Three Rivers Builders

The Three Rivers House

2015 Race to Zero Student Design Competition

Carnegie Mellon University

ZERO ENERGY READY HOME

U.S. DEPARTMENT OF ENERGY

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Carnegie Mellon University

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17 March 2015

Race to Zero Organizers

Re: Carnegie Mellon School of Architecture Team

Dear Sir/Madam:

As the faculty advisor to the Carnegie Mellon 2015 University Race to Zero project team I affirm that these students have successfully completed the DOE Building Science Training Course.

In addition to other coursework in the CMU School of Architecture the students have taken, 48.752 | Zero Energy Housing, 48.315 | Environment 1: Climate & Energy, and 48.722 | Building Performance Modeling.

Yours truly,

Stephen R. Lee, AIA
Professor & Head
Track Chair, Master of Science in Sustainable Design Program

Figure 1 - Letter from our advisor

Three Rivers Builders

The Three Rivers House

Project Summary

The Confluence House, located in Pittsburgh, PA, is a super-insulated, Passive House style home located with easy access to public transportation and located within walking distance of numerous amenities. Even without the rooftop PV panels, the home achieves an impressive HERS score of 35, an important attribute in Pittsburgh's cloudy and cold climate.

Relevance of Project to the Goals of the Competition

This design attempts to find cost-effective solutions for all energy efficiency and IEQ aspects of through the design of an integrated system. Intelligent, integrated design can bring down the cost of ZEB's to be affordable to almost anyone who wants one.

Design Strategy and Key Points

The Confluence House is designed for a cold climate with little sun. High insulation and minimal thermal bridging take precedence in this climate, and the long periods of rain and dampness make air sealing and moisture management high priorities. Ease of construction and cost effectiveness are addressed through the design of an integrated construction system utilizing prefabricated materials for fast construction times. High air sealing and minimal envelope penetrations are complemented by an ERV, and all heating and cooling is provided by a small ground source heat pump.

Project Data

1424 Fallowfield Ave., Pittsburgh, PA

- IECC Climate Zone 5A
- 1640 Square feet
- 3 Bedrooms, 3 bathrooms, 2 stories
- HERS Score: **35** without PV; **-5** with PV
- Monthly energy costs: $53 without PV, -$1.50 with PV

Technical Specifications

- Wall Insulation = **R-37**
- Foundation Insulation = **R-41**
- Roof Insulation = **R-50**
- Window Performance = **U-factor: 0.18 – 0.22, SHGC: 0.24 – 0.39**
- Ground Source Heat Pump - **COP 5.1, EER: 15.7**
- Energy Recovery Ventilator - **Effectiveness: 83% sensible, 77% total**
- Instantaneous Gas Water Heater EF: **0.95**

1 TEAM QUALIFICATIONS

1.1 OUR TEAM

We are a diverse group of graduate students with backgrounds is engineering, biology, architecture, art and design. With a broad array of skill-sets and professional design and engineering experience, we approach this project with passion for improving the built environment. We come from programs that research approaches to sustainable design and construction methods, designing for indoor environmental quality, building with consideration for mechanical systems and operation, and which use computational tools for calculating the material and energy impacts of a structure. We are architects, engineers, construction managers, artists and scientists.

1.2 QUALIFICATIONS

Zoe Kaufman, Project Co-Lead

Student: Master of Science in Sustainable Design, Carnegie Mellon University

B.S. Biology, Stanford University

Having studied biology as an undergraduate, Zoe has redirected her focus to understanding how the built environment and the natural environment can best interact with one another. As a student in Carnegie Mellon's M.S. in Sustainable Design program, she is inspired to design architecture as a part of the surrounding world, both locally and on a larger scale. She is interested in applying scientific principles and tools to help analyze the effectiveness of design decisions on this project, and her current graduate assistant research includes investigating how quantitative design tools influence the design and operation of commercial buildings. She aspires to build homes and other structures that set creative examples of how to view sustainability from the perspective of building science with an integrated-systems approach.

Timothy Spencer, Project Co-Lead

Student: Master of Science in Sustainable Design, Carnegie Mellon University

B.A. Studio Art, Central Washington University

LEED Green Associate

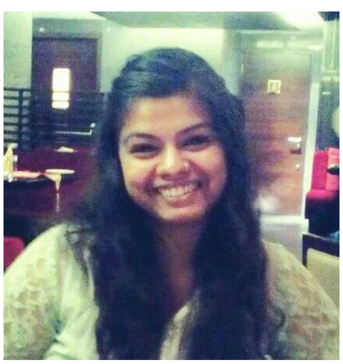
As a student in the Master of Science in Sustainable Design program at Carnegie Mellon University, Timothy is interested in how access to nature in buildings promotes health and quality of life, and in how to increase the market share of green buildings. Prior to this, he worked as an architectural and structural drafter at Alpine Design Inc., an architecture firm in Washington State specializing in custom homes. He has also worked as an independent contractor in theatrical set design and public art where he worked with public, non-profit and for-profit entities. He is currently a graduate assistant with research on how school building design affects learning and health outcomes.

Swapnil Banzal
Student: Master of Architecture, Engineering & Construction Management, Carnegie Mellon University
B.Tech Civil Engineering, Indian Institute of Technology, Bombay, India

In the past, Swapnil has worked as a project manager for Highway Infrastructure Pvt. Ltd. on projects that included affordable housing in New York City, and bridge construction in India. He hopes to apply his experience in affordable housing and project cost analysis to this project in order to design a home that is not only sustainable but affordable. He currently works with a team of Carnegie Mellon researchers on a Department of Defense project to develop an Intelligent Dashboard tool for facility managers based on an algorithm that balances occupant comfort with energy efficiency.

Rohit Motwani
Student: Master of Architecture, Engineering & Construction Management, Carnegie Mellon University
B.Eng. Civil Engineering, Rajiv Gandhi Technical University, Indore, India.

Rohit is a graduate student at Carnegie Mellon University, with interests in real estate design and development, embedded commissioning, probability and estimation methods for engineering systems and engineering economics. Rohit hopes to bring his experience with wastewater treatment research to this project, which he works on with School of Architecture department head Stephen Lee. Before this, he worked as a civil engineering intern on a variety of projects ranging from commercial to residential. Working on design development of these projects, he gained both a grasp of urban scale and an understanding the issues involved in the site planning of an institution. His responsibilities included on-site design execution, preparation of construction drawings, construction documentation, detailing, and cost estimation and coordination.



Prachi Gupta
Student: Master of Science in Sustainable Design, Carnegie Mellon University
B.Arch Aayojan School of Architecture, Jaipur, India

Before pursuing a Master of Science in Sustainable Design from Carnegie Mellon University, Prachi worked as an architect on projects including a resort for the Oberois Group, India, and various residential projects. During this time, she learned the importance of using on-site resources and discovering techniques for effective cost cutting. She has worked on residences of different sizes and for families with different needs, and gained experience creating designs that fulfilled a client’s requirements while achieving a strong aesthetic design. In the future, she plans to design structures that support sustainable community development, and which are integrated with the environment, thus enhancing occupant living conditions.

Stephen R. Lee, Faculty Advisor
Professor & Architecture Department Head, Carnegie Mellon University

AIA, LEED AP

Professor Lee's activities focus on issues of systems integration, material innovation, renewable energy and the integrated design process for high performance commercial and residential architecture. He is a LEED accredited professional and provides sustainable design consulting services for institutional and commercial clients in Europe, Asia, Canada and the United States. He has been involved in many innovative sustainable projects and has advised three Solar Decathlon, and his consulting work has resulted in new standards for healthy, flexible, adaptable and energy and environmentally effective buildings in the PA Commonwealth. Professor Lee is the Head of the Carnegie Mellon University School of Architecture and is the track chair of the CMU Master of Science in Sustainable Design degree.

1.3 CARNEGIE MELLON & SUSTAINABILITY

Carnegie Mellon University's commitment to excellence in its Architecture department extends to building performance in terms of comfort, productivity, and sustainability. Its graduate programs include Architecture-Engineering-Construction Management, Building Performance & Diagnostics, Computational Design, Emerging Media, Sustainable Design, and Urban Design and are led by a diverse faculty with backgrounds in engineering, architecture, computer science, and urban planning. Above all, Carnegie Mellon strives for interdisciplinary collaboration in all its endeavors and challenges students to work together across diverse backgrounds to achieve superior, whole-systems-thinking results.

Our team consists of students from backgrounds in sustainable design, construction management, architecture, civil engineering, studio art, and biology. Each student has attended the Building Science Seminars offered by the Building Science Corporation, along with various building science courses offered at Carnegie Mellon, listed below.

1.4 RELEVANT BUILDING SCIENCE COURSES AT CARNEGIE MELLON

- **48752** Zero Energy Housing

Net zero energy construction has gone from concept to policy in just a few years, but built examples are still rare. What does it take, technically, to achieve net zero and what else, beyond technical requirements, advances or impedes a net zero future? 48-752 is a graduate level class that explores net zero energy design and construction in the residential sector.

- **48722** Building Performance Modeling

This course introduces fundamentals and computational methods in building performance modeling. Topics include: modeling and design, overview of thermal, visual, and acoustical domain knowledge, integration of performance simulation in computer-aided design, introduction to the application of advanced computational building simulation tools, case studies and design assignments on the application of simulation in the evaluation and improvement of building performance.

- **48795** LEED Buildings & Green Design Concepts

LEED, Green Design and Building Rating in Global Context is a graduate level mini-course that examines holistic, integrated strategies for sustainable building design, construction and operation. The course is organized within the framework of the US Green Building Council's LEED Rating System: location, site, water, energy, materials, and the interior environment.

- **12748** Mechanical/Electrical System Design for Buildings

This class covers HVAC, Electrical, and Plumbing systems for buildings, calculating heat loss and heat gains, as well as operating costs with various fuels and system types. We size building electrical systems and look at alternative generation, smart metering and new lighting systems. Plumbing includes sizing water, drain and vent lines along with system design. Focus of the class will be on energy conservation and use, and how future systems will meet this criteria.

- **48729** Productivity, Health, & the Quality of Buildings

Given the growing demand for green buildings by federal and private sector clients, professional practices are 'tooling up' all over the world to deliver high performance, environmentally responsive, 'green' buildings and communities. However, investments in green, high performance building solutions and technologies are still limited by first-cost decision-making, and life cycle tools are still largely inaccessible to professionals. This course explores the relationship of quality buildings, building systems, and land-use to productivity, health, well-being and the environment.

- **48315** Environment I: Climate and Energy

This course introduces architectural design responses for energy conservation, human comfort, and the site-specific dynamics of climate. Students combine an understanding of the basic laws of comfort and heat flow with the variables of local climate to create energy design guidelines for their own work. The state-of-the-art in building energy conservation and passive heating and cooling technologies are presented. To stress the significance of architectural design decision-making on energy consumption and comfort, full design specifications and calculations are completed for a residential-scale building.

- **48723** Performance of Advanced Building Systems

Advanced Building Systems Integration is a graduate level course that focuses on commercial building performance achieved through systems integration. We explore the design and technical strategies that support sustainable high performance; the design, construction and operation processes that are likely to produce sustainable high performance buildings; and the current state of theory versus practice.

- **12714** Environmental Life Cycle Assessment

Cradle-to-grave analysis of new products, processes and policies is important to avoid undue environmental harm and achieve extended product responsibility. This course provides an overview of approaches and methods for life cycle assessment and for green design of typical products and processes using the ISO 14040 family of standards. This includes goal and scoping definition, inventory analysis, life cycle impact assessment (LCIA), interpretation, and guidance for decision support.

Other Relevant Courses:

Infrastructure Management • Building Information Modeling • GIS • Engineering Economics • Real Estate Development • PCI Design Studio • Probabilistic Modeling • Embedded Commissioning

2 DESIGN GOALS

2.1 EXECUTIVE SUMMARY

Our name, Three Rivers Builders, is a reference to Pittsburgh, where our home is located, where the Monongahela and the Allegheny Rivers form the Ohio River. The chilly, overcast climate of western Pennsylvania presented a significant design challenge to our team, and to meet this challenge, we attempted to clarify as many goals as possible early on. In setting out to design a Net Zero Energy home, our team embraced an integrative design process that considered energy use, cost, HVAC systems, aesthetic design, indoor environmental quality, and visitability all at once, rather than attempting to add each after the design had been completed. Consideration for length of plumbing pipes was considered in the placement of rooms, better enabling us to meet the EPA's Watersense standard. Parametric energy modeling was conducted to optimize the envelope in the early stages of design in order to use the results as design decision support. Wherever and whenever possible, different aspects of the building were considered together, rather than separately. Our team, a group with diverse backgrounds and skill sets from civil engineering to neurobiology, had many conversations early on to better understand how each aspect of the building would affect others. In this way, we were able to consider the fundamental drivers of energy use and environmental quality from the beginning, rather than attempting to apply fixes to the many problems inherent in typical construction methods after the fact. Our team also set a series of goals by which we measured our success along the way. Through the successful application of these goals, even before we installed PV panels, we were able to achieve an impressive HERS score of 35. With PV panels, our HERS score dropped to -5, meeting our goal of net zero source energy.

