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Building Envelope for Energy-Efficient Residential Homes, A Case Study for the U.S. Department of Energy Challenge Home Student Design Competition

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BUILDING ENVELOPE FOR ENERGY-EFFICIENT RESIDENTIAL HOMES,

A CASE STUDY FOR THE U.S. DEPARTMENT OF ENERGY CHALLENGE HOME STUDENT DESIGN COMPETITION

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ABSTRACT

With the continuous rise of population and expansion of urban areas, the need for additional housing and infrastructure is growing rapidly. Building sector is consuming a vast majority of the natural resources to meet the needs of urbanization and is in need of efficient, sustainable solutions that are viable for the customer, the economy and the environment. The building sector is both the problem and the solution to the issues of the carbon footprint of our society (Architecture 2030, 2011).

The envelope (roofs, walls, and foundations) and windows typically account for 36% of overall energy use, or about 14.3 quads in residential and commercial buildings combined, at an annual cost of $133 Billion. A well designed building envelope can impact 51% of the building energy loads (U. S. Department of Energy National Energy Technology Laboratory, 2009). The purpose of this research is to assess selected types of residential home envelopes and their components. Comparative analysis was used to evaluate the thermal performance and thus the applicability of these components for modern residential buildings, as embodied energy and toxic emissions were also important factors. The research is mainly focused on townhomes as one of the sustainable types of neighborhood development (USGBC, LEED Neighborhood Development program).

The assumption is that the high performance of the envelope is correlated to the reduction of heating and cooling loads in the interior and consequently, the overall energy and resource consumption of the building through its life-cycle. The derived hypothesis would be that by selecting an appropriate, high-performing building envelope assembly will ameliorate the overall performance of the building, thus lowering its environmental impact in terms of resource depletion and carbon emissions. Further benefits for the users include high levels of

thermal comfort, health indoor air, lighting for daily tasks, noise control and an overall reduction in the whole-house energy consumption. This resource management could potentially reflect on the construction budget and later on, the utility costs.

In order to address the research questions through the most relevant data, a mixed methods approach was selected. Exploratory method, focusing on qualitative research during the first phase was used to examine and document the correlation of different assembly types with their respected components and the thermal performance of the whole envelope. Moreover, quantitative data for the observed characteristic of the assembly components (mostly cavity insulation types) provided numerical values that were compared in order to derive conclusions about different components' lifecycle performance and impact. The quantitative research portion gave firm data necessary for triangulation of the hypothesis and findings gathered in the qualitative, descriptive portion of the research. The research has been informed by examples and case studies elaborated in the literature review.

The residential attached unit assessed as the case study was designed for the 2014. DOE Challenge Home Student Design Competition. This small footprint, two story townhome unit, was designed to achieve high-performance throughout its lifecycle. Several envelope assemblies were taken in consideration, the decisions being informed by the EEBA (The energy & Environmental building Alliance) and US Department of Energy's Building America Program "Houses That Work" educational training course. The individual assembly parameters were assessed in energy modeling software (REM Rate and HEED) and addressing the issues considering maintenance and durability, as well as construction cost analyses, a specific combination of strategies has been selected. The 1,354 sq.ft residence features SIP and high mass concrete walls, Frost-Protected Shallow Foundations, high performance glazing (U-0.16; SHGC-0.561), a green roof and all ductwork distributed inside the conditioned space. Passive strategies are complemented with efficient active systems including ductless Mini-Split heating and cooling backup units, air circulation through integrated ERV and Radiant Floor Heating. Construction cost strategies included right-sizing and value engineering, elimination of duct systems, elimination of basement, application of prefab or engineered components that lower labor costs and reduce construction waste.

As a result, this affordable end-unit part of a five-home row housing development for Denver's Sustainability Park was designed to achieve LEED Platinum and Energy Star V3.0 Certification while remaining within financial reach to local families earning Denver's median income. With a Home Energy Rating System (HERS) Index of 7 (100 being the 'standard new home'), this all-electric home, is projected to use between 1,157 KWh/year (REM Rate) and 2,263 KWh/year (HEED) and 91% less energy than the LEED Reference Home (Tajsic et al. Aries House. U.S. Department of Energy Home Challenge Student Design Competition. Unpublished)

High-performing building envelopes designed with sustainable practices in mind have a potential to lower the overall energy consumption of a building throughout its lifecycle and reduce its carbon footprint. Moreover, it's important to select building materials that have the potential to offset the embodied energy of their production through the benefits of their performance within a system. Smart material procurement for wall and ceiling cavity insulation, its proper sizing, installation and maintenance are key for achieving maximum performance of the assembly. Durable, well-sealed sealed envelopes make up for a healthy, long lasting building enclosure that requires the least amount of maintenance or replacement and contribute to the indoor air quality and thermal comfort of the building.

Topics relating to these issues have a high potential to be evaluated in other research endeavors or tested through different case studies.

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This thesis is dedicated to my father who always encouraged me to strive for excellence and my mother who was giving me unconditional love to the very last moment.

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1. INTRODUCTION

With the continuous rise of population and expansion of urban areas, the built environment is consuming the vast majority of the natural resources and is one of the main contributors to the overall environmental impact of the society (Hawken & Lovins, 1999). The contemporary lifestyle dictates a fast paced, vastly spreading industrial production to meet all of the demands of modern society. This industrial expansion is directly influenced by the population growth and the need for additional housing and infrastructure.

For these reasons, the building sector is in need of efficient, sustainable solutions that are viable for the customer, the economy and the environment. These new homes should serve as models of design efficiency, complimenting their context and contributing to the richness of the neighborhood.

The starting point of this study is the assumption that building envelope and insulating materials are a major contributor to the overall carbon footprint of the built environment due to their mass use. The general research question that can be derived from this issue is - what poses as a sustainable solution for the design and construction of building envelopes? The variables include environmental impact components of a particular envelope assembly such as carbon emissions of its components and ozone depletion potential. Other attributes include resource depletion due to mass use of materials that are incorporated into the assembly and the construction waste generated upon its installation. Moreover, another important factor is the local climate at the building site. Determining what type of an enclosure is appropriate for the climate, which materials to use and in what type of an assembly is key to achieving high performance of the envelope.

Through high performance of its life-cycle, a specific enclosure has the potential to reduce the overall heating and cooling loads of a building, thus reducing its overall impact. Observing the values of these variables can provide us with a comparative overview of different available materials and components. The interpreted data may be used to make an informed decision on the type of the envelope assembly appropriate for the project at hand in terms of management of the assembly's overall environmental impact both form production and post-construction waste disposal.

High-performing building envelopes designed with sustainable practices in mind have a potential to lower the overall energy consumption of a building throughout its lifecycle and reduce its carbon footprint. Moreover, it's important to select building materials that have a potential to offset the embodied energy of their production through the benefits of their performance within a system. Smart material procurement for wall and ceiling cavity insulation, its proper sizing, installation and maintenance are key for achieving maximum performance of the assembly. Durable, well-sealed sealed envelopes make up for a healthy, long lasting building enclosures that require the least amount of maintenance or replacement and contribute to the indoor air quality and thermal comfort of the building.

The need for use of sustainable practices in the building sector has been recognized among the professionals for some time now. There are many institutions, organizations and programs that offer recommendations for both new construction and future development, as well as retrofits and performance upgrades for existing buildings. Some of these recommending institutions include U.S. Environmental Protection Agency, U.S. Green Building Council (USGBC), U.S Department of Energy Building America Program, The Energy & Environmental Building Alliance (EEBA), Architecture 2030's 2030 Challenge, and The Green Building Initiative (GBI). Whether these guidelines come from local or international sources, the message is the same – best practices are necessary in urban expansion and the building sector for sustainable development. The building sector is both the problem and the solution to the issues of the carbon footprint of our society (Architecture 2030, 2011).

Following chapters will address the research and evaluation of selected envelope assemblies for high-performance building enclosures in modern residential construction. A comparative evaluation of several enclosure components, mostly focusing on cavity insulation types served to inform the decisions applied for the case study townhome unit, put together by UNLV's student team for the DOE Challenge Home Student Design Competition. As part of this case study, the chapters will discuss envelope assembly strategies and building components that have a general influence with the performance of the enclosure, as part of an urban-residential housing unit model, applicable for the climate, context and the target market.

With sustainable practices as principal guidelines, the purpose of this study is to review several strategies for design and construction of a high-performing building envelope, focusing mostly on wall and roof assemblies. The practical application and performance of some of the appropriate strategies will be further addressed in the case study. Through these discussions, several observations were made and could serve as exploration topics for future research. These issues potentially include issues related to whole life-cycle analysis of an envelope assembly in a specific location and climate, research related to resource management, strategies for deeper market recognition of sustainable practices, recommendations for new environmental policies or construction practice guidelines.

2. REVIEW OF THE LITERATURE

The expression 'sustainable development' refers to meeting the needs of our society at present without compromising the ability of future generations to meet their needs (World Commission on Environment and Development, 1987). Unfortunately, meeting the needs of the planet's growing population and rapid urbanization is directly correlated to resource depletion caused by mass production of materials and products. As the population is growing, so does the need for additional housing and infrastructure. This need for additional resources is particularly pressuring in the so-called 'BRIC' countries group (Brazil, Russia, India and China), creating an imbalance in the demand-end of the production (Kibert, 2013). As an example, the global prices of steel increased by over 50% in 2011 due to the increase in demand on the Chinese market influenced by large scale expansions in the building sector.

Building construction is one of the least sustainable branches of industry, consuming almost half of the total available resources (Hawken & Lovins, 1999). In the U.S., residential and commercial buildings are the largest energy consuming sector, accounting for about 40% of total annual energy use (39.7 quadrillion British Thermal Units (Btu's) of energy (quads)). Residential buildings consume 22% and commercial buildings 18% of the building sector total (U. S. Department of Energy National Energy Technology Laboratory, 2009). In general, the public is far more aware of the carbon emissions caused by transportation, however, by comparison, transportation accounted for 34.3% of CO2 emissions and industry just 21.1% in 2010. in the United States (Architecture 2030, 20111). Moreover, construction waste contributes about 40% of solid waste streams in developed countries, with most waste associated with the demolition phase (UNEP SBCI 2010).The tables below show a breakdown of the impacts the building industry has in terms of resource consumption and pollutant emissions.

Estimate of global resources used in buildings

Resource	**(%)**
Energy	45–50
Water	50
Materials for buildings and infrastructure	60
Agricultural land loss to buildings	80
Timber products for construction	60 (90% of hardwoods)
Coral reef destruction	50 (indirect)
	25 (indirect)

Table 1. Estimate of global resources used in buildings

Estimate of global pollution that can be attributed to buildings

Pollution	**(%)**
Air quality (cities)	23
Climate change gases	50
Drinking water pollution	40
Landfill waste	50
Ozone depletion	50

Table 2. Estimate of global pollution that can be attributed to buildings

The fact is that this realm of production is responsible for an alarming amount of the total carbon footprint, construction waste and resource depletion. With the climate change caused by global warming, it is necessary to have a clear plan for sustainable development of the building sector. Structures should be designed to have a synergic relationship with their natural environment, utilizing the site configuration and characteristics of the local climate to their benefit instead of working to repel them.

The companies and organizations related to the building sector need to take a leading role in the implementation of materials and processes that are less harmful to the environment. The concept of eco-efficiency originated from the

World Business Council for Sustainable Development (WBCSD) in 1992 and it describes the "delivery of competitively priced goods and services that satisfy human needs and enhance the quality of life while progressively reducing ecological impacts and resource intensity throughout the products' life-cycles to a level commensurate with the earth's estimated carrying capacity" (Kibert, 2013). Eco-Efficiency describes the fundamental practices needed for sustainable development of the production sector, equally applicable to the building sector itself. The seven elements of Eco-Efficiency as defined by the WBCSD are the following:

1. Reducing the material requirements of goods and services
2. Reducing the energy intensity of goods and services
3. Reducing toxic depression
4. Enhancing materials recyclability
5. Maximizing sustainable use of renewable resources
6. Extending product durability
7. Increasing the service intensity of goods and services

The total energy consumed in acquisition and processing of raw materials, including manufacturing, transportation and final installation is referred to as the embodied energy (Kibert, 2013). These features of any given component of a building assembly need to be assessed prior to selection and installation. Lowering the embodied energy by making prudent decisions in design and construction of buildings can lead to reductions in energy and water consumption while lowering the amount of pollutants released into the atmosphere.

That is why it is necessary to evaluate the properties of the building components closely and produce a meaningful report on best practices appropriate for the application and context.

A life-cycle analysis (LCA) of a material, product or a whole system is a method determining the level of environmental and resource depletion impact that the observed items have. By interpreting and comparing the tabulated data regarding resource depletion, carbon emissions, water use, Global warming potential, ozone depletion and toxic releases of observed materials, for example, one can make an informed decision on the appropriate product selection. Moreover, a LCA can also include numerical data on the level of production or post construction waste that a specific product carries. To sum up, in order to make decisions that will ameliorate the standing of the building sector in the environmental context, one must look at the whole picture, not just the performance of the building components, but also the embodied energy and account for the overall LCA of the system.

The need for sustainable solutions in the building sector has been recognized several decades ago but has grown much stronger in the recent years. There are a number of organizations and programs worldwide that offer resources and guidelines for high performance and sustainable development in the building sector including the U.S. Environmental Protection Agency, U.S. Green Building Council and its Leadership in Energy and Environmental Design (LEED) rating system, U.S Department of Energy Building America Program, The Energy & Environmental Building Alliance (EEBA), The Green Building Initiative (GBI) Architecture 2030's 2030 Challenge. Moreover, these organizations, as well as energy and performance rating systems for buildings throughout the world are helping set the new standards for design and construction, raising the bar for assembly performance while aiming to reduce its impact on the environment. In lieu of these efforts, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers' (AHSRAE) goal is to improve commercial building codes by 30 percent by 2010.

One could argue the validity of particular strategies recommended by these programs or rating systems such as LEED or comparable systems worldwide, but in general, these sets of recommendations lead to a common goal –turn the building sector from a problem into a solution for sustainable development.

The Energy Independence and Security Act of 2007 (EISA 2007) calls for all new commercial buildings to be net-zero energy by 2030 (Center for Climate and Energy Solutions, 2013). Zero-energy buildings (ZEBs) are buildings designed with sustainable practices, and low energy demand for its comfortable performance met through the on-site renewable energy systems. Looking at the building as a system of components directly influencing each other, one can conclude that the components of a building envelope directly affect heating and cooling loads of the whole building.

The envelope (roofs, walls, and foundations) and windows typically account for 36% of overall energy use, or about 14.3 quads in residential and commercial buildings combined, at an annual cost of $133 Billion. A well designed building envelope can impact 51% of the building energy loads (U. S. Department of Energy National Energy Technology Laboratory, 2009). The assumption is that implementing strategies that assure its superior performance can assist in a reduction of energy. Further benefits for the users include high levels of thermal comfort, healthy indoor air, and abundance of light for daily tasks, noise control and a reduction in the utility costs through lower energy consumption.

All of these aspects present compelling reasons for further investigations in best practices for building envelope assemblies. A general hypothesis for this research is that the high performance of a building envelope, designed and constructed with sustainable practices in mind can reduce the environmental impact of the built environment in terms of resource depletion and pollutant emissions.

Building envelopes need to be designed to withstand the elements and hold up against weathering. However, to fulfill its full performance potential, a particular envelope assembly should not just serve to protect itself from climate, but on the contrary - use it to its advantage. To utilize the benefits offered by the local climate and site configuration, one could seek to implement passive design strategies. These include strategic massing and building forms, proper orientation, optimal high-performance fenestration placement and surface areas, shading techniques and application of thermal mass (Johnston & Gibson, 2008.). Strategically placed thermal mass elements absorb and retain heat, slowing the rate at which the sun heats a space and the rate at which a space loses heat when the sun is gone. Furthermore, homes that incorporate high thermal mass offer excellent performance under anticipated elements of nature, such as pests, fire, earthquakes, hurricanes and tornadoes, and can stand for many decades without structural degradation (Braun, 2003). The assumption is that complimenting these strategies with high-performing active systems can result in a whole building energy consumption and performance optimization, high levels of thermal comfort and reduction of utility costs for the owners.

Integrated design approach, involving professionals from related fields is key for achieving a harmonic integration of building components and systems. It is, however, crucial to select strategies that truly complement each other and perform well as a wholesome system. Proper sizing of both active systems and building materials for building envelope is critical for high performance, construction waste diversion and cost control.

3. RESEARCH METHODS AND OBSERVED CHARACTERISTICS

3.1 Purpose and methodology

The purpose of this research was to interpret several strategies for design and construction of a high-performing building envelope, with sustainable practices in mind. A caste study was used to demonstrate how the selected enclosure affects the performance and resource consumption of a small-footprint residential townhome model. An overview of the advanced strategies and applicable materials was mostly focused on wall and roof assemblies. Through comparative analysis of thermal performance and embodied energy data, selected materials were interpreted and conclusions were drawn based on their applicability to the case study.

The assumption is that high performance of the envelope is directly correlated to the reduction of heating and cooling loads in the interior and consequently, the overall energy and resource consumption of the building through its life-cycle. The derived hypothesis would be that selecting an appropriate, high-performing building envelope assembly will ameliorate the overall performance of the building, thus lowering its environmental impact in terms of resource depletion and carbon emissions.

In order to address the research questions, a mixed methods approach was selected. Exploratory method, focusing on qualitative research during the first phase was used to examine and document the correlation of different assembly types with their respected components and the thermal performance of the whole envelope. Moreover, quantitative data for the observed characteristic of the assembly components (mostly cavity insulation types) provided numerical values that were compared in order to derive conclusions about different components' life-cycle performance and impact. The quantitative research portion gave firm data necessary for triangulation of the hypothesis and findings gathered in the qualitative, descriptive portion of the research.

3.2 Research Questions

Through literature review, several research questions emerged. Derived from the problem, being the tremendous environmental impact of building sector in general, the starting point of this study was to identify the key variables that will help state the questions properly. The variables further investigated in this research include:

- Embodied energy of materials
- Thermal conductivity of materials
- Required insulation levels (for specific areas)
- Envelope durability (elements that can affect the assembly performance)

Through literature review, it was determined that the envelope itself typically accounts for 36% of overall building energy use, at an annual cost of $133 Billion (U. S. Department of Energy National Energy Technology Laboratory, 2009). Materials that comprise the building envelope are the main factors in determining its overall performance. This is particularly true for insulation materials due to the percentage of the assembly they comprise. Through deductive reasoning, one could argue that the insulation materials are therefore major contributors to the overall impact of the built environment due to their mass application. The assumption is that choosing materials that are more environmentally friendly and sizing them correctly, will reduce their impact to the environment in terms of resource depletion, carbon emissions, water use, Global warming potential, ozone depletion and toxic releases. At the same time, these materials still need to pose a viable solution in terms of thermal comfort and a healthy indoor environment.

There are many implications involved with the production and mass application of these components. To fully understand their advantages, but also potential hazards, this study will attempt to answer several important questions:

- Do the selected envelope assemblies and insulation materials have a potential to reduce the overall environmental impact of a building and consequently, the building sector?
- Do the reviewed assemblies and insulating materials present a competitive solution for residential townhomes in terms of their thermal performance?
- Are building envelopes that feature materials with higher embodied energy still a possible solution for sustainable envelope assemblies of residential townhomes?

3.3 Material evaluation

The insulation materials were observed based on two major categories, their thermal properties and the life-cycle assessment. Thermal properties of the selected materials were synthesized from data collection and the literature review and interpreted through the method of comparative evaluation. These thermal properties included the thermal resistance values of the material [R - BTU/(h °F ft^2)] and the material density. The thermal resistance (R) of an insulation layer is equal to the thickness of the material divided by the conductivity of that material.

The material components were incorporated into typical wall assemblies and their performance was compared to the standard construction practices.

The impact assessment and its interpretation will hopefully support the assumption that these alternative assemblies can assist in offsetting their embodied energy through high performance of the assembly, reducing overall energy consumption of the building they are a part of. Through previous coursework at the University of Nevada Las Vegas and the Building Sciences and Sustainability concentration curriculum, and informed by the literature review, an information base on the insulation materials available on the market was formed.

Out of this database, the following insulation materials were selected to be evaluated based on their preliminary characteristics observed in the previous coursework:

- Cellulose - dense pack and loose fill
- Recycled cotton – denim batt
- Wool insulation - sheep’s wool
- Spray-in foam
- Rigid insulation boards

Tying in to the stated hypothesis that high performance of a building envelope, designed and constructed with sustainable practices in mind can reduce the environmental impact of the built environment in terms of resource depletion and pollutant emissions, the favorable outcome would be to show that selected materials are applicable for these purposes.

3.4 Case study overview

The residential attached unit assessed as the case study was designed for the 2014. DOE Challenge Home Student Design Competition. This small footprint (1.354 square feet), two story townhome unit was designed to achieve high-performance throughout its lifecycle, aiming for a home energy rating system (HERS) score well below 100, being the typical new home. The goal was to design a component assembly that will come near a HERS score of 0, presenting a Zero-Net Energy building. Several envelope assemblies were taken in consideration, the decisions being informed by the previous coursework, EEBA and US Department of Energy's Building America Program “Houses That Work” educational training course. Envelope materials were assessed individually to determine if they are appropriate for the location, context and set performance goals. However it was important to assess the assembly as a whole system of components to determine the overall performance. The Oak Ridge National Laboratories has led the building industry in defining whole wall R-value that tests the thermal resistance of an entire wall section. As an example, by looking at a standard 2×6 wall with an R-19 fiberglass insulation, the whole assembly turns out to have only R-13.7 when the thermal bridging of studs every 24 inches is considered (Kosny & Christian, 2001). The conclusion is that an envelope assembly should not only be observed as a sum of thermal resistance properties of its individual components, but as one entity. For the case study evaluation, the individual assembly parameters were assessed in energy modeling software (REM Rate and HEED) and addressing the issues considering maintenance and durability, as well as construction cost analyses, a specific combination of strategies was selected.

4. DISCUSSION ON SUSTAINABLE PRACTICES FOR ENVELOPE ASSEMBLIES

As noted in the previous chapters, the literature suggests that in order to reduce the demand-side energy consumption in the construction sector, it's important to build durable, stable, high performing structural enclosures that have the ability to reduce the average heating and cooling loads of a building of comparable size, type and location, at the same time, amounting in less construction waste. The performance of the envelope will influence the amount of operational energy use over the building's lifecycle, but the starting point is to identify the appropriate envelope components, by making selections that will work with the design context and project program. Moreover, properly sizing the components and applying sustainable building practices will ensure that the environmental, social and economic dimensions of the design at hand come together.

The designed assembly will be less impactful to its environment, providing a healthy, comfortable enclosure for the users while posing as a high performing cost-effective solution that continuously cuts down the consumption and, therefore, the bills (Kibert, 2013).

As different standards and observed properties apply to different materials, in some cases it is challenging to make a direct comparison between two products. Depending on raw materials and production process, insulating materials can exhibit properties that are not as relevant for other materials (Pfundstein et al. 2008). That is why it's much more productive to observe a system as a whole, as a series of interconnected functions of its components and how those performances fare for the typology, placement and local climate of the building. It is important to evaluate which set of components will best suit the respective requirements of the design context.

