

## Hybrid Prefabrication: prototypes for green residential construction

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### Abstract

University students, under the direction of faculty members from different disciplines- including architecture, landscape architecture, architectural engineering/construction management, and communications, developed and tested a Hybrid Prefabricated/Site-Built system for green residential construction. This hybrid model combines the economic advantages of prefabrication with the merits of on-site construction. The team tested the hybrid concept through a design-build process that resulted in two prototype homes, an 800 square foot (sf) zero-energy home designed for the 2007 National Renewable Energy Laboratory (NREL) Solar Decathlon competition and a 1000 sf two-bedroom affordable prototype home that demonstrates the market potential of the hybrid concept. Both homes serve to advance and promote the hybrid prefab system and the use of residential-scaled solar energy systems and energy-efficient construction. The zero-energy home will serve as a Hybrid Renewable Energy Systems (HyRES) laboratory and will be used for teaching, research, and outreach programming. The marketable prototype is a residence for visiting faculty to the Northern Cheyenne reservation and a model for future homes that will be built through a design-build collaboration between the University and the Northern Cheyenne Housing Authority. The hybrid prefabricated/site-built system provides a model that addresses affordability, transportability, constructability, adaptability, durability, and sustainability in prefab design.

### Introduction

Prefabrication and modular construction is being widely recognized in green residential building. Articles and exhibitions, including the National Building Museum's *The Green House: New Directions in Sustainable Architecture and Design* (May 2006-June 2007) and MOMA's *Home Delivery: Fabricating the Modern Dwelling* (July-October 2008), are bringing the relative merits and versatility in design of prefabricated architecture to public attention. The factory controlled construction environment and methods of prefabrication offers benefit to the green building residential market, particularly in the construction of complex systems. Prefabrication improves on-site efficiency and often decreases construction time; in addition it "helps to address health-and-safety concerns on-site" since a factory environment can be considerably safer than a construction site.<sup>1</sup> Prefabrication also addresses issues of project delivery, allowing complex or difficult to install systems to be completed in the factory by trained labor, thus minimizing costs for contractors. Whether using prefabricated elements or fully pre-assembled modules, recognized benefits include increased product precision, standardization of components, decreased labor and construction cost for improved productivity and profitability, shorter assembly and on-site construction time, and improved quality-control. Specifically related to green design, modular building methods are often "tighter," sometimes translating to improved durability, and can be detailed for improved energy-efficiency, factory working conditions minimize waste and increase recycling, and off-site prefabrication may reduce the impact of site construction work on neighboring areas.<sup>2</sup>

Despite the benefits of prefabrication, there are limitations that are addressed through site-specific design. Site-specific designs optimize solar orientation and passive solar design strategies. They benefit from adaptation of local vernaculars and construction methods and provide opportunities to reuse materials or take advantage of materials and suppliers close to the site.

By combining advancements in prefabrication with the advantages of site-specific construction, the 2007 Penn State Solar Decathlon Team developed a conceptual design strategy for a hybrid prefabricated/site-built

system for green residential construction that can be widely adapted and deployed with primary applications in rural communities. The team tested the hybrid concept through a design-build process that resulted in two prototype homes, an 800 square foot (sf) zero-energy+ home designed for the 2007 National Renewable Energy Laboratory (NREL) Solar Decathlon competition and a 1000 sf two-bedroom affordable prototype home that demonstrates the market potential of the hybrid concept.<sup>3</sup> Inspired by the respect for the sun of the Cheyenne Indian Nation, known as the Morning Star People, this narrative outlines a conceptual design and construction strategy for the MorningStar homes. Both homes serve to advance and promote the hybrid prefab strategy and the use of residential-scaled solar energy systems and energy-efficient construction. The zero-energy+ home will serve as a Hybrid Renewable Energy Systems (HyRES) laboratory and will be used for teaching, research, and outreach programming. The marketable prototype is a residence for visiting faculty to the Northern Cheyenne Reservation and a model for future homes that will be built through a design-build collaborative project between the University and the Northern Cheyenne Housing Authority.