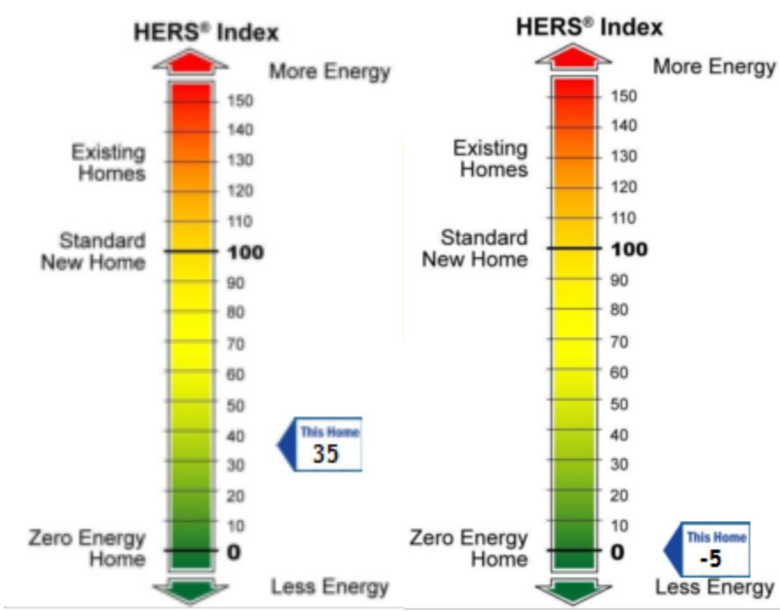


Figure 2 - HERS score before and after installing PV panels.

2.2 WELL-ROUNDED, REALISTIC, AND VERSATILE DESIGN

Our team set out to design a Net Zero Energy Home, as defined by the DOE's Zero Energy Ready Home standard while meeting the following additional goals:

1. **Net Zero Source Energy**
2. **Cost Effectiveness**
    a. The combined mortgage and utility bills are equal to or lower than what they would be in a comparably sized code-built house.
    b. The home is affordable to the median consumer in the area.
3. **Ease of Construction**
    a. Design a construction system that is simple and versatile, for which prefabricated elements can be used to erect a weather-tight envelope in one day with an experienced crew.
    b. Design a construction system which could be used in a variety of climate zones with minor adaptations, and which could be implemented in many areas of the world, taking into consideration constraints of material availability and typical local construction methods.
4. **Visitable by persons with disabilities**
    a. All important functionalities of the house are located on the first floor.
    b. The entrance's main access point is reached through an integrated ramp/stairway/garden.
5. **High standard of interior environmental quality**
    a. Meets superior standards of air quality.
    b. Is thermally comfortable.
    c. Makes excellent use of daylight.
6. **Aesthetic Appeal**
    a. Design a home that is visually interesting and desirable to the median consumer.
    b. Design a home that meets a high standard of livability through a well-designed floor plan, adequate lighting, and access to nature.
    c. Provide a sense of openness to make a relatively small home feel larger.
7. **Occupant behavior**
    a. Recognize that occupant behavior often does not match predictions, especially when occupants are expected to put in effort to frequently alter their environment (e.g. turning off lights, adjusting shades, setting back the thermostat).
    b. Make a robust house that relies less on occupant behavior and more on intuition and reliable design, including a Home Energy Management System.

2.3 OUR GOALS

2.3.1 Net Zero Source Energy

The three Rivers Team set several goals early on in the design process that have carried through the design of this home. One was to meet the standard of net zero as measured at the source, i.e. the total source energy used, and the total source energy produced must net to zero. This choice was made because the source energy, rather than site measured energy, is a better indicator of a number of other issues with energy use, such as greenhouse gas emissions, energy costs, and the strain that excessive energy consumption places on our outdated energy infrastructure.

2.3.2 Cost Effectiveness

Another goal our team decided to set early on was to create the lowest cost home that we could. This goal needed to be balanced with other goals of energy efficiency, quality of design, and livability. The challenging climate of Pittsburgh has both a cooling load and a heavy heating load, receives 3.76 kWh/m^2/day of solar radiation (NREL Red Book, 1994) and has only 59 clear days per year (CurrentResults.com, 2015). This forced us to focus on the precise placement of insulation and strategies to minimize thermal bridging wherever possible, as it would be extremely expensive and impractical to make up the difference with PV panels.

2.3.3 Ease of Construction

In addition to insulation strategies, our team decided that because quality construction and the necessary materials to meet zero energy are quite expensive, costs must be minimized in other ways. The strategy employed to do this was to use prefabricated and panelized material whenever possible in order to minimize construction time and job-site inefficiencies. Because factories have all materials organized and easily accessible with little time spent setting up equipment, labor inefficiencies can be greatly reduced (Lee, 2015). Later in the design process, our team set a goal of designing a home for which, with an experienced crew, a crane, and a foundation already in place, a completely weather-tight shell could be erected in a single day of work.

2.3.4 Designing a Versatile Building System

Rather than addressing only one home on one site, out faculty advisor, Steve Lee, challenged us to go further, by designing a construction system that was versatile and could easily be adapted to any climate in the world so as to provide a method that could be referred to for the creation of zero-energy homes. We initially considered many construction methods and materials which might be both versatile enough to meet the needs of ZEB design, as well as readily available worldwide. We examined steel, concrete, and wood construction, as well as shipping container homes, modular systems, panelized systems, and the many challenges of both site built and prefab construction. Ultimately, we were forced to narrow our scope due to pressures such as the inability to transport large, prefabricated units through the narrow streets that exist in much of the world, and material availability. For example, in India, home construction is almost exclusively concrete, a material which would perform poorly in Canada or Scandinavia. Given these constraints, we designed a system which could be adaptable to any region where space conditioning is the norm (unlike Singapore or Central America), and where wood construction is available. Because it uses EPS, parts of our system must be manufactured through industrial processes. Given these constraints, our system achieves a high degree of adaptability and versatility through addressing challenges of heat loss/gain, moisture migration, air sealing, and constructability in a way that can be constructed quickly and easily. For any such location, only a few simple adaptations are necessary to alter the system to be climate appropriate.

2.3.5 Water Efficiency

The world currently faces a water crisis. 97% of the Earth's water is seawater, and only 1% of the remaining 3% freshwater is located on the Earth's surface.

As only some of the U.S. currently experiences drought, it is easy to overlook locations like Pittsburgh, which have wet climates. However, Pittsburgh has its own concerns with water stemming from its antiquated combined storm and sewer system that renders potentially clean water contaminated and causes serious water pollution problems during overflows resulting from heavy rains.

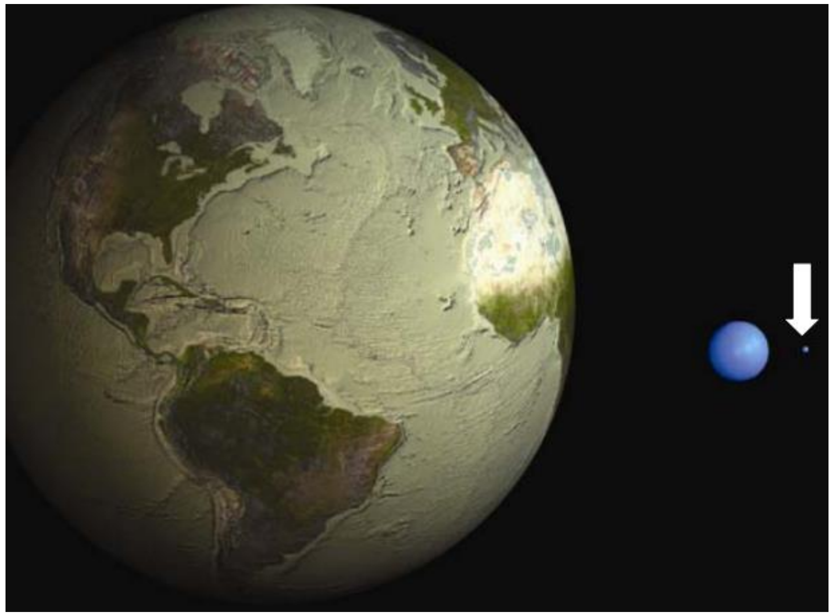


Figure 3 - Illustration by Jack Cook, Woods Hole Oceanographic Institution. The large sphere represents the Earth's volume of seawater, and the arrow points to the sphere representing the total volume of fresh water.

Thus, water is a precious commodity even in the wet climate of Pittsburgh, especially when considering runoff. This design addresses this concern through rainwater harvesting and storage that is used for irrigation on site when needed, encompassing a zero-runoff plan.

2.4 Method to Achieve Design Goals

Each design goal on our list fundamentally impacts the other goals. Care was taken at every step of the design process to consider all of these goals and how each decision impacted all others. Instead of simply designing to satisfy the adopted code (IECC 2009), the team strove to design for the future, turning toward IECC 2015 and observing the trends in evolving codes so as to predict how the most time-enduring design could be achieved. Additionally, the team used NREL's Net-Zero Energy Building Renewable Energy Supply Option Hierarchy as the preferred strategy to achieve net-zero. Preliminary design focused on innate energy efficiency of the house, including optimized insulation and sun-angle calibrated slatted shading devices. As soon as a basic schematic was available, energy modeling in EnergyPlus 8.1 was performed with the assistance of DesignBuilder v4. Parametric simulations were carried out to optimize the performance of each envelope element for both energy use and occupant comfort based on the ASHRAE 55 comfort zone. Following this, footprint-supply renewable energy methods were applied to take the home from efficient to net-zero.

2.5 Project Elements

2.5.1 House Type

The Three Rivers home design is a single-family detached house built in an infill site outside of Downtown Pittsburgh. Floor plans are shown below. The house spans east-west with the south façade exposed.

2.5.2 Location

The home is located at 1424 Fallowfield Ave., a vacant lot in Mount Lebanon, a southern neighborhood of Pittsburgh, PA. The lot was formerly the site of a condemned home which was recently demolished, and utility connections already exist on the site, reducing the initial cost of construction.

Figure 4 - View of the proposed house.

2.6 Pittsburgh Climate

The Pittsburgh climate is predominantly cold, but does also include a heating load. Summers can be uncomfortably humid, and winters are cold and dry. The following design conditions apply in Pittsburgh:

	Value	Reference
IECC Climate Zone	5A	IECC 2009
Winter Design DB Temp	5°F	ASHRAE 2009 Fundamentals
Summer Design DB Temp	86°F	ASHRAE 2009 Fundamentals
Summer Design Wet Bulb Temp	73°F	2006 Virginia Plumbing Code
Sky Cover	65%	EPW
Annual Average Ground Temp	50°F	EPW
HDD65F	5053	2006 Virginia Plumbing Code
CDD65F	654	CLRsearch.com
Latitude	40°N	2006 Virginia Plumbing Code
Annual Hours of Sun	2021	CurrentResults.com
Annual Clear Days	59	CurrentResults.com
Average Daily Solar Radiation	3.76 kWh/m^2/day	NREL Red Book; PVWatts

Table 1 - Climate Details

2.7 Design Strategies for Pittsburgh

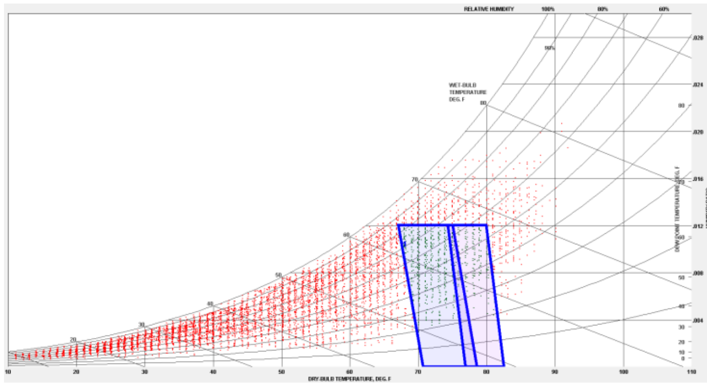


Figure 5 - Psychrometric chart for Pittsburgh, PA using ASHRAE Standard 55-2013

Strategy	Comfort Contribution (Percent of Year)
Normal Outside Conditions	10.1%
Insulation	23.9%
Sun Shading	7.3%
Passive Solar Gains (Low Mass)	7.9%
Conventional Heating	51.5%
Dehumidification	6.9%
Conventional Cooling	3.4%

Table 2 - Comfort Strategies, Climate Consultant 6.0, 2015

The primary design solution for Pittsburgh's cold climate is superinsulation to capture internal gains and minimize conventional heating. Moderate passive solar gains are available through careful window placement; however, sun shading of windows is a priority with or without this strategy, as Pittsburgh can be uncomfortably hot and humid in the summer.