Nevertheless, for quality control purposes, thermal insulation materials have a set of standards, as their performance is tested and recorded prior to being approved for application in construction (Pfundstein et al. 2008). The standards that regulate thermal and sound insulation materials include American Society for Testing and Materials' (ASTM) thermal insulation standards, International Organization for Standardization- ISO - 91.100.60: Thermal and sound insulating materials, Deutsches Institut Fur Normung (DIN) Standards from Germany, and others.

4.1 Strategies for maintaining envelope durability

Proper sealing is key for keeping a tight envelope – air leaks can be responsible for 25% of the heat losses (Straube, 2012). Integrity of both air barrier and waterproofing membrane are important to prevent unnoticed leaks. Capillary action or the ability of water to flow through the material from wet to dry is another issue to prevent. Water moves through materials based on their wicking properties. For instance, placing a capillary break (damp proofing or membrane) over the footing of the foundation could reduce the potential capillary action (Lstiburek & Brennan, 2005). Prevention of moisture in the system keeps envelope durable, products referred to in the literature are house-wrap and felt paper. When installing these barriers, it's important to make sure there are no holes on the product. Moreover, when connecting several sheets together to wrap the envelope, the installer needs to make sure that the upper course of the sheet is overlapping the lower course to seal the seams (Johnston & Gibson, 2008.). Common strategies to determine if the enclosure has weak points in terms of infiltration is by conducting a blower-door test or by means of thermography – recording heat changes on the building envelope through thermal imaging via special IR camera (Johnston & Gibson, 2008.). The points most prone to have air leakage and heat losses are areas around the door or window frames, on different systems interface points (different siding materials), insulation or vapor barrier issues at penetration points, and leakage at geometry variations and finally, issues at out of sequence work (deteriorated or badly installed assembly).

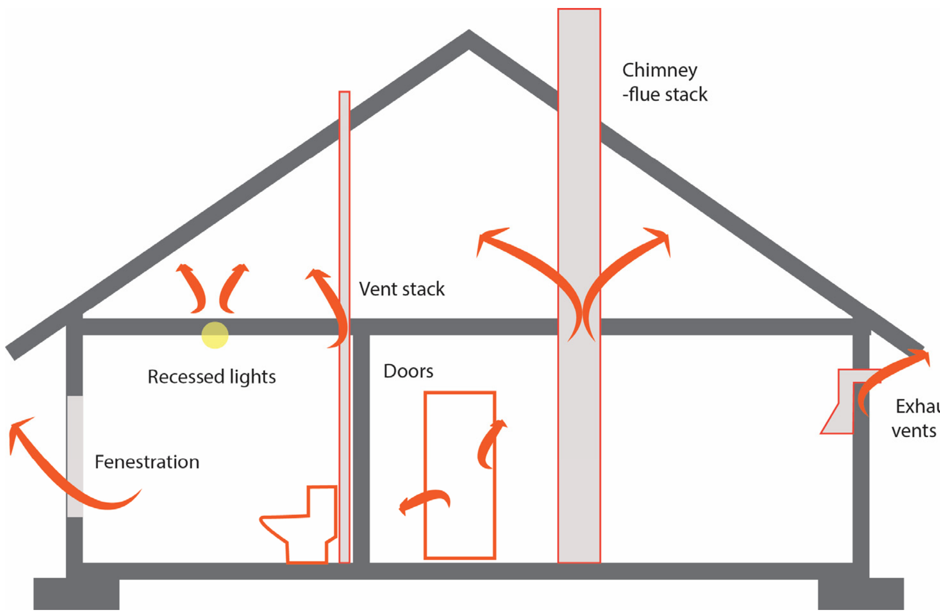


Figure 1. Potential penetration caused air leakage points in the assembly

Tight envelopes are durable and healthy, however a well-sealed house is a tight house, thus it's necessary to provide fresh air into the interior and get the stale air out. Natural ventilation is an environmentally friendly, low-tech solutions, however a healthy home would benefit from having backup mechanical systems for air-filtration, such as a heat recovery ventilator (HRV) or an energy recovery ventilator unit (ERV). In addition to keeping the indoor air fresh and healthy, mechanical ventilation helps pressurize the house properly (Johnston & Gibson, 2008).

4.2 Noise reduction in envelope assembly

Choosing the right components for the building enclosure can improve its noise reduction properties. This is much needed in urban areas, especially for multifamily or attached residential units. In order to dampen the sound waves, a barrier in the assembly needs to be placed in a way that it blocks the line of site between the noise source and the interior of the building. To effectively reduce sound transmissions, building enclosure needs to have a recommended Sound Transmission Class (STC) of 45 or higher, especially for attached units. The STC value of an assembly is describing how well its components can block off sound.

STC Ratings of specific wall assembly types

Assembly type	STC rating
2 x 4 studs, batt insulation, double layer of 5/8"gypsym on both sides	34-39
2 x 4 studs, double layer of, batt insulation, 5/8"gypsym on both sides	43-45
Staggered 2 x 4 studs, double layer of 5/8", batt insulation, 5/8" gypsum on both sides	46-47
Double 2 x 4 wall with air space, 5/8" gypsum, batt insulation	56-59

Table 3. STC Ratings of selected wall assemblies, source STCRatings.com

The typical 2x4 construction with cavity infill does not have the most effective sound deadening properties. A much better sound-proofing solution would be an envelope assembly that includes structural insulated panels (SIP), with a fiber-cement board siding and efficient windows. As cavity fills, cellulose and foam insulation are much more effective as sound deadening mediums than commonly used fiberglass (Johnston & Gibson, 2008.).

Adding C-channels perpendicular to the studs can dampen the sound waves. Channels act as shock absorbers, greatly reducing vibrations from passing through the wall. Absorbent mat is used inside the wall to cushion the channel/drywall and to provide an absorbent compartment to trap sound waves. The resilient channel technique by itself typically adds 3 to 5 (or more) Sound Transmission Class (STC) points to an otherwise identical assembly.

4.3 Shading strategies as an envelope efficiency factor

Strategic shading of the building envelope is crucial for controlling heat gains. If constantly exposed to the sun, the envelope, especially glazing will not perform to its best potentials. By conducting a sun study, one can determine where the critical areas are. Moreover, rules of thumb for fenestration placement in respect to building orientation are the best start to ensure that the envelope uses the climate to its advantage. Common shading strategies include - awnings, window boxes, insulated or non-insulated roll down shades, interior shades, movable shading – horizontal and vertical louvers. Landscape features can also serve as means for shading – placing evergreens on North will block off wind in winter, while deciduous trees on South can protect the envelope in summer, while letting the heat in at winter time.

4.4 Sustainable practices for building envelope components

A building envelope or enclosure is usually comprised of foundations, wall assemblies with structural support, a roof system and openings. Sustainable practices discussed in the reviewed literature recommend a number of strategies for high performance of these components with an accent on lower environmental impact. These recommendations are elaborated as applied to each of the components of the envelope in the following paragraphs.

4.4.1 Foundations

Foundations are a key component of the building envelope, anchoring the structure and protecting the enclosure from heat losses and water penetration from the ground (Johnston & Gibson, 2008.). Therefore, it is important that the foundations are firstly, designed and sized correctly, insulated to minimize heat transfer and waterproofed to keep the interior healthy and comfortable. Major considerations also include responsible sourcing of the material and using only needed amounts of concrete for the assembly and the requirements dictated by the building code, and more so, the climate zone where the structure is built. Concrete is a vastly used product and its imperative to source it correctly and thus aid in the reduction of carbon emissions caused by its production. Moreover, wood forms for setting the foundations present a somewhat irresponsible utilization of wood and also comprise a big portion of the total construction waste. Using properly sized forms, such as plywood or metal forms that can be potentially reused would be beneficial in this respect.

For a slab on grade construction, great and cost-effective solution is frost protected shallow foundations (FPSF). The National Association of Home Builders' researchers have developed a foundation system where the perimeter of the footing can be as shallow as 16" and can be used in cold climates throughout (NAHB, 2004). The rigid insulation is placed below the concrete slab on grade while the footing itself is insulated in two ways – horizontally, along the exterior length, and around the perimeter of the slab, right above the frost line.

The proper specification of insulation products is paramount to the success of an FPSF application. Insulation products are classified by an R-value for above ground dry conditions, however if the application is below ground, the required R value must be calculated to assure efficiency in the moist environment (NAHB, 2004). When designing for particular climate zones, it is important to make sure at what depth the frost line forms. The starting point is to determine the Air-Freezing Index (AFI) for the site location. The AFI presents an "indicator of the combined duration and magnitude of below-freezing temperature occurring during any given freezing season" (NAHB, 2004). The map of Air Freezing Index Map can be obtained from the IRC or the National Climate Center (NCDC). Then, the needed insulation levels can be determined based on the AFI. This is the so-called 'simplified' method of determining insulation minimums. A much more complex, 'detailed' calculation is a flexible approach that allows the designer to utilize experience and as an example may opt to provide vertical wall insulation only, horizontal insulation only at the corners, or provide horizontal insulation around the entire building. In the detailed approach, foundation depths can be modified by balancing them with the amount of horizontal insulation (NAHB, 2004). The table below summarizes needed levels of insulation depending on AFI for heated buildings (example homes with minimum average monthly indoor temperature higher than 64°F (18°C)).

Air Freezing Index (°F100)	**Vertical Insulation R-value Dimensions Footing**	**Horizontal Insulation R- Depth**		**Horizontal Insulation Dimensions (in inches) (Figure 2)**			**Minimum Footing Depth (in inches) (Figure 2)**
		Along walls	At corners	A	B	C	D
<1,500	4.5	NR	NR	NR	NR	NR	12
2,000	5.6	NR	NR	NR	NR	NR	14
2,500	6.7	1.7	4.9	12	24	40	16
3,000	7.8	6.5	8.6	12	24	40	16
3,500	9.0	8.0	11.2	24	30	60	16
4,000	10.1	10.5	13.1	24	36	60	16
4,500	12.0	12.0	15.0	36	48	80	16

Table 4. Minimum Insulation Requirements for FPSFs in Heated Buildings

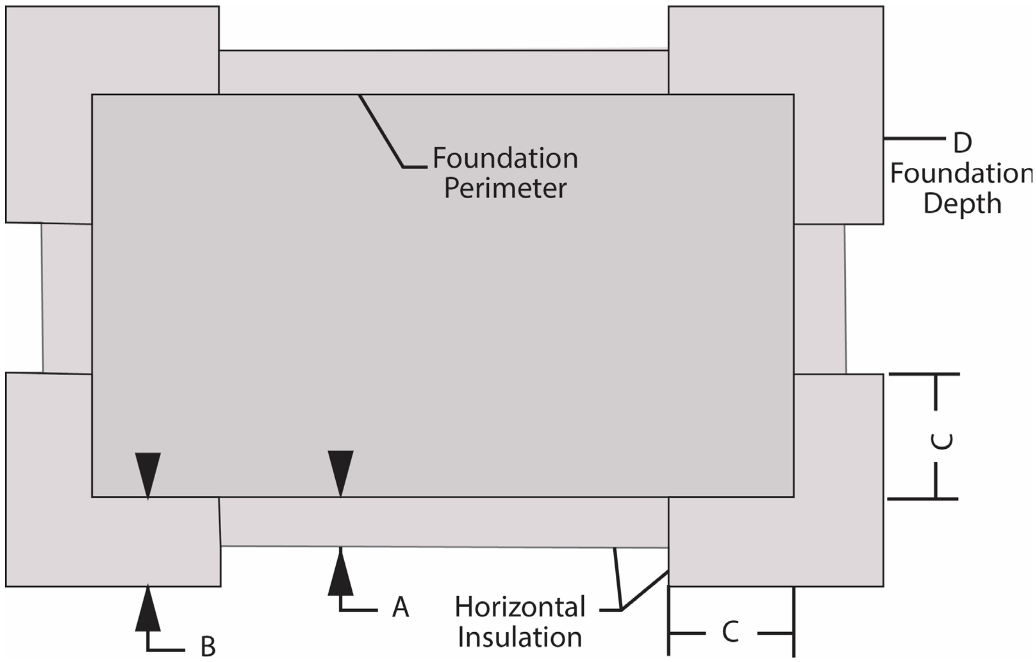


Figure 2. FPSF Simplified Design Parameters for heated buildings

The geothermal, ground heat is trapped by the layer of rigid insulation at the perimeter, protecting the slab from cold. Below the insulation is a layer of non-frost susceptible sand, followed by a layer of compacted gravel fill. These foundations require a lot less labor – less excavation and consequently, less material used. This is both cost effective and more environmentally conscious, considering the carbon emissions caused by concrete production.

Frost protected shallow foundations are most suitable for slab-on-grade homes on sites with moderate to low sloping grades (NAHB, 2004). Some of the benefits of FPSF over standard foundations include:

- Reduction of about 4% of the cost of a conventional slab-on-grade home
- Reduction of excavation costs and labor time
- Minimized site disturbance, and enhanced frost protection

- Reduction of concrete amounts and reinforcement used on the structure, therefore a reduction in overall resource depletion

The difficulty with mass application of FPSF is that it's a fairly new technique, not yet widely embraced by the builders and local building codes. Informing the customers on the benefits of this strategy could help with the expansion of FPSF application in modern homes and building expansions.

Another type of foundation that combines structure and insulation are insulated concrete forms (ICF). These forms are stacked like blocks and consist of two outer layer of extruded-polystyrene rigid forms held together by spacers. The cavity is then filled with concrete that is therefore insulated from both sides. The exterior side of the forms need to be additionally waterproofed if in direct contact with the soil.

A fairly new system on the market combines the ICF assembly with an innovative solution for reduction of construction waste caused by concrete forms. The system, called 'Fab-Form Monopour' uses sheet-plastic footing, Fastfoot, to mold and form concrete foundations. The system uses the ICF block itself to form the footing, thereby eliminating all footing forming lumber. The reinforced high density polyethylene sheet-plastic footing form is unrolled and installed under ICF molds. The sheet-plastic serves as a proof membrane, preventing ground moisture wicking into the footing concrete, keeping the envelope healthy. According to Richard Fearn, the owner of Fab-Form Industries, Ltd., the labor time is cut down by two days and installation costs are typically reduced by 20%.

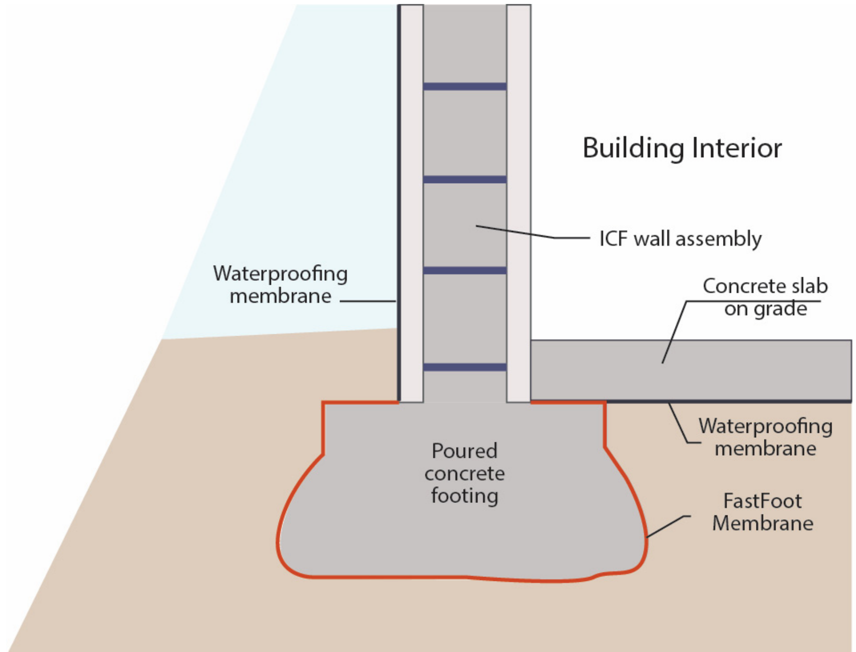


Figure 3. FabForm Monopour foundation and wall system, adapted from manufacturer's data

The system has the ability to achieve a more accurate foundation, as the contractor can adjust and align his foundation even on pour day. The monopour method provides a stronger foundation without any cold joint and eliminates the second pump and second concrete return, saving money. Moreover, the membrane prevents ground moisture from entering the concrete footing. Finally, the FastFoot foundation system eliminates all forming lumber, stakes and associated labor to build and strip footing forms. A 100' roll of Fastfoot membrane forms the same amount of concrete as 1,500 pounds of lumber.

Risks associated with this foundation technology involve possible occurrence of uplift and settlement if the pour is not done carefully. The top of footing can produce uplift if the footing concrete is not allowed to set sufficiently. Settlement can occur through failure of the side support, failure of the attachment of the support to the ICF block, and settlement of side support pad in the ground. To eliminate this risk, as Fern recommends, the contractor must allow for the footing concrete to set before continuing with the second lift and using bracing.

It cannot be stressed enough that resource management is a highly important issue in the building sector. Consequently this is true for construction of foundations and other envelope mass components that require large amounts of concrete. Adding a percentage of recycled content can reduce the need for raw materials (Kibert, 2013). As an example, Fly ash can be successfully used to substitute a portion of the Portland cement in the concrete mix, thus lowering the carbon footprint of the concrete production (8% contribution to the C02 releases in the industry). Fly ash is a by-product of coal energy plants, and very difficult do dispose of. However, when added to the concrete mix it can chemically bond with the cement and ameliorate the strength and durability of concrete. Typically a 15% fly ash mix is common, however as recommended by the Green Builder organization, best practices in sustainable construction would employ a 30% Fly ash Class C mix . Moreover, adding fly ash to the concrete mix can contribute to the compressive strength of the mix – up to 500 psi more than conventional mixes (total up to 3.500 pounds per square inch). This way the need for production of Portland cement can be reduced, lowering a portion of the carbon releases, while fly ash as a bi-product is reused for a new purpose (Johnston & Gibson, 2008).

4.4.2 Fenestration for high performing building envelope

Balancing window area to the relative mass of floors and walls illuminated by sunlight is key for having an efficient enclosure. The higher the volume of mass, the more glazing area can be placed – for example, the denser the slab, the more glazing can be added (for instance concrete slab versus wood flooring) (Total Environmental Action, inc.1980). A way to balance window area to square footage of south facing rooms is to estimate the window portion as 8-12% of the total floor area (Johnston & Gibson, 2008.). The best way to verify the decisions and glazing area is to evaluate the proposed ratios in energy modeling software such as REM Rate, HEED or BEopt (Clarke, 2001).

Achieving optimal daylighting without hindering the thermal properties of the whole envelope assembly is critical when planning for fenestration placement and sizing. Selecting high performing windows will ameliorate the envelope performance, and several factors should be considered when selecting the products. The National Fenestration Rating Council (NFRC) offers a standardized format for performance comparison of windows. The performance characteristics include:

- U factor of a window, or its ability to reduce the heat flow through the assembly (the lower the value the better performance a window has – it is more resistant to heat flow)
- Solar Heat Gain Coefficient, or the amount of heat transmitted through the glazing (lower values are better)
- Visible light transmittance – lightness of objects seen through the window
- Air leakage - amount if air in cubic feet passing through a square foot of the assembly
- Condensation resistance – higher values are better as they denote the ability of a window to resist condensation

The type of glazing is very important in the selection process as the number of panes in the assembly, along with their ability to resist heat flow, are the most important factors for an efficient window assembly. Modern windows can incorporate high-performance glass with a high resistance to heat flow. A single pane of glass has the insulating level of R-1, however the single glass pane windows are rarely used in modern construction. Double-glazed assemblies have a much better thermal performance, R-2 (U-0.5, even down to 0.3), with an optimal space between the panes of 0.5". High-efficiency windows go up to triple-pane assemblies with U-factors as low as 0.15, can in addition incorporate argon or other gas fill in between the panes for additional insulation (U.S. Department of Energy's Windows and Glazings Program). Moreover, modern glass types can have various coatings such as low-e film (reflects infrared energy toward the warm side of the glass), fritting, tinting, self-cleaning film, thermographic films (window tints based on the heat gains on the exterior).

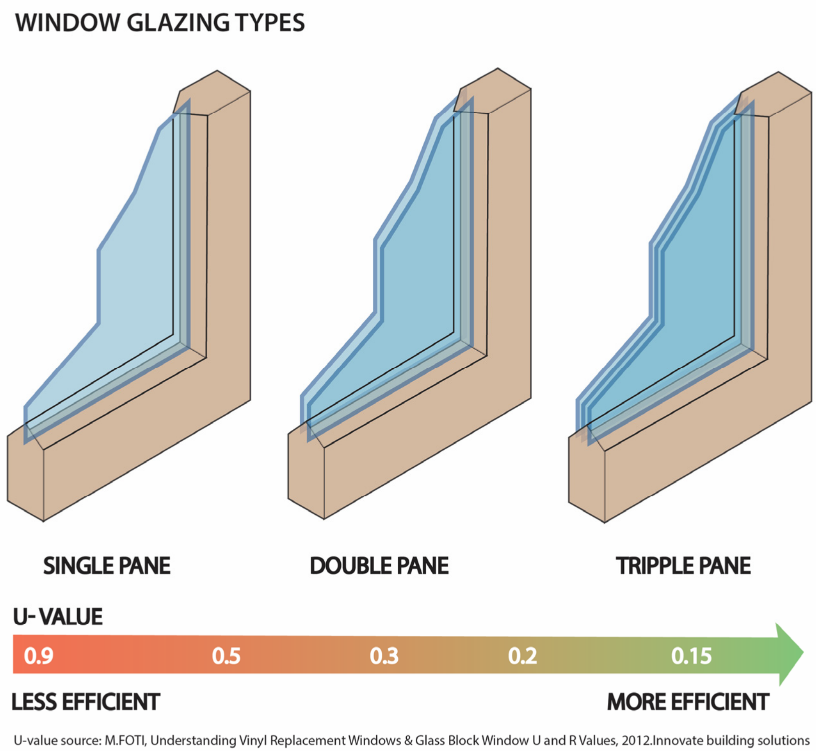


Figure 4. Diagrammatic overview of basic window types with their respective U-values

When considering frames, their durability and tightness play a big role. Typically, fiberglass, extruded PVC and vinyl-clad wood frames tend to be more durable than wood frames and require less maintenance. These frames are also more resistant to warping and termite attacks.

U-VALUES FOR WINDOW FRAME TYPES

Frame material	U- value
Aluminum (no thermal break)	1.9-2.2
Aluminum (with thermal break)	1.0
Aluminum-clad wood/ reinforced vinyl	0.4-0.6
Wood and vinyl	0.3-0.5
Insulated vinyl/ insulated fiberglass	0.2-0.3

Table 5. Overview of respective U-values for selected window frame types

Fiberglass is very durable and due to its structure, the frames and the glass expand at the same rate. It has a higher cost among other things because it has to be additionally coated. Some of the manufacturers of fiberglass frames currently on the market are Owens Corning, Andersen and Marvin. Owens Corning even has a line fiberglass windows with insulated frames (Fine Homebuilding Program). Aluminum-frame windows are durable, requiring little maintenance, however, evident in Table 5, they are very conductive.

Spacer materials are another important component in the window assembly, as they can be a weak point of the window and potentially allow air or moisture to build up in pockets between glass panes. As a comparison, spacers made from epoxy allow for thermal breaks and therefore can reduce heat losses at the glass edge (Johnston & Gibson, 2008.) Metal window spacers are more conductive and therefore can increase thermal bridging.

