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ABSTRACT

Low-energy and passive buildings, particularly in northern climates, typically do not have highly glazed facades as windows are traditionally the least insulating and highest-air leakage component of the building envelope. Most energy standards restrict the window-wall ratio to 40% or less. Although windows provide many benefits that enhance building performance and occupant comfort through passive heating, daylight and views, most of these benefits are overshadowed by excessive window area and lack of solar protection. Consequently, window assemblies are often considered a liability causing problems such as increased heating loads due to daily net-heat loss, glare, and increased cooling loads due to overheating. Most buildings with high window-wall ratios (WWR) are considered to be energy inefficient. However, recent advances in glazing technology, shading systems, thermal mass, and control systems now allow highly-glazed facades to become potential net-energy producers. The 74.3 m^2 (800 ft^2), North House entry into the 2009 Solar Decathlon, placing 4th overall, is a proof-of-concept of how a highly glazed building with a 75% WWR can be a net-positive building completely powered by an on-site photovoltaic and solar thermal system.

1. INTRODUCTION

The North House is an inter-disciplinary, inter-institutional research project with the aim of delivering a prefabricated net-energy positive 800 ft^2 home, designed to respond to the Toronto climate zone, to the National Mall for the U.S. DOE 2009 Solar Decathlon and continuing post-occupancy evaluation. Over 80 students and faculty from the University of Waterloo in Waterloo, Ontario, Ryerson University in Toronto, Ontario, and Simon Fraser University in Vancouver, British Columbia worked collaboratively on a variety of research areas. Five primary inter-related design and research goals were identified that focus on the occupant, system, and building requirements for sustainable living. First, as a House for Climate Extremes, research addresses the challenge of designing for the variable Canadian climate. Holistic Solar Living focuses on generating a lifestyle that maximally incorporates the benefits of the sun while responding to the longer summer and shorter winter days. Thirdly, the Distributed REsponsive System of Skins (DReSS) focuses on providing a responsive envelope system that is capable of adjusting solar gains to maintain occupant comfort while consuming as little energy as possible. The Adaptive Living Interface System (ALIS) integrates controls and sensors with an interactive user interface which empowers the occupant with both system control and feedback. The fifth research aim focuses on creating a series of Customizable Components that extend the aspirations of the North House beyond a single entity to a set of component prototypes that can be applied to future projects. The main approach that the team has taken in developing North House is to determine what levels of performance can be achieved in a low-energy building with current and developing technologies. As a result, economic viability was not a main concern and it is hoped that in the future, the costs of these custom systems will be reduced through production and commercialization at larger scales.

This paper focuses on the design and performance of Distributed REsponsive System of Skins (DReSS) and how it relates to the overall passive heating and cooling strategies deployed by North House. Space heating demands dominate all other energy end uses in buildings in northern climates. Therefore, to develop a low-energy building, it is important to minimize this load by using a highly insulated thermal envelope and make use of passive solar heating. Unfortunately the lack of solar availability during the winter months makes it difficult for traditional passive designs to be effective due to the requirement for larger glazing areas. The DReSS strategy is a unique alternative to traditional static passive design as it provides a dynamic facade composed of shading and high performance glazing layers that allow a higher WWR to increase solar gain and daylighting. The components of DReSS are a highly insulated opaque building envelope that isolates interior temperatures from changes in outdoor temperatures, a dynamic shading system to manage solar gain, a high-performance glazing and frame system to ensure daily heat gains are not outweighed by nighttime losses, and finally in-floor phase change material for thermal storage and interior temperature regulation.

DReSS is fully responsive. An integrated control system that actively responds to changing indoor and outdoor conditions manages the various components to maintain building performance and occupant comfort through passive means, limiting the need for the active mechanical system. This freed the design team from the constraints of traditional static passive strategies, characterized by relatively low WWRs and allowed a highly glazed envelope to expand the small 42 m^2 (454 ft^2) living space to encompass the entire landscape and connect the occupant visually to the outdoors. DReSS allowed the project to combine a specific design ambition with the performance of a low-energy building.