## Design

The MorningStar design-build concept combines the economic advantages of prefabrication with the merits of on-site construction. The MorningStar Homes were developed through a collaborative, multi-disciplinary/multi-organizational effort at the Pennsylvania State University that engaged an "educational footprint" of over 900 students, faculty, and staff, from across the University. Curriculum integration was coordinated through two well-established education and research programs: the Center for Sustainability at Penn State (CfS) and the American Indian Housing Initiative (AIHI).<sup>4</sup> A Core Team of approximately 20 students, guided by faculty advisors primarily in architecture and architectural engineering, coordinated project integration. The hybrid concept was developed for the Solar Decathlon proposal to support the mission of AIHI and to provide a model for future homes. Students in a vertically integrated elective architecture course (Arch497C) led the design process.<sup>5</sup> The Arch 497C class generated schematic designs that further developed ideas generated through university-wide green design competitions and an additional class of 100

Architectural Engineering Students. In April 2006, the Penn State team began analyzing the schemes with the intent of selecting one concept for further development and refinement. The selection process included two filters: (1) to analyze the designs based on the criteria set forth by the Solar Decathlon Rules and Regulations and (2) to evaluate the design through a "House of Quality" process which helped to prioritize and weight multiple criteria defined for the MorningStar mission.

The Solar Decathlon Rules and Regulations that directed the final selection centered around two key requirements: (1) the need to transport the home and (2) the issue of producing sufficient energy from the photovoltaic (PV) system during the competition.

To develop a House of Quality, the Penn State team quickly identified positive features of individual design proposals and detailed a list of overall qualities associated with all the schemes. The team decided on four important priorities that the home should express: the ability to: (1) adapt to multiple programs and environments, (2) have a didactic quality to embrace and communicate the variable functions of the building components, (3) increase the perception of openness and maximize space, and (4) communicate both natural and technical sustainable principles.<sup>6</sup>

### *Market Concept and Conceptual Model:*

MorningStar is intended to serve as the first solar home in a community. Inspired by Penn State's continuing partnership with the Cheyenne Indian Tribe and the AIHI projects, the concept improves previous initiatives directed towards community development by introducing an architecture that leads to new sustainable ways of living. The design goal is to demonstrate a practical and flexible structure that is easily adapted to multiple contexts. In addition, the MorningStar Home serves as a model to explore and demonstrate regional solutions in which energy efficient systems, including solar electric, can be customized and affordably integrated into new or retrofit building projects.

To develop an architecture that is adaptable, the conceptual model simplifies the MorningStar Home into three basic components: a "Technical Core" that houses the mechanical aspects of the design, a "Living

Space” that integrates working, sleeping and eating functions, and a transitional “Breezeway” that acts as a buffer zone between the supporting technical functions and the supported communal functions of the home. (Figure 1)

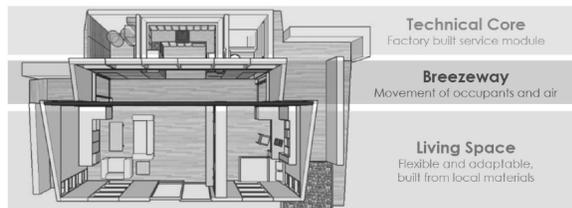


Fig. 1. Three components of home

The Technical Core is designed as a standardized module that can be easily prefabricated, mass-produced, transported and integrated into a custom configuration. Containing the technical functions of the house (including the air, water, and energy distribution), the core is designed to allow equipment to be easily maintained, added, removed, or replaced in a “plug and play” fashion. With a tight envelope and high thermal resistance values of the walls and roof, the technical core reduces the need for energy by organizing the plumbing and ductwork to minimize line losses and to create opportunities for synergies between systems such as the recapturing and reuse of heat.

The home’s Living Space can be customized around the Technical Core to work with site conditions and meet occupant needs. The Living Space’s enclosure is a panelized assembly, using regional methods and materials. Unlike the Technical Core, the Living Space would not be prefabricated, but assembled by volunteers and local laborers to promote community and economic development in the region of deployment.

The Breezeway defines a path along which the home is able to expand. This zone incorporates passive solar systems configured for a specific geographic region. The Breezeway is a feature of visual interest and connection to the environment, depending on the application and preference of the homeowner. For example, in the case of the MorningStar Homes, the breezeway is oriented East/West with a point of reference towards the Morning star (Venus) and the rising sun, connecting the home to the traditions of the Northern Cheyenne Tribe.

