 2700 k to neutral 4000 k and daylight 5400 k. This allows different lighting actions in different areas, taking care of physiological and psychological needs. For example: Bedroom lighting is activated when the alarm clock sounds.

The ceiling strip lights are high efficiency linear fluorescents with step dimming to provide general, ambient illumination. The floor lights are three-color strip LED fixtures mounted beneath textured and tempered glass panes. The floor mounted LEDs are capable of producing warm white or a full spectrum of colors and can be controlled independently or in groups. The blinds and lighting are linked to the central home automation system. The full functionality of all systems is available to the occupant directly through the mobile touch pad interface or pre-programmed 'moods' may be selected. For instance, setting the *dinner party* 'mood' sets the blinds to open, turns on the LED spot over the dinner table, selects dim warm white floor illumination and edge-lights the canopy over the front door (Figure 8/9). Selecting the *bedtime* 'mood' closes the blinds, turns on a dim night-light in the bathroom, and awakens the occupant at the pre-set time with gently increasing sunrise hues in the floor lights.

Construction

Although novel in approach and form, the double façade system is assembled from standard components. The LivingLight team worked closely with manufacturers to make the best use of their existing product lines. The aluminum framing systems for the inner and outer layers of the façade were selected to optimize performance and economy for their particular functions. The outer layer is framed with Kawneer TriFab VG 451 components with concealed vertical mullions.

Figure 10 Section through the south façade from BIM model Figure 6 Façade elevation

In keeping with the function of the outer layer as air barrier and heat reflector, its framing system is not thermally broken and its 9/16” laminated glass from AGC has low-e hard-coating facing the interior of the façade cavity. In contrast, the inner layer is the primary insulating system. It makes use of thermally broken Kawneer 7500 series curtain wall components and 2” insulated glazed units from Serious Materials. The IGUs are made up of two panes of ¼” tempered glass sourced from AGC with two additional internal films and are filled with argon gas for an R-value of 11 (Figure 10).

The primary reason that storefront and curtainwall systems were chosen for this project was their relative ease of customization. These systems allow for facades to be tuned to exact energy efficiency, privacy, and operability requirements. The inner layer of the LivingLight façade incorporates operable thermally broken ISOWEB casement windows, translucent and transparent insulated glazed units, and white oak veneered mullion caps. Additionally, aluminum framing systems lend themselves to retrofit applications and greater ease of maintenance. In the LivingLight house, the layers of the façade are structurally independent of one another with the outer layer being exterior glazed and the inner layer being interior glazed. This allows for the replacement of damaged glass from either side and opens up exciting possibilities for adding a second façade layer to existing buildings with minimal impact on structure or tenants.

4.0 The Dynamic Double Façade

The Living Light house makes extensive use of glass for transparency, daylighting, and spatial connection to the surrounding environment. A dynamic double façade system, made up of suspended film, highly insulated (R-11) interior glass and single-pane exterior glass, is implemented along the majority of the north and south facades of the home. Alternating translucent and transparent panes allow for views of the landscape while maintaining a sense of privacy for the occupant.

The north and south facades become the stage upon which the building comes to life. Sandwiched between the two panes of glass is a motorized horizontal blind system which blocks solar radiation, or sunlight, before it reaches the conditioned space. The blind system is programmed to provide proper lighting and shading throughout the year. It also provides more privacy when desired. The cavity within the system is also integral to the mechanical system of the home.
Development of the energy efficiency measures of the double façade required research into four key areas:

- Heat gain in the facade cavity
- Location and type of blinds
- Design of shading overhang
- Integration with ventilation and HVAC

The double façade was designed based on data from both predictive modeling and a constructed prototype. Based on ISO standard 15099, students and faculty developed a code to model heat transfer coefficient and solar heat gain coefficient in the façade. In addition, the WINDOW program (version 6.3.19) created by Lawrence Berkeley National Lab (LBNL) was used to benchmark the new code for SHGC. At normal incidence, WINDOWS predicts a SHGC of 0.70 as compared to the derived number of 0.697. Hence students developed a working code capable of predicting the radiation, convection and conduction occurring in multiple-pane windows (Figure 11).