2. DReSS: A PASSIVE DESIGN APPROACH

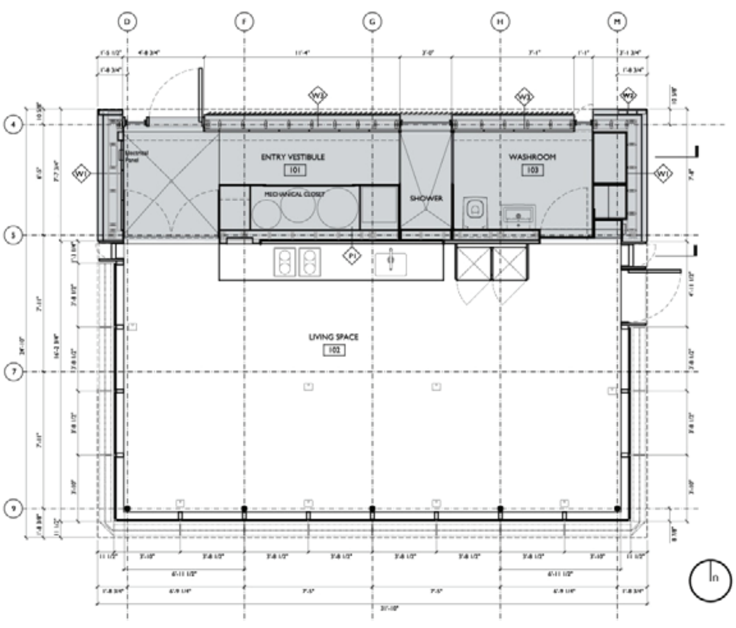

Figure 1: North House Plan showing *densepack* to the north.

2.1 Form

The design and engineering of North House was driven by the unique constraints of the Solar Decathlon, the most important two being a solar envelope preventing shading of adjacent sites, and the constraints of shipping. Assembly, disassembly and shipping provided challenges for detailing an airtight envelope as well as informing dimensions and building planning. The design team developed a panelized component system for the glazed living space anchored to a rigid service module, dubbed the *"densepack"*, containing the HVAC system, services, washroom and kitchen hook-up. The heavily insulated densepack faces north and contains minimal glazing and an airlock entry to prevent drafts in the adjacent flexible living space. Fully glazed, this space extends into the landscape, dissolving the boundary between inside and out. With this design, the house takes on a compact form that has a greater internal volume to surface area ratio, ideal for minimizing space-conditioning loads. The fully glazed south-, east-, and west-facing facades with the exterior mounted dynamic shading system combined with the highly insulated opaque components of the envelope creates an enclosure that manages solar gain, glare and daylighting, and allows daytime gains to outweigh nighttime losses.

2.2 Opaque Assembly

The first component of the DReSS system is the opaque assemblies forming the envelope of the *densepack*, roof, and floor panels. Typical of cold-climate low-energy design, a very high thermal resistance was set in early schematic designs using building simulations to determine the acceptable minimum thermal resistance values. Hygrothermal analysis performed with WUFI suggested that a fully vented rainscreen wall system should be used for the vertical faces of the assembly. This design allowed for the use of Building Integrated Photovolatic Panels (BIPV) as the exterior cladding layer on the east and west walls, thus combining electrical power generation with the building envelope. These panels, in combination with south facing panels incorporated into the fascia, effectively extend daytime electrical power generation of the home to the early and late parts of the day as well as the shoulder and heating seasons characterized by low sun angles.