Another important consideration is how the windows operate, as some operating types have lower air leakage rates than others, which can affect the envelope efficiency (U.S. Department of Energy).

4.4.3 Sustainable practices for structural systems

Advanced framing techniques for the building structure are on a path to become a new standard as they employ solutions that are geared towards responsible resourcing of materials, mainly wood, through right sizing of framing elements thus reducing the amounts of used resources. Right sizing of structural elements is also an important factor for reduction of construction waste. The goal is to size the elements in the way that the excess material falls under 10%. In terms of material selection, engineered and responsibly sourced or Forest Stewardship Wood (FSC) is the way to reduce deforestation or soil erosions caused by either cutting down of trees or over usage of a specific plot of land for planting. Structural framing is a vast, comprehensive topic and thus, this research will only touch on general good practices in modern construction.

Even though vastly applied in North America, wood framing is rare in Europe where massive systems or prefabricated structural elements are much more present in residential construction. Some of these alternatives include concrete masonry (CMU) blocks, autoclaved-aerated concrete blocks, and vastly popular in the Balkan region – clay blocks.

Clay blocks are a bit on the pricier side as a whole assembly solution but they are more environmentally friendly, almost 60% lighter than solid concrete blocks, non-flammable and have good thermal and sound insulation characteristics. These bricks are also resistant to rotting, denting, warping, and termites.

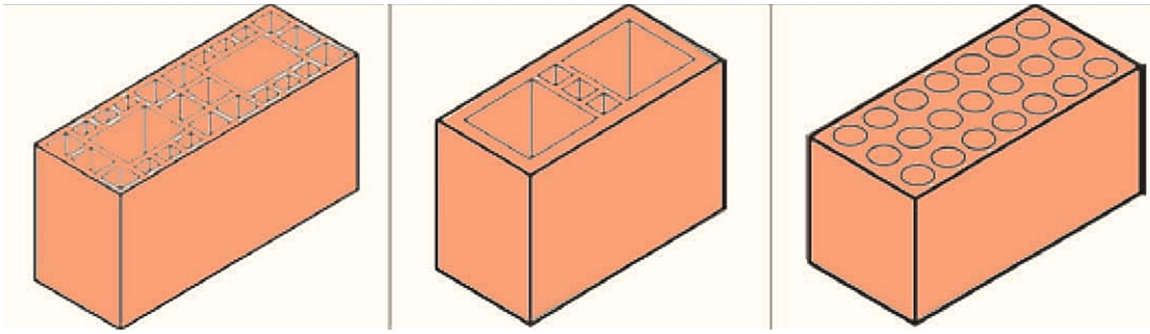


Figure 5. Masonry clay blocks, diagrammatic view

A downside of this building material is that clay is very porous and therefore needs to be protected from moisture penetration. Masonry units from clay blocks are still present in certain parts of the world, mainly South and Eastern Europe as well as parts of Asia and South America. In the U.S. one of the first versions of clay blocks that initially lacked today's durability, has been applied in residential construction in the period from 1930 to 1950 (Reeves et al. 2006).

Another alternative to wood framing are structural insulated panels (SIP). These panels combine insulating properties with structural integrity, soundproofing, moisture control and general assembly durability. A typical SIP panel consists of an insulating foam core, sandwiched between oriented strand boards (OSB). Due to the higher R levels (3.9-4.4 per inch) of foam type insulators, SIP tend to perform better than standard insulation batts (Structural Insulated panel Association).

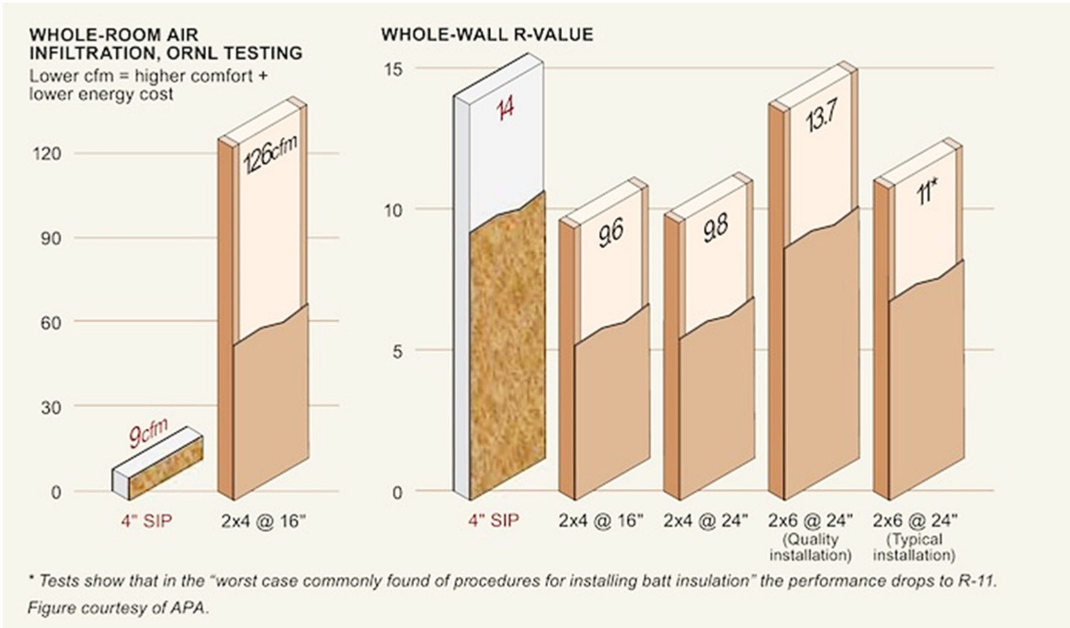


Figure 6. R-Value and Air Infiltration Test comparisons between SIP panels and standard assembly construction

The R-value of insulation is determined using the guarded hot plate test in a controlled environment, where there is no air movement, at a temperature of 75°F. In comparison to SIP, studies conducted by the Department of Energy's Oak Ridge National Laboratories (ORNL) show that as outside temperatures get colder, the R-value of fiberglass insulation decreases. ORNL tested loose-fill fiberglass attic insulation rated at R-19 at a variety of temperatures. When outside temperatures dipped to -8°F, the R-19 insulation performed at R-9.2, as infrared imaging revealed convective currents inside insulation. In contrast, the rigid foam insulation used in SIPs performed better in colder temperatures. Expanded polystyrene with a stated R-value of R 3.9 per inch at 75°F was tested at R-4.2 at per inch at 50°F and R-4.4 per inch at 25°F. Moreover, because the insulation is enclosed within the OSB boards in SIPs, they are not subject to convective currents like fiberglass insulation (ORNL, Structural Insulated Panel Association).

These panels are cut to size and delivered to the building site ready for assembly. This drastically cuts down construction time and therefore labor costs. With panes that don't have studs pre-foamed into the assembly, controlling moisture and air penetration between studs and foam is critical during construction as it can be very impactful to the overall performance of the envelope and comfort levels in the interior. Moreover, it's important to properly seal the seams between panels and flash the rough openings before inserting doors and windows. Running pipes or wires through exterior SIP walls is not ideal as it can reduce its performance, but if those openings are well caulked, those issues can be avoided. For panels that are sandwiched between OSB boards, waterproofing is imperial, thus a continuous membrane should be applied as a whole house wrap. The case study described in the later chapters features a new, innovative SIP type that eliminates OSB boards and integrated structural framing as a pre-foamed element. This new assembly type is a product of RayCore Company and features a radiant-foil air barrier on both sides of the panel that helps eliminate thermal transfer through integrated wood members. The properties and benefits of these panels are discussed more in the case study chapters addressing the wall assembly strategies.

4.4.4 Alternative envelope assemblies

Some of the alternative envelope assemblies include straw bale blocks, adobe and rammed earth construction. Straw bale walls are a low tech construction method that draws lessons learned from the past.

One of the historic examples of a similar method of application would be certain types of huts in the Balkan area. From 13th century, onward to 17th, a great portion of the population had to constantly be on the move because of the restless times and wars in the region, and thus had to quickly build inexpensive types of dwellings. These houses were called – 'bondrucara', with later, more complex and structurally stable versions - 'pletara' and 'chatmara' (Petrovic,1997).

These homes had stone foundations, wood construction, and a straw infill with mud sealant over the wall. This was the early version of a stucco finish. One of the oldest examples of this type of straw infill homes from 1850 was still standing in Belgrade, Serbia before completely collapsing in 2010.

Figure 7. Example of straw cavity infill home in Serbia,

house of Mr. Dimitrije Mirković, 1850.

Figure 8. Details of Mr. Dimitrije Mirković's house from 1850.

Modern straw bale elements can be used in two ways – either as an infill with supporting structure, or the bales can be formed into structural walls and stacked together. Straw is a renewable source, can be harvested locally, it is relatively inexpensive to source, and it has a high R value. A bale of straw's R value can come to 28 ft^2 °F hr/Btu (Johnston & Gibson, 2008.). The stucco finish protects it from pest infestation and fire. The bale clusters are pinned together, covered with wire mesh and then finished with stucco to make them weather tight and durable. Las Vegas' Springs preserve features a beautiful example of straw bale construction in several facilities on the property and offer a great education program, spreading the knowledge about the assembly.

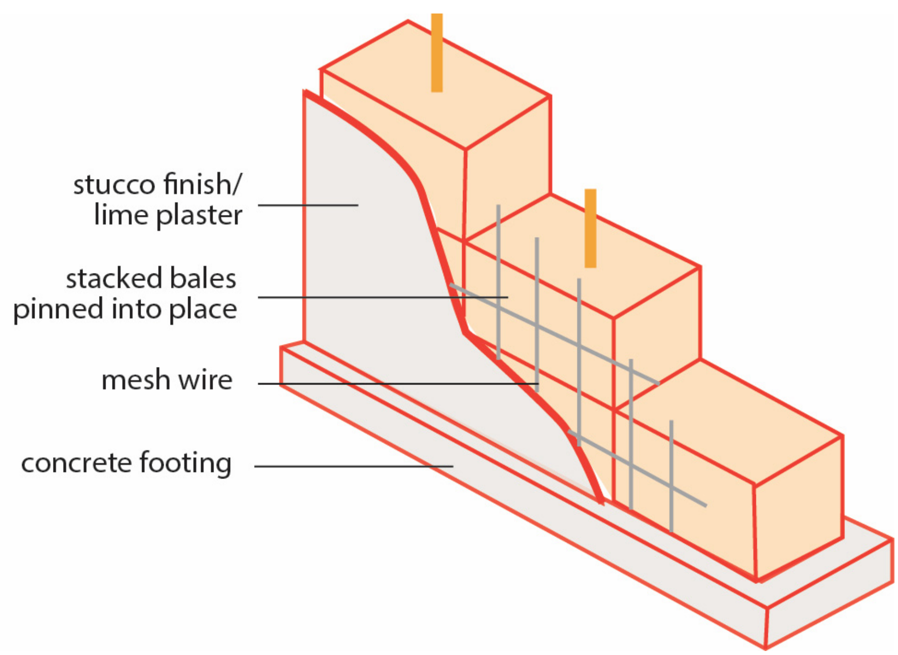


Figure 9. Structural straw bale wall assembly diagram

Rammed earth and adobe construction are indigenous to the Southwestern US and Mexico. Earth is the basic raw material for the building envelope, however not any type of soil will do. Traditional adobe house are made from earthen bricks dried in the sun, laid in courses to form walls.

Modern versions of adobe bricks are stabilized with cement they make up for very thick walls. Rammed earth construction consist of a soil mix with a small amount of cement, compacted with hydraulic tools; walls can be up to 2 feet thick. The basic building material for this assembly is inexpensive, however the process to build it is, as it requires specialized equipment and long labor process. These materials have a great ability to passively cool a building by absorbing heat gains and then re-radiating them at the end of the cycle. Its high hygroscopic values also allow it to passively control the humidity in the interior, due to the porousness of the material.

4.5 Review of selected insulation types

Smart material procurement for wall and ceiling cavity insulation, its proper sizing, installation and maintenance are key for achieving maximum performance of the assembly. Durable, well-sealed sealed envelopes make up for a healthy, long lasting building enclosure that requires the least amount of maintenance or replacement and contribute to the indoor air quality and thermal comfort of the building. As thermal insulation is a major contributor to the overall carbon footprint of the building sector, it is necessary to turn to solutions that are less impacting to the environment or that have a potential to offset the whole building energy consumption through high performance. Insulation is a key part of designing for climate. The insulation levels or the overall R value of the house needs to be higher than the minimums required by the local energy code (U.S. Department of Energy). In the new, green homes, the R values of an assembly often times come up to 50% more than the code requirements (Johnston & Gibson, 2008.). It is however important not to have a much too excessive amount of insulation as its performance will not be significantly better and thus a portion of the material might be wasted.

The figure below shows the minimum required insulation levels for specific locations in the U.S. (U.S. Department of Energy).

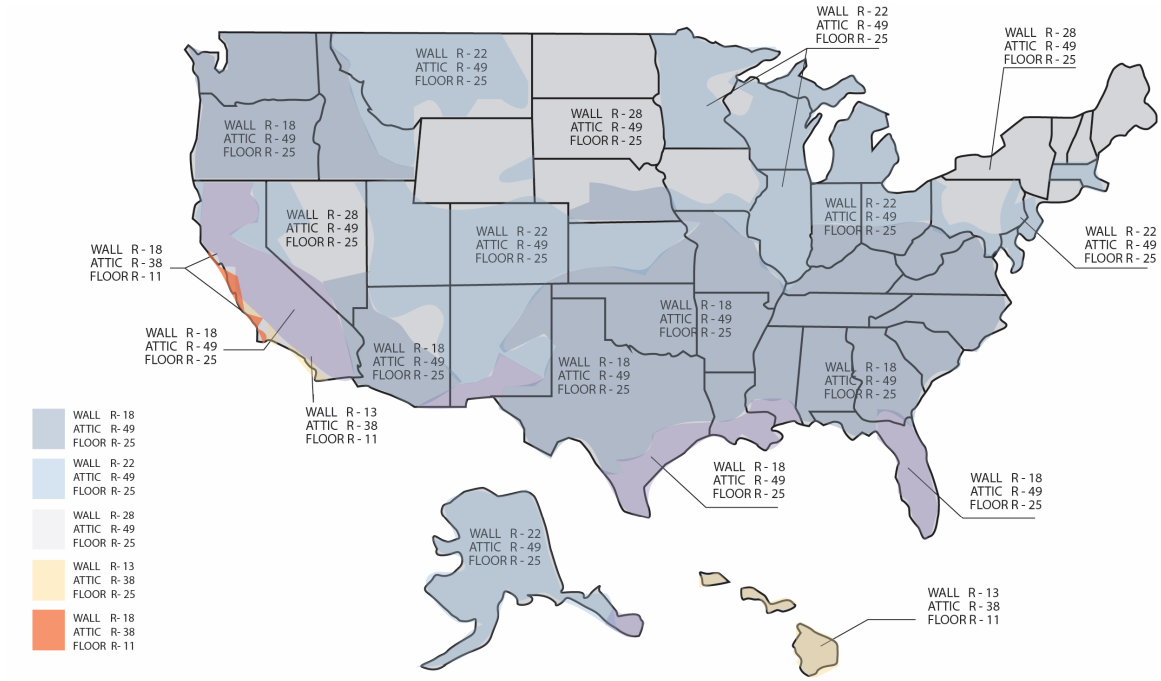


Figure 10. Minimum R values for specific parts of the envelope, Recommended by U.S. Department of Energy, 2009

The following insulation materials are frequently addressed in current discussions on advanced building strategies and green concepts (Green Building Advisor, EEBA, USGBC, Building America Program and other sustainable practices resource databases and discussion forums). There is a number of advanced insulation materials being developed and tested at any given moment and they are truly the harbingers of a greener, more efficient and environmentally responsible future for the building sector. This research will however only touch on the products that are readily available on the market and to a degree present in the modern construction.

The overview of the insulation materials will include the following products:

a. Cellulose - dense pack and loose fill

b. Recycled cotton – denim batt

c. Wool insulation - sheep's wool

d. Spray-in foam

e. Rigid insulation boards

4.6 Qualitative data for selected insulation types

4.6.1 Cellulose insulation

To form the batt sheets, the scrap paper flakes are mixed with fibers and binders, pressed in steam and then cut after drying. Powdered boric salts in the cellulose mix make the recycled newsprint fire-resistant – it will char but not burn. The R-value of this insulation type is 3.4-3.7 per inch.

By using post-consumer material, this recycled product can, along with improving the energy efficiency of the envelope, reduce its environmental impact in comparison to a standard assembly (with fiberglass cavity insulation for example). According to Cellulose Insulation Manufacturers Association (CIMA), this material has a very low comparative embodied energy (0.94–3.3 MJ per kg), even 20 to 40 times less than mineral fiber solutions.

Cellulose insulation has low toxicity - doesn't contain formaldehyde and is made from recycled content (approximately 80% postconsumer recycled newspaper product). As this material is highly hygroscopic, it must be well wrapped with a waterproofing membrane and the installer needs to make sure that there are no holes in the sheets (Johnston & Gibson, 2008.).

Typical application is as assembly cavity – it can be used to insulate wall assemblies and also in the roof assembly and suspended floors. It is important to properly calculate the weight of the material needed for a particular assembly, particularly for roof cavity insulation. Inadequate quantities of cellulose insulation can cause the ceiling to sag, for example if installed at R-38 on ½" ceiling gypsum board. In this case, a necessary measure would be to switch to 5/8" ceiling board (Bynum, 2001). The so-called 'dense pack' cellulose insulation is installed through blow-in methods. The loose cellulose flakes are pushed into the cavity at densities of 3.5-4 lb/ft^2 through a high-velocity insulation blower at 100 ft/s. The air, trapped between cellulose fibers contributes to the insulating values of the material. (Bynum, 2001). A newer method for loose fiber cellulose insulation is associated with 'fiberization' of the newspaper material - separating it into fine flakes to make the whole assembly fuller.

Cellulose insulation has a very comparative cost on the market, the price per square foot per R-value is $0.03, however, because of the specific installation conditions and special tools, the labor costs are fairly high – around $55 per hour (Home Wyse – job cost estimation). The issue remains with these relatively new insulation materials that the customer acceptance of the product is mainly based on fulfillment of regulatory requirements, as it is difficult to obtain building permits with innovative solutions in place. Cellulose insulation materials are currently covered by several standards, one of which is ASTM C-739 – Standard Specification for Cellulose Fiber Loose-fill cavity insulation. The table below summarizes some of the characteristics of cellulose insulation.

Cellulose insulation R-value per Inch: 3.4 – 3.7
Strengths: lower embodied energy, low cost, high recycled content, reaches all corners of the cavity, good for attics with lots of cavity space, widely available, good sound deadening properties
Weaknesses: hygroscopic and not very air tight, potential for mold growth, non-recyclable if treated with boric acid, problems with sagging if not correctly installed

Table 6. Cellulose insulation characteristics – summary

4.6.2 Wool insulation

Wool insulation is a fairly inexpensive material that is highly renewable in certain areas with related branches of industry. Sheep wool is a product popular especially in New Zealand, though some manufacturers are emerging in Colorado and mid-America. As the product is not yet fully tested, there might be an issue with regulations and obtaining permits as the product requires a national technical approval. The material consists of pure sheep's wool and a percentage of recycled sheep wool. The raw material is cleaned and sprayed with additives. The batt is treated with boron compounds to protect against rodents, insects and mold, and it contains no chemical irritants. The thin fibers are separated from the wool and carded to form 'carded fleece.' These fleeces are laid over each other diagonally, compacted and needled to form batts. Fire-resistant and self-extinguishing, completely biodegradable (Pfundstein et al. 2008). Wool has a very high inflammation point of 560°C due to its high Nitrogen content of ~16%. Wool is self-extinguishing due to its high Limiting Oxygen Index (LOI=25.2), meaning that in order to completely burn wool, an oxygen content of 25.2% is necessary, whereas air only has 21% (Zach et al. 2012; SheepWool Insulation). The material is highly hygroscopic –

capable of absorbing a substantial amount of moisture and then drying out without damage. It can absorb up to 33% of its own weight in moisture.

Recycling of this product is not easy which can come as a surprise. Undamaged wool can certainly be recycled, though if the wool contains boric salt additives it must be disposed of in a landfill or incinerated (Pfundstein et al. 2008). The application is similar to that of cellulose insulation, sheep's wool can be installed in batts or as blown in loose material. It can be applied as insulation for wall cavities, between floors or at attic or loft ceiling level.

As sheep wool insulation is a niche product, it is important to be aware of where the raw material is coming from. Transportation of the resources contributes to the embodied energy of its production. Even though it derives in part from recycled content, this product has an embodied energy level of 20.9 MJ per kg (almost 8 times more than cellulose insulation, for example, however less than glass fiber insulation -28 MJ per kg).

Sheep Wool insulation R-value per Inch: 3.5 - 3.8
Strengths: renewable material, good for retaining heat in winter and keeping it out in summer, inherently flame retardant and self-extinguishing, biodegradable, doesn't settle due to the high elasticity of the wool fibers
Weaknesses: embodied energy of the manufacturing process – origin of the raw materials, few manufacturers and trained builders available

Table 7. Sheep wool insulation characteristics – summary

4.6.3 Cotton batt

Cotton insulation can either be produced from the fibers in the seed pods of the cotton plant or, alternatively, recycled from an existing product, for instance – blue jeans. It is commonly available in batts with an R-value of R-3.4 per inch. It consists of kraft paper facing made from polyester fibers (25%) and cotton scrap (75%). The polyester improves tear strength (Bynum, 2001). Just as cellulose and wool, cotton flakes need to be treated with boric salt flame retardant impregnation. Cotton insulation consists of 85% recycled cotton and 15% plastic fibers that have been treated with borate -- the same flame retardant and insect/rodent repellent used in cellulose insulation. One product uses manufacturing trim waste from blue jeans. As a result of its recycled content, this product uses minimal energy to manufacture. It has high absorbency levels – it can absorb up to 80% of its weight in moisture; yet it takes very long time to dry, thus it is better to waterproof it tightly and keep it dry. Cotton insulation is also nontoxic, and can be installed without using respiratory or skin exposure protection. However, cotton insulation costs about 15% more than fiberglass batt insulation (U.S. department of Energy, Insulation Materials). One of the products available on the market is UltraTouch cotton batt made from 85% recycled denim. The R value per batt varies from 13 to 21 and is limited to cavity space. UltraTouch contains no harmful airborne particulates eliminating health concerns regarding particulates in the surrounding environment and includes an EPA registered fungal inhibitor to resist the growth of mold or fungi. Moreover, this product meets the Environmental Specification 1350 Indoor Air Pollutant testing used for California Public Schools (UltraTouch Technical Specifications data). As any other batt insulation, cotton needs to be carefully installed to avoid sagging in the cavity over the years caused by gravity.

Cotton insulation R-value per Inch: 3.4
Strengths: post-consumer material, easy to handle, good fire retardant, impedes the growth of fungus and mold, high Noise Reduction Coefficient to effectively reduce airborne sound transmission including traffic, airplanes, radios, television, and conversation, contains no chemical irritants, requires a minimal amount of energy to manufacture
Weaknesses: sagging, higher cost to standard assemblies, doesn't dry quickly

Table 8. Cotton insulation characteristics - summary

4.6.4 Spray-in foam

Spray-in foam products are most commonly made of Polyurethane, Phenolic Cementitious or Polyisocyanurate. They have a high R value, up to 6.5 per inch, and they are an excellent air sealing product. To avoid the urethane content, advanced foam materials are made with soybean shells. Another aspect that was improved in the newer products is the blowing agent. The blowing agents that fluff up the ingredients as they are applied had a portion of ozone-destroying compounds, but the content has been significantly reduced. Some types of foam can even be foamed with water (Hall, 2010).