Because a conventional heating system will be necessary over 50% of the time, care must be taken to select an extremely efficient system that works well for this climate.

Net Zero design in Pittsburgh faces the added challenge of cloudiness. With only 2021 hours of sun, and 59 clear days per year, Pittsburgh is one of the cloudiest places in the country, ahead of both Portland, OR and Seattle, WA. This makes solar energy generation difficult, and added emphasis must be placed on energy efficiency to offset the large solar array that will be necessary.

2.8 Lot Size & Configuration; Orientation

1424 Fallowfield Ave. is a foreclosed lot where the previous condemned home was torn down. The lot currently sits empty and is available for sale for $2500. As a result, the lot was not as significant a factor in the cost of the building as it might have been, and existing utility lines are available to use, avoiding the additional cost of adding new underground connections.

The lot itself is 60' x 115' with the long side facing south. Situated on the southern slope of a hill, this lot has excellent sun access for both passive and active solar design. The home directly to the south is low, and ample space on the lot is available to avoid shading of the proposed home by neighboring buildings.

Figure 6 - Site location with topography using ArcGIS

2.9 Neighborhood and Community Setting

1424 Fallowfield Avenue, Pittsburgh, PA

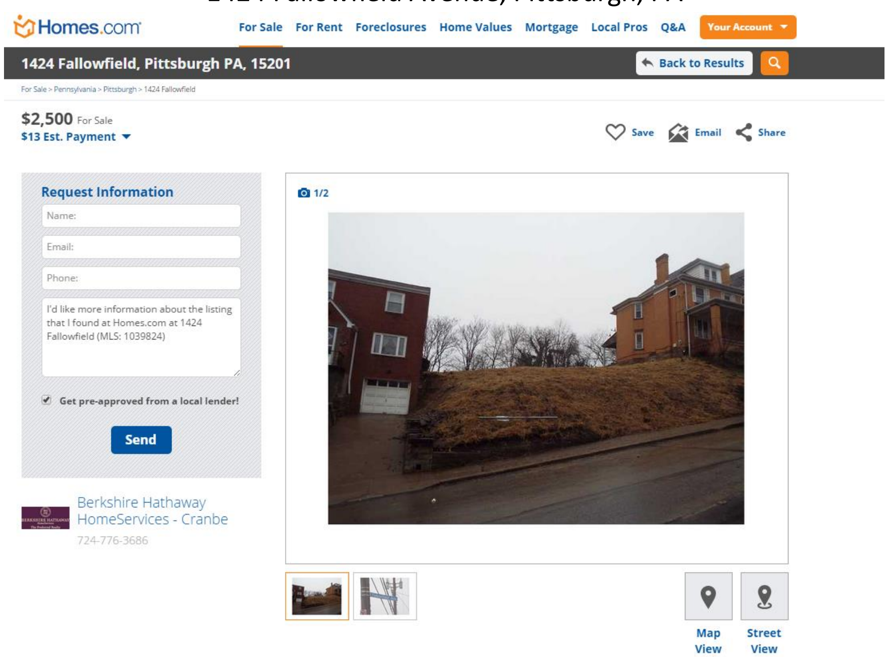


Figure 7 - Real Estate Lot Profile

2.9.1 Transportation

- Walking Distance (0.2 miles) to the Fallowfield light rail Station
- 23 minutes by light rail from Fallowfield Station to downtown Pittsburgh
- 0.2 mile walk to nearby market district (Broadway & Hampshire)
- 0.3 mile walk to Beechwood Elementary School
- 0.5 mile walk to Brashear High School, Seldom Seen Greenway & Tropical Park

2.9.2 Visual Integration

- Urban infill site
- Visual design is intended to embrace a modern, high-performance take on surrounding Pittsburgh architecture

2.10 Positioning and Layout

The Three Rivers team opted for a simple design and small overall footprint for two reasons:

1. Avoid unnecessary construction costs, material use, and space conditioning.
2. Keep the building size and shape manageable for the simple structural design.

An open-plan layout was designed to allow easy flow throughout the house and provide natural light to all necessary spaces. By combining the kitchen, living area, and dining space, unnecessary walls are eliminated. The bottom area is also open to the upstairs, creating a connection through the center of the house and using the double height to further open the space.

Figure 8 - The side-banger style house enters through the open living space, and more private rooms are located past the stairway to the west and upstairs, thus creating a hierarchy of public and private space.

Figure 9 - Interior view showing the double height cutout space in the dining.

Daylighting was considered during the preliminary and schematic design phases to achieve properly lit environments at the appropriate times of day, which is further discussed in the *Lighting* section.

A truly integrated design process was used to promote less waste with more integrated systems. The upper kitchen cabinetry becomes a channel for ducts and pipes, and the layout is designed to place all water fixtures centrally to reduce pipe lengths and hot-water wait time. The cross-laminated timber floor also acts as a visually stunning lower-level ceiling.

2.11 Occupants and Accessibility

Our design is flexible in terms of the potential occupants. A three -home, it is ideal for young families, and can house up to four people by American standards of comfort and privacy. However, while two bedrooms are located upstairs, one is located downstairs, which is important as multigenerational living and elder parents living with children becomes more common. The location of the home allows for easy access to local businesses, schools, and transportation to downtown Pittsburgh, making it an excellent choice for people from many different lifestyles.

Care was taken to ensure that the first floor of the home contains everything that would be needed for living, allowing a greater degree of accessibility for both visitors and occupants with disabilities. Pittsburgh's hilly terrain can be extremely challenging to the disabled, with homes built on hills above the road, many of which require ascending a steep incline to enter the house. This was the case at the Fallowfield Ave site. While location of the home at another site would have allowed for easier accessibility, by acceding to this challenge the majority of Pittsburgh will remain effectively off limits to the disabled. In order to address this, an integrated stair-ramp was designed to allow easy ascent of the hill to the Fallowfield site. Integration of the ramp with the stairs provides an equal-access entry point so as not to separate differently abled people from one another. A 5' turning area is kept clear in the downstairs bathroom, and while much of the first floor is open-plan, each door located on the ground floor has 18" of clear floor space next to the door on the pull-side.

2.12 Sustainability

2.12.1 Prefabrication

10-25% of typical site built construction materials end up as waste. Because the home can be almost entirely prefabricated, construction waste is minimized throughout the process. On average, prefabrication companies waste only an impressive 2-4%. A prefabricated home has a reduced waste stream, and thereby a reduced carbon footprint during construction. Murus, the company chosen to fabricate the home's exterior SIP walls, is local to western PA, further reducing building's ecological footprint through reduced transportation energy use.

2.12.2 Net Zero Energy Calculation Strategy

Four types of net-zero strategies are typically used: site, source, financial, and carbon emissions. The Three Rivers team quickly decided against the financial model because of its lack of environmental connection. While it is important that the house be affordable, design efforts are better spent on curbing the harms of energy production and use than ensuring a $0 annual bill. This led to the decision to focus on source energy, as it encompasses the consequences of both the use and the production of energy. While it is often tempting in net-zero design to opt for net zero site energy because of easy direct measurement and simplification of all systems into electricity only, source energy evaluation addresses the source of environmental issues related to energy use. In the US, a unit of consumed electricity requires the production of 3.14 times the amount of this electricity at the power plant, whereas only 1.05 units of source-produced natural gas is required for 1 unit of natural gas used. In Pennsylvania, which receives 40% of its power from coal, and 35% from nuclear (EIA, 2015), avoiding grid source electrical use whenever possible is ecologically preferable. The Three Rivers team decided to employ this whole-system thinking to the design, and thus we landed on the target of net-zero source energy.

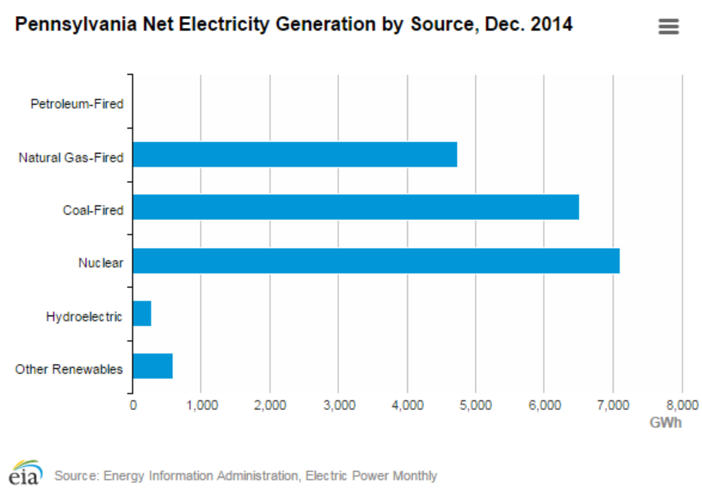


Figure 10 - Pennsylavania Grid Electric Sources

2.12.3 Rainwater Harvesting

As mentioned before, only 1% of freshwater is on the Earth's surface. This makes conservation of water and optimized use of available water almost obligatory.

Rainwater percolates through the ground to finally add to the ground water table. In urban centers like Pittsburgh, most of the ground surface is covered by tall buildings and impervious surfaces. This leads to overburdening of city sewage infrastructure, such as drains, catch basins, and municipal water treatment plants. Pittsburgh has a combined sewer system that floods in the event of heavy rainfall. Since the water has no way to percolate in the ground, it ends up mixing with the sewage and black water. This clearly isn't a wise use of fresh rainwater.

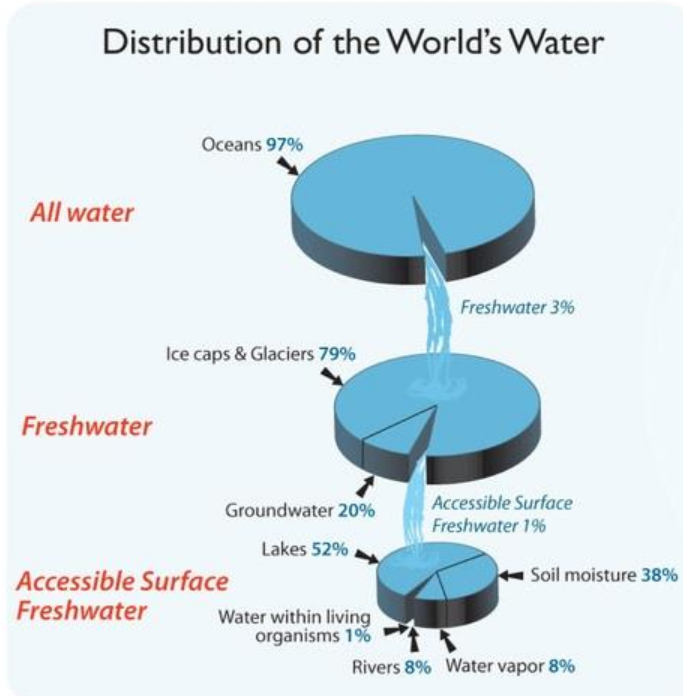


Figure 11 - Division of world's water (CK-12 Foundation, 2015).

Rainwater harvesting is a solution that results in saving energy, water, and money and also contributes to environmental conservation. The following figure depicts the average water usage in a standard Pittsburgh household.

We notice that over 30% of the water is used for watering plants and lawn alone. A large amount of this, if not all, can easily be replaced by rainwater without installing an expensive rainwater harvesting mechanism. Pittsburgh has an average annual precipitation of 34.8 inch which is fairly dissevered throughout the year, thus ensuring a significant harvest potential.