The modules of the home are a series of layers oriented and organized by geographical directions for educational, conceptual and solar optimization purposes. The three main components are layered side by side along the north-south axis – the Living Space to the south, the Breezeway as the central corridor, and the Technical Core to the northern side of the home. The overall placement of the building is dictated by the orientation of the sun, espousing the basic theory of sustainable living. The Technical Core houses active systems, using energy generated from the sun to fuel the home. The Living Space benefits from the south-facing façade as it absorbs and filters light to generate or dissipate heat. The Breezeway takes the middle ground, acting as a passive ventilation and light infiltration system and distributing active systems. The division of the home into three functional zones allows one to understand sustainable design in its complimentary motives. The southern façade of the living space teaches about the absorption and reflection of sunlight and the possibility of solar collection. The Breezeway introduces methods of efficient human flow, effective air ventilation and light infiltration. The technical core, as a display case for sustainable technologies, provides visual cues and hands-on information about renewable energy production systems.

#### *Customization:*

MorningStar can be customized as a locally relevant and user-responsive design. To customize the design, the conceptual model passes through a number of “sieves” identified by local characteristics of the community. These characteristics include cultural values, climatic aspects, material availability, landscape and site variables, construction methods, economic factors and other issues of relevance to the final configuration of the home. Based on the priority given to each sieve, various aspects of the model are “personalized” and become tangible in the home. The design of the MorningStar home then serves as an educational model for the community, acting as a testing ground for feasible technologies and as a demonstration tool on local and sustainable practices that will enable wider deployment of these concepts in a particular region. (Figure 2)

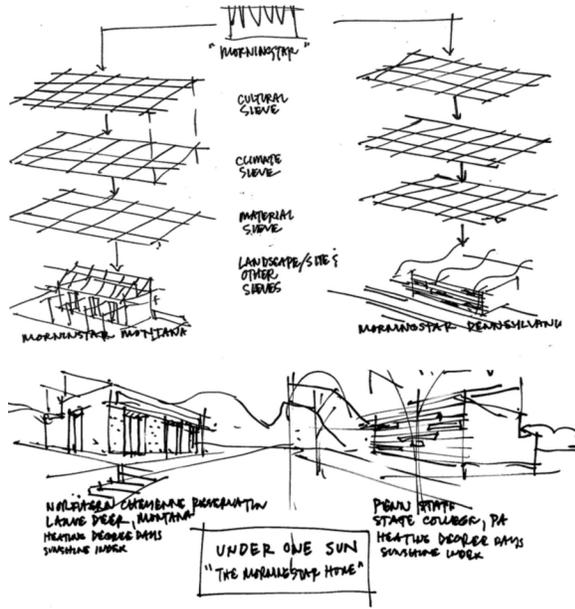


Fig. 2. *The MorningStar Concept; Customizing the Home thru the Sieve Process. Conceptual sketch by Scott Wing, Associate Professor of Architecture*

To further develop and test the conceptual model, two home designs were pursued in regions with different climates and cultural values; one as an entry for the Solar Decathlon competition and future use at the Center for Sustainability at Penn State, and another as a home for faculty at Chief Dull Knife College (CDKC) on the Cheyenne Indian Reservation.



Fig. 3. Photograph of MorningStar Pennsylvania

**MorningStar PA** (figure 3)

Transportability, constructability, and deconstructability played a major role in the customization of MorningStar Pennsylvania (MorningStar PA). To minimize transportation

and speed construction and disassembly in Washington D.C., MorningStar PA was designed and built in two prefabricated modules. A hinged roof and forklift compatible components further streamlined construction and eliminated the need for a crane. Student- and volunteer-friendly components reduced the need for skilled labor and encouraged participation. MorningStar PA was designed for the Penn State community and Central Pennsylvania climate with the competition and transportation requirements held paramount. At the Penn State Campus, the home will be sited at the Center for Sustainability to serve as a residence, outreach facility, and research laboratory. Here, the didactic features of the home will display and demonstrate available sustainable technologies and new strategies for sustainable living, as a net-zero+ home. The prototype was designed to respond to two different performance modes adjustable to the *competition mode* on the National Mall and the long-term *operational mode* at the Center for Sustainability (CfS) on Penn State’s campus. (Figure 3)