Spray-in foam products are, however, on the higher end of costs for insulation materials while the certified installers need to have special equipment to install this type of insulation (Hall, M.2010). The customer needs to understand the full potentials and performance levels of this material to accept the upfront cost which can be significantly higher, compared to standard construction. The price per square foot per R-value of open-cell foam is $0.17, and for closed-cell foam up to $0.25. Labor costs are also higher because of the specific equipment the installers need to have, but the amount of time needed for installation is much shorter compared to traditional solutions. Another issue with spray in insulation is that, especially in wall cavities, the top irregular surface will need to be flattened and trimmed off diverting non-biodegradable construction waste to the landfill. Even though these are issues that shouldn't be overlooked, a high performance and air-tightness that this product can add to the building envelope can rule in favor of this material. Even though the embodied energy of sprayed-in foam is higher than some other products, for example – natural fiber insulation (88 MJ per kg, almost 30 times more than cellulose insulation), this material has the potential to offset a portion of its production impact with ameliorated performance of the envelope as a whole.

Foams are available in high and low density, open cell and closed cell structure. The difference between high and low density cell foam is the degree to which they allow water vapor to pass through. Low density foams are more vapor permeable but they for effective air barriers. Foams expand on contact; that is why they are great for sealing even the smallest cracks. The typical depth of installation is 2.5" to 3" – not necessarily filling the entire assembly cavity (Bynum, 2001).

Spray-in Foam R-value per Inch: Open-cell foam – 3.5-4 ; Closed-cell foam – 5-6.8
Strengths: air tight installation reaches all corners of the cavity, good for whole house installations except locations susceptible to moisture, high performing
Weaknesses: more expensive than batts or cellulose, will absorb moisture, installation produces excess foam that must be trimmed and disposed of, higher embodied energy

Table 9. Spray-in foam insulation characteristics - summary

4.6.5 Rigid insulation

Rigid insulation types include Expanded polystyrene (EPS), Extruded polystyrene (XPS) and polyisocyanurate. The performance of these rigid foams depends on their base polymer and the type of the blowing agent. Rigid foam insulation applied to the outside of a building reduces thermal bridging and air infiltration while moving the dew point inward to reduce the risk of condensation inside wall cavities. Rigid boards have been used throughout the years as an effective under slab insulator and have very low thermal conductivity, high compressive strength and good moisture resistance (Hall, 2010).

EPS boards are appropriate for low-moisture environments; they use steam or pentane to expand the foam pellets into a sheet product. They are the most inexpensive and vastly applied type of rigid insulation.

XPS uses hydrochlorofluorocarbon (HCFC), a compound consisting of hydrogen, chlorine, fluorine and carbon. This product has been improved over the years, yet there's still 10% of gas emissions that come from a production process of the product.

Same is true for polyisocyanurate or polyiso boards that have R-7.5. There are ones that use a non-HCFC blowing agent, but their R value is reduced to R-6. This is because even when even small quantities of CO2 are introduced into the mix, they appear to be beneficial for the foaming process. Polyiso boards can be applied over roof sheathing to reduce the heat buildup on the attic. This type of board has OSB board on one side as a nail base for felt paper and shingles. They are a very befitting product for retrofitting. When installing any of these board types it is important to use adhesives that won't dissolve the panel surface and destroy the panel. As these materials have a very high level of embodied energy 88.6-101.5 MJ per kg, it is important to size them properly to avoid unnecessary production and post-construction waste management. The cost of these materials are higher than standard insulation material products but significantly lower than, for example, spray-in foam ($0.07-0.10 for rigid insulation versus $0.17-0.25 for spray-in foam).

Rigid Insulation R-value per Inch: Polyiso board: 6 – 7; EPS board: 4; XPS board: 5
Strengths: readily available on the market with proven high performance, easy installation, can be airtight if sealed/taped at the seams
Weaknesses: higher embodied energy, higher cost, potential to absorb moisture, lower fire resistance

Table 10. Rigid insulation characteristics – summary

4.7 Quantitative data for selected insulation types

Quantitative data has the task to list and compare the variables related to LCA and thermal performance of the observed materials. Side by side comparison can be used to make general conclusions. However, as stressed earlier, the most meaningful interpretation of these materials will come through their performance assessment within a particular envelope.

Table 12 lists the values of insulating material properties critical for their thermal performance:

- R-value, thermal resistance (derived from thermal conductivity and thickness of a particular material)
- Thermal conductivity – capacity to conduct heat, lower values indicate better insulating properties
- Density – quotient of mass and volume occupied by that mass, low density usually indicates high porosity which leads to a decrease in in thermal conductivity i.e. better thermal insulation of the material
- Specific heat capacity – ability of a mass of a material to store heat
- Water vapor diffusion resistance – resistance to moisture distribution in the body of material

Type of material	R- value [ft2hr°F/Btu]	Thermal conductivity, λ [W/(mK)]	Density [kg/m^3]	Specific heat capacity, c [J/(kgK)]	Water vapor diffusion resistance, μ[-]
Fiberglass - Standard	2.2-3.2	0.040	20-200	600-100	1-2
Cellulose	3.5-3.8	0.040-0.045	30-80	1700-2150	1-2
Cotton	3.4	0.040	20-60	840-1300	1-2
Sheep Wool	3.5-3.8	0.040-0.045	25-30	960-1300	1-5
Polyisocyanurate (PIR)	6.0 -7.0	0.023	40	1470	50-200
Polystyrene, expanded (EPS)	4.0	0.035-0.040	15-30	1500	20-100
Polystyrene extruded (XPS)	5.0	0.030-0.040	25-45	1300-1700	80-200
Polyurethane foam (PUR)	3.5-6.8	0.024-0.030	30-100	1400-1500	30-200

Table 11. Insulating material properties related to thermal performance

To understand the environmental impact of an insulation material it is important to look at several parameters that comprise LCA of the observed materials. As discussed previously, some materials will have a much more favorable performance but the LCA factors might show that the environmental impact of their application do not justify the application. It is important to look at these values as a set of variables influencing each other. Understanding the relationships between those variables can help in their manipulation.

Table 13 lists the values of insulating material properties related to their environmental impact and resource depletion:

- Embodied energy of the material from non-renewable sources, high values are a red flag as depletion of fossil fuels for industrial purposes needs to be lowered.
- Embodied energy of the material from renewable sources – favorable values
- Global warming potential of material production and disposal related to carbon emissions
- Ozone depletion potential caused by material production and disposal

Type of material	**Embodied energy, non-renewable [MJ per kg]**	**Embodied energy, renewable [MJ per kg]**	**Global warming potential – carbon emissions [kgCO2eq.]**	**Ozone depletion potential [kgC2H2]**
Fiberglass - Standard	40.4	2.4	2.81	0.00016
Cellulose	4.2	0.4	0.23	0.00003
Cotton	18.1	13.6	0.02	0.00082
Sheep Wool	16.4	20.6	0.24	0.00066
Polystyrene, expanded (EPS)	81.0	0.4	2.64	0.00094
Polystyrene extruded (XPS)	107.1	1.3	3.73	0.00278
Polyurethane foam (PUR)	101.5	4.4	13.7	0.00048

Table 12. Insulating material properties related to environmental impact

4.8 Observations derived from mixed methods evaluation approach of selected insulation materials

Foam based insulating materials have lower thermal conductivity levels and, therefore, superior thermal resistance values, however, as previously discussed, they have a much higher amount of embodied energy and higher cost. Specific heat capacity properties of insulating material determines how much heat can be stored in its body depending on its mass. Materials with higher specific heat capacity in the summer months have a positive effect on the interior climate – the higher the capacity, more mass can be stored (Pfundstein et al. 2008). Table 12 shows that cellulose has a very high specific heat capacity, and this is due to its configuration. In terms of water vapor diffusion, fibrous materials have very little resistance – only marginally different diffusion resistance to that of air. Rigid foam products have a much higher resistance. It can be determined from Table 12 that foam based materials and cellulose insulation have the most favorable combined properties when looked at as a set. Cellulose insulation is also favorable because of its lower embodied energy levels and percentage of recycled content. In the LCA parameters, materials that have the most favorable properties are cotton and sheep wool as they have the highest potential for production from renewable sources. Sheep Wool, however, has a higher global warming potential than cotton; the reason most likely being the production process itself, mainly the chemical cleaning of the wool. It is curious that data presented in "Insulating Materials: Principles, Materials, Applications" (Pfundstein et al. 2008) doesn't list a higher renewable sources potential for cellulose insulation materials. The reason for this might be that the authors used values for only post-consumer type of cellulose insulation which doesn't directly come from a renewable source.

5. CASE STUDY

5.1 Academic focus on building science

Advanced building technologies were the core focus of Building Sciences and Sustainability curriculum as part of the architecture program graduate studies. Topics discussed in the literature review, such as building sector's impact on the environment, population increase and urbanization and the sustainable development that needs to steer them was discussed in courses such as ABS 635 – Sustainable Design Principles, CEM 680 – Sustainable construction, ABS 741 – Integrated building systems and through studio design and independent research.

The exploration of advanced building strategies geared towards energy-efficient residential buildings was thoroughly researched in Professor Fernandez's course ABS 632 – Solar Energy Applications in Architecture. In the summer of 2013, this course focused on the U.S. Department of Energy Challenge Home Student Design Competition and the Rocky Mountain Institute Superefficient Housing Challenge. This research was used as a learning vehicle to demonstrate "real world" design and engineering solar applications through a series of case studies the course conducted. The class had a goal of producing a conceptual design for a residential home in Denver that would be both environmentally responsible and cost-effective, featuring the best design interventions guided by building science recommendations. Students used databases (U.S. Department of Energy – EnergyPlus weather data) and software (Climate consultant) to collect climatic data. Furthermore, the students used energy modeling software – HEED, to assess and optimize their design. At the end of the course, student teams presented their conceptual designs that met or exceeded the energy code, striving to a zero net energy home.

The class was a great preparation not only for the competition design development, but also for any sustainable building construction endeavor in future studies or professional career.

5.2 High performance residential attached homes – a case study for DOE Challenge Home Student Design Competition

As previously discussed in the literature review chapter, rapid urbanization and rise of population leads to expansion of the built environment and infrastructure. However to avoid an even more severe impact on the environment, solutions for sustainable, energy-efficient homes that are at the same time attainable and affordable for the population are a research endeavor that merits extensive research.

A group of students from UNLV School of Architecture and Howard Hughes School of Engineering teamed up with several faculty advisors and professor Alfredo Fernandez-Gonzalez as the head coordinator, to pursue the Rocky Mountain Institute Superefficient Housing Challenge and then later on tie in with the U.S. Department of Energy Challenge Home Student Design Competition. As for myself, after being appointed to the Team leader role, it was necessary to assemble a team of dedicated and most of all excited students that share the interest in sustainable building practices and systems and wish to embark on this ambitious journey.

Parallel to my team leader duties, I was conducting research on different building enclosure assemblies, their performance, market appeal and viability for the Denver climate. The conducted research expanded from envelope assemblies to high performing cavity insulation types as I observed that it is a resource so vastly utilized and in need of responsible procurement, sizing, installation and maintenance.

As noted, upon assembling the preliminary team roster, we embarked on the journey of understanding, evaluating and interpreting the guidelines and data tied to the both of the competitions.

5.3 UNLV's integrated team approach to the design process

In order to ensure a well-rounded understanding and a comprehensive approach to the competition requirements, we formed Team Mojave - a multidisciplinary student group, with different realms of expertise, all having rich backgrounds and vast geographical diversity. Our team name emphasizes the strong connection we have to our environment, here in Las Vegas, as we suite our designs to compliment the context and enrich their surroundings, with the cultural background of a particular place in mind.

Architecture and Engineering students of different academic levels teamed up for initial brainstorming meetings to determine the course that the design will take. Ideas were exchanged through many charrettes as we came to conclusions as a group, learning one from another. The students from engineering disciplines donated the time to work on the project outside of their curriculum, and the groups periodically met to coordinate and brainstorm, with the team leader present at each meeting. Several members of our team have substantial experience in the design-build process, as they played key roles in the 2013 Solar Decathlon competition where UNLV was ranked first in the nation.

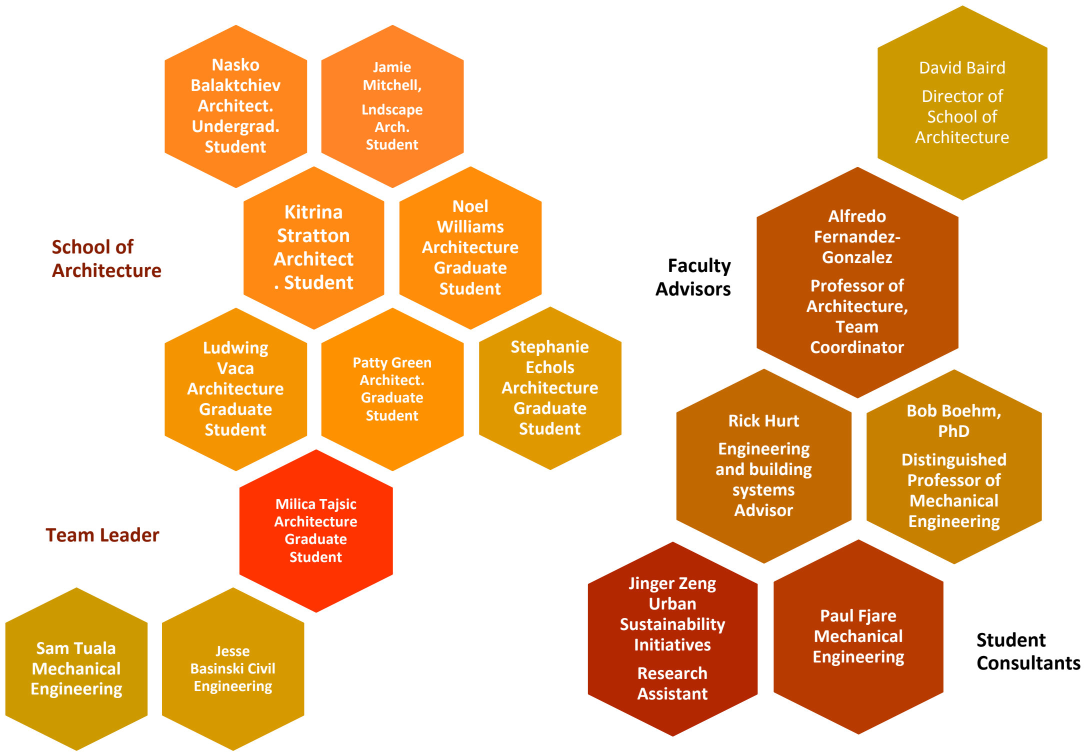


Figure 11. UNLV's Team Mojave Student members, faculty advisers and consultants

In the concept design stage, the integrated team brainstormed different forms of the house were proposed for evaluation of passive design, spatial arrangement and energy efficiency. During the schematic design, best practices for small space living and whole-house energy optimization were explored. Approach to the mechanical, electrical and plumbing systems in the house was determined. Our faculty advisers allowed the team creative freedom and nurtured our research endeavors. Team members had a unique opportunity to receive academic advice from faculty members of branching departments. It was a truly a rewarding experience and a great learning opportunity.

The design team came up with a comprehensive strategy list as follows:

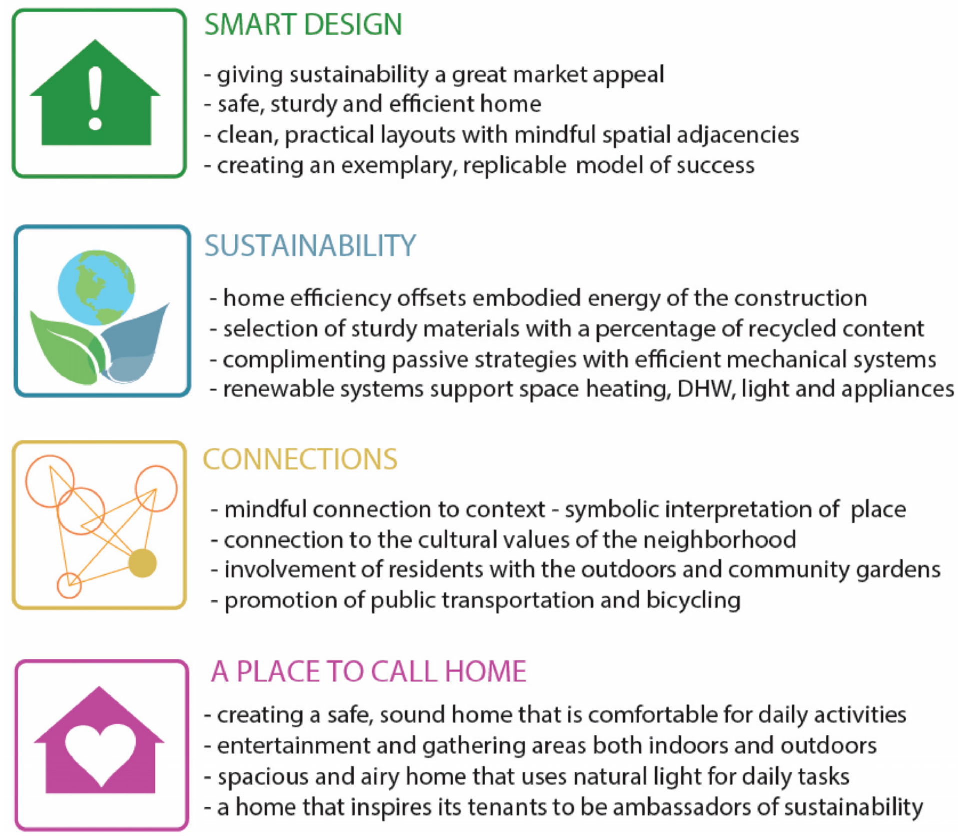


Figure 12. Integrated team decisions and design goals

Throughout the design phase, all involved disciplines met up to exchange ideas and new research findings that could improve the design of our house. Members of the team were introduced to all of the parties involved with the competition and the competition guidelines. The team carefully reviewed and discussed the materials provided by Department of Energy (DOE), Rocky Mountain Institute, Home Innovations Research Lab, Environmental Protection Agency (EPA), Energy Star, Colorado Energy Office (CEO), Denver Housing Authority (DHA) and other parties involved with the competition. These resources were thoroughly investigated and used as guidelines to achieve the zero-net energy design and high-performance of the residence. The building science curriculum presented by EEBA "Houses that Work" was a great resource for us to learn about the advanced strategies geared towards maximum performance of building enclosure and systems. As a team we took notes of the strategies applicable to our project and followed up with precedent research and availability of the assemblies components on the market. The team reached out to manufacturers and industry professionals for some real-world experience tips and best material procurement recommendations.

Performance standards and branding were set. Students working directly in energy software, REM Rate and HEED, were assessing how the products and systems are working as a whole.

5.4 Rocky Mountain institute (RMI) super-efficient housing challenge background and mission

Starting with the Rocky Mountain Institute Super-efficient Housing Challenge, we looked at the big picture first, the overall mission of the project. Denver Housing Authority (DHA) envisioned an extensive plan to transform an existing urban neighborhood, Curtis Park, into a typologically diverse, interconnected and accessible urban residential block.

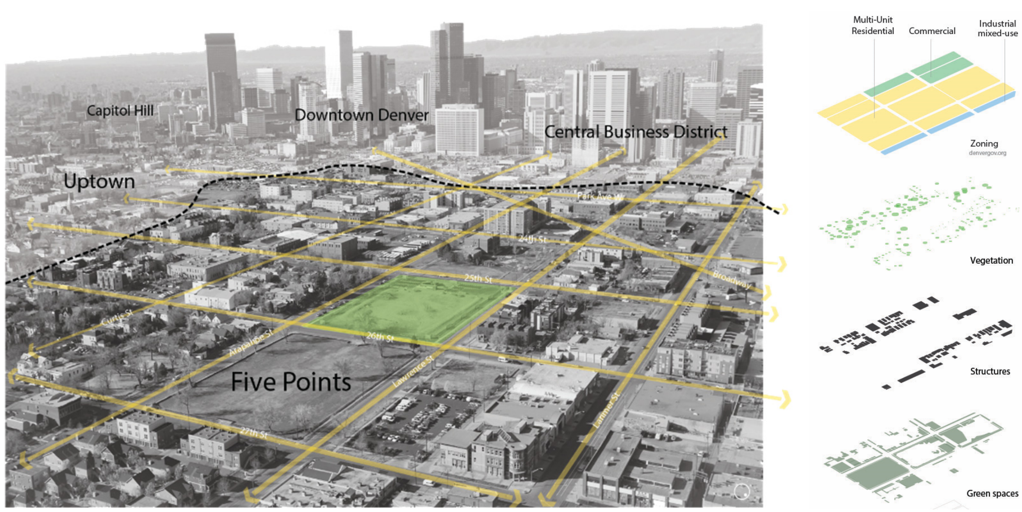


Figure 13. Site location and adjacent areas

The city had originally intended to create a community of mixed income rental housing and two hundred units of for sale housing. The future development of Curtis Park aimed to connect the residential area with the urban core of Downtown Denver through appropriate transition of building typology, heights and neighborhood aesthetics and a network of two-way streets. As our team tackled the design of a new master plan for the building block between Lawrence and 26th street, our intent was to create a dynamic, accessible residential block that is at the same time safe, well lit and befitting for neighborhood children to play and enjoy the outdoors.

Figure 14. Neighborhood context - building envelope forms and aesthetics

RMI had planned to develop this lot as series of five unit townhome clusters. The functional and spatial guidelines required a small footprint attached townhome design solution, with accessible flat roof and a zero-net energy ready system integration. This super-efficient, energy offsetting home was to be designed for a mid-income, young family of three or four members and their pet.

5.5 DOE Challenge Home Student Design Competition format and regulations

This was the inaugural year for the competition, as DOE announced, it will be held on a two-year cycle that alternates with the Solar Decathlon. The Decathlon's off year in the United States will serve as the award-year for the Challenge Home competition.

The competition was based upon a real-world scenario where a builder needs to update an existing product line (house plan) to a high-performance house design or is developing a new high performance home product line. Each team needed to design a home for a specific location and thus use relevant site, climate data and homebuyer demographic profiles for context and other architectural integration considerations. The student teams had a choice to either redesign the existing floor plan or create a new house design that satisfies the project requirements.

The newly designed homes needed to be cost-effective from the buyer's perspective –showing that the monthly mortgage payment, insurance, utility, maintenance, and taxes are neutral or cash-flow-positive as compared to the calculated affordability based on the Median Family Income. The designs were required to achieve at least the DOE Challenge Home energy performance level, evaluated through REM Rate Energy Modeling Software. The designs were for zero energy ready homes, meaning their high performance features can reduce the energy bills, while renewable energy systems help offset the remaining energy use.

In order to be qualified as a team, all architectural and engineering student team members were required to complete a six-course building science curriculum, "Houses that Work," presented online by EEBA and take a series of online tests administered by EEBA.