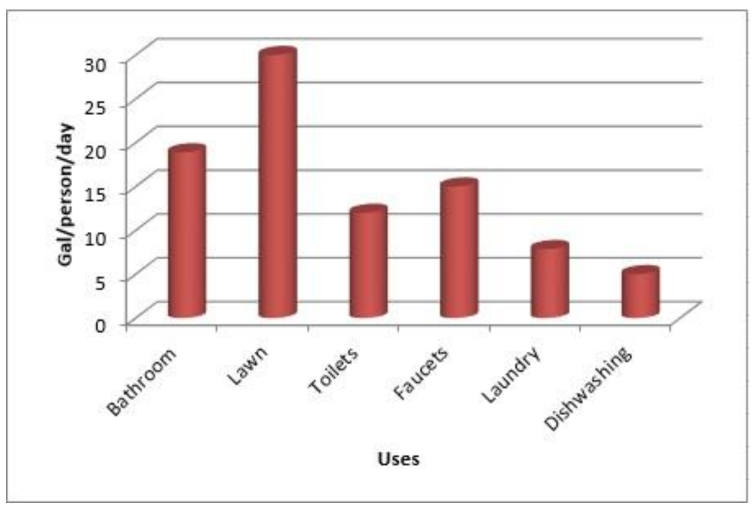


Figure 12 - Average water usage in Pittsburgh household

The Three Rivers house has a steep roof pitch running North-South, providing a catchment area of around 1000 sq-ft. Table 3 is the anticipated monthly rainwater collection given this area:

The design utilizes the rainwater for watering the lawn, plants, and landscape on the site, which accounts for over 30% consumption of the total household water. Water through the sloping catchment area is channeled into a 6" half-round gutter, after which it flows into a water storage tank of 825-gallon capacity. A mesh filter will ensure primary screening of water.

The water tank is designedly placed 6-8 feet above the ground level to provide enough potential energy and pressure to maintain an adequate water pressure in the flexible garden hose that is movable across the site boundary.

By using rainwater capturing, less stress is put on the municipal system at once, and the captured water can be used later for irrigation on site, which also eliminates the use of potable water for irrigation purposes. When potable water is saved, it also reduces energy use, as water treatment is another energy-intensive process that is often not considered since it occurs offsite.

Month	Rainwater Collection (Gal)
January	1789
February	1396
March	1889
April	1864
May	2038
June	1864
July	2088
August	1864
September	1889
October	1353
November	1964
December	1696

Table 3 - Onsite Rainwater Collection by Month

2.12.4 Forest Stewardship Council

The engineered wood materials chosen for the structure and interior flooring are widely available from Forest Stewardship Council (FSC) certified, sustainable harvested sources. Construction documents specify that all of these products are to be sourced from companies which meet FSC standards.

2.12.5 Beetle Fell

Rising temperatures in California have led not only to draught, but to increasing deforestation. Bark beetles, which die at freezing temperatures, have reaped the benefits of climate change, and are moving farther and farther north, devouring the inner layer of bark in our western forests, killing thousands of acres of trees. This wood, if it decomposes, releases the stored carbon that has built up over its life back into the atmosphere, further contributing to climate change, and creating a dangerous feedback loop. If harvested quickly, these trees make an excellent source of sustainable wood, and their carbon content can be sequestered in buildings rather than returned to the atmosphere. Cross laminated timbers and glulam beams are ways in which this abundance of wood can be cost effectively integrated into buildings, lending structural strength and beauty to the home as well.

2.13 Programs & Standards Met by this Design

Zero Energy Ready Home

Energy Star V3

EPA Watersense

EPA Indoor airPLUS

Passive House

Table 4 - The various energy standards met by the 'Three Rivers House'

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3 Envelope Durability

3.1 Design for Versatility

This envelope is part of a construction system which is designed to perform well and be easily constructed in any area of the world with significant space conditioning requirements, and where wood and EPS construction materials are available. The design of the envelope revolves around the goal of ease and speed of construction. We estimate that an experienced crew could assemble a weather-tight envelope in one day of work, not including the foundation, although the helical steel pier foundation system was also chosen for speed of construction time.

3.2 Goals

Our team approached design of the building envelope with these goals: create a high-performance construction system which meets the following criteria:

1. Super-insulated and air sealed to extremely high levels
2. Very low thermal bridging
3. Easy to erect
4. Durable and long lasting
5. Termite resistant
6. Moisture and mold resistant
7. Can work in a variety of climate zones with minor modifications to insulation levels and pest control strategies.

3.3 The Three Rivers System

The envelope consists of four glulam wood frames which are divided into widths of no more than 14' for ease of truck transportation after prefabrication. These frames bear on helical steel piers, and provide support for prefabricated panels which form the envelope and interior floors.

Figure 13 - Construction System Framing

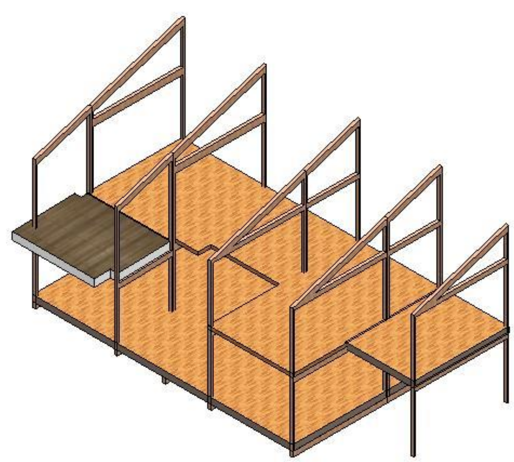

Figure 14 - Construction System Flooring

The ground floor consists of a continuous layer of PermaTherm galvanized steel SIPs which come in 3'-10" widths and span the length of the floor over top of the lower cross beams. The second floor is cross laminated timber (CLT) slabs in 4' wide segments which likewise span between the upper cross beams of the frames. Second floor areas exposed to the outdoors use SIP panels rather than CLT.

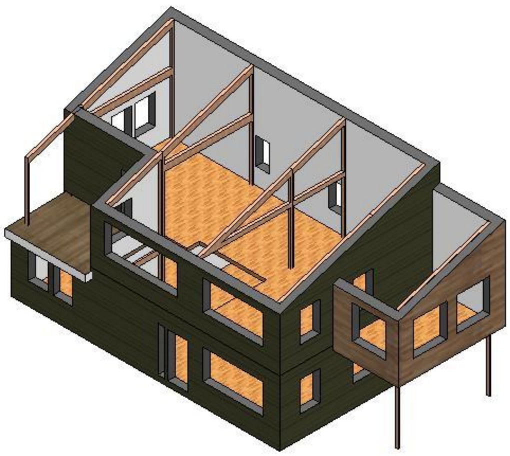

Figure 15 - Wall Attachment

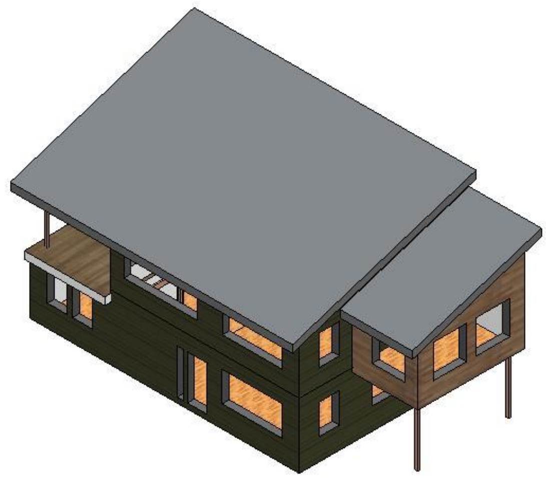

Figure 16 - Roof Attachment

Because the floor panels do not extend past the edge of the framing, wall panels are able to continuously sheath the building, eliminating the need for a rim joist, and minimizing heat loss. Murus OSB SIP walls are then added, bolted to the outsides of the frames with Headlok panel screws.

Finally, PermaTherm galvanized steel SIP roof panels are added spanning in the same direction as the floor panels. Because the SIP panels do not need to provide structural bearing for the roof, there is no need for the bearing plates traditionally used in the tops of SIP wall panels, which add to thermal bridging. Instead, the eave walls are cut at a bevel, and a 1/4" gap is left between the wall and the roof panels. A channel is routed in the underside of the steel roof panels over top of the wall as a thermal break, and both the channel and the 1/4" gap are then filled with polyurethane expanding foam insulation. Caulking is applied at the interior seams of all SIP panels to prevent vapor migration, and the interior walls are coated with a semi-vapor-permeable, VOC-free paint.

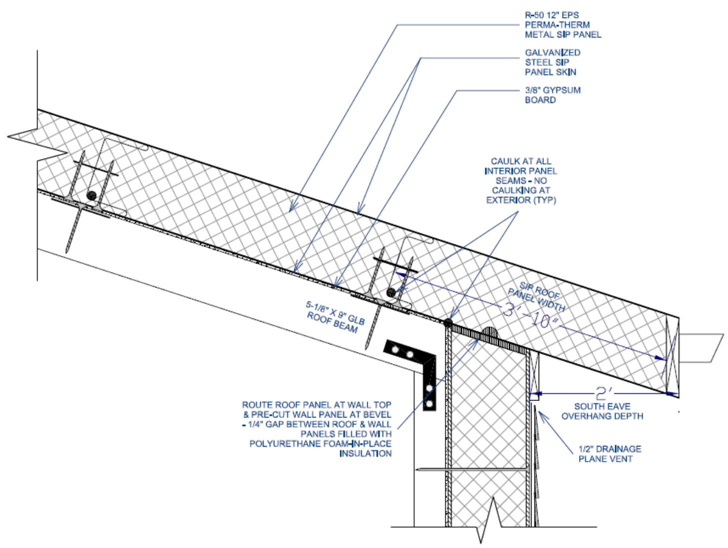

Figure 17 - Roof Construction Detail

This structural system was designed to eliminate as much thermal bridging as possible. While a normal stem wall or slab foundation has significant heat loss at the foundation perimeter, this assembly allows us to wrap our insulation continuously around the bottom corners of the structure. Because the interior floor (Cross Laminated Timber) bears entirely on the interior wood frames, it does not penetrate through the wall system and there is no rim/band joist through which heat may escape. The only places where the structural framing penetrates the envelope are at the points where the wood framing system makes contact with the pier foundation. The building thereby stands on tip-toes, avoiding contact with the cold Pittsburgh winter. In order to model this system in REM/Rate as accurately as possible, the wood frame penetrations were treated as a band joist. These penetrations have a barely noticeable effect on overall building loads. By reducing thermal bridging in this manner, lower levels of insulation are necessary to achieve the same effective assembly R-value, thus reducing material costs, which in a SIP assembly can be quite high.

3.3.1 Structural Spans

	Product	Total Uniform Load	Allowable Span L/240	Reference
Roof	12" Steel SIP	45	14'	(Permatherm.net, 2015)
1st Floor	10" Steel SIP	50	12'	(Permatherm.net, 2015)
2nd Floor	3-1/2" CLT	50	14'	(CST Innovations, 2015)

Table 5 - Structural Spans of Proposed Products

3.3.2 Cross Laminated Timber

The internal second floor includes no joists, but is made up of cross-laminated-timber (CLT) slabs in 4' wide by 3-1/2" thick segments which easily span between the structural frames. This allows the frames to be spaced farther apart, eliminating some framing costs. Because the CLT itself serves as structure and finish floor, and because of the extreme ease of installation with the assistance of a crane, the increased material cost of CLT do not translate into increased final costs and may reduce the overall price of the home. Because of the wood mass of a CLT, the panels also have a stabilizing effect on indoor humidity levels, absorbing and releasing moisture to enhance thermal comfort, as well as adding to acoustic and visual appeal.

Figure 18 - A Close-up of the CLT Slab (CST Innovations, 2015)

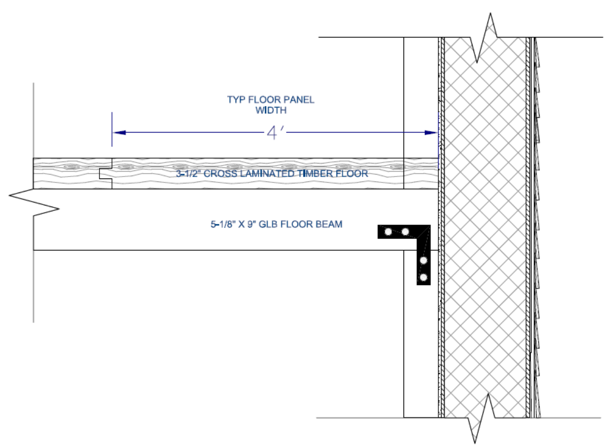

Figure 19 - Typical CLT floor attachment detail

3.3.3 PermaTherm SIPs

The ground floor and roof systems consist of PermaTherm metal SIP panels which designed for refrigerated warehouses, and which are available in lengths which can easily span the 40' length of the house. Because PermaTherm SIPs were originally designed with refrigerated warehouses in mind, for which space conditioning costs can be extremely high, thermal bridging is a make or break issue. One innovative strategy to minimize thermal bridging is the inclusion of a 10 gauge steel spline inside the insulation, which allows the panel to be drilled into from the inside with self-tapping screws but keeps the metal connectors from bridging all the way to the outside. This way, no metal connection is ever made between the inside and outside. This can be seen in Figure 20.