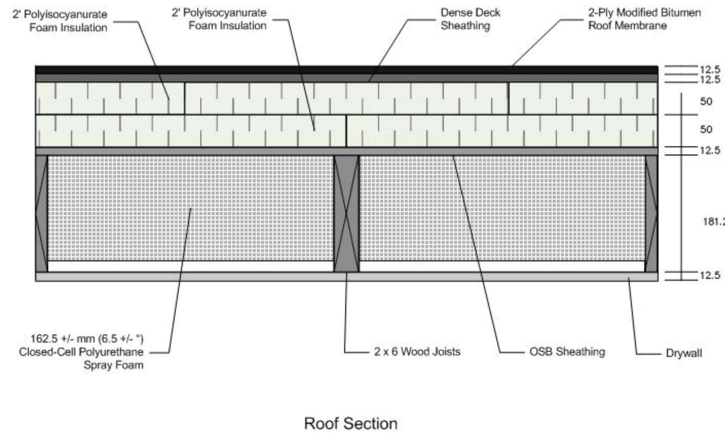

Figure 2: North House Roof Section

Careful structural framing design avoided thermal bridging. The *densepack* uses offset 2 x 4 and 2 x 6 FSC-certified wood studs to create a continuous 254 mm (10") thick assembly with no through-and-through thermal bridges. The cavities were filled with R-7.2/inch polyisocyanurate foam insulation to create an airtight R-72 enclosure. Offset studs also allowed interior and exterior requirements for framing to be separated, allowing the 2 x 4 studs to be spaced at an average of 610 mm (24") to match the mounting system for the cladding panels. The 203 mm (8") thick roof panels were wood framed with foam insulation and an average 100 mm thickness of continuous sloping insulation, creating a total thermal resistance of R-70. Floor panels were 203 mm (8") thick for R-57 and are intended to be installed on an insulated crawl-space in a final installation. To maintain air- and water-tightness during the temporary installation, compressive foam gaskets, at 80% compression, were installed at joints.

2.3 Responsive Dynamic Shading System

One of the most unique features of DReSS is the automated Dynamic Shading System. With a highly insulated building envelope and highly glazed facades, the inherit risk of overheating can negate the benefits of passive heating. In order to mitigate this risk, an effective shading device is required to control solar gain. Numerous options, products and assemblies have been investigated by the design team and included fritted glass, aluminum louvers on custom designed motors, fabric textiles, sliding grilles and exterior venetian blinds. All of these options are technically adequate, but provide a range of technical and installation challenges. The venetian blind system was selected as an off-the-shelf lightweight modular product designed specifically for exterior applications. The blinds include a proprietary controller that is able to automatically adjust the slat angle to the position of the sun through solar positioning based on the facade's latitude, longitude and orientation. This offers a high degree of control that allowed designers to create four modes of operation: fully retracted to allow solar gains and daylight, deployed with slats parallel to the sun for direct solar gain, deployed with slats perpendicular to the sun to block direct solar gains, and fully closed to block off all solar radiation. To make the dynamic shading system responsive to both indoor and outdoor environmental conditions, custom drivers and algorithms were developed to allow it to interface with the Central Home Automation System (CHAS). The CHAS monitors interior and exterior temperature, and relative humidity to coordinate the operation of the forced air hydronic HVAC system with the dynamic shading system to optimize passive contributions based on the set-points defined by the building occupant, refer to Fig. 3.

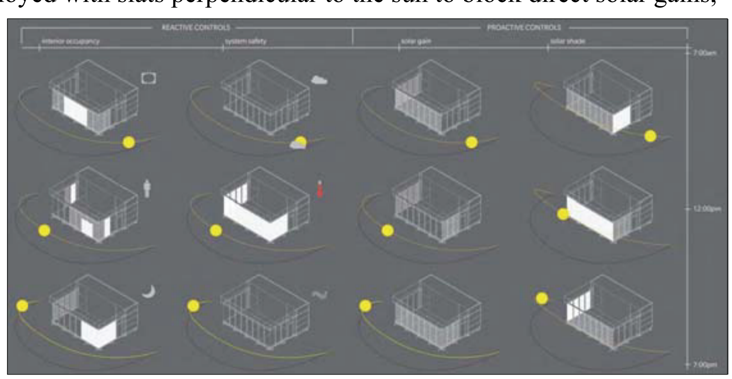

Figure 3: Operational Diagram of the Dynamic Shading Device *(credit: D. Schellingerhoudt and L. Nette)*