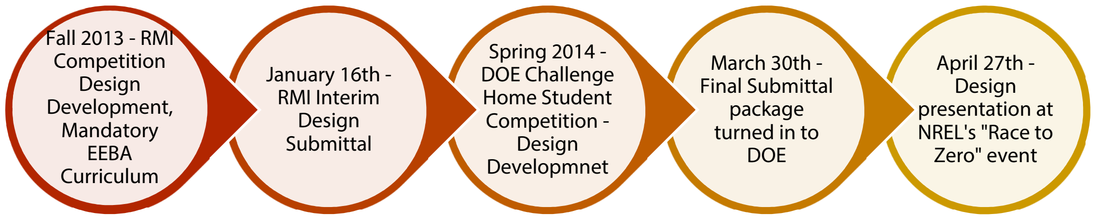


Figure15. Competition timeline

UNLV's Team Mojave competed along with 27 other schools and we presented our proposal at National Renewable Energy Laboratory's (NREL) Education center on April 27th, 2014. At the "Race to Zero" competition presentation event. Each team had 25 minutes to present their design, following by a Q&A session with the five judge panel. The judges were national experts including leading high-performance builders, building science professionals, and researchers.

Teams were judged based on the set design goals, multidisciplinary team integration, and home performance, integrated building systems, renewable energy systems plan and achieved certifications. Below is a table summarizing the elements each team was judged upon. Results in terms of score breakdown were not shared with teams upon the completion of the judging event.

SECTION	SUBJECT AREA	MAX POINTS	JUDGE RATING SCALE
A	Team qualifications	20	0-5
B	Design goals	20	0-5
C	Financial analysis	12	0-5
D	Envelope durability	16	0-5
E	IAQ Evaluation	16	0-5
F	Space Conditioning	16	0-5
G	Domestic Hot Water	5	0-5
H	Lighting and Appliances	5	0-5
I	Zero Net Energy Use	5	0-5
J	Construction Documents	5	0-5
	Weighted total for required subject areas		0-100
K	Extra Credit		0-5
		Total project points	0-115

Table 13. Judging criteria table, DOE Challenge Home Student Design Competition

5.6 Architectural Design features and constructions goals

The team wished to emphasize a sustainable design approach by applying the best building science practices. The holistic design was based on resource consumption and utilization of renewable and rapidly growing resources, while posing a viable solution for its future residents.

Furthermore, the team aspired to design not just an efficient, cost-effective dwelling, but a comfortable and secure home that the tenants will love and raise their families in. Raising the awareness of the positive environmental impact that this type of a super-efficient dwelling will have can lead to development of new sustainable neighborhoods. Our mission was to have a desirable, marketable product that educates and inspires the buyer to explore a healthy, sustainable lifestyle. The team has set clear goals and intends to employ integrated building practices to identify the most impactful strategies for achieving those targets. The identified key guidelines are:

- Site and context - greysite development, use of landscape features and microclimate and integration with the cultural values of the existing neighborhood
- Initial resource management - mart material procurement, local material recommendations, selection of sturdy materials that reduce maintenance, waste management
- Durable Building Envelope - solar access planning, minimize north facing windows, cross ventilation (properly designed floor partitions), thermal mass distribution – smart insulation, SIPs walls and roof assemblies with high R-values, foundation optimization, prefab options, movable insulation techniques
- Energy efficiency strategies and systems - PV, Solar Heating / DHW, Electric light efficiency, Energy star appliances
- Water conservation - efficient fixtures and well-designed plumbing system, aerators and low flow fixtures
- IAQ, Space conditioning and thermal comfort, well-sealed, tight and healthy home
- Reduce the environmental impacts of building construction and operations by employing strategies such as bioclimatic design, energy modeling and advanced framing strategies. Offset embodied energy of the material with efficient life cycle and performance of the home itself
- Client-oriented, practical and cost effective design that is replicable for the Denver area
- Set measurable baselines that can be verified through third party resources

As a team, we understood the need to complement the existing context and designed the exterior of our newly proposed townhome to have a recognizable neighborhood character and yet feature fresh, intriguing elements that will secure great market appeal. We achieved this through prudent materials choices and proposed geometries that are attractive, inviting and functional. This sturdy, sound home is interacting with its context and creating visual interests from the street level.

Starting from the macro scale, the newly proposed master plan features walkways and promenades gathering neighbors around community gardens and in the core of the site by the proposed bioswale designed to retain the drainage water and reduce the runoff from the site. Waste reduction and recycling within the newly developed lot was another one of our concerns. We indicated areas for waste drop-of that are set away from the front yard, to maintain the views of the home. Yet, these are easily accessible for the tenants and the waste disposal services.

Figure16. Newly proposed master plan developed by UNLV's team Mojave

This case study townhome was designed as an end unit to the row of five homes and features a combination of best construction practices discussed in the literature review. We wished to emphasize how passive building design techniques can work together with efficient system backup, ensuring high level of thermal comfort in the interior throughout the year. Moreover, the passive design decisions we made proved to be highly efficient as our annual heating and cooling loads were dramatically lowered from ones of a standard home of comparable size and program. The energy efficient mechanical systems, proposed as a safe backup, are a seamless support to the healthy indoor environment.

Figure 17. Five unit efficient townhome cluster designed by Team Mojave

Though this townhome is planned for property with a distinctly small building footprint it is designed to feel spacious, open and flexible. Balancing the need to maximize passive thermal strategies and providing maximum visibility and connection to the outside spaces and surrounding community, the placement of glazing and shading devices was of considerable consideration. The result is generous glazing on the south-east facade with easy shaded access to the garden and outdoor kitchen in the summer and desirable heat gain and warming views in cooler months when the sun is low. The centralized staircase provides multiple functions as well. In addition to vertical circulation it also acts as a central light well on both living floors and a vertical ventilation shaft for the entire home.

In addition to laundry and storage, the back airlock is the connection to the extension of the kitchen into the outdoor area. Providing a virtually seamless view through the space encourages use of the vertical garden, outdoor cooking and dining as well as use of the community garden and urban farm.

Where the ground floor is designed to be open, visible and flexible the second floor provides quiet privacy and a generous bonus space for alternative work or entertainment functions as well as guest sleeping quarters with access to the shared bath. The centralized placement of the bonus space eliminates the need for any isolated circulation waste and is sunlit by both the clearstory glazing above the shelving unit and the light-stairwell. The bedrooms are light-filled and well-proportioned for furniture placement.

All units have a roof access through an enclosed airlock that serves also as a lightwell and continues into a mechanical room on the Northwest. The accessible roof deck can be used for open-air laundry drying, as a relaxation area or maybe even a hobby or small home repairs area. The deck continues into a rectangular patch of extensive, low cost green roof that ameliorates the heat gain issues of the home on the Southeast side. Moreover, both the PV and solar Thermal systems are located on the roof level, adjacent to the mechanical room and are easy to access for maintenance or upgrades.

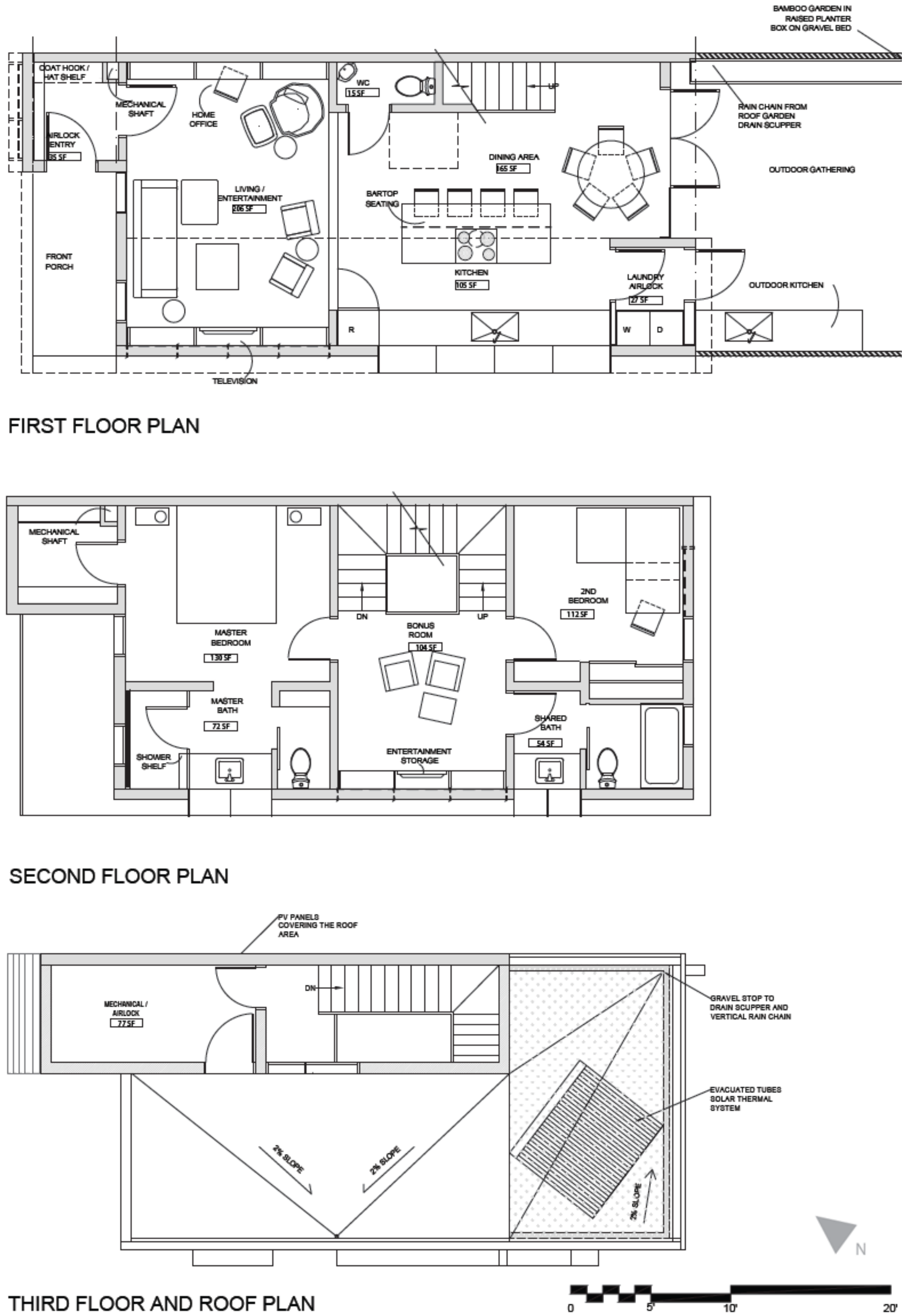


Figure 18. Townhome end-unit floorplans

This attached unit combines high mass walls, structural insulated panels (SIPs) as the exterior wall enclosure and shallow frost-protected foundations with a concrete slab on grade. Wrapped in wood siding boards and durable fiber-cement, the envelope features thoughtfully placed windows allowing natural daylight to enter the home while maintaining comfort within the interior. By choosing engineered FSC wood products for framing, we wanted to emphasize the importance of smart material procurement, and proper sizing of construction elements. These techniques lead to reduction of the amount of lumber used to build a home while maintaining the structural integrity of the building.

To maintain a healthy indoor environment and help the building's envelope last for many years, it was critical to ensure that the foundation, walls and roof properly separate conditioned and unconditioned spaces.

Moisture control, flashing and sealing cracks and openings as well as insect and pest repellence, and an efficient ventilation strategy were our tools for keeping this home healthy and durable.

Recognized benchmarks and verification tools were used to ensure that the design is being shaped in the best possible way. By consulting with the resources provided by Department of Energy (DOE), Rocky Mountain Institute, The Home Innovation Research Labs (formerly the NAHB Research Center), Environmental Protection Agency (EPA), Energy Star, Denver Housing Authority (DHA) and other parties involved with the competition the team was be able to compare project goals to relevant benchmarks and ensure that we are on the right track. The building science curriculum from EEBA and Green Builder College program, "Houses that Work", provided us with invaluable guidelines and led towards a holistic design solution of our model home.

5.7 Building envelope durability strategies applied in the case study

Using advanced building techniques and guided by the "Houses that work" curriculum from EEBA and Green Builder College program, the goal was to create a thermally ultra-efficient envelope that qualifies for Energy Star certification and is compliant with 2012 IECC envelope insulation levels. It was necessary to design a sturdy, sound envelope that is both ultra-efficient and cost effective, thus several different envelope assemblies were evaluated to reach the energy performance target.

Moreover, as required by the Energy star rating, in order to achieve high performance of the insulation, all ceiling, wall, floor, and slab insulation shall achieve RESNET-defined Grade I installation.

Through literature review, the following criteria emerged as crucial for achieving high performance of a truly sustainable building envelope:

- Responsible procurement of materials, or utilization of high performing materials that will offset their embodied energy through reduction of energy consumption of the enclosure throughout the building's lifecycle
- Durable materials resistant to weathering, elements and pests
- Engineered wood elements and proper sizing of building materials
- Construction waste diversion and management
- Tight, well-sealed and waterproofed assemblies

Energy modeling guided the envelope optimization to achieve the highest performance. After several iterations, in order to achieve the set goals of thermal performance and comfort, it was determined that the high efficient envelope, appropriate for this housing unit, would need to have a recommended R value of the following:

- Green roof : R-62 (Engineered wood I-joists, cellulose insulation cavity infill, XPS boar
- Exterior walls: R-58 (SIP panels with polyurethane foam core, 2x6 studs)
- Floor: R-11 (slab on grade frost protected shallow foundation with XPS board)

5.8 Featured envelope system overview

The case study house was designed to withstand the elements and hold up against weathering. However, the goal was not just to protect itself from climate, but use it to its advantage. To utilize the benefits offered by the site, the team sought to implement passive design strategies.

5.8.1 Thermal mass

The home features high mass walls and an exposed concrete slab on grade, crucial to good passive solar heating design. These mass elements were strategically placed to absorb and retain heat, slowing the rate at which the sun heats a space and the rate at which a space loses heat when the sun is gone. Moreover, homes that incorporate high thermal mass, offer superior performance under anticipated elements of nature, such as rodents, insects, fire, earthquakes, hurricanes and tornadoes, and can stand for many decades with no structural degradation.

Thermal breaks both in the slab and in walls were purposefully placed to prevent heat flow between conditioned and unconditioned space. Figure 19. illustrates the placement of thermal mass in the unit.

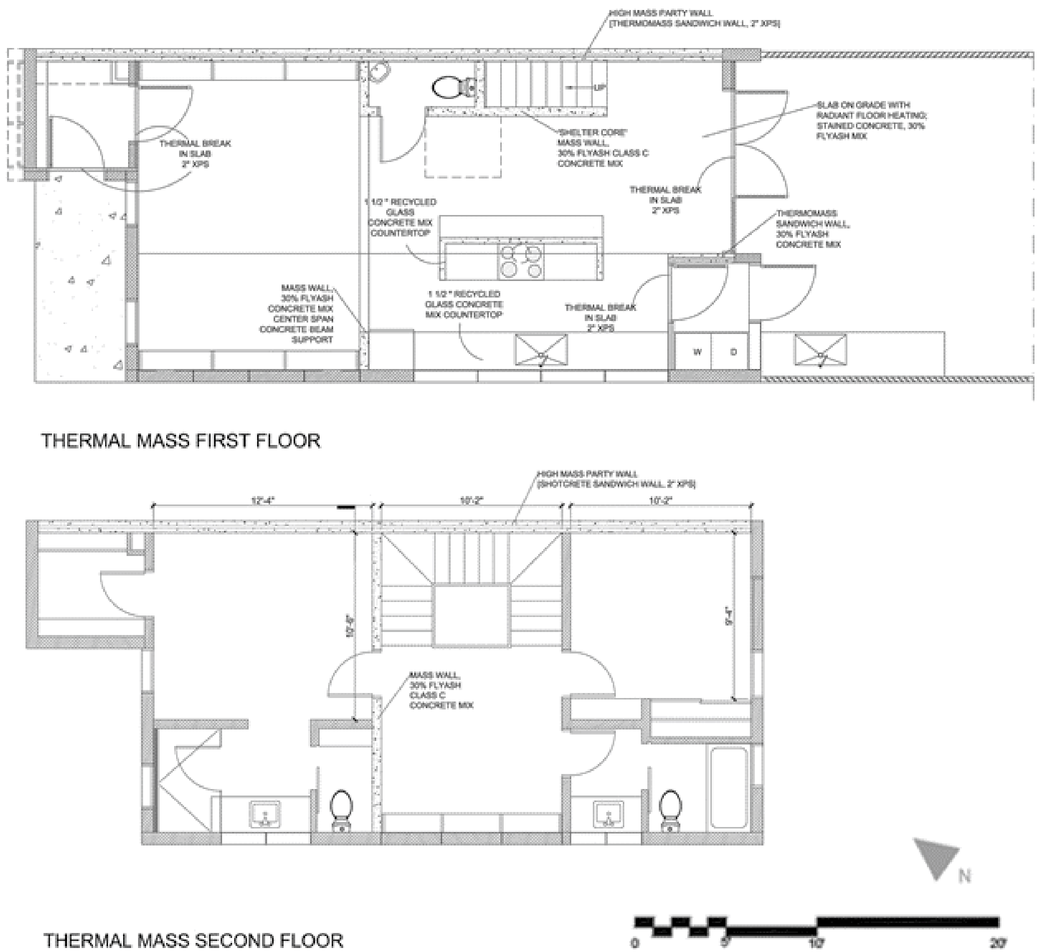


Figure 19. Placement of thermal mass in the unit

Concrete is relatively inexpensive and is one of the most durable and flexible construction materials available. However, it's important to specify a concrete mix that will lower its embodied energy by using a substitute for the cement portion. Fly ash is one of the byproducts of burning coal to create electric power and its carbon content is a major concern. However, this product can serve as a great substitute for Portland cement. Fly ash has several characteristics that make it a great ingredient for a concrete mix, it is a recycled material with great strength and durability and it's very inexpensive. In the "Green from Ground Up", Johnston and Gibson (2008.) recommend, a 30% Class C Fly Ash concrete is an ideal substitute for a portion of the Portland cement content.

The recommended concrete mix:

- Portland cement Kaiser type-I-II (59% Tri Calcium Silicate)
- Fly ash ISG- 26% residue on 325 mesh
- 3/8" gravel (estimated free moisture 2%)
- Top sand (estimated free moisture 6%)
- Water
- Type C or E water reducer (preferably type E for faster set)

The 35 feet long party wall between units was an ideal place to incorporate thermal mass. This wall features Thermamass system, with a ½" of a natural mineral artisan plaster finish on both sides. This product, Ecco Stucco's Muralime is composed of hydrated lime and very fine aggregates.

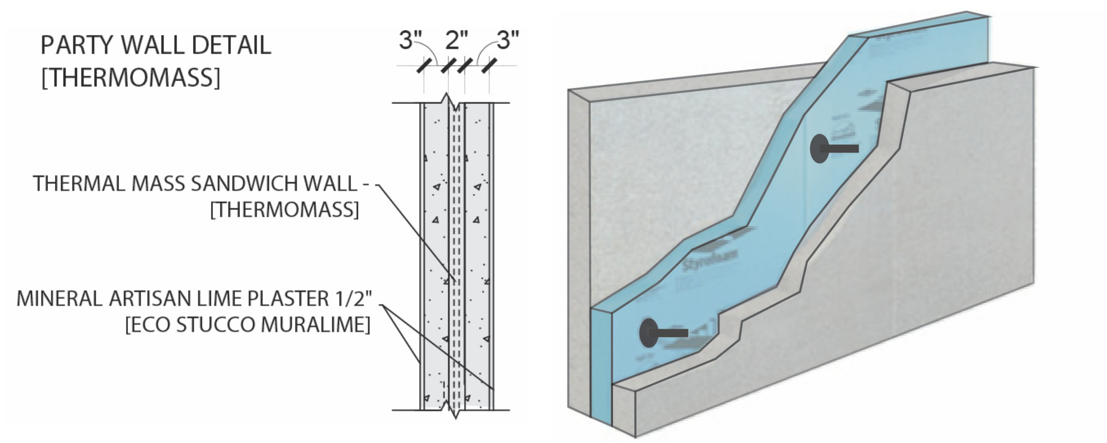


Figure 20. Unit party wall assembly - Thermomass concrete sandwich

The Thermomass insulation systems feature high-strength, non-conductive fiber-composite connectors and rigid 2" XPS insulation in the center of the assembly. Thermomass System SC is a patented insulation system designed to create a structurally-composite concrete sandwich (Thermomass concrete insulation systems, 2014). The system is forces the two wythes or layers of concrete to act together structurally, creating a thinner panel, reducing resource consumption and material cost.

The two main components of the system are series of fiber-composite connectors and extruded polystyrene insulation. The XPS insulation between two layers of concrete significantly improves the R-value of the constructed wall over concrete alone. An un-insulated, 200 mm (8 in) thick concrete wall achieves an R-value of 0.11 m2•K/W (0.64 ft2•h•°F/BTU) compared to 0.88 m2•K/W or (5.0 ft2•h•°F/BTU) for only 25mm (1 in) of extruded polystyrene insulation.

The connectors are tested in accordance with ICC Acceptance Criteria 320, verifying their compliance with the building code. The grid of connectors behaves like a verendeel truss to resist the loads imposed upon the panel without sacrificing insulation coverage. This is key in creating a thermally efficient and structurally sound composite wall panel. CC Series connectors are pultruded with 426,000 E-glass fibers, dipped in a vinyl-ester resin, formed under heat and pressure, cut to length and over-molded with a polymer collar. The particular choice of material is important because connector material must be compatible with concrete, thermally non-conductive and exceptionally strong. Connectors susceptible to alkaline attack that have a thermal coefficient of expansion higher than that of concrete should not be used as sandwich wall wythe ties. The fiber composite bar used in the CC Series connector has a thermal conductivity of 1.0 W/m•°K (6.9 BTU•in/ft2•h•°F). This compares to values of 40.68 W/m•°K (182 BTU•in/ft2•h•°F) for stainless steel, 81.59 W/m•°K (365 BTU•in/ft2•h•°F) for mild steel and 2.79 W/m•°K (12.5 BTU•in/ft2•h•°F) for concrete, respectively (figures presented on the Thermomass website information base). Therefore, Thermomass fiber composite connectors minimize thermal components that would otherwise create a thermal bridge. Typically, the connectors are spaced at 460 mm (18 in) on center transversely and 400 mm (16 in) on center longitudinally. Thermomass systems have been proven in the laboratory testing; Stork Twin City Testing

Corporation extensively evaluated the CC Series connectors and deemed them in good accordance with International Code Council-Evaluation Services (ICC-ES) AC320 acceptance criteria.

To save up on transportation costs and give an opportunity to local builders and material suppliers, the party wall would be constructed as a 'Tilt-Up' system. Panels are produced on-site by using the building floor slab as the primary casting surface. The detailed process as described in the manufacturer's installation guide (available at Thermomass.com) is as follows:

1. The exterior layer of concrete is poured and leveled. Then the pre-fabricated, pre-drilled insulation sheets are arranged on top of the unhardened concrete according to the individual panel drawings. Thermomass connectors are inserted through the predrilled holes. After placing lifting devices, bracing inserts and required reinforcement, the structural wythe is poured.
2. Once cured, these panels are lifted into place to form the building envelope. The high strength of the Thermomass connectors hold the sandwiched layers of concrete and insulation secure during the entire process.