Category	Modeling Tool(s)
Envelope/Heating and Cooling Loads	EnergyPlus
Double Glass Façade	Analytical Computer Code, COMSOL 4.0a, EnergyPlus
Photovoltaic Power Production	Solyndra Energy Yield Forecast Tool
Appliance and Misc. Electric Load Consumption	Excel
Roof Loads	STAR

Figure 11 Energy Modeling Software

A physical prototype was constructed with south-facing glazing configured in both single and double facades. Both were monitored with thermocouples to measure the temperature gradients between the inner and outer glass surfaces and the air temperature distribution inside the double façade air cavity. Thermocouples were also used to record the exterior and interior temperatures and pyranometers were used to measure the vertical and horizontal solar irradiance incident on the south facing façade. The data shows that for a summer day with strong solar irradiance, the air temperature in the façade air cavity will experience a 10°C temperature gain, under natural convection. In the winter the air cavity showed a 15°C temperature gain due to natural convection (Figure 12).

From this data it was determined that a strategy of exhausting the cavity in summer and admitting the warmed air in winter was feasible. Additionally, it was determined that the inner layer of the façade would need to be substantially insulated. The data suggests areas of future study in the areas of variable blind systems incorporating reflective ad low-emittance coatings.

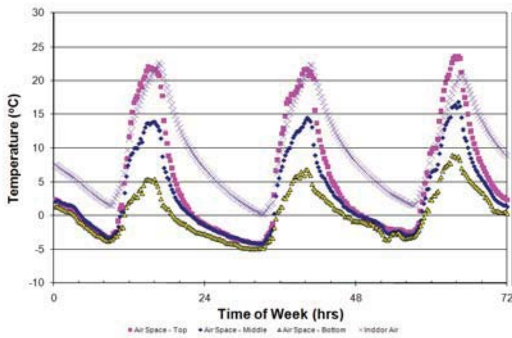

Figure 12 Winter façade cavity temperatures

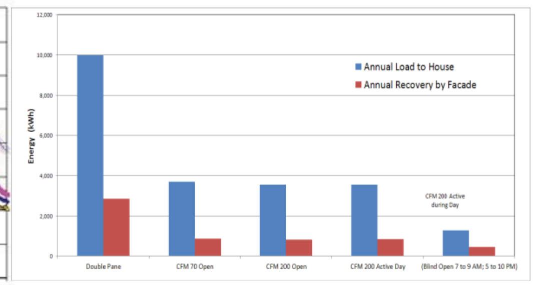

Figure 13 Optimal façade configurations and energy balance

A model of the LivingLight house was created with EnergyPlus software. The model was first run to simulate performance over a full year with a standard window of double pane glass as control and compared to multiple runs with the double façade in varying configurations of cavity airflow and blinds. The optimum configuration was achieved with the cavity ventilation at 200 cfm (set by the Energy Recovery Ventilator) during daylight hours only with the blinds open from 8 AM to 10 AM and 5 PM to 10 PM only. This scenario seems to track well with actual occupancy of the home and yields a 90% reduction in house load comparable to the control case (Figure 13). All models predict some condensation forming on the exterior façade in the early morning hours.

Simulations were created using EnergyPlus software to model the effect of thermal loading on the façade with blinds in the cavity, inside the conditioned space, and without blinds. Contributing interior loads were calculated based on the Building America (BA) Research Benchmark Definition. It is important to note that the software was unable to calculate the active airflow of the unique double façade therefore the model introduces some error by approximating performance with an unventilated cavity. Even so, the study proved that blinds exterior to the conditioned space reduced the cooling energy by 47.4%. Placing the blinds in the cavity allows for the best performance between summer and winter conditions (Figure 14). The heat radiated to the cavity by the black blinds can be scavenged in winter and exhausted to the exterior in summer.