A trade-off in the design, specific to the Pennsylvania prototype, was to favor high mass for passive solar collection over lightness for transportation, therefore significant structure was required. The two modules were constructed on steel chassis, serving as the floor structure. A recycled steel structural frame at the perimeter of the home and along the breezeway is intentionally exposed to represent Pennsylvania’s steel industry. The size of the modules were mostly defined by transportation and competition regulations and by the panelized Structurally Insulated Panel (SIP) wall and roof construction (supplied by Murus, a Pennsylvania based manufacturer). The marriage line of the two modules is along the south edge of the breezeway, and an umbilical chase at the breezeway floor allows electricity and hot water for the radiant floor heating system to be distributed to the Living Space module.

The Technical Core module, “a compact energy management system,” includes the kitchen, bathroom, laundry niche, and mechanical space program elements required by the competition, and all primary wiring, ductwork, and plumbing “plug-ins” for the home. It was designed to be mass-produced and shipped based on economies of scale. The Technical Core module is clad in brilliant blue Trespa paneling, detailed as a pressure-equalizing rain screen, to identify it as the prefabricated

component of the home. The Breezeway component was constructed integrally with the Technical Core module for transportation. This central element peaks at just under the 18-foot height limit imposed by the competition and provides views to the sky and the green roof on the Technical Core and diffuse daylighting for the two modules through north-facing clearstory windows. When conditions outside are appropriate for the State College area, motorized operable windows facilitate natural ventilation through the space. Two evacuated tube panels, visible through a skylights centered on the breezeway, provide high-temperature hot water. The Living Space was preassembled and married to the Technical Core on site. The open floor plan of the Living Space is flexible and adaptable to different resident needs. Glazed windows and doors are aligned for passive ventilation and to visually extend the Living Space. The interior "Movable Wall" storage unit separates the bedroom and living/dining area; it can be slid to provide more space in individual areas when needed. The Living Space demonstrates materials that are regionally appropriate and significant to the permanent site location, including reclaimed Pennsylvania Black Slate cladding. The finished floor is 1" thick locally quarried bluestone to distribute heat from the radiant floor heating tubes and to provide some mass for solar heat collection in the winter. Built-in furniture, designed and crafted by Penn State students and staff, highlight sustainably harvested Pennsylvania hardwoods, including American Elm from Penn State's Allen Street Mall. (Figure 4)

To facilitate use as an education tool and research laboratory, the flexibility of the Technical Core accommodates ongoing and future research projects related to sustainable practices. The team pursued passive-solar design strategies, advanced high-performance engineering (including solar-electric) and information feedback systems for the zero+ energy home. The approach was to reduce energy loads via conservation and efficiency, effectively capture and use solar energy, and reclaim waste energy. The layered south façade is an occupant-operated passive-solar control. On the exterior of the façade, "Exterior Sliding Panels" (EPSs), composed of locally manufactured recycled steel and white oak harvested from a single fallen tree from the Penn State campus, allows residents to regulate light penetration and solar heat gain. The folded slatted shelves can be adjusted to control light and moved along the façade for

functional and aesthetic manipulation of the elevation. On the interior, the Milk Bottle Wall, symbolic of Pennsylvania's dairy industry, diffuses winter light and, as an ongoing research project, can be filled with various mediums to test thermal-mass storage applications. As an energy collector, MorningStar PA makes use of multiple solar technologies. For electrical energy production, two high-efficiency AC solar arrays are mounted on the south-facing sloped roof: a 5.7 kW fixed array over the Living Space and a 2.3 kW adjustable array along the Breezeway. For efficiency, AC power was directed from the inverter directly to AC loads only storing excess power. For the competition, this excess energy was stored in large-capacity batteries; on the permanent site the home will be grid-tied. A modern version of the slate cladding, Solarplate (manufactured by Atlantis Solar) arrays on the east and west facades provided DC power to dedicated LED lighting devices, eliminating the need for inverters. Digitally controlled LED lights, sandwiched between the polycarbonate glazing system in the north-facing clerestory, will be linked to streaming weather data. The changing colored lights correspond to weather predictions to alert the occupants and passers-by of the next day's weather forecast and related energy production. To highlight research initiatives, the MEP systems interface with a Direct Digital Control (DDC) monitoring system providing real-time response and predicted data related to the energy use and production. The system will allow occupants to understand the effect that their behavior has on the home's energy balance and help them develop more energy efficient behavior patterns.