More information about this product is available at manufacturer's website at http://www.thermomass.com/

The house features a 6" exposed concrete slab on grade with integrated radiant floor heating tubes. We wanted to incorporate a sufficient slab thickness for heat storage and leave the slab exposed for those purposes, but we also wanted to treat it for durability and aesthetic reasons. To soften up the harsh finish of the concrete and seal it additionally, we recommended treating the slab with SoyCrete, a non-toxic sealant from EcoProcote.

This ensured that the properties of a concrete slab are preserved while bringing aesthetic appeal to the interior. SoyCrete features a patented soy ester modified dispersion technology; it's non-hazardous, low VOC, acid-free concrete stain.

Figure 21. Concrete slab bio-based sealant – SoyCrete

5.8.2 Foundation system

To support the structure of the home and provide a sturdy base that keeps the interior healthy and dry, we needed a durable, cost-effective solution for our foundation system. After assessing the currently available options and required code compliance, the team came to a decision to implement the shallow frost protected foundation (FPSF) system.

FPSF system was chosen because of its effectiveness for the Denver climate and most of all an impressive 15-21% reduction in material usage and labor costs over standard foundation systems (NAHB Research Center). As discussed previously, in order to determine the needed levels of insulation and footing depth for FPSF, the first step was to find the AFI for the location, in this case Denver. AFI values for locations in the United States are available at the National Climatic Data Center (NCDC) website. As it revealed, Denver is at the lowest level of air freezing index, AFI = 478 (weather station Denver WSFO), which falls into the first category range of ≤1500. The minimum required footing depth for this AFI index is 12 inches. To achieve better thermal mass performance from the slab (from 3" to 6"), the footing was increased to the next increment of 14 inches to accommodate the whole assembly. This decision was also beneficial for the loads of the structure above, especially the live loads from renewable systems on the roof level. Insulation below the slab is XPS board with R value of 10. The total R-value of the slab on grade was R-11.2, acceptable due to the specific performance of the FPSF system (confirmed by DOE). Horizontal insulation was also not required for the AFI index of the location, however it was added because the slab incorporated a hydronic system to avoid any chance of heat losses.

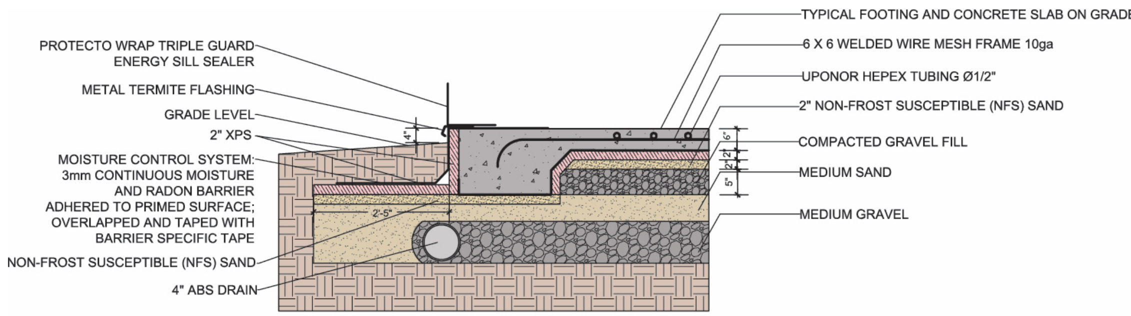


Figure 22. Frost Protected Shallow Foundations featured in the case study

5.8.3 Wall assembly

After evaluating several types of wall assemblies in terms of thermal performance versus embodied energy and potential costs, Structurally Insulated Panels emerged as the best performing system. SIPs present a viable solution for the climate; they can comprise a durable, tight system and have a relatively short return of the investment period. Other assemblies that were evaluated included the following:

- Advanced framing construction, 2x6 studs; 5.5″ fiberglass bat insulation, R - 21
- Spray-in foam wall construction, 2x6 studs; High density polyurethane foam, R-30
- Insulated Concrete Form (ICF) Walls (thermal mass application); 5″ Expanded Polystyrene, R-20
- Exterior Insulation Finish Systems (EIFS) wall construction, 2x6 studs; 5.5″ of blown cellulose, respective R value – 28

- Double wall construction 2x6 exterior, 2x4 interior with offset studs; 9.5" of blown cellulose, R-33

Some of these strategies, such as fiberglass cavity insulation with 2x6 framing, were abandoned because of the cost of the amount of insulation needed to reach the minimum required wall assembly of R-28 (Johnston & Gibson, 2008). The advantage of this system was that it is very widely spread, and there are lots of skilled professionals that have experience with this type of construction. However, to reach a thermal resistance value of over R-44 (50% more of the minimum required for location, R-22) the wall cavity would need to be thicker to accommodate more fiberglass or an overwhelming amount of rigid insulation would have to be installed on the exterior of the assembly.

Thermal bridging was another important criteria, and that is where spray foam wall assembly, for example, didn't fare well. This was due to the observation that thermal bridging could occur through the framing, bottom plate, and top plate which will lead to a reduction in the effectiveness of the spray foam insulation. A decrease of even R-10 could occur because of thermal bridging, potentially lowering the whole assembly R value to only R-20. Moreover, the foam may create an air barrier decreasing thermal losses through air leakage. Although spray-in foam has high thermal resistance, its embodied energy, as well as issues with material cost and the cost for labor of certified builders with special equipment, it did not get included into the selected assembly as a whole house insulator. Other types of foam for the purposes of sealing were still recommended. These include urethane foam sealants for rough openings and penetrations through the envelope caused by ducts, recessed lighting, plumbing or electrical system.

Same issues of thermal bridging can occur with the ICF construction although moisture is well locked out because of the system assembly (Building Science Corporation, Enclosures that work). In Europe, ICF wall systems for the whole-house wall enclosure is not uncommon as many builders and contractors are highly skilled in this type of construction. A system similar to ICF was used for the party wall (Thermomass SC system). Moreover, to achieve the desired high R-value of the exterior walls, the ICF assembly would have to be very thick, and the small footprint of the home was limited to a very narrow, rectangular form. Additional wall thicknesses would take up the much needed interior space. Finally, ICF walls are very sturdy; though this may come as a disadvantage for any future modifications of the home as one would have to drill through solid concrete.

EIFS wall assembly was a contender as it requires minimal changes to standard construction practices and, therefore, more builders are skilled in executing the job, reducing the risk factor for errors or badly executed connections. Durability risks associated with these wall assemblies involve moisture damage related to rain water penetration (Building Science Corporation, Enclosures that work). However to reach the goal R value for the tight, high performance enclosure, the wall insulation cavity would have to be upgraded to a better performing - more expensive material.

Double wall construction provides high R values (2x10 or 2x12 framing is usually needed to achieve R- 30, using cellulose or fiberglass insulation), however, framing lumber can be very expensive and doubling-up the amount increases costs both in material and labor (Aldrich et al. 2010). As any, wall cavity assembly, this system is more favorable for electrical wiring and plumbing pipe installation in comparison to full volume rigid infill. As the gap between the two walls is filled completely with insulation, there is no thermal bridge through the wall system.

Because window and door openings in the inner frame wall must be carefully aligned with windows and doors, framing the interior wall can sometimes take more time than the exterior framing. Builders of double-wall homes estimate that time needed for the interior framing is 4-5 person-days for approximately 100 linear feet of exterior wall (Aldrich et al. 2010).

Typical densities for dense-blown cellulose insulation in standard 2x6 framed walls are 3-3.5 lbs/ft3. Studies have shown, however, that slightly higher densities (near 4 lbs/ft3) may be required in the larger cavities of double walls to prevent settling (Aldrich et al. 2010).

Simple geometry is important for these types of assemblies as many angles on the volume can reduce the wall's performance and drastically increase construction time and cost.

There are a number of SIP manufacturers on the market and it was challenging to select the ones that will guarantee the best results. Finally, after consulting industry professionals and conducting a literature review, a very interesting, and fairly new system singled itself out with both manufacturer reported performances, but also the performances of the case studies where the system was featured and evaluated.

The product selected for the case study exterior walls was RayCore SIP system. These panels come in several types of assemblies. Aiming towards advanced framing strategies, the pre-foamed in place studs in the panels can be positioned either as 12" on center staggered studs or 16" or 24" on center studs. The system features high R values depending on the panel thickness. The following table illustrates per inch R values of different insulating materials in comparison to polyurethane foam in RayCore panels. R-Values show below are in accordance with the ASTM C518 Standards at 75°F.

Per inch R-VALUES AT 75°F	R-Value/ Inch	R-Value 2x4 (3.5")	R-Value 2x6 (5.5")	R-Value 2x8 (7.25")
RAY-CORE Polyurethane Foam	7	24.5	38.5	50.7
Spray-in Foam	5.8	20.3	31.9	42.0
Extruded Polystyrene (EPS)	5.0	17.5	27.5	36.2
Expanded Polystyrene (XPS)	4.0	14	22	29
Fiberglass	3.2	11.2	17.6	23.2
Cellulose	3.5	12.25	19.2	25.3

Table 14. Per inch R-values of selected insulation materials based on ASTM C518 Standards at 75°F

Temp (°F)	K-factor (Btu in/ft^{2}h°F)	R Value per inch
20	0.1221	8.19
30	0.1260	7.94
40	0.1303	7.67
50	0.1347	7.42
55	0.1369	7.30
60	0.1391	7.19
70	0.1437	6.96
75	0.1460	6.85
80	0.1482	6.75

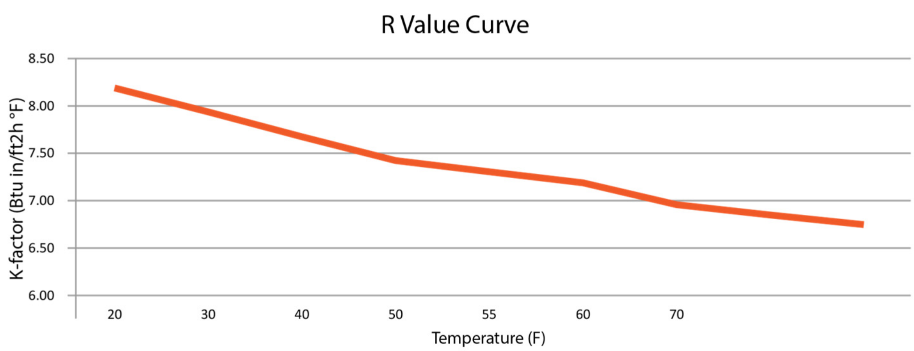


Figure 23. RayCore polyurethane foam core thermal conductivity test based on ASTM C518

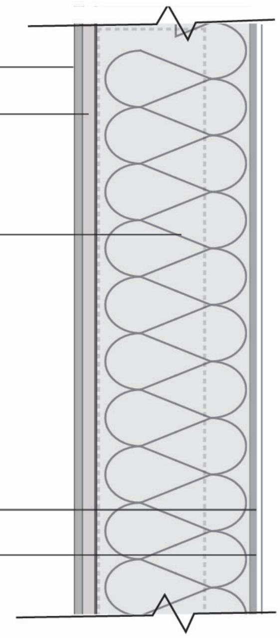
The assembly selected for the exterior walls of the unit and the portion of the angular roof assembly is a highly efficient component product consisting of 2x6 Spruce-pine-fir lumber studs prepositioned 16″ on center with polyurethane foam insulation molded in place between studs and foil radiant vapor barrier applied to the exterior sides of the panels. The integrated foil radiant vapor barrier on both sides helps eliminate the thermal transfer through the integrated wood members by 89% (RayCore Inc). The RayCore headers fit within 7.25" wall applications and can be built and shipped up to 12 feet in length.

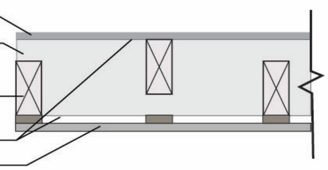
RayCore Wall Panel Features:

- Foamed in place staggered wood studs, 2x6 @ 16″ O.C.; 4′ wide and up to 12′ in length
- R-7 value per inch of polyurethane foam
- Polyurethane Foam Insulation, Class 1 Fire Rated
- Paper thin Foil Radiant Flame Retardant Vapor Barrier on both sides of the panel
- Superior Sound Deadening Properties
- Lightweight and easy to install

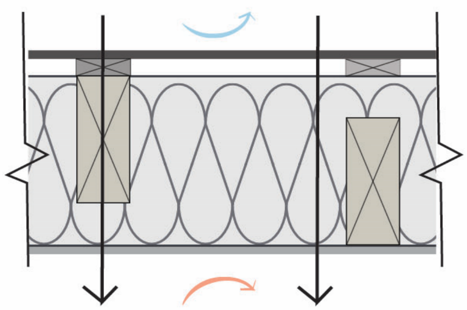
Component pieces are code approved: Foam - UL 15744R, Foil - UL R4461; Studs are SPF lumber or better, molded in the panel at 16" or 24" o.c.

RayCore SIP panels combine three labor tasks into one: framing, insulating and wrapping. With integrated studs, all the issues and delamination concerns as seen in other SIP panels are avoided. The insulated headers provide both thermal and structural stability to the envelope.





Wall assembly R-value Insulation Calculation



	A	B
1. air film exterior	0.17	0.17
2. fiber cement board	0.67	0.67
3a. furring	1	-
3b. air space 1" reflective	-	2.12
4a. 2x6 frame	5.5	-
polyurethane	-	8.75
4b. polyurethane	-	50.75
6. gypsym board	0.65	0.65
7. air film exterior	0.68	0.68
	R_A=8.67	**R_B=63.79**

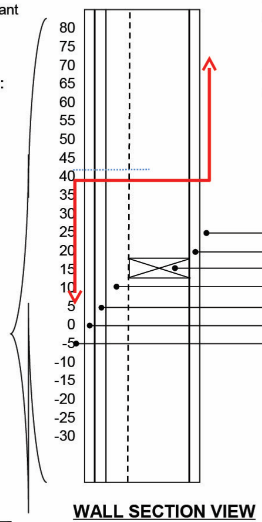
R=0.1x8.67 + 0.9x63.79
total R=58

Figure 24. Case study envelope with RayCore panels – assembly properties

Glaser Method Dew Point Calculator-James Brew

Enter Data
Caculation
Resultant

Temperature Scale (deg. F):



Indoor Relative Humidity 40%

Dew Point: 44.6

70
Indoor Design Temp. (deg. F)

3.3
Outdoor Design Temp.(deg. F)

Wall: Raycore SIP (staggered studs) with integrated foil radiant barries on both sides

Component	Thickness (inches)	R- Value ($ft^2\cdot°F\cdot hr/Btu$)	F Diff.	Temp. Degrees F Interior Surface	Exterior Surface
Indoor air	n/a	0.68	2.1	70	67.9
Gypsum board	0.625	0.65	2.0	67.9	65.9
SIP - Stud	5.500	5.5	16.9	65.9	49.0
SIP - Polyurethane insulation (R-6.8 per inch)	1.750	11.9	36.6	49.0	12.4
Air-space (reflective)	1.000	2.12	6.5	12.4	5.9
Fiber cement board	0.500	0.67	2.1	5.9	3.8
Outdoor air	n/a	0.17	0.5	3.8	3.3

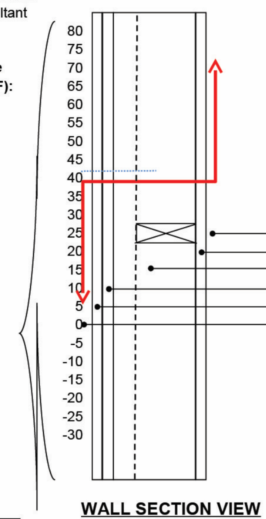
TOTAL R-Value 21.69

BTU/hr/SF 3.1

Glaser Method Dew Point Calculator-James Brew

Enter Data
Caculation
Resultant

Temperature Scale (deg. F):



Indoor Relative Humidity 40%

Dew Point: 44.6

70
Indoor Design Temp. (deg. F)

3.3
Outdoor Design Temp.(deg. F)

Wall: Raycore SIP (staggered studs) with integrated foil radiant barries on both sides

Component	Thickness (inches)	R- Value ($ft^2\cdot°F\cdot hr/Btu$)	F Diff.	Temp. Degrees F Interior Surface	Exterior Surface
Indoor air	n/a	0.68	0.8	70	69.2
Gypsum board	0.625	0.65	0.8	69.2	68.3
SIP - Polyurethane insulation (R-6.8 per inch)	7.250	49.3	61.4	68.3	7.0
Air-space (reflective)	1.000	2.12	2.6	7.0	4.3
Fiber cement board	0.500	0.67	0.8	4.3	3.5
Outdoor air	n/a	0.17	0.2	3.5	3.3

TOTAL R-Value 53.59

BTU/hr/SF 1.2

Deg. F	70.00		
F to C	21.11		
Es	25.00		
E	10.00		
Td (C)	6.98	44.56	Dewpoint in F
lnE	2.30		
-lnE	-2.30		

Figure 25. Dew point calculation output for case study wall assembly

As RayCore panels feature a foil facer on the interior side as well as on the exterior, the dew point of the interior air is not as relevant- the applied sheathing has not one but two class-I vapor retarders between it and the interior air, as well as air-impermeable insulation. The interior can be kept at a 60% RH all winter and not produce a measurable change in moisture on the exterior sheathing (Green Building Advisor).

As discussed previously, there is a level of environmental impact issues involved with the production of closed cell foam, however the integrated rigid polyurethane foam in these specific panels, uses a specific formula which has zero ODP (ozone depletion potential) and is a non VOC material - the panels have no formaldehyde or glass fibers.

The SIP panels allow for easy installation of pipes and electrical wires. It's necessary to properly seal holes around electrical wires, plumbing pipes and ducts with expanding urethane foam. Considering that the studs are formed in place prior to on site construction, no moisture can be trapped between the studs and the panels, as this is a common issue that needs to be carefully attended.

RayCore SIPs cost about 1% more than conventional framing and pays for itself in energy saving in 2.1 years, in an average. On average the cost for construction would be about $90 more on a 1500sq foot home to use RayCore SIP panels in comparison to standard construction (RayCore Inc). That investment will however reflect on the utility bills, overall thermal comfort and durability the home. Benefits of the system include its energy-saving design and reduced installation time, reducing the labor costs which can be significant. The high insulation value of the panel results in lower heating and cooling loads, which translates into energy cost savings. The team was expecting that the implementation of these panels will results in a straight, impact-resistant composite wall with less air, dust, pollen and sound infiltration.

5.8.4 Fenestration

Over the course of the design process, the type and amount of glazing was highly important for the design of this case study home. Both functional and aesthetical path that the team took required generous glazing surfaces to create a seamless connection to the outdoors.

However, upon evaluating our initial design and entering the full window schedule into the energy modeling software, it was clear that the amount of glazing was diminishing the performance of the envelope as a whole. Some compromises had to be made. As one of my tasks was to ensure that the envelope performs to the best of its potential, the design needed to go through several iterations and evaluation cycles in the energy modeling software until we reached an optimal solution that fits well with both the program and design aesthetics, while ensuring best performance. We reached a reduction of around 33% in openings on the enclosure, as the glazing area came down to 254.81 ft^2 which is compliant to the DOE Challenge Home requirements (Tajsic et al. *Aries House. U.S. Department of Energy Home Challenge Student Design Competition*).

In terms of window assembly, the final product we selected was the Geneo line from German company Rehau, triple glazed with Low-e glass and with a very low U value - 0.16 and a SHGC factor of 0.62. The total cost for all windows and exterior doors came to $16.000. The cost was justified because of the high performance of the product and the overall benefit to the building enclosure as a system.

5.8.5 Roof Assembly

The roof plane of each unit is designed with multiple purposes in mind. Often, the roof's sole purpose is to provide shelter and enclosure, and we wanted to give it a greater variety of purposes. As noted earlier, the very south area is envisioned as a green roof. The parapet wall there is substituted with a wire railing that ensures safety and complements the aesthetics of the home. This area also houses the solar thermal evacuated tubes. The remaining of the roof deck is covered with a sturdy waterproof composite material and would be used as a sundeck, space for open air laundry drying, and perhaps as an outdoor workshop - being adjacent to the mechanical and storage room. The above roof structure, where the mechanical and storage room is placed, as well as the vertical circulation via stairwell, is made out of sturdy SIP walls. Its angular shape was perfect for laying out the PV system. This careful planning allowed short connections between the PV and solar thermal system and the mechanical room.

For the purposes of simplifying the narration of assembly components, the roof plane of these units has been divided into three sections: Northwest flat roof plane, Southeast Green Roof assembly, Angular roof planes. On the unit itself, these three assemblies complement each other and work as a cohesive system.

5.8.5.1 Northwest flat roof plane

To reduce the construction waste on our site and eliminate the need to specify 10% or more lumber for framing, as part of the building enclosure - roof assembly, laminated veneer lumber products and engineered wood I-joists were selected as preferred products. RedBuilt products such as Red-I joists - lightweight joists were deemed suitable for use in the roof assembly and also floors. These I-joists reduce waste, as they are manufactured to resist twisting and shrinking, and they can be cut to size at the factory, so there's virtually no time or material waste prior to installation. These joists, as well as the RedLam beams specified for the framing of the second floor, are available with FSC credits. As stated on manufacturer's website, "By making better use of every tree, RedBuilt produces cost-effective, consistently available engineered wood products that reduce environmental impact. The result is a quality wood product that offers superior strength and reliable performance."(RedBuilt Corporation).

The 1.75"x14" I-joists provide ample space for placement of dense pack cellulose insulation with an R-value of 3.4 per inch. Moreover, this product allows for easy mechanical access—knockout holes for ventilation and flexible conduit are provided in the web of the Red-I joists.

To assist drainage, the lower roof plane is sloped 2% towards an interior drain that connects with the home's plumbing system. It features a composite buildup finish - Dex-O-Tex Weatherware. Weatherwear is a multi-layered trowel applied waterproofing and wearing surface, it is designed for use as a pedestrian traffic bearing and waterproofing system. It is a monolithic cover with layers of integrated flashing, slip-sheet and a self-healing waterproof membrane. This rubber cement roof finish is easily maintained and is environmentally friendly - Low VOC, No Hydro Carbon, Solvents, or Isocyanates.

The roof assembly was carefully detailed to explain not only structural components but also elements for waterproofing and air-sealing. Figure 26. illustrates the northwest roof assembly.