Energy Plus Results	Max Heating Load (Btu/hr)	Total Heating Energy (kBtu)	Max Cooling Load (tons)	% Difference in Max Cooling Load	**Total Cooling Energy (ton-hrs)**	**% Difference in Cooling Energy**
No Shading	15,656	16,003	2.24	0	**3,231**	**0**
Interior Shading	16,662	17,399	2.39	+6.7%	**3,365**	**+3.8%**
Exterior Shading	15,419	16,185	1.26	-43.8%	**1,700**	**-47.4%**

Figure 14 Blinds analysis results

In addition to studying the blinds, the EnergyPlus model was used to predict the effect of horizontal shading on the south façade. The analysis was run with no overhang and again with an overhang of 50% transmittance. The model overhang was based on the LivingLight house's cylindrical CIGS-based photovoltaic panels with a horizontal projection optimized to block summer sun and allow lower angle winter sun. The benefit of the shading provided by the overhang is an additional 18% reduction in cooling energy (Figure 15). [1]

	Max Cooling Load (tons)	Total Cooling Energy (ton-hrs)
No Overhang	2.69	3,940
PV Overhang (50% transmittance)	2.24	3,231
Percent Difference (%)	16.7%	18%

Figure 15 Shading overhang analysis results

The Living Light house uses a dynamic envelope strategy utilizing an ERV (Energy Recovery Ventilator) and passive solar heating from the double glass façade. The home automation and control system allows easy control of the three ventilation schemes including heating, cooling, and whole house ventilation.

In the cooling mode, fresh air will be introduced to the space through the north façade and the relatively cool air will then exchange heat in the ERV with the stale air being exhausted through the south façade, thus cooling the cavity (Figure 11). In the heating mode, the air flows through the façade cavities will reverse (Figure 12). Solar irradiance will heat the south façade cavity so that fresh air pulled through it will increase in temperature. Stale air will be exhausted through the north façade, heating the cavity, which helps to buffer any additional heat losses. The heating and cooling modes of operation are depicted below.

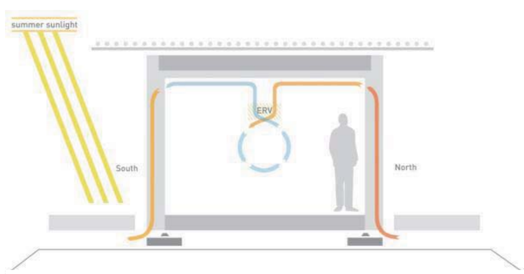

Figure 11 Summer cooling mode showing ventilation through the double façade.

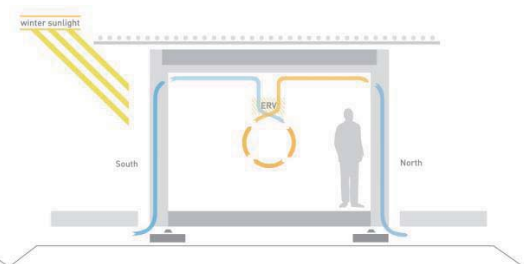

Figure 12 Winter heating mode showing ventilation through the double façade.

The whole house ventilation scheme takes advantage of favorable outdoor conditions during which temperatures are between 60 and 76 °F with relative humidity near 50%. This comprises 25% of the year in Southern Appalachia and is comparable to weather patterns in the competition city of Washington D.C. When these conditions arise, the automation system alerts the occupants that whole house ventilation is an energy saving strategy. Should the occupant wish to use this setting, they may select it and open the operable windows of the north façade to bring in the cooler fresh air while keeping the south windows shut to reduce heat gain. This setting will turn off the mini-splits and allow a small duct fan to ventilate the entire house. About 70 kWh of cooling energy, about 6%, can be saved using this mode.

This is an important feature of the Living Light house as it demonstrates the possible energy savings in buildings with inefficient cooling systems. It was expected that this system would save more energy but because of the efficiency of the mini-splits, the savings of this system were reduced. [2]