Under automated operation, the CHAS and exterior blind controller work together to determine the state and angle of the blinds based on the need to heat or cool to meet the user-controlled temperature set-point. The blind controllers also receive feedback from a rooftop photometer and anemometer which senses both sunlight and wind speed. By default the blinds are programmed to retract below 100 lux of light and at wind speeds over 12 m/s. The CHAS also features user overrides with which the user can set each individual blind to any desired mode. Once set, the Graphical User Interface (GUI) would turn red indicating that the system is no longer performing at its optimal passive state while not inhibiting the owner from having complete control over their domestic environment.

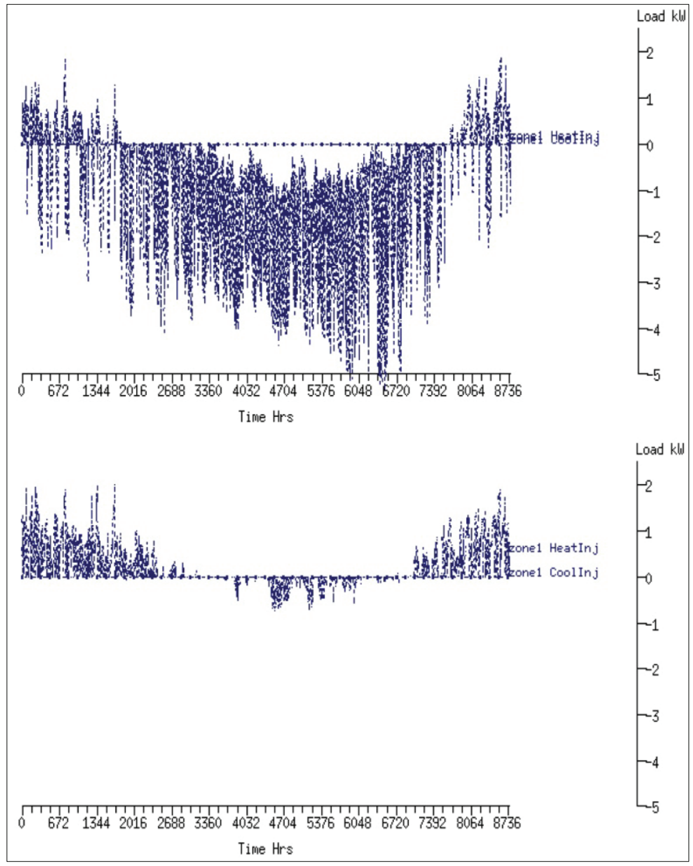

Figure 4: Contribution of Dynamic Shading to annual heating / cooling loads. (Top) North House with unprotected glazing, (lower) North House with dynamic shading.

With the exterior venetian blinds, the highly glazed facade optimizes winter passive heating with summer passive cooling. Annual building energy simulations have played a pivotal role in driving the design of the dynamically shaded façade. Energy models evaluated in ESP-r, summarized in Table 1 and Fig. 5, show the sensible cooling load is reduced by 75% in the best case scenario of fully closed slats during cooling periods. This refined control of solar gains allows the house to be thermally and visually conditioned with minimal energy, more so than a static shading system, refer to Fig. 4. The adjustable control of solar energy into the interior ensures a space that is controlled not just seasonally, as with fixed shading devices, but hour-by-hour. A consequence of the reduction of sensible loads during hot and humid conditions is that high interior humidity levels may result if the cooling system is sensibly controlled, or conversely, cool interior temperatures may result if humidity control is employed. A dedicated dehumidifier, or a re-heat loop integrated into the cooling system, would maintain occupant comfort while the shades reduce the sensible solar heat gain entering the space.