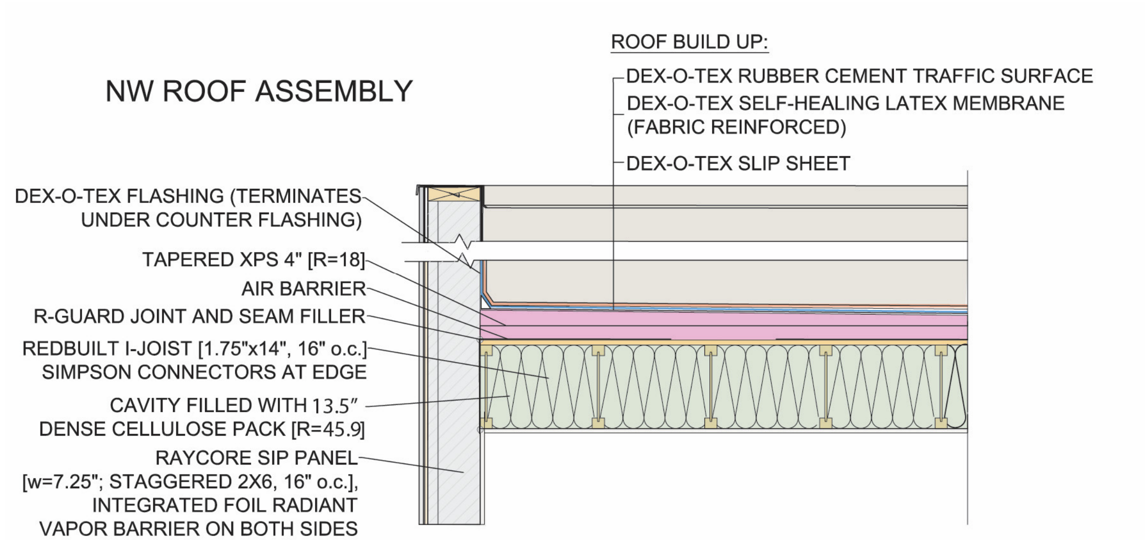


Figure 26. Northwest roof assembly of the case study home

5.8.5.2 Southeast green roof assembly

To complement the small hydroponic wall in the back of the house, and serve as a connective thread to the community gardens beyond, an extensive green roof is proposed in the very south portion of the flat roof terrace (173 ft^2). This type of a green roof has a lower front cost and is easy to maintain, requiring no additional irrigation. The benefits of implementing a green roof are numerous and thus can serve as an argument to offset the higher cost of installation ($12-$22 per ft^2) in comparison to standard roof assembly (~$7 per ft^2, flat built-up roof). The extensive sedum mix has the lowest initial cost of any type of green roofs. Some of the benefits that green roofs can provide are retention of rainwater and potential return of this water to the atmosphere through evapotranspiration. Moreover, the retention of stormwater and delay of runoff can ease the stress of on stormwater infrastructure and sewers, mitigating the need to expand or renovate related infrastructure by posing as a decentralized system. Green roofs can have acoustic insulation benefits in areas of high noise. In the aspect of solar gain, green roofs reduce the heat flux through the roof by preventing direct heat gain in the summer and minimizing heat loss in the winter, thus resulting in less energy needed for cooling or heating. This form of energy saving will not only reflect on the tenant's budget but will also translate into fewer greenhouse gas emissions while fostering biodiversity on the site. Moreover, as the green roof assembly covers the waterproofing membrane and protects it from UV rays thus expanding the lifespan of the waterproofing twice as long as conventional roofing, postponing the need for repair or replacement.

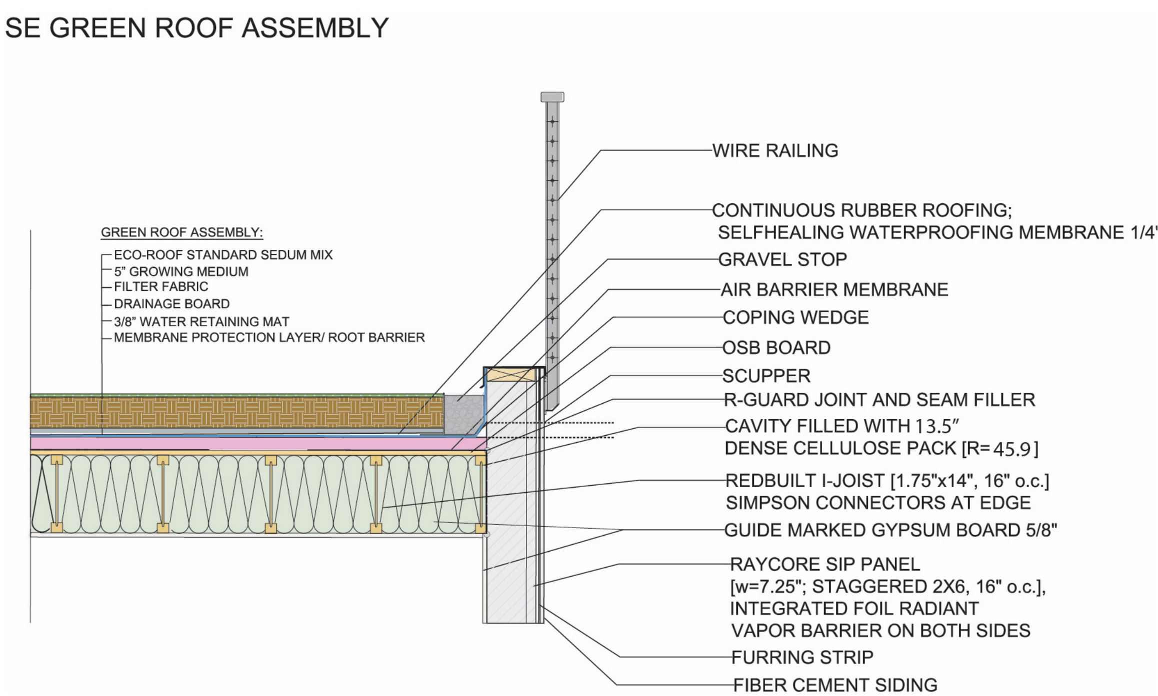


Figure 27. Southeast green roof assembly of the case study home

5.8.5.3 Angular roof plane

The angular roof structure features a durable, flame-resistant standing seam metal roof. The Metal Roofing Association (MRA) recommends a galvanizing thickness level of at least G-90 for residential applications and an AZ-50 or AZ-55 designation for galvalume coatings. The primary benefit of this material choice is its longevity, as metal roofs reportedly last two to four times longer than roofs with asphalt shingles. This product is lightweight and effective in preventing the spread of fire. In addition, metal roofing is made with a large percentage of recycled metal—often 95 percent—and when its useful life is done, it can be recycled again. This was very important to the strategic design approach, as we had the end of life material disposal in mind.

The standing seam metal roof proved to be a good base for mounting the eight-panel PV array.

5.8.6 Exterior finishes

Some of the biggest considerations apart from envelope durability were maintenance and weathering of the enclosure materials. Seeing that the exterior is exposed to the elements, it was necessary to select a finish that will resist water penetration and insects while also withstanding to the sun.

While superior material quality was the procurement guideline, costs played a big role in the decision. Seeing that the unit is intended for a mid-income family, construction funding had to be controlled and the exterior cladding costs were a major player in them due to the material quantity dictated by the surface area.

After reviewing of the selected options, fiber cement boards were chosen to coat the enclosure, because of their cost and durability advantages and dimensional stability.

This product is water-resistant and non-combustible, resistant to rot, fungus & vermin attack. The panels are composed of cement, sand, and autoclaved cellulose fiber to increase its strength and dimensional stability. The fiber is added as reinforcement to prevent cracking. Fiber cement has a great range of panel and board siding finishes. We chose large boards (CBF fiber Cement Siding - Silbonit) in a modern, stone grey finish for the main rectangular volume of our house. The overhang is also covered with fiber cement, in a complimentary, graphite tone. These Silbonit cladding sheets require no regular maintenance to uphold their finish, properties and strengths. This type of siding was also a great match for the rain screen assembly system that was to be featured as a part of the envelope. These facade components are cladded onto the building with furring strips. The furring strips create an air gap between the façade and the wall. This "rain screen" design reduces conduction into the wall and assists with drainage of the envelope, improving its durability. The furring strips are fastened onto the RayCore SIP panels' continuous rigid foam insulation board with an integrated radiant vapor barrier is on both the outer and the inner layer of the rigid foam insulation board to further reduce radiant heat gain into the house and prevent moisture from passing through the assembly.

A warm, cedar texture finish of the angular vertical volume, crowned with the angular roof structure is chosen to contrast and soften the modern simplicity of the main volume. As mentioned earlier, cost and maintenance were big factors in decision making, thus some aesthetic compromises had to be made. The angular form on the front façade, as well as the first level southwest façade were originally envisioned with an amber color, engineered wood finish. The selected siding product was Altru Wood's FSC Cedar siding boards, as the intention was to use responsibly grown, engineered wood. The aesthetics of it perfectly matched the neighborhood 'flavor' and context. If sealed and coated against severe weathering and termites, the product seemed highly appropriate for as unit's siding.

However, after getting the price quotes ($12.200 versus $4.100) and comparing the properties and maintenance recommendations from manufacturer's specification data, the product selection shifted to another fiber cement siding manufacturer. These boards mimic the tone and texture of the cedar wood siding very truthfully, while maintaining the aesthetic standard that was set for the façade. There is a vast selection of myriad fiber cement siding manufacturers who have products that are claiming to simulate a natural, 'realistic' wood finish, but it is important to identify the ones that do it with a high craft.

The selected siding product for the angular roof form and the first floor side façade, Weatherboard (CertainTeed Fiber Cement), is a NGBS (National Green Building Standard) Green Certified product, and qualify for LEED material credits as the product includes more than 30% post-industrial recycled material, termite resistance, and ISO 14001 accreditation, which is an international standard that CertainTeed manufacturing facilities meet for minimizing environmental impact. These boards can provide the customers with complete environmental transparency through third-party GreenCircle Certification, as well as the LCA product data approved by NIST (The National Institute of Standards and Technologies) for use with it's BEES (Building for Environmental and Economic Sustainability) online product selection program. WeatherBoards Cedar Lap siding is manufactured to mimic the texture of natural wood in various exposures. The TrueTexture wood grain appearance is achieved with the first-transfer system using real cedar boards (CertainTeed Fiber Cement).

Exterior shading consists of overhangs and 8" corten steel window boxes that help with the heat gain issues. Along with their functional value, the shading boxes on the Northwest and Southeast façade serve another purpose. The side fins are connected to two boxes, on the top and bottom. The top box is masking off the roll down exterior shade mechanism, while the bottom one can be used as a small planter box. They match each other in form and wood-like finishes and provide a complimentary contrast to the corten steel sides, as well as the grey tone of the large fiber cement boards on the façade. Since the selection of the interior and exterior roll-down shades was a research area of another team member and final decisions were made in a team consensus, these will not be further elaborated. The selection, however provided necessary additional shading and, as shown in the energy modeling simulation, ameliorated the performance of the building enclosure. Please refer to our team's proposal book for any additional information.

Exterior Finishes:

Fiber Cement Boards
Cement Board Fabricators Inc.
http://cbf11.com/

Fiber Cement Weather Board
CertainTeed Fiber Cement
http://www.certainteed.com/

Corten Steel
ReclaMetals LLLP
http://www.reclametals.com/

Entryway Concrete Stain
SoyCrete
http://www.ecoprocote.com/

Figure 28. Exterior finishes incorporated into the envelope assembly of the case study home,

Source for textures – manufacturer data (Cement Board Fabrications, CertainTeed Fiber Cement, ReclaMetals LLLP, EcoProcote)

Figure 29. Exterior render of the case study units produced by team Mojave,

Aries House. *U.S. Department of Energy Home Challenge Student Design Competition*

5.9 Air sealing and moisture control for durable envelopes

As required by the Energy star rating, in order to achieve high performance of the insulation, all ceiling, wall, floor, and slab insulation shall achieve RESNET-defined Grade I installation. The insulation including both SIP walls and insulation in the roof assembly, would be placed without misalignments or gaps in all wall cavities along the thermal barrier of the house. As SIP walls already feature a foamed in place studs, the application of these guidelines will mostly be reflected in the proper installation of blown in dense pack cellulose in the roof assembly cavity. Grade I installation requires that the insulation material uniformly fill each cavity side-to-side and top-to-bottom, without substantial gaps, or voids around obstructions, and be split, installed, and fitted tightly around wiring and other services in the cavity.

Moreover, as the studs are already foamed into the SIP panel, moisture penetration into the assembly is avoided during actual construction.

On the interior side of SIP walls, we proposed placement of guide marked gypsum boards. This product features guide marks to identify the location of studs, joists, rafters, or trusses, and is intended to simplify the process of cutting and installing gypsum board. It helps installers find framing members and make accurate cuts without having to draw as many lines as conventional gypsum board installation requires. Marks are printed on the paper covering at distances commonly used for spacing framing members. Grid marks consist of an "X" printed on the paper surface in rows parallel to the long dimension of the board. The rows run along each tapered edge and in parallel rows spaced 16” from edges to help installers find fastening points for walls framed at 16” inches on center. The marks are spaced at 4-inch intervals along each row to facilitate fastening along studs and are easily covered with standard paint.

By using passive strategies for the reduction of and cooling loads ductless systems paired up with ductless mini-split systems, we were able to reduce the amount of duct penetrations through the envelope. The duct work that had to be placed was routed through conditioned space, as all hot and cold water pipes are to be insulated when running through the denoted mechanical chase in the airlock space. Flashing, sealing and taping around door and window openings is imperial for proper moisture control in the envelope assembly. Moreover, the seams between SIP panels was adhered and sealed with a liquid flashing membrane before being taped. We recommended FastFlash a Prosco R-Guard product developed to prevent the unwanted movement of water and air through building envelopes. This product is recommended as a liquid flashing membrane in rough openings and to counterflash waterproofing and air barrier components in new or existing wall assemblies. It produces a highly durable, seamless, elastomeric flashing membrane. This product allows same day installation of windows, doors and other wall assembly, waterproofing or air barrier components. FastFlashcan be used to adhere, transition and counter-flash through-wall sheet flashing.

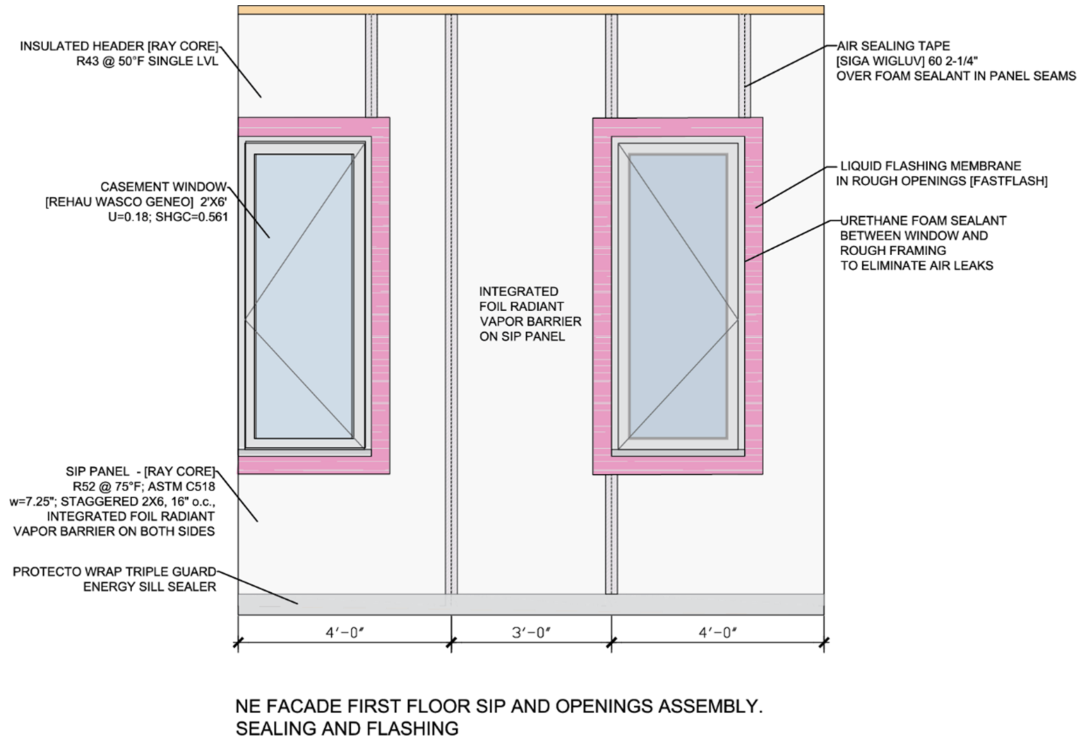


Figure 30. Flashing and sealing around rough openings and at SIP seams

The products listed were selected after reviewing the technical specifications provided through the manufacturer's website and upon review consisting of several case studies, of which one of the most notable (and high performing) is the Bulitt Center in Seattle, Washington – a building with the Living Building Challenge Certification.

As previously discussed, the amount of glazing is an important factor for several reasons. We carefully assessed the best placement, glazing ratios and daylighting techniques to get the best, most effective placement and sizing of openings. The utilization of daylight was a major factor, however we wanted to make sure that the implemented fenestration will have the smallest possible contribution to heat losses.

It was critical to add details for flashing of rough openings and sealing the air gaps between frames and opening. These techniques will allow the selected doors and windows to operate to their best tested performance.

5.10 Building systems integration

5.10.1 Indoor Air Quality

In the selection and specification of interior materials and finishes, primary factors were conditions allowing consistent and superior indoor air quality on move-in and for long-term occupancy. Exposed polished concrete used for the ground floor inherently contains low to negligible levels of VOCs and would be finished with Soycrete, a soy-based sealer with a VOC <25 g/l. SoyCrete Architectural Concrete Stain is a bio-based decorative concrete stain brand engineered for speed, durability, and the lowest cost per square foot. It delivers a wide array of variegated natural color effects without the use of toxic acid, reactive, or film forming polymer stains. This home qualifies for the EPA IndoorAir Plus certification.

The house is designed with an open stair lightwell in the center of the building. By opening and adjusting windows at the third floor level, when the conditions are adequate, stack ventilation can be induced up the stairs and vented through the high windows. By opening the windows in the occupied rooms, this draft can be utilized to provide natural cooling during warmer weather. Window placement and openness of space on the first level allows for completely unobstructed natural ventilation for the entire floor.

To maintain high indoor air quality, the team followed ASHRAE's guidelines for air exchange by including a balanced mechanical ventilation scheme to assist the home's natural ventilation. We achieved this with an energy recovery ventilator (ERV), that exhausts air from the house while it draws fresh air in; at the same time, it transfers sensible and latent heat between air streams to 'pre-condition' the incoming air. This reduces ventilation latent loads, correspondingly reducing heating and cooling loads of equipment. The ERV is strategically placed on the second floor, adjacent to the stairwell where the air can travel and reach all parts of the home.

The home is designed to use ceiling fans for comfort and ventilation when needed. Complementing the ERV, the two bedrooms and living room downstairs, include an adjustable-speed ceiling fan to assist with air circulation and stratification. Variable speed fans can be used in an occupied room to provide direct convective cooling of the occupants. The bathrooms have an ENERGY STAR exhaust fans with integrated LED light to prevent humidity induced by the shower and bathroom sink from impacting the rest of the home. Moreover, fans were proposed to exhaust air and fumes from the bathrooms, laundry and kitchen but they also remove humidity at the source. This is Important to maintain indoor air quality and reduce latent loads inside the home. The exhaust fans were selected to provide the required air removal efficiently without generating too much noise. These fans incorporate a lighting fixture, so there is no need for drilling additional penetrations into the envelope for a separate light source in the ceiling.

5.10.2 Space Conditioning: Solar Thermal System with radiant floor heating and auxiliary system strategies

The active systems incorporated in the design include a solar-thermal collection and storage system. This system uses highly efficient evacuated tube collectors to collect solar radiation and through a glycol water heat transfer fluid transfer the heat to a storage tank. The home features radiant floor heating systems, integrated with a concrete slab on grade on the first level and placed below the floor of the upstairs bathrooms and bonus room.

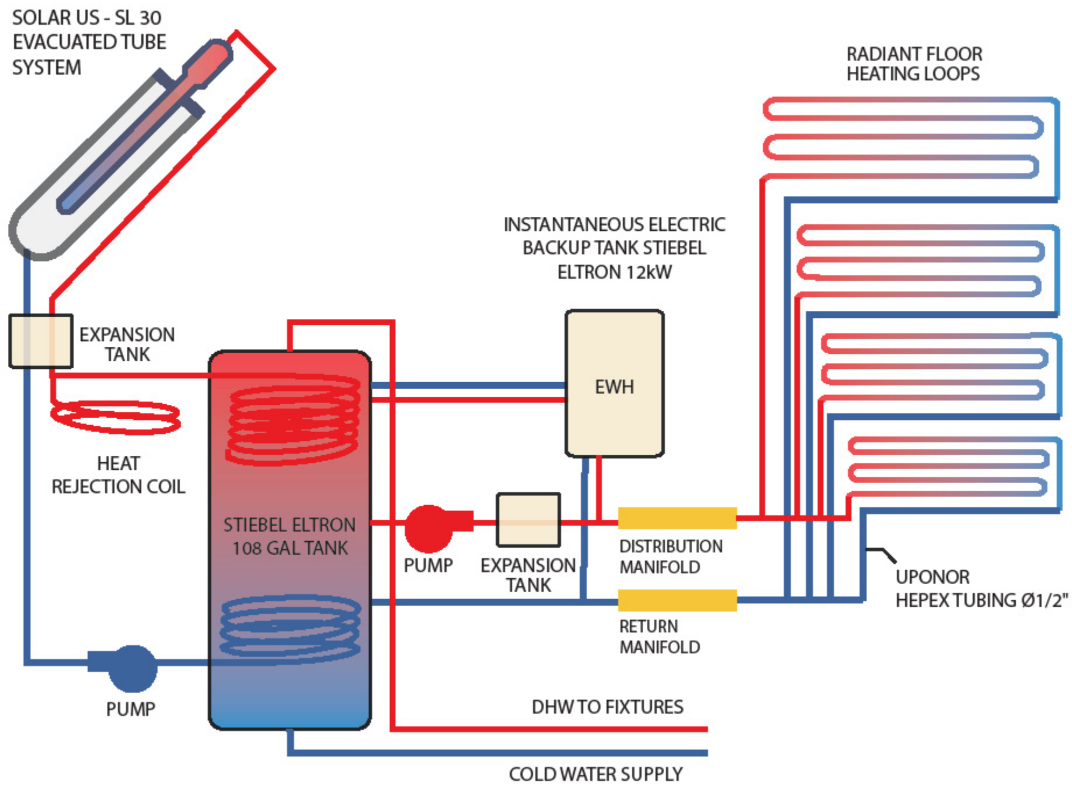


Figure 31. Diagram of solar thermal system

Energy modeling simulations confirmed that the house performs great with the passive systems and thermal mass in place, however, to provide auxiliary mechanical heating and cooling to the home, a mini-split heat pump system is incorporated into the design. This system uses three highly efficient ductless wall hung indoor units that are connected to a single outdoor unit. When used accordingly, these systems serve as a low-energy consuming backup to the passive design of the home. It is crucial though that the occupants understand the basics of passive solar heating and cooling so that they wouldn't hinder the performance of thermal mass walls and floor slab by employing mechanical system backups when the conditions don't call for them.