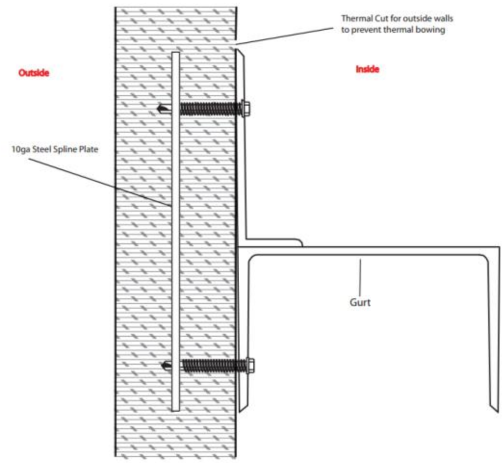

Figure 20 - Steel SIP Panel Attachment Detail (Permatherm.net, 2015).

3.3.4 Murus SIPs

Murus is a Pennsylvania SIP manufacturer, and one of the largest SIP producers in the country. The walls consist of Murus OSB skinned SIP panels which provide the building with shear value. These panels provide a high degree of air sealing (Figure 21). Once this system is erected, the attachment of roof and wall finishes can be done quickly and easily. Because Murus SIP panels come with drywall pre-attached, interior finishing time will also be greatly reduced.

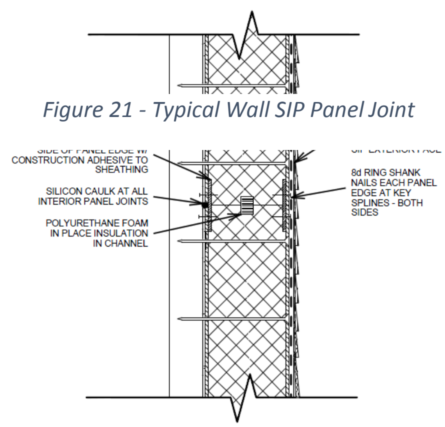

Figure 21 - Typical Wall SIP Panel Joint

3.3.5 Versatility Benefits

Given this simplicity and ease of construction, this type of system can be easily adapted to a variety of climate zones, conditioning requirements and environmental threats, given the availability of materials.

- Variable thicknesses of SIP panels allow easy customization of insulation levels
- Wood frame construction allows for easy customization of building layout and form
- Steel SIPs are durable to moisture in a variety of climates and conditions
- PermaTherm SIPs provide extremely good resistance to vertical loads for high snow load areas
- Pier foundation provides resistance to pests and minor flooding

- Method of construction is appealing in terms of construction time and ease of assembly
- Increased material costs are made up for in decreased construction labor costs

3.3.6 Windows

Alpen high performance windows were chosen to achieve high performance at a reasonable price. Fiberglass frames make the windows durable and expand/contract only as much as the building envelope. Argon and krypton fills combined with triple glazing layers, along with thermally broken and insulated frames, give these windows very low thermal conductivity, beyond the requirements of Energy Star for Homes. As windows become proportionately the most expensive aspect of a zero-energy house, they should be optimized to deliver proper performance. While it is often difficult to find desirable visible transmittance values in triple-glazed windows, Alpen has relatively high VT, even with low SHGC. Additionally, the windows are rated by the NFRC with very low air and water infiltration.

Alpen 525 Series dual pane, 1 low SHGC film			
			
	East/West Single-Hung	North/South Picture	North/South Single-hung
U-value	0.21	0.18	0.22
SHGC	0.24	0.47	0.39
VT	0.44	0.62	0.51
Gas Fill	Krypton	Argon	Krypton

Table 6 - Alpen Window Properties (Alpenhpp.com, 2015)

3.3.7 Doors

This home uses Therma-Tru insulated, Energy Star rated exterior doors. These doors are in the Classic Craft American Style Collection and have a U-factor of 0.17.

3.3.8 External Window Shading

Two different types of external shading strategies were employed in this design. The first is a simple roof overhang which extends 2' out from the exterior wall surface as seen in Figure 23. This overhang is based on NREL Blue Book recommendations (Figure 22) for south facing window shading in Pittsburgh, though the height of the overhang above the window is slightly lower than recommended due to design constraints.

The second type of external shading is a trellis above the first floor south-facing windows, which shades the deck area. This trellis is designed with fins at 30° from the ground plane such that the majority of sunlight in the heating season is allowed to enter the house but the majority is excluded during the warmer months. In Pittsburgh's overcast winters, there is little risk of overheating due to solar gain.

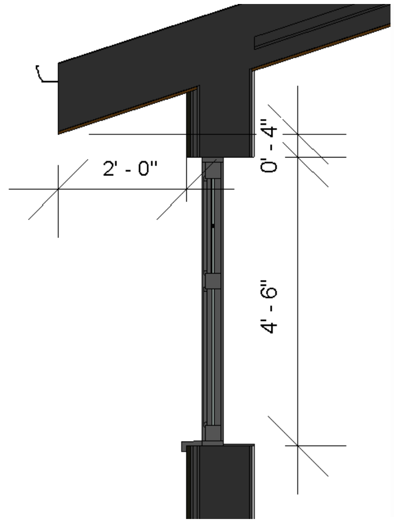

Figure 22 - Typical South External Solid Shading Detail

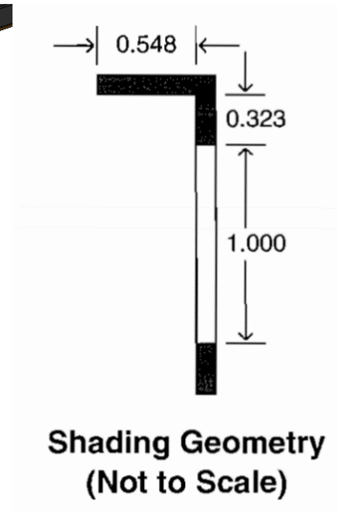

Figure 23 - NREL Recommendation for Pittsburgh South Shading (NREL, 2015)

Parametric energy modelling for both energy use and comfort was performed on both of these strategies and can be found in Section 6.1 - EnergyPlus Parametrics.

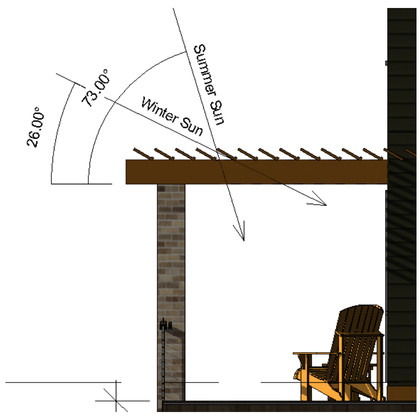

Figure 24 - Trellis Shading in Summer & Winter

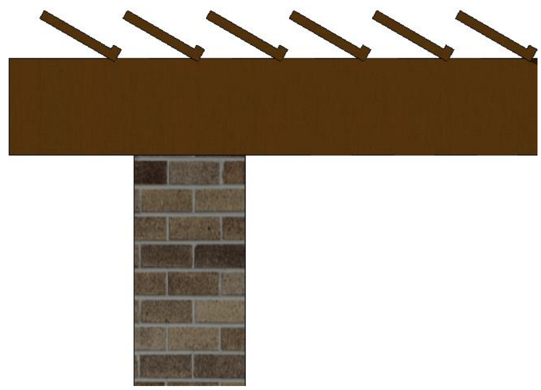

Figure 25 - Trellis Shade Profile

In order to shelter the deck area from rain as well as summer sun, a strip was added to each fin in the trellis to catch water. The entire trellis is at a gentle 2% slope to the west.

3.4 Moisture

Industry partner Michael Sypolt, a Pittsburgh building scientist, was consulted to better understand how this building envelope would perform hygrothermally. Michael Sypolt's software uses TMY weather data to examine the amount of condensation a particular assembly will experience throughout the course of a year. In his words, our assembly performed so well it was "boring." Temperatures at all points in the critical layers of the envelope were well above the dew point. He attests that, "Both interior and exterior sides of the wall have very little chance of condensation unless sustained humidity levels of 95% or more are observed for extended periods of time." Below is a comparison between his analysis of the SIP wall and roof assemblies and a more conventional wall construction.