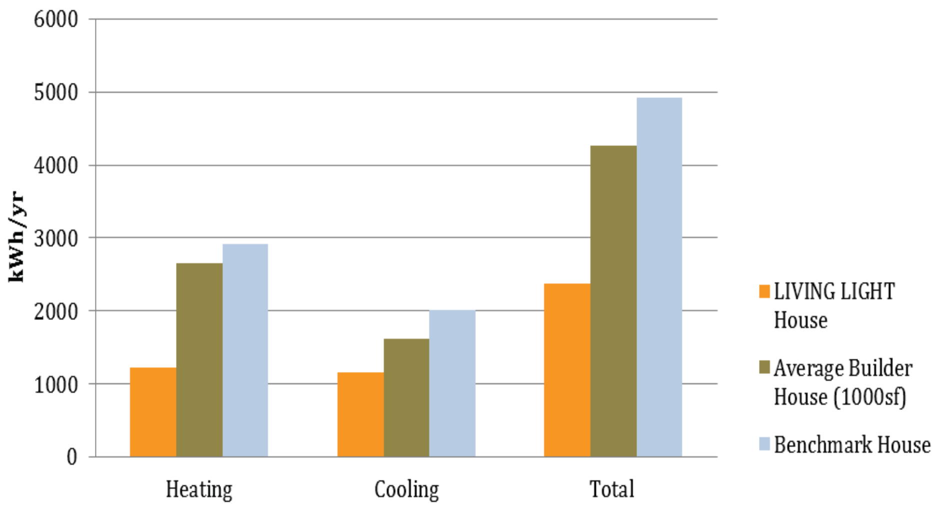

Figure 13 Heating and cooling comparison

The energy recovery ventilator (ERV) is used to ventilate while minimizing energy loss in the Living Light house. The ERV exchanges sensible and latent heat between fresh and stale (exhaust) air streams. When the outside temperature is relatively low, the ERV pre-heats and adds humidity to the incoming fresh air. In the summer months or when the temperature is relatively high outside, the ERV pre-cools and dehumidifies the incoming fresh air. The utilization of the ERV in the Living Light HVAC system helps to reduce heating and cooling costs normally associated with bringing in fresh, outdoor air (Figure 13).

5.0 Future research

The LivingLight house is currently touring cities in the region as an outreach, education, and engagement tool for sustainability and energy efficient building technologies. After the tour, the LivingLight team has plans to monitor the home's performance through an embedded sensor suite and weather station. With a year's data in hand, the home will serve as an experiment station for modifications to optimize its performance. A few intriguing lines of research already identified by the team include:

- Studies of the psychological benefits of natural daylighting, variable daylight spectrum LED lighting and biophilia (instinctive positive response to natural materials) in residential environments
- Further net reduction in energy required to heat and cool the home by increasing the airflow through the façade ventilation system
- Methods to eliminate early morning condensation on the outer façade including short periods of reversed ventilation cycle
- Development of new blind materials to variably augment either emissivity or insulation in the façade cavity

CONCLUSION

The value of the LivingLight project can be positively measured on three scales. First, as proof of concept for an innovative double façade system, the house has demonstrated a new technology that is functional, robust, aesthetically integral, and scalable. Second, as a pedagogical tool, the project has created a multidisciplinary platform for the collaboration of multiple departments and opportunities for students to gain hands-on experience with emerging building technologies.[3] Third, the LivingLight house proved to be a strong competitor in the 2011 Solar Decathlon. In addition to securing team standing with its first ever proposal, the house ranked first in Energy Balance, third in Engineering, fifth in Architecture, and eighth overall. [4]

Figure 14 Exterior

Figure 15 Visitors Touring the Living Light House

ENDNOTES

[1] Synopsis of post-competition Mechanical Engineering Final Report compiled by graduate students Steven Coley, Matthew Berwind, Isaac Bosley, and professors William S. Johnson and William S. Miller of the Department of Mechanical, Aerospace, and Biomedical Engineering. Report submitted to DOE and NREL October 24, 2011.
[2] Coley, S. 2012. Symposium Presentation, "University of Tennessee's Living Light House, the Design and Analysis of a Net Zero Energy Home for the 2011 Solar Decathlon," presented at the ASHRAE 2012 Annual Meeting, Chicago, Ill.
[3] E. Stach, J. Rose, A. Howard, "UT Zero Energy House - Sustainable Design-Build as a Teaching Tool", Purdue University, Ray W. Herrick Laboratories, 2010 Purdue Compressor Engineering, Refrigeration, Air Conditioning and High Performance Buildings Conference, 7/2010
[4] Solar Decathlon website, Official Scores and Standings, www.solardecathlon.gov.