Table 1: North House Shaded and Un-Shaded Annual Space Conditioning Demand

Case	Sensible Heating Load [kWh/yr]	Sensible Cooling Load [kWh/yr]	Total Space Conditioning [kWh/yr]	Total Load per unit area [kWh/yr/m^2]
Unshaded	1486	7284	8770	143.3
Dynamically Shaded	1572	1838	3410	55.7

2.4 Glazing and Frame System

The glazing system, as the third layer in DReSS, is key to the success of the passive strategy since it is the most sensitive part of an otherwise benign building enclosure, as glazing alone is responsible for solar gains, daylighting and the majority of heat loss. Given the large WWR and the dynamic shading system that significantly reduces the annual cooling load, it is paramount that the glazed facade is able to balance daytime passive solar gain with nighttime heat loss. To do so, a low U-value with a moderate Solar Heat Gain Coefficient (SHGC) and Visible Transmittance (VT) is needed to optimize heat losses, solar gains and daylight.

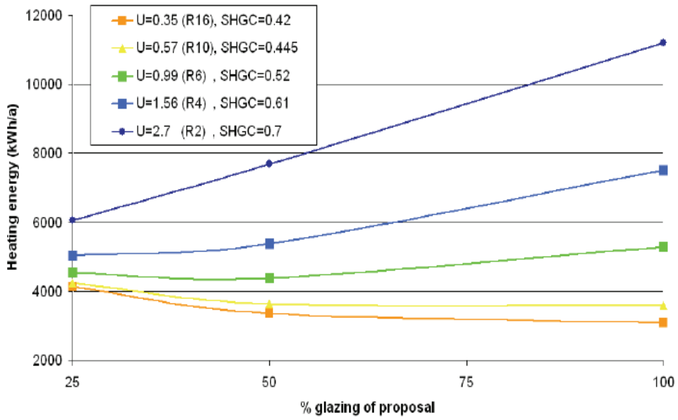

Figure 6: Effect of Glazing Properties on Annual Heating Energy

Similar to the shading analysis, annual building energy models were developed in ESP-r to determine the performance criteria required to create a glazed facade that is net-energy positive. The results, shown in Fig. 6, plot the annual heating load against the various percentages of the glazing area of the proposed WWR. The results suggest the Insulated Glazing Unit (IGU) should have a U-value less than 0.99 W/m^{2}K (R>6) and a SHGC above 0.4. Although not taken into account in energy simulations for heating and cooling loads, a Visible Transmittance of above 0.4 is also desirable for daylighting. With dynamic shading and glazing meeting these performance metrics, a higher WWR correlates to a higher passive contribution to heating and cooling. Further, a key aspect of the passive heating strategy is that solar gains are directly transmitted through the IGU and on to the floor to charge the PCM. Thus maintaining a high to moderate solar transmittance was important. This level of performance also eliminates the need for perimeter heating, decreasing mechanical complexity and connections from the *densepack* service module into the living space.

Various glazing combinations have been analyzed with different types of glass, films, coatings, gas fills and configurations ranging from double- and quintuple-glazed IGUs to double facades. U-values of all windows have been analyzed under standard NRFC-100 winter night-time conditions. The Lawrence-Berkeley National Laboratory's (LBNL) WINDOW5 and the University of Waterloo's VISION4 programs were used in combination and provided in-depth analysis of spectral properties, thermal resistance and surface temperatures. This analysis has yielded a priority list of glazing construction that has been continually referred to as limitations were discovered during the design process.

The IGU selected is a Quad-Glazed Krypton-filled unit comprised of two 6.35 mm sheets of clear low-iron glass sandwiching two sheets of Heat Mirror 88 (HM-88) mylar films with low-emissivity (low-E) coatings on glazing surfaces 3, 5, and 7 (refer to Table 2). The coatings are a soft-coat low-E with emissivities in the order of 0.04, 21 times lower than clear glass. Low-E coatings minimize long-wave thermal radiation transfer across the cavity which typically accounts for about 60% of the thermal transmission in typical IGUs (Hollands et al., 2001).