Fig. 4. Montage of images illustrating MorningStar PA materials

This feedback is subsequently used to optimize performance based on the various occupant use strategies and to examine the performance of the home in a manner that will inform future versions of the prototype. For research and educational purposes, the control system will document performance changes based on the insertion and replacement of solar technologies in the home.

### MorningStar MT

The development of a marketable prototype was an important competition of the Solar Decathlon. The Penn State Team designed and built an actual marketable prototype in a representative target community, the Northern Cheyenne Indian Reservation in southeastern Montana. MorningStar Montana (MorningStar MT) was adapted from the hybrid concept to address some of the principles established by the American Indian Housing Initiative (AIHI), a design-build partnership that focuses on introducing sustainable building technologies to American Indian reservations. By applying the MorningStar Home to the AIHI program, the team intends to improve affordable housing

through energy efficient systems by placing an emphasis on the adaptation of solar technologies, the potential to mass-produce technical core units, and the utilization of unskilled labor during construction. While MorningStar Pennsylvania acts as a living laboratory, MorningStar Montana was developed as part of a direct community-based relationship reinforcing the initial marketable framework. MorningStar MT serves as a visiting faculty residence at Chief Dull Knife College (CDKC) on the Northern Cheyenne Indian Reservation, in Lama Deer, Montana. The prototype home is larger than MorningStar PA, providing an additional bedroom to accommodate a small family and office space for the faculty member. The goals set by the team for adapting the Hybrid Concept for the marketable prototype were:

- **Livability:** Maintain an open, central floor plan to allow comfortable movement between different spaces of the home and easy adaptation by frequently changing residents, while engaging the occupants in seasonal adjustments.

- **Buildability:** Combine the economies of manufactured housing with panelized components and details that engage volunteers and students in a community-build construction process.
- **Flexibility:** Promote regional, site specific, and personal adaptability. The prefabricated core joins a site-built living space made of regionally appropriate “materials of opportunity” addressing site specific constraints and the need for frequent interior reconfiguration.
- **Economic Viability:** Establish the feasibility of solar energy in low-income communities and help assess Energy Efficiency Measures (EEMs) with actual costs rather than assumptions.

The Penn State Solar Decathlon Team, community volunteers, Penn State students, alumni, and faculty constructed MorningStar MT in June and July of 2007 during a three-week “blitz-build.” The actual cost of the prototype home was \$110,000 in materials. The site and foundation was prepared prior to the Team’s arrival. The Technical Core was manufactured in ten days by the Penn State Solar Decathlon Team on the University Park Campus and transported to the prepared construction site. Because research and development of the building systems was not a prioritized goal for MorningStar MT the mechanical room was significantly smaller, reducing the overall size of the Technical Core module for transportation with a standard trailer. Future prefabrication of the *Technical Core* will be constructed on the reservation in cooperation with the Northern Cheyenne Housing Authority in an effort to provide stable employment to skilled labor in healthier and safer working conditions, eventually mass-producing the modules to reduce costs and continually improve quality.<sup>7</sup>

Students and volunteers poured a concrete slab for the living space after installing tubing for the radiant floor heating. The site-built Living Space employs panelized systems for easier and faster construction to promote volunteer and community participation with a goal of providing jobs for unskilled labor. Panelized interior walls can be regionally pre-manufactured using local resources, reducing construction time and allowing for some reconfiguration of spaces by the residents. A long-standing effort of AIHI has been to adapt and deploy strawbale construction as a viable

sustainable building technology for the Montana climate. In keeping with this strategy, the exterior walls of MorningStar MT are constructed using densely packed strawbales, providing a load-bearing and extremely well insulated wall. To establish an even tighter envelope, MorningStar MT’s door and window openings and structural headers are framed out in SIPs to minimize thermal bridging. In keeping with Cheyenne tradition, MorningStar MT’s entry door faces east, greeting the Morning star. The open portion of the Living Space, living/dining and office area, face southeast providing for some passive gain in the winter and celebrating the movement of the sun across the front of the home. The Breezeway, the main circulation through the home, is oriented from east to west, maintaining long views through the home and into the surrounding landscape and providing for cross-ventilation. Ceiling fans and north-facing operable clerestory windows further promote natural ventilation and daylighting, minimizing the need for overhead electric lighting and mechanical ventilation for much of the year. Like MorningStar PA, the dining room table is centered on the home and oriented from north to south, aligning with centered windows that reiterate the cardinal orientation of the home.