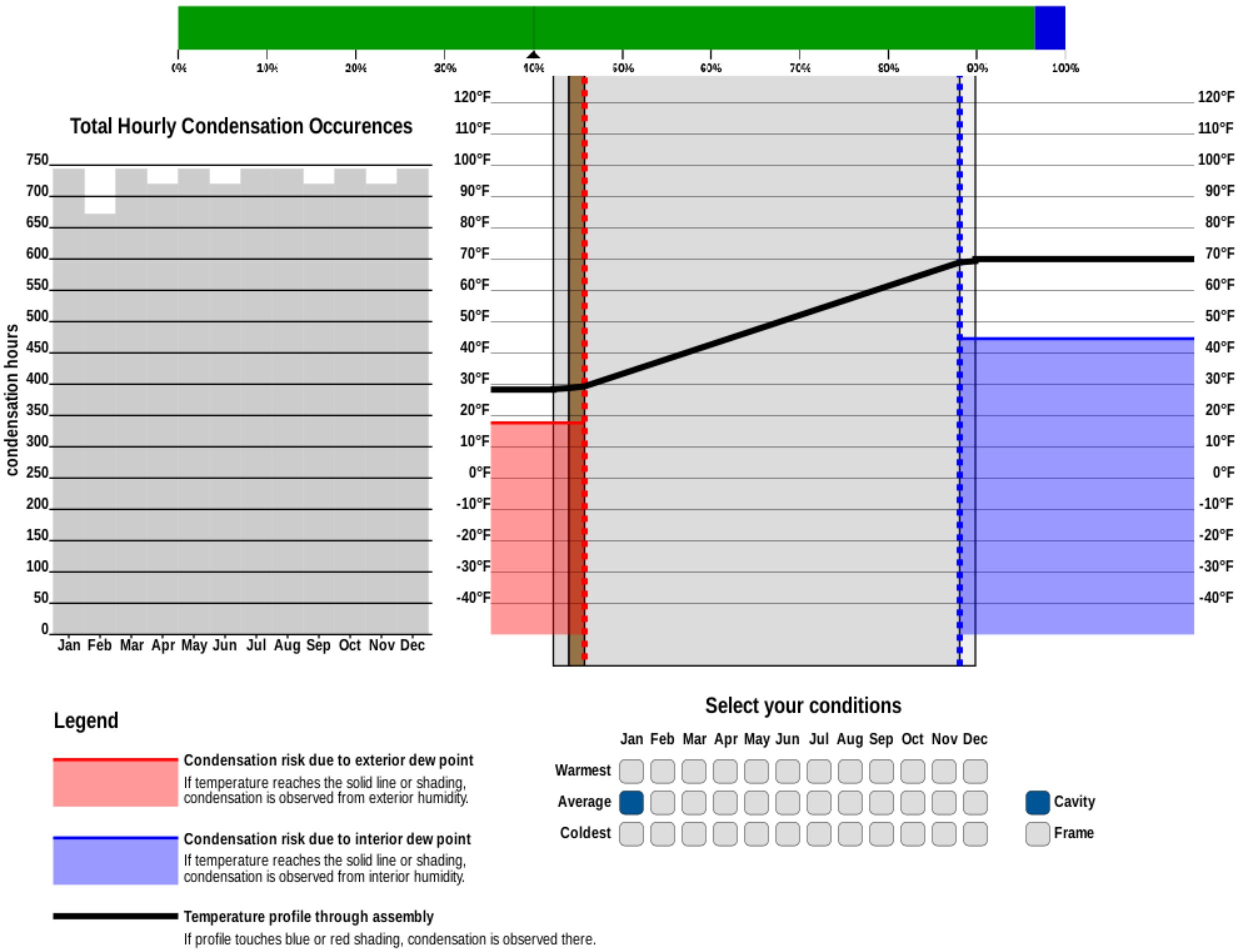

Figure 26 - SIP assembly hygrothermal analysis

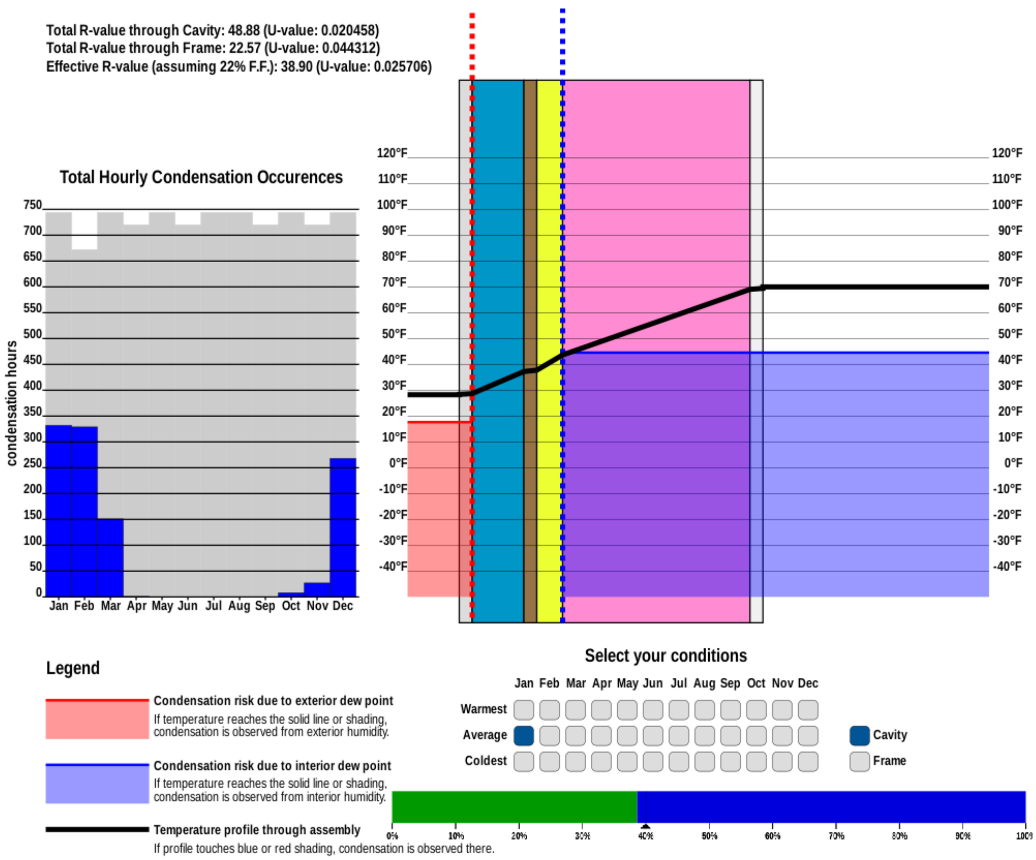

Figure 27 - Comparison wall construction hygrothermal analysis

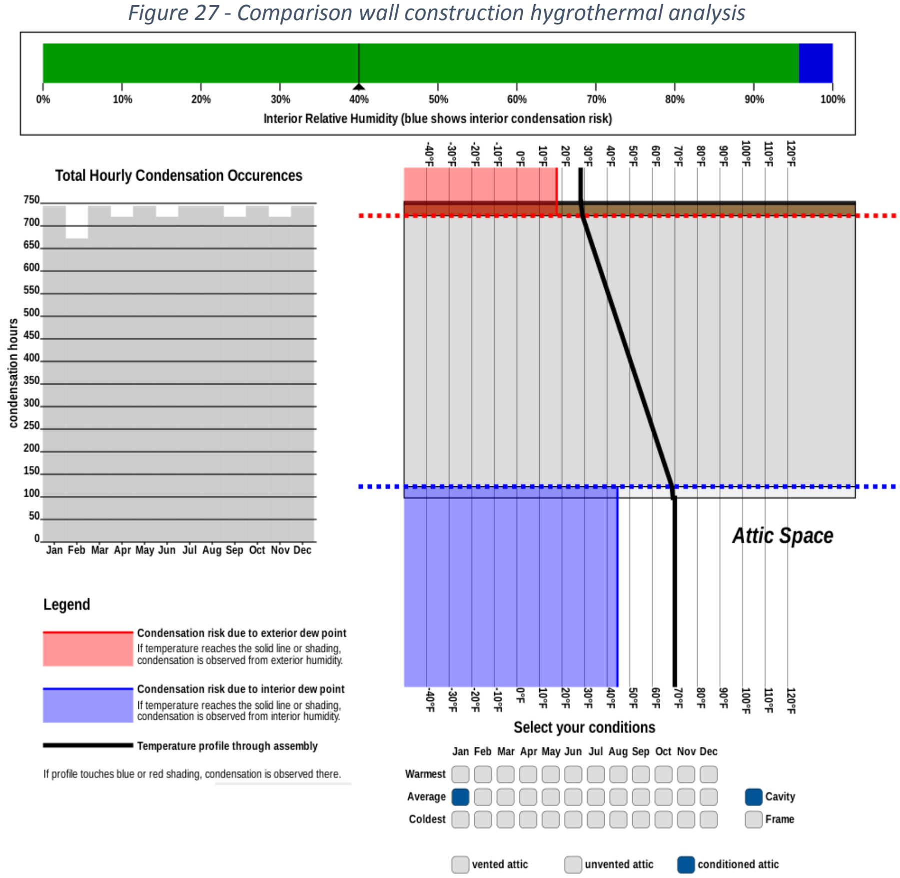

Figure 28 - SIP roof hygrothermal analysis

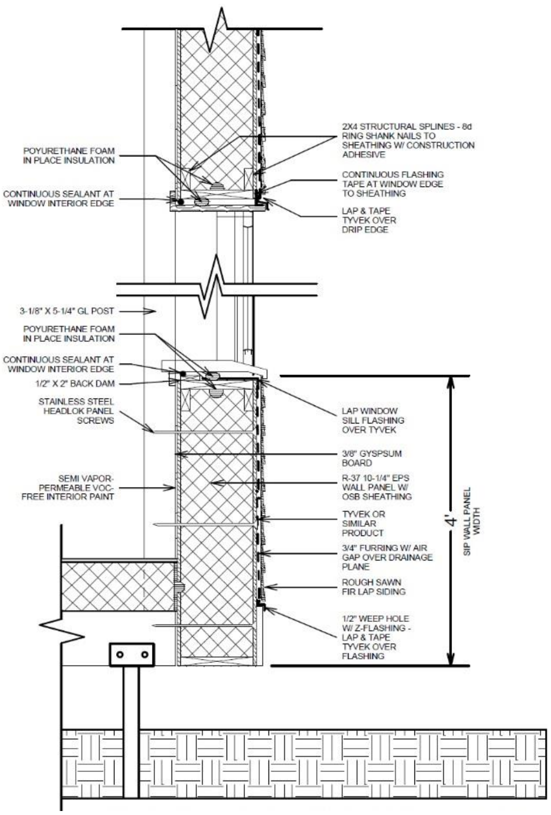

Figure 29 - Typical Wall Construction

The true threat to this envelope is the danger of SIP seam rot, as has been documented by the Building Science Corporation. Our earlier designs included traditional OSB skinned SIPs on all envelope surfaces. In order to combat SIP seam rot, we planned to create a vented over-roof to allow the assembly to dry. However, when PermaTherm galvanized steel SIP panels were selected, this negated many of the dangers of seam rot, as well as eliminating the added cost of a vented over-roof and added roofing material. The steel roof panels are caulked at interior surfaces to provide a full air and vapor barrier.

The walls, which are a traditional OSB skinned SIP, continue to have a vented drainage plane to prevent rot of the OSB skins. Tyvek is used as a water barrier at the panel surface, and furring strips are added to offset the wood cladding away from the house by 3/4". Each piece of Tyvek overlaps the piece below and is taped at each seam, rather than stapled. At the bottom of each drainage plane is a weep-hole with z-flashing to allow water to escape and air to enter to facilitate drying. The bottom layer of Tyvek is lapped and taped over this flashing.

Drainage of bulk water is provided on the roof by the PermaTherm galvanized steel SIP surface and the normal overlapping inherent in the design of PermaTherm SIPs (See Figure 17).

In the walls, a vented drainage plane is sandwiched between Tyvek and the exterior cladding, with weep holes at the bottom and vents at the tops to allow for air flow and fast drying of any moisture which reaches the wall (see Figure 29).

3.5 Pest control

Many of the materials specified in our design are highly pest-resistant or impenetrable. Steel pier foundations hold the building up above the ground, away from danger. The majority of the underside of the house is a galvanized steel skinned SIP panel. However, the structural supports which carry these panels are wood and must be treated with borate in order to resist pests in areas where they are a danger to the building. While Pittsburgh is not a high risk area for termites, our goal is to create a versatile building system which could be applied to other climate zones. In extremely high risk areas, these supports could be traded for steel beams, or SIP panels could be 'hung' from them in order to encase the beams within the SIP panels themselves. However, this measure would contribute to thermal bridging, which we have attempted to minimize. Because termites tend to be more common in warmer climates, this thermal bridging may be less problematic in such areas. In this design, we have opted for simple borate treatment.

3.6 Radon

The area is at high risk for radon, but by lifting the floor above the ground, we eliminate the risk of pulling radon up from the ground by avoiding contact with the ground.

3.7 Envelope Description

Element	**Description of Layer (outside to inside)**
Roof Assembly	• Standing Seam Roofing • 30# Felt for bulk water drainage • R-50 PermaTherm Galvanized Steel SIPs • Gypsum Board or T&G Pine (Optional)
Wall Assembly	• Fiber Cement Siding • 3/4" Furring with vented drainage plane • 30# felt for bulk water drainage • R-37 Murus OSB SIP panel • SIP Integral gypsum board
Floor	• R-41 PermaTherm Galvanized Steel SIPs • Finish Floor

Windows	Alpen HPP 525 Series
	• U-values : 0.18-0.22
	• SHGC: 0.24-0.39
	• Visual Transmittance: 0.44-0.62
	• High-performance assembly
	    ○ Double pane with interior suspended coated film
	    ○ Fiberglass frames with foam-insulated spacers

Exterior Doors	Therma-Tru Door • Classic Craft American Style collection • Fiberglass insulated • U-0.17

Table 7 - Envelope Description

3.8 ENERGY STAR for Homes Envelope Requirements

	Energy Star Requirement	Proposed Design
Window U-Factor	0.27	0.18-0.22
Window SGHC	Any	0.24-0.39
Door U-Factor	0.21	0.17
Ceiling R-Value	49	50
Wall R-Value	20 or 13+5c.i.	37
Floor R-Value	30	41
Ductwork	</= 10' outside thermal envelope	No ducts outside thermal envelope
Duct Leakage	</= 8 CFM_{25}/100 feet of duct	Target: 8CFM_{25}/100ft of duct
Infiltration	</= 4 ACH_{50}	Target: 1.5 ACH_{50}

Table 8 - Energy Star Envelope Requirements

3.9 References

Complex Three Dimensional Airflow Networks. Building Science Insights. (2010, February 19). Building Science Corporation. Retrieved March 21, 2015, from http://www.buildingscience.com/documents/insights/bsi-036-complex-three-dimensional-air-flow-networks

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4 INDOOR AIR QUALITY EVALUATION

4.1 CONTEXT

The mechanical system was designed in such a way as to ensure high comfort levels and superior air quality, in addition to energy savings. Given that the home is designed to be built very air-tight, ventilation is a key contributor to the home's experience. Additionally, Pittsburgh is known for having poor air quality, as the region ranks #6 in the US in particle pollution (American Lung Association, State-of-the-Air, 2014). In November, 2013, Allegheny County was ranked in the top 2% for cancer risk due to air pollution (http://www.post-gazette.com/news/environment/2013/11/21/Report-Allegheny-County-in-top-2-percent-in-U-S-for-cancer-risk-from-air-pollution/stories/201311210326). In order to consider a home design as high-performing, Pittsburgh's high levels of small particulate matter mandate that air filtering be a high priority.

Figure 30 - Allegheny County Air Quality (State-of-the-Air Report, 2014)

4.2 EQUIPMENT

The RenewAire GR90 ERV was chosen because of its high performance specs and compatibility with fine filters, and it has been field-tested by this project's consulting MEP specialist and is known to perform well in the local area. The GR90 completely separates supply and exhaust air and has the ability to operate at between 40 and 110 cfm, which is suitable both for ASHRAE Standard 62.2 calculated requirement of ventilation rate = .01*(conditioned floor area) + 7.5(#bedrooms +1) or the prescribed requirements of 60 cfm. The model itself is designed to operate at the calculated 45cfm. Both the ERV and the ground-source heat pump have filters to address the relevant needs. The ERV is outfitted with a MERV-13 filter to catch small particulates and pollens from the outside air, and the heat pump, which receives inside air and air from the ERV, has a MERV-11 filter, which can filter indoor air pollutants. Equipping the ERV and heat pump units with filtration beyond the EPA Indoor airPLUS requirement of a MERV-8 filter ensures high air quality of virtually all air that reaches the occupants.