The challenge of using multiple glazing layers is designing an IGU with a low U-value while maintaining a moderate SHGC. As a consequence, HM-88s were chosen over films with lower emissivities for its clarity and solar transmittance while a lower emissivity was chosen for surface 7. In addition, heat transfer across the IGU is further reduced by replacing air across the glazing cavity with Krypton fill gas to reduce convective heat transfer. Krypton is a denser noble gas with lower convective heat transfer properties compared to air that also has a lower optimal IGU cavity width of 9 mm, as opposed to 12.7 mm, to minimize convective heat transfer. Reducing the cavity width reduces both the overall U-value of the IGU and its overall thickness, important criteria for units with multiple layers. The dimension and configuration also reduces acoustic transmission.

Table 2: North House Quad-Glazed IGU Centre-Glass Properties

Thickness [mm]	**U-value [W/m^{2}K]**	**R-value [hr.ft2.F/BTU]**	**SHGC**	**VT**
35	0.474	12	0.404	0.543

The weakest point of any IGU is at the edge region. This IGU product is typically manufactured with a highly conductive steel spacer to keep the plastic films from rippling. Working directly with the manufacturer, a proprietary low-conductance has been substituted. A custom order, the North House IGU's remain the largest dimension of this product currently manufactured and the first units to use this spacer.

Despite specifying a high performance IGU, much of its desired performance is lost through a poorly designed conductive frame. To meet the R-9 system-wide thermal resistance requirement and the unique assembly and disassembly requirements of the Solar Decathlon, a custom curtainwall system was developed. It was determined that the system be stick-framed, able to be assembled and disassembled in 6-8 hours, not make use of permanent sealants, and be thermally resistive. Architecturally, the desired appearance was to eliminate vertical caps to emulate a 2-sided Structural Silicone Glazed (SSG) facade. To satisfy these constraints, an iterative process has been used involving North House Architecture and Engineering teams, the fabricator, IGU manufacturer, and two experts with experience designing custom window systems. THERM has been used to determine accurate system-wide R-values, and mock-ups were created to test assembly, disassembly, fabrication techniques, and appearance of over 35 variations.

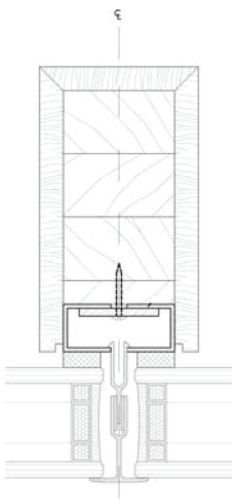

Figure 7: Vertical Mullion Detail
(credit: Kevin Schorn)