Fig. 5. MorningStar MT construction sequence illustrating site-built Living Space assembled around prefabricated Technical Core

The kitchen of the Technical Core is also centered on the home, maintaining traditional community/family gathering around meals.

The Breezeway roof of MorningStar MT is oriented and angled to optimize solar gain for the photovoltaic array mounted to the roof. Unlike the net-zero+ goal of MorningStar PA to provide enough solar energy for the home with excess to sell back to the grid, the smaller array on MorningStar MT supplements the energy needs of the home, making overall energy costs more affordable and providing alternative power to remote rural customers in the event of a power outage. (Figure 5)

In a collaborative effort between Penn State and the Northern Cheyenne Housing Authority, plans are in progress to implement a new housing program on the Northern Cheyenne Indian Reservation that will allow for the local construction of technical cores and the development of a community-built housing program to pursue the construction of more homes using the MorningStar concept. The MorningStar MT prototype is now open to the community to assess initial reactions about the appeal and marketability of the home. This project advances the partnership between Penn State and the Northern Cheyenne Tribe, and the efforts of the American Indian Housing Initiative (AIHI) at Penn State. The relationship adapts and deploys sustainable housing methods to address the housing challenges facing the Northern Cheyenne other Native American tribes and remote rural communities in the U.S.

## Conclusion

MorningStar presents two prototypes for green residential construction that illustrate the benefits of understanding and adapting to the perceived constraints of modular, prefabricated construction methods and transportation regulations. By assembling the Technical Core in a manufacturing environment, quality and durability can be assured and continually improved. Labor and construction costs can be reduced through ease of assembly of complex systems in a controlled environment, and on-site construction time is minimized. The MorningStar "sieve" concept provides a method that addresses site-specific conditions, idealizing orientation for passive and active solar strategies, taking advantage of local traditions, methods, and "materials of opportunity" for increased durability,

adaptability, and overall sustainability. The hybrid concept supports an inclusive construction process that employs both scarce skilled labor for the construction of the Technical Core and provides jobs for unskilled labor and takes advantage of local resources in the site-specific assembly of the Living Space.

## Acknowledgements

The Pennsylvania State University 2007 Penn State Solar Decathlon Team.

## Notes

<sup>1</sup> Rowlands, Martyn. "Delivering the benefits of prefabrication" in *Modern Building Services (MBS) journal*, Portico Publishing Ltd, February 2007. [www.modbs.co.uk](http://www.modbs.co.uk)

<sup>2</sup> Davis Langdon & Everest. "Prefabrication and Pre-assembly" in *Cost model*, Building: issue 06. February 2002. [www.building.co.uk](http://www.building.co.uk)

<sup>3</sup> The Solar Decathlon joins 20 college and university teams in a competition to design, build, and operate the most attractive and energy-efficient solar-powered house, [www.solardecathlon.org](http://www.solardecathlon.org)

<sup>4</sup> For information about the Center for Sustainability at Penn State see [www.cfs.psu.edu](http://www.cfs.psu.edu); For information about AIHI see [www.engr.psu.edu/greenbuild/index.asp](http://www.engr.psu.edu/greenbuild/index.asp)

<sup>5</sup> Twelve (12) 2nd-4th year architecture students participated in the "neXt house: small, affordable, sustainable" Arch 497C course instructed by Lisa D. Iulo, Assistant Professor of Architecture and Scott Wing, Associate Professor of Architecture.

<sup>6</sup> Penn State Solar Decathlon Team, David Riley, Faculty Advisor, Lisa Iulo Co-Faculty Advisor, other faculty and student members of team: Solar Decathlon Design Development submission. Submitted June 13, 2006.

<sup>7</sup> Torres Arriaga, Claudia, Penn State Solar Decathlon Team, David Riley, Lead Faculty Advisor, Lisa Iulo, Co-Faculty Advisor, other faculty and student members of team: Solar Decathlon Competition submission to NREL: Marketable Prototype description and cost estimation. Submitted August 07, 2007.