Still, windows are operable so that occupants can choose to use natural ventilation and cooling strategies in the swing seasons, since offering no operable windows could cause claustrophobia and inhibit biophilic connection to the outdoors.

The ERV is to be paired with the Panasonic WhisperGreen ceiling fan (one in each bathroom) for easy operation, smart controls, and proper pairing with the specified ERV, as preferred by the HVAC consulting industry partner. The fans are multi-speed with a time delay option so that the fan can operate at lower speeds when dehumidification and restroom pollutants do not contribute to the load, taking the responsibility of fan operation off of the occupants. A CO2 sensor also controls the operation, allowing inside air to be replaced by outside air only when necessary. Often, occupants are absent, and the air remains suitable for long periods of time, during which fan and ERV operation would be a waste of energy. Thus, the CO2 sensor integrated with the ERV ensures proper air quality exactly when it is needed.

Figure 31 - RenewAire GR90 (Renewaire.com, 2015)

Figure 32 - Panasonic WhisperGreen Vent Fan (Panasonic.com, 2015)

4.3 MATERIALS

Another design decision affecting indoor air quality is the use of materials that do not off-gas and that do not retain moisture. While radon is discussed in the previous section, other construction materials also contribute to indoor air quality. For example, no carpet is used in the house, and only non-VOC finishes are applied, ensuring that inside air really does remain superior to outside air in this environment. Especially in a tightly built house, VOCs and formaldehyde are liabilities that can become trapped in the breathing air. Using hard surfaces for flooring mitigates moisture concerns, as recommended by EPA Indoor airPLUS. The hard-wood floor and cross-laminated timber floor/ceiling between the first and second floor are simple solutions to maintaining air quality and preventing moisture issues, along with the moisture-robust SIP construction system. To guarantee that no additional sources of air pollution are introduced into the enclosure, no attached garage is included, which means no fumes from cars adjacent to the conditioned envelope. Instead, ample street parking is provided, as is the norm in this neighborhood. Accessibility is maintained by providing a ramp from the street to the house.

4.4 MOISTURE MANAGEMENT

See Section 0 -

Moisture in *Envelope Durability*.

In addition to well-controlled moisture in the building envelope, the house uses a cross-laminated timber (CLT) floor, which acts as a moisture mass similarly to how concrete or masonry can act as thermal mass. When the air is moist, the CLT absorbs some of the water, and it releases it back into the air when humidity is lower, thus acting as a buffer for indoor humidity.

4.5 Air Quality in a Tight House

Additionally, while most building envelope penetrations have been avoided in the Three Rivers House, a well-designed vented range hood is installed in the kitchen to remove cooking contaminants and grease. The range hood is wider than the width of the stove top and has variable speeds up to 300 cfm. This is discussed further in the section on *Space Conditioning*.

Cooling peak load was calculated to mandate 427 cfm, and 1 ton of cooling is generally designated for 400 cfm. Cooling capacity of the heat pump is 12.3 kBTU, fitting right in with the specified requirement. Shown below are the calculations used for sizing heating and cooling equipment, as well as sizing individual ducts. (See *Supplemental* for equations and calculations.)

	Heating (btu/hr)	**dT (F)**	**Cooling (btu/hr)**	**dT (F)**	**Req. Cfm heating**	**Req. Cfm cooling**
Great room	5674	33	4284	29	159	137
Bedroom (1st floor)	928	33	1272	29	26	41
Mechanical	773	33	1195	29	22	38
Bath (1st floor)	760	33	1103	29	21	35
Bedroom (2nd floor) + closet	1956	33	1440	29	55	46
Bath (2nd floor) + linen	539	33	1193	29	15	38
Master bath + linen	709	33	1270	29	20	41
Master bed + closet	2103	33	1604	29	59	51
	Total heating:		Total cooling:		Total	Total
	13442		**13361**		**377**	**427**

Table 9 - Load calculations by room

In terms of EPA Indoor airPLUS's focus on construction debris in mechanical ducting, quick, low-labor construction of this house will ensure less construction debris overall, contributing to cleaner ducts during installation. Additionally, construction mandates will be laid out to avoid contamination inside mechanical equipment. The filters are to be installed only after construction is complete.

4.6 References

Hopey, D. (2013, November 21). Report: Allegheny County in top 2 percent in U.S. for cancer risk from air pollution. Pittsburgh Post-Gazette. Retrieved March 22, 2015, from http://www.post-gazette.com/news/environment/2013/11/21/Report-Allegheny-County-in-top-2-percent-in-U-S-for-cancer-risk-from-air-pollution/stories/201311210326

Indoor airPLUS Program. EPA. (n.d.). Retrieved March 21, 2015, from http://www.epa.gov/indoorairplus/

Most Polluted Cities - State of the Air 2014. (2014). American Lung Association. Retrieved March 22, 2015, from http://www.stateoftheair.org/2014/city-rankings/most-polluted-cities.html

5 Space Conditioning

5.1 Approach

The approach to mechanical systems encompassed both comfort and energy savings. Comfort is evaluated in terms of thermal, acoustical, and visual sensation. The team also felt that it was imperative to be innovative in HVAC design in order to meet the goals of zero energy, prompting the team to move beyond even 2015 IECC or Energy Star requirements, toward an integrative-systems approach to space conditioning.

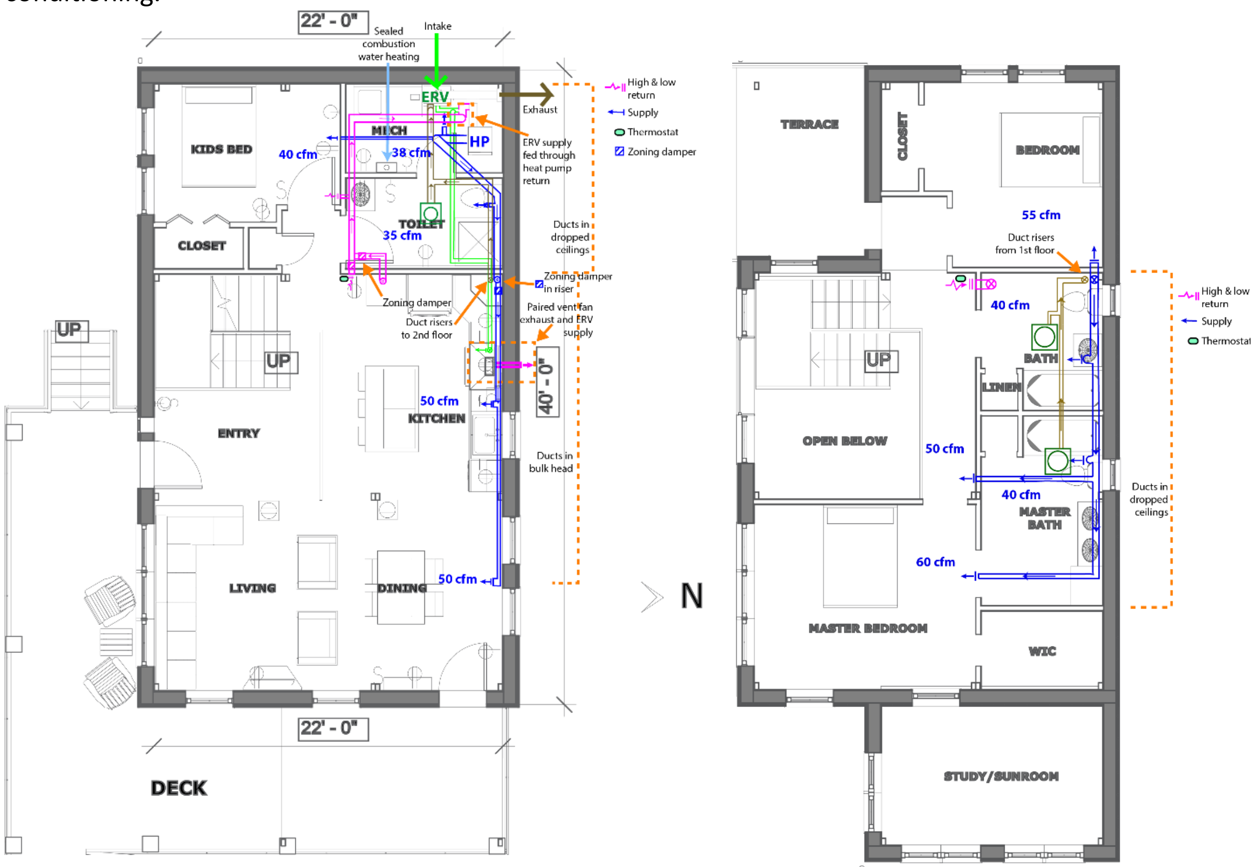


Figure 33 - Overview of mechanical plan

Although space conditioning using water can sometimes be more resource-efficient and boasts claims of higher comfort levels than do forced-air systems, radiant systems were avoided to achieve faster response times for heating and cooling and lower overall costs. It is also not practical to use radiant systems for cooling in residences because of condensation issues, so separate duct work would be required.

5.2 Geothermal Heat Pump

The Three Rivers team decided to use geothermal technology for several reasons. First, ground source heat pumps can be extremely energy-efficient when sized correctly and use "free energy" from the ground. Pittsburgh's ground temperature remains at 50°F just a few feet below the surface, while the air temperature fluctuates to extremes throughout the year. Exchanging heat with the ground provides this "free energy," which is supplemented by a heat pump to reach the desired supply air temperature. Because ground temperature is more favorable than ambient air temperature for the vast majority of the time, a ground-source heat pump is an efficient choice. Secondly, the site offers sufficient land area to install horizontal geothermal wells (3 50-foot lengths of coiled pipes), which are less expensive than vertical wells, as less drilling and labor are required. Although the first-cost of any geothermal system will be higher than standard space conditioning systems, savings over time can more than make up for the initial investment; not to mention that energy is saved from the start. Maintenance of heat pump systems is also minimal.

The ground source heat pump chosen for this house (see Table 9 and *Appendix*) is the Water Furnace 5 Series 012, which is preferred by, and whose performance has been evaluated by, the consulting HVAC specialists. The unit's capacities match those needed by the house during peak times, and its EER and COP far exceed those required by Energy Star for Climate Zone 5A.

	Cooling capacity (Btuh)	EER	Heating capacity (Btuh)	COP	Pump GPM	Ventilation fan min. efficiency (cfm/watt)
Energy Star for Homes		12		3.5		1.2
IECC 2015						1.4
Proposed design	12,300	15.7	14,800	5.1	4	4

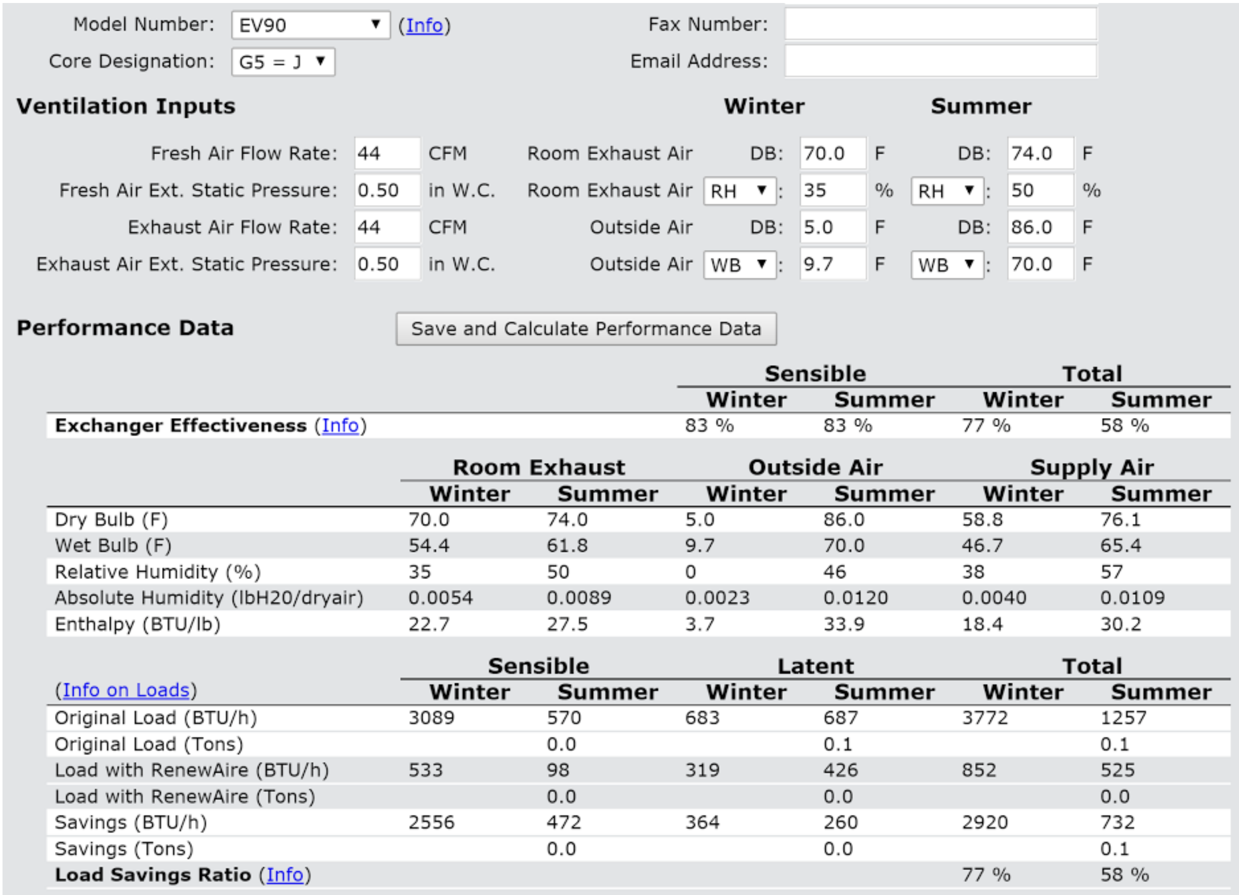
Table 10 - GSHP specifications

Although the heat pump is electric and therefore calls into question source energy use, its COP is much higher than 3.14, which more than makes up for the site-to-source energy conversion.