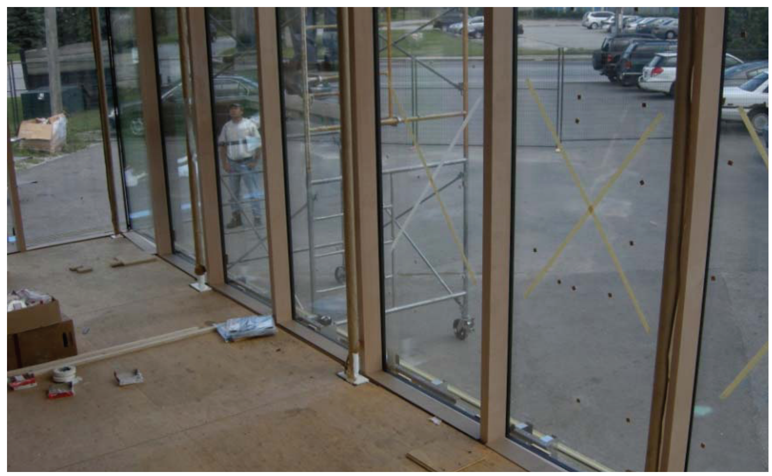

Figure 8: Photograph during construction showing frame and IGU

A built-up wood frame system with a poplar core and 9.5mm (3/8") quarter-sawn Douglas Fir veneer was selected over aluminum or vinyl because of the insulating value of wood (refer to Fig. 7). By comparison, current thermally-broken aluminum curtainwall systems with a high-performance double glazed unit can have a system-wide R-value as low as 2 (Carmody, et al,2004). The sill and head use a mechanically fastened fibreglass pressure plate to fix the top and bottom edges of the IGUs. A powdercoated aluminum cap creates a clean finish that matches the flashings and finishes on the exterior. To achieve the SSG expression, numerous vertical methods of affixing the glass and sealing the facade were evaluated, including recessed clips, caps with aerogel, and nylon blocks with extensions of glass lites on the IGUs. The final version features a custom-milled nylon 'T' with rubber snap-in cap. Engineering calculations required vertical support of the IGUs to avoid bowing of the glass and the snap-cap system achieves this without conductive metal fasteners. Thus, the vertical and horizontal caps are completely non-conductive. Compressive foam gaskets, at 80% compression, at the sill and head joints where the system connects back to the building structure provide a vapour and air seal without needed permanent treatments such as silicone or self-adhering air/vapour barriers.

2.5 Phase Change Materials

The in-floor PCM is the final component of DReSS and is an integral part of the passive strategy. Like traditional forms of thermal mass, PCMs store heat from the incoming direct solar radiation incident on the floor of the living space. The heat collected during the day is then slowly released during cooler periods and at night, thereby moderating interior temperature fluctuations to reduce peak heating and cooling loads. However, unlike traditional forms of thermal mass, such as concrete or stone, PCMs are able to collect and store heat by taking advantage of the latent heat required to change a material from a solid to liquid. During this transition, the temperature of the object and its surroundings do not change while it releases or absorbs large amounts of heat. This offers a significant heat storage capacity in a relatively small volume. All materials change phase at different temperatures unique to their properties. For passive solar buildings, the desired phase change temperature is within the internal comfort zone, between 20-24^{o}C. A total of 62.1 m^2 of PCM was installed directly underneath the engineered hardwood floor finish. Specifically engineered to melt at 24^{o}C (76^{o}F) and solidify at 22^{o}C (72^{o}F), it is a proprietary salt-hydrate solution encapsulated in 15 mm thick polypropylene panels. With a latent heat capacity of 158 kJ/kg, the panels have an approximate heat storage capacity of 62.6 kWh. Because the PCM is not directly exposed to the interior space, the conductivity of the floor finish plays an important role in the performance of the PCM. With the engineered maple flooring, a delay in the order of 15 minutes was estimated to absorb and release heat into the space, marginal in comparison to other finishes. The effect of thermal mass on the energy performance of the home is significant. ESP-r simulations predict the overall space conditioning load of the home is reduced from approximately 2800 kWh/yr to less than 2000 kWh/yr.

3. NORTH HOUSE ENERGY BALANCE

From the onset, Team North used an iterative process of computer simulations to assess the performance of the building and its systems. The feedback from such models was important in the continuous evolution of the design. The design and integration of specialized components and systems required the use of various simulation programs. WUFI, WINDOW5, and THERM5 have been used to simulate the building envelope and TRNSYS has been used simulate HVAC equipment and PV power generation. ESP-r and EnergyPlus have been used to determine internal loads and evaluate the effectiveness of the DReSS system. The results of both models are in general agreement, thus only the ESP-r results are presented. Both models reflect the following conditions:

- The climate file chosen is a Toronto CWEC file. CWEC files contain hourly weather observations representing an artificial one-year period and are used specifically for building energy simulation.
- Heating / Cooling Set-Points for energy simulation are set at 21˚C and 25˚C. Although the 2009 Solar Decathlon Rules require the house be maintained between 22.4˚C and 24.4˚C during competition, the set-points for the energy model more closely reflect a typical condition.
- Occupancy: The Solar Decathlon design brief asks for a live-work scenario. Thus, 2 occupants were assumed to be in the house at all times for the purposes of simulation.
- Ventilation Rate: Set according to ASHRAE 62.2 which requires 7.5 cfm/person and 0.01 cfm/ft^2 of floor area for a total of 21.7 cfm or 0.20 ACH.