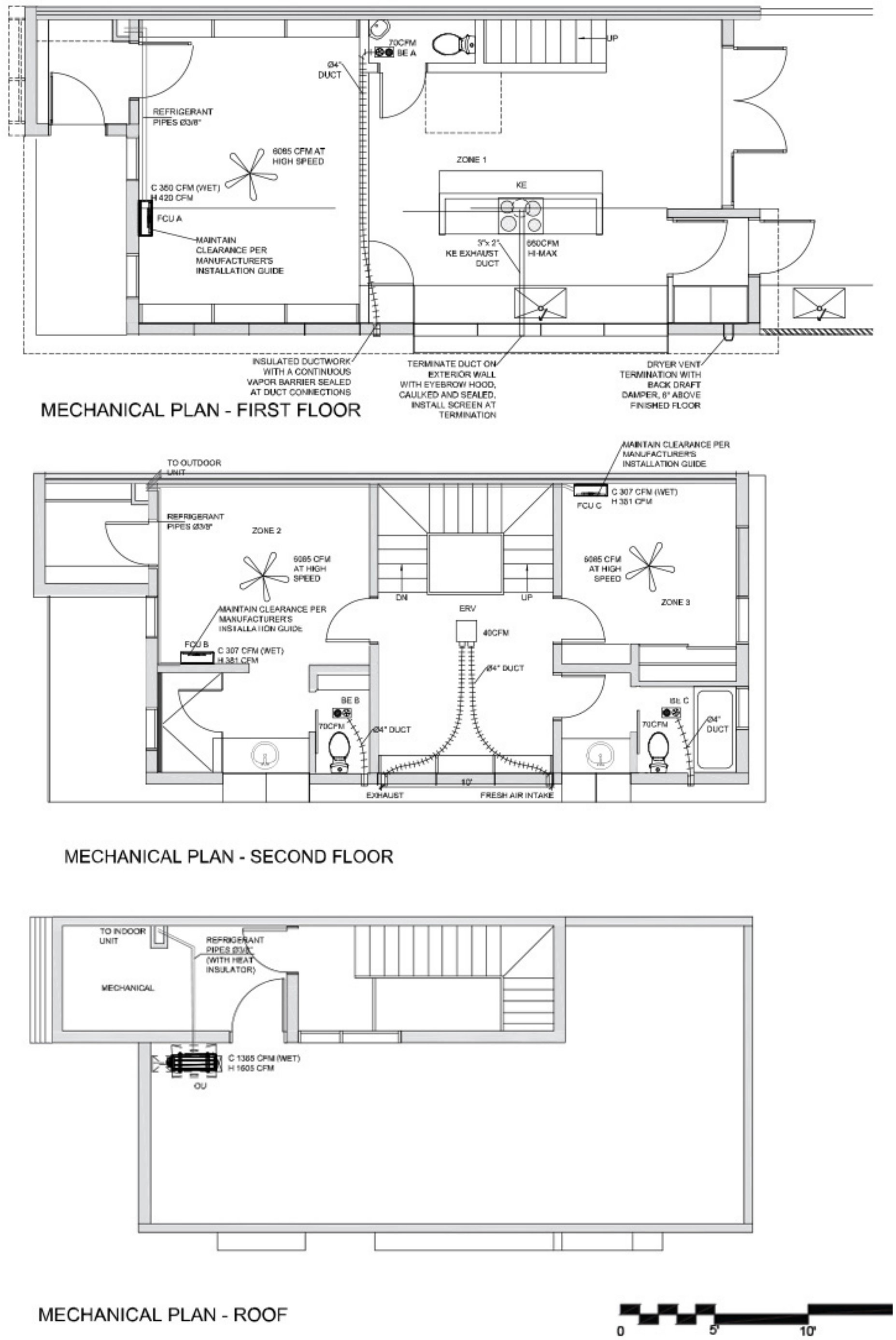


Figure 32. Mechanical plan - location of mini-split units, ERV and fans

5.10.3 Domestic Hot Water

We designed a well laid out plumbing system that features only the most efficient Water Sense labeled fixtures. Moreover, the energy for all of the domestic hot water will be provided through a solar thermal system installed on top of the south green roof level. The evacuated tubes are positioned in a way to reach the best possible performance while shielding a portion of the plants of the green roof from excessive solar heat. Even though the system of 30 evacuated tubes and 108 gal tank have the capacity to support the home's needs, an instantaneous tank will supply the hot water as a backup.

Where vent and drain pipes run through the SIP wall, foam sealants will be applied into the cracks and over the pipe to close any gaps and secure the pipe in place. Smart grouping the fixtures together allowed for minimum penetrations into the envelope.

5.10.4 Zero Net Energy Ready Home

Along with the solar thermal system, to offset the remaining electrical energy use in the unit, roof mounted solar photovoltaic (PV) system was designed for the home. The designed PV system consists of eight 327W SolarPower panels. This system is mounted on the third floor, on the angular roof structure. It is accessible from the main roof plane for inspection, maintenance and cleaning. The system located on this high roof is less affected by shading from trees and neighboring buildings. The panels are subjected to less dust, leaves and debris which will decrease maintenance cost. The racking for the roof mounted system allows a ventilation space behind the panels to help cool them. The system also helps by shading the upper roof and reducing solar gain to the roof structure. The panels of the upper roof were mounted at a low inclination angle to provide more power during the summer peak load periods caused by air conditioning. Moreover, the angle of the roof structure allows for minimal mounting elements for the PV panels, lowering the live load on the roof plane and reducing equipment costs.

5.11 Case study performance data

Energy modeling software, REM Rate and HEED, were used for verification of the suggested design strategies and helped with their proper adjustment. The team consulted the provided materials to verify that the design strategies meet the code requirements and lead to a viable, high-efficiency solution.

Energy modeling assessments were run from the beginning of this process and evolved all the way until the construction phase. The results from the energy analysis always served as a feedback for the options posed. Load calculation for heating and cooling and the electrical design system were considered carefully and iteratively for thoughtfully sizing of the solar components and mechanical equipment. Tight, high performing envelope and additional thermal mass contributed to the reduction of both heating and cooling loads of the assembly. Moreover, Building Information Modeling (BIM) was used to simulate a whole system integration of this case study model.

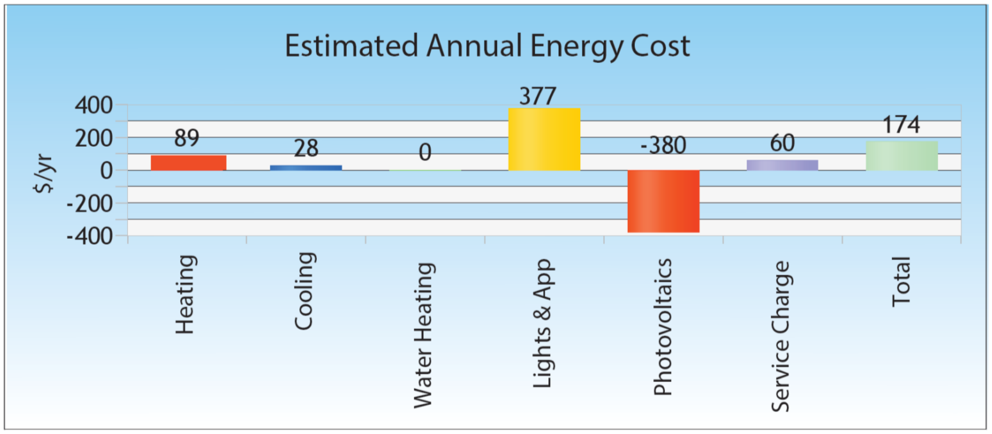
Parallel to these processes, we were constantly running cost estimate updates, evaluating different available products of comparable performance. This strategy ensured that the construction costs don’t go much beyond the set limit of $180.000. Total construction costs added up to just a bit above that target - $186.000 which is a very cost effective solution for the quality and performance of this house, a competitive entry on the market and a viable solution for a mid-income family in Denver.

The decisions made in value engineering process were monitored through constant updates in the energy modeling software to confirm that the changes in product and quantity still guarantee the desired performance. This process was a great learning curve in terms of setting priorities for product selection and qualities.

Finally, we were able to reach LEED Platinum and Energy Star V3.0 Certification for the home while remaining within financial reach to local families earning Denver's median income. With a Home Energy Rating System (HERS) Index of 7 (100 being the 'standard new home'), this all-electric home, is projected to use between 1,157 KWh/year (REM Rate) and 2,263 KWh/year (HEED) and 91% less energy than the LEED Reference Home (Tajsic et al. Aries House. U.S. Department of Energy Home Challenge Student Design Competition). As a reference, a standard home in Colorado has a HERS rating of 100 and annual energy consumption of 29,893 KWh/year (EIA - Household Energy Use in Colorado, 2009).

Achieving a favorable construction cost was an important goal, but only second to achieving high performance of the home that will potentially offset some of its embodied energy of construction through its life-cycle operations. We achieved that through ensuring that the employed strategies, previously discussed in this research, are contributing to a drastic load reduction compared to a standard home.

Summary of this home's performance as evaluated by both REM Rate and HEED Energy modeling software is shown in Figure 33.



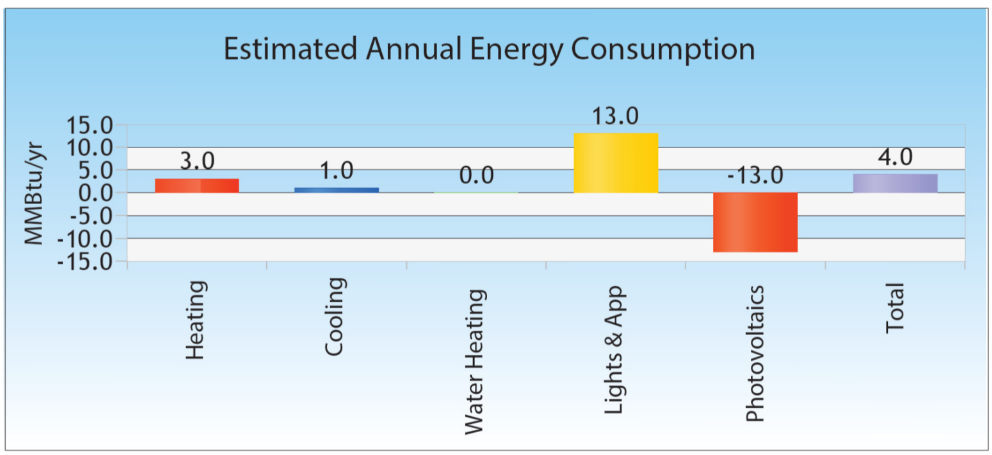
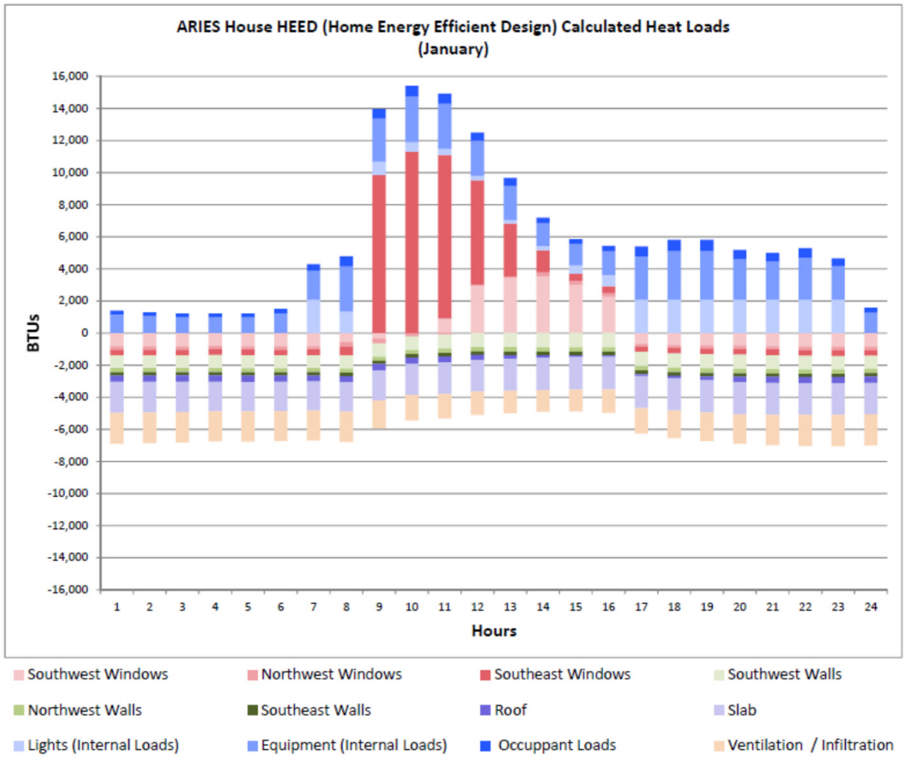


Figure 33. Estimated Energy Consumption and annual costs

The charts above show that the major energy consumption in the home can be attributed to lights and appliances shown as one entity in the bar. However, those respective loads are mostly related to appliances that were chosen to meet the highest performance and with Energy Star label where applicable, however, due to the budget constraints we were not able to select top of the shelf products for each appliance. These cutbacks were mostly made in the value engineering phase. All lighting fixtures were selected with LED or compact fluorescent lamps that completely minimized the consumption of the lighting in total.

In terms of the building envelope, most heat losses were occurring in the area of the openings, doors and windows, and it took several iterations to select the products that meet the set goals. As discussed earlier, we have set on Rehau windows and large south doors with U-vaue - 0.16 and a SHGC factor of 0.62.

Placement of thermal breaks, entryway and roof access airlocks and the back laundry sunspace minimized the heat losses even more. SIP panels act as a very tight enclosure and with proper sealing, they proved to be extremely efficient. Figure 33. was generated from heating and cooling data generated from HEED energy modeling software (Tajsic et al. Aries House. U.S. Department of Energy Home Challenge Student Design Competition). Selected months, January and June are critical in terms of load levels. The graphs on the next page show exactly how marginal are the loads generated by the walls.



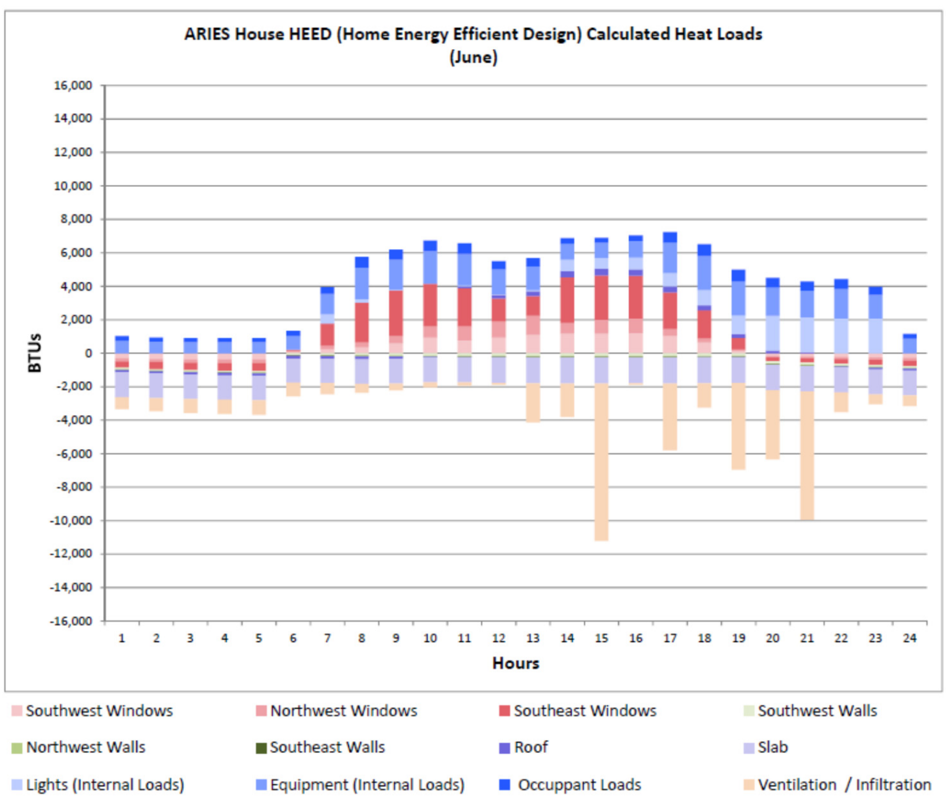


Figure 34. Heating and cooling loads of the unit during critical months

Below, table 15. summarizes some of the strategies and performances of this case study home.

Technical Information	
Water Heating	Solar Thermal System, 30 tubes; Instantaneous water heater backup, Electric
Cooling	Air-source heat pump, Electric, 26.0 SEER
Heating	Radiant Floor Heating, Air-source heat pump Electric, 10.0 HSPF
Ventilation System	Balanced: ERV, 40 cfm, 23.0 watts.
Photovoltaic System	2.6 kW array
Building Shell Features	
Foundation type	Shallow Frost Protected Foundation
Wall assemblies	Mass Concrete Sandwich Walls, SIP
Roof assemblies	Flat roof - Engineered wood I-joists, dense pack cellulose cavity insulation
Window surface	254.81 sq. ft.; U-value- 0.161, SHGC - 0.561
Annual Energy Consumption and Savings	
Electricity consumption	1,157 kWh
Energy use intensity	5.06 KBtu / sq. ft
Annual savings	$1,952

Table 15. Home strategies and performance statistics

Finally, the selection of advanced building strategies earned this model home several certifications including LEED Platinum, Energy Star V3.0, EPA Indoor airPlus Program, EPA Water Sense for New Homes Program, IBHS Fortified for Safer Living Program, DOE Challenge Home Quality Management Guideline.

Figure 35. DOE Home Efficiency certifications generated as an output from energy modelling evaluation of the case study home

The attached townhome end-unit is designed under the 2011 Denver Amendments to the 2009 International Residential Code (IRC) as recommended by the organizers of Denver Challenge along with 2011 National Electrical Code (NEC) and NEPA 13D code.

6. CONCLUSIONS

It has become clear that the building sector is in need of efficient, sustainable solutions that are viable for the customer, the economy and the environment. These new homes should serve as models of design efficiency, complimenting their context and contributing to the richness of the neighborhood. High-performing building envelopes designed with sustainable practices in mind have a potential to lower the overall energy consumption of a building throughout its lifecycle and reduce its carbon footprint. As thermal insulation is a major component of the building envelope for several of its components, consequently it is a great contributor to the overall carbon footprint of the building sector. Smart material procurement for wall and ceiling cavity insulation, its proper sizing, installation and maintenance are key for achieving maximum performance of the assembly.

Triangulation of qualitative and quantitative data gave some answers to the questions that emerged in the literature review. These observations are, however, based on reported values for certain products. Further research and testing are needed to confirm or disprove that the investigated products actually perform as reported in the literature or by manufacturers. This is particularly important for SIP panels discussed in the case study (RayCore SIP).

If these products are indeed performing as stated, then the hypothesis that proper selection of materials can reduce overall environmental impact of the built environment can be deemed accurate. Special PUR foam used for RayCore SIP panels is reportedly produced in a way that is less damaging to the environment (RayCore Inc) and paired with excellent thermal resistance (R-7) they present a good solution for residential townhomes. Cellulose insulation has been present on the market for some time, and tested is various studies. Assemblies with values higher than R-30 are difficult to achieve with cellulose as the only insulator, however, paired up with rigid insulation boards on the exterior, this assembly becomes very high performing. In the case study example, we used cellulose as cavity insulation for the flat roof assembly and added 2 inches of rigid board XPS over it. The depth of the structural I-beams (1.75" x 14") provided ample space for 13.5 inches of dense pack cellulose (R-3.4), with combined cavity thermal resistance of 45.9 BTU/(h °F ft2). Coupled with 2 inches of XPS board (combined R-10), and the green roof layers (5" of soil), the thermal resistance of the assembly came up to R - 62.

FPS foundations were an ideal solution for the climate and slab on grade with integrated radiant floor heating. This system provides needed levels of insulation and structural stability while using up a lot less concrete – material resources and is the least impactful foundation system in terms of construction carbon releases. Moreover, this system calls for a lot less excavation and labor and, therefore, is a much more economical solution.

Minimizing heat losses with thermal breaks in the assembly and by planning airlocks between conditioned and unconditioned envelope enclosures proved to be a good strategy. Large amount of glazing was a significant issue and had to be bridged both by reduction in glazing surfaces and selection of high performing doors and windows (U value - 0.16, SHGC factor of 0.62). The windows were also a significant financial contribution to the overall costs ($16,000 of total $186,000). The reduced amount of glazing (254.81 sq ft) complied with the allowed levels (IECC, DOE Certification), allowed for an ample amount of daylighting and with the largest amount of glazing placed on the southeast side of the unit, contributing to the efficiency of passive strategies featured in the home.

In the end, this all-electric home is projected to use between 1,157 KWh/year (REM Rate) and 2,263 KWh/year (HEED) and 91% less energy than the LEED Reference Home (Tajsic et al. Aries House. U.S. Department of Energy Home Challenge Student Design Competition). As a reference, a standard home in Colorado has a HERS rating of 100 and annual energy consumption of 29,893 KWh/year (EIA - Household Energy Use in Colorado, 2009). It can be concluded that the advanced strategies in terms of right material selection, right sizing, proper installation – sealing and flashing, resulted in an efficient envelope assembly for the case study home in terms of heating and cooling load reduction and resource consumption impact. The reported performance is a result of integration of prudent envelope assembly strategies and efficient systems and proof that all of the building elements need to be considered as a whole.

Finally, it can be concluded that the selected insulation materials did contribute to the overall efficiency of the case study townhome and, therefore, have the potential to do so in other applications if implemented correctly. Contributing to the efficiency; thus load reduction results in slower resource depletion and lower environmental impact. Selection of materials that have a higher percent of renewable raw materials or a recycled content (e.g. cellulose insulation)

Poses a great solution for the current market of residential townhomes and sustainable urban expansion in general. Proper placement and sizing of these materials results in good thermal performance of the envelope assembly. The one remaining research question is - are materials with higher embodied energy still a possible solution for sustainable envelope assemblies of residential townhomes? Further research is needed in order fully to answer this question. Foam based insulation has great properties and thermal resistance; however those materials carry a very high level of embodied energy. Nevertheless, their performance has the potential to offset the carbon emissions and ozone depletion caused by their production. Testing various PUR foam based products, for example, and assessing the full impacts throughout their life-cycle (positive and negative) will yield best results for determining their overall carbon impact.

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Department of Architecture and Urban Studies

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Public and Commercial buildings concentration, GPA : 3.84

Work Experience

University of Nevada Las Vegas - Fall 2012 – May 2014

Graduate Assistant:

CFA 101 - Introduction to Environmental Design; class discussion, grading, documentation

AAD 180 - Fundamentals of Design; class discussion, grading, documentation

Telegroup ltd : 2006-2012, Belgrade, Serbia

CAD Technician (2006-2009) : preparation of 2D and 3D graphic data and other graphic design requirements -regional projects for design and integration of navigation, signalization, telecommunication, radio relay and MSAN/DSLAM networks

Project Design Assistant (2009-2012) : Technical wing expansion project, Nikola Tesla International Airport in Belgrade, Serbia; Telegroup HQ reconstruction and expansion project design; Environmental impact reports of signalization expansion networks; Bid documentation preparation

Achievements	Graduate studies research and investigations in advanced geometry award, University of Nevada Las Vegas, Professor Randall Stout, AIA, 2013 UNLV certificate of Achievement, Professor Alfredo Fernandez-Gonzalez, 2014 Diploma thesis Academic honors, Head of the Department of Architecture and Urbanism and the professors committee, Varna Free University Chernorizets Hrabar, 2011.
Interests and Activities	Focus courses and topics: Sustainable development in architecture, Passive design strategies, On-site and building integrated renewable energy systems, Responsible resource management, Reclaimed and bio based building materials, Cradle to Cradle, LCA investigations, Capital Investment Renewable Energy Projects, Sustainability and energy efficiency upgrades and retrofits for industrial facilities and hospitality, Disaster relief structures Rocky Mountain Institute Denver Super-efficient Housing Challenge - Team Leader, 2013 U.S. Dept. of Energy Challenge Home Student Design Competition - Team Leader, 2014 USGBC member, UNLV Student Chapter, 2013-2014 The National Society of Leadership and Success member, 2014 UNLV Take Back the Tap Campaign, 2013
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