The results of the ESP-r model, presented in Fig. 9, show the drastic reductions in space conditioning loads attributed to the effect of each DReSS element such as high performance glazing, dynamic shading, and PCM. With the space conditioning loads dramatically decreased to less than 2000 kWh/yr (32.7 kWh/yr/m^2), the remaining heating and cooling loads along with other end-uses can be easily met with on-site renewable generation. Accounting for operational efficiencies, auxiliary equipment of the HVAC system, appliances, and plug loads the total annual energy consumption of the home is estimated at 4400 kWh/yr or about 70 kWh/yr/m^2 of conditioned space.

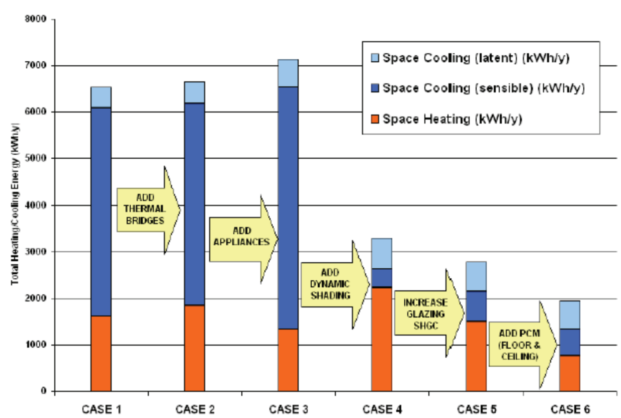

Figure 9: Effect of DReSS on Predicted Annual Space Conditioning Loads

The breakdown of estimated annual energy end use and predicted energy production from the photovoltaic and solar thermal arrays, shown in Fig. 10, suggest that with current technologies low energy buildings with large WWRs can be designed and operated in northern climates.

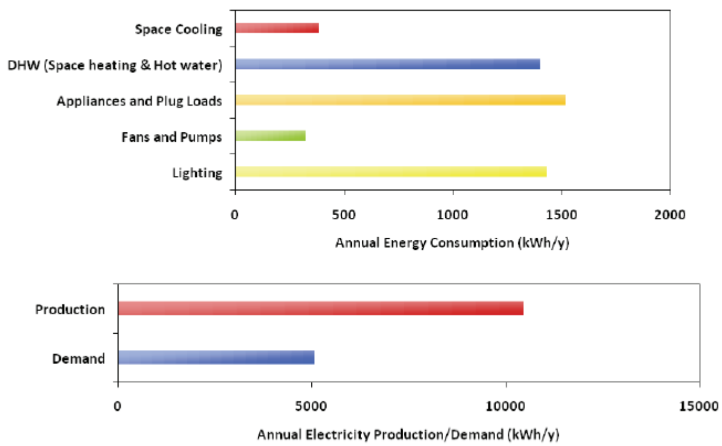

Figure 10: Predicted Annual Energy Consumption by End Use and Production

CONCLUSION

The advantages of a high performance fully glazed facade, using leading-edge, commercially available IGUs, coupled with a dynamic shading device, although counter intuitive, is demonstrated with computer simulation. DReSS achieves this predominantly passive level of performance through the interaction and integrated design of its components. Each piece works in concert to provide passive heating, heat storage, daylighting, views and active solar control to significantly reduce lighting and space conditioning loads in the challenging and variable northern climate. Although this instance of DReSS is used in a residential application, it can be easily applied to larger non-residential buildings since these conditions are similar to most commercial buildings where internal gains often lead to great annual and peak cooling loads. The North House Project's DReSS approach to passive design demonstrates that highly glazed facades can be turned into a net energy design feature rather than a liability.

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