When sizing equipment based on heat gain and heat loss calculations, it is important for many reasons to size the system properly. One must not over-size the system, especially with regards to cooling equipment, for several reasons. For one, Energy Star prohibits oversizing equipment by more than 15%, but the real downfall of overestimating equipment needs is two-fold: discomfort and inefficiency. Chapter 17 of the 2013 ASHRAE Handbook Fundamentals explains that oversizing of cooling equipment leads to sporadic operation and discomfort resulting from improper delivery of air volume and temperature. As mentioned previously, sporadic operation also detracts from the system's ability to dehumidify. Heat gain and heat loss calculations for peak design conditions were done using Manual J. Sometimes backup systems are specified when using ground-source heat pumps, but if sized properly for peak heating needs, no backup is needed. In this case, heating capacity is sufficient for peak loads, so no separate backup systems are proposed. By this reasoning, equipment was sized to match the cooling and heating peak load demands without excess capacity. Thorough calculations promoted investment in proper high-efficiency equipment selection rather than investment in oversized systems.

5.3 ERV

An Energy Star energy-recovery ventilator was chosen, as specified previously, for its high efficiency in the applied location, as calculated below through RenewAire's ERV Calculator. An ERV was chosen over an HRV because it can help maintain slightly higher humidity levels during winters, which tend to be cold and dry in Pittsburgh.



Model Number: EV90 (Info) Fax Number:

Core Designation: G5 = J Email Address:

Ventilation Inputs

				Winter			Summer	
Fresh Air Flow Rate:	44	CFM	Room Exhaust Air DB:	70.0	F	DB:	74.0	F
Fresh Air Ext. Static Pressure:	0.50	in W.C.	Room Exhaust Air RH:	35	%	RH:	50	%
Exhaust Air Flow Rate:	44	CFM	Outside Air DB:	5.0	F	DB:	86.0	F
Exhaust Air Ext. Static Pressure:	0.50	in W.C.	Outside Air WB:	9.7	F	WB:	70.0	F

Performance Data Save and Calculate Performance Data

	Sensible		Total	
	Winter	Summer	Winter	Summer
Exchanger Effectiveness (Info)	83 %	83 %	77 %	58 %

	Room Exhaust		Outside Air		Supply Air	
	Winter	Summer	Winter	Summer	Winter	Summer
Dry Bulb (F)	70.0	74.0	5.0	86.0	58.8	76.1
Wet Bulb (F)	54.4	61.8	9.7	70.0	46.7	65.4
Relative Humidity (%)	35	50	0	46	38	57
Absolute Humidity (lbH20/dryair)	0.0054	0.0089	0.0023	0.0120	0.0040	0.0109
Enthalpy (BTU/lb)	22.7	27.5	3.7	33.9	18.4	30.2

	Sensible		Latent		Total	
(Info on Loads)	Winter	Summer	Winter	Summer	Winter	Summer
Original Load (BTU/h)	3089	570	683	687	3772	1257
Original Load (Tons)		0.0		0.1		0.1
Load with RenewAire (BTU/h)	533	98	319	426	852	525
Load with RenewAire (Tons)		0.0		0.0		0.0
Savings (BTU/h)	2556	472	364	260	2920	732
Savings (Tons)		0.0		0.0		0.1
Load Savings Ratio (Info)					77 %	58 %

Figure 34 - ERV performance data

5.4 Systems Integration

The ERV and heat pump are not treated as entirely separate entities. Through an integrated systems approach, the two are combined to minimize energy use and maximize comfort. Outside air enters the ERV, is filtered, and exchanges sensible and latent heat with exhaust air. Next, this supply air is put directly into the return air duct of the heat pump, which flows to the heat pump to be heated or cooled further. Then this air is ducted throughout the house and conditions the space while also providing fresh air. This integration means that, especially on very cold days, supply air is not supplied directly into living spaces and will not detract from occupant comfort.

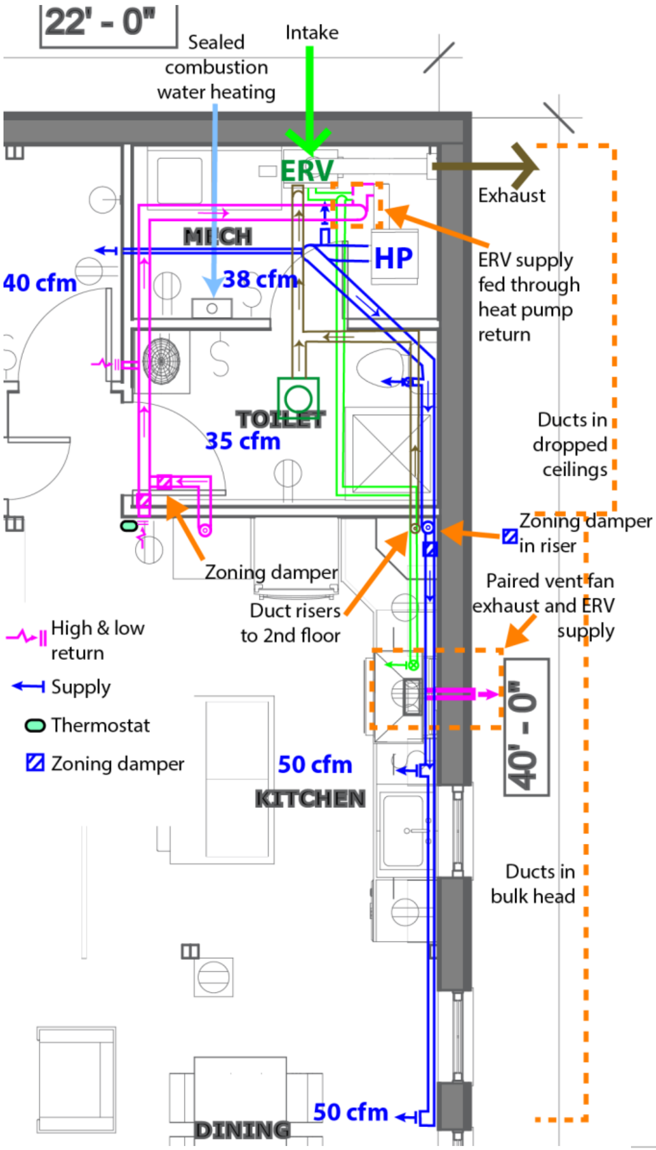


Figure 35 - Second floor mechanical plan

As shown in Figure 33, the house is designed to require only a very simple mechanical system. Ducts (sized using Carrier's Air Duct Design chart) span the length of the house, as shown in Figure 36 and Figure 35, but are able to reach each room with little duct work, thanks in part to an open first floor plan. Still, sufficient air mixing occurs by locating supply air throughout the length of the house and providing return air away from the supply.

Ducts are all located within the thermal envelope, as per Zero Energy Ready Home specifications, and are insulated to prevent condensation and inefficient delivery. During construction, it is to be put in the construction contract that duct leakage adhere to IECC 2015 requirements and Energy Star requirements for a rough-in test and postconstruction test. They must also be flushed out for 48 hours prior to occupancy, as suggested in LEED for Homes.

Return air is taken in through both high and low return grilles because during the summer, heat will need to be returned up high, and during winter, cold air should be returned lower down. A return is provided near the stairs on the second floor to pull air back into ducts before it falls.

Air is exhausted through the bathroom through variable-speed Panasonic WhisperGreen ventilation fans, which, combined with the return air, is balanced with the supply air. The vent fans also have a delay timer to continue to evacuate moisture and odor for a short time after the occupant leaves the restroom.

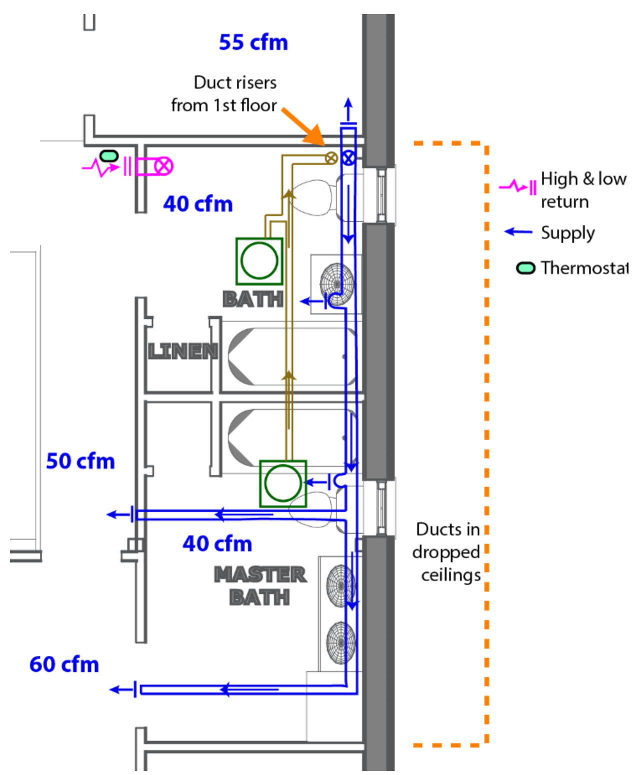


Figure 36 - First floor mechanical plan

For make-up air to the kitchen, air is supplied from the ERV through a duct in the range hood. This method has been applied for commercial purposes to maintain comfort for chefs working in front of stoves. This technique of supplying make-up air from the ERV instead of directly venting from the outside also prevents the house from becoming depressurized as a whole by short-circuiting the system. Because make-up air is supplied close to the exhaust air in the kitchen, this air will mix only with the air in the immediate area and then be taken out as exhaust air containing cooking contaminants. This system maintains equal pressure and prevents infiltration resulting from depressurization.

5.5 Controls and Zoning

The heat pump is controlled by two separate wireless Wiser thermostats, which are compatible with geothermal heat pumps and programmable (meeting Zero Energy Ready Home guidelines), and they offer remote control of the HVAC system, lighting, and other appliances (discussed further in *Domestic Hot Water, Lighting, and Appliances*). The occupant can shut down systems any time whenever they are not needed so that forgetting to turn the heat down is no longer a major mistake. The Wiser thermostat is easy to use and operates on 4-event/day, 7-day schedules so that again, the efficacy of the net-zero design does not rely on perfect occupant behavior.

The upper and lower floor are zoned separately from one another through zone dampers, as illustrated above, because different conditioning strategies may be desired on each floor, and heat may rise and gather at the second floor. Separate zoning of each floor leads to higher comfort levels and lower energy use. While not included in the conditioned envelope, the sun space cantilever on the second floor is intended to be its own zone and is fully insulated on all faces. When weather permits, the room can be used as a study or retreat, and the door can be opened to this area to transfer heat gained in this east-facing room in the morning to supplement the rest of the house with heat from solar gains.

5.6 Acoustics and Visual Considerations

Because forced air systems can cause noise if ducts are sized too small, ducts were sized with the equal friction method, where supply ducts were sized for 0.1 w.g. per 100 ft maximum, and return ducts were sized for 0.08 w.g. per 100 ft maximum. Bathroom exhaust duct sizing and space conditioning duct sizing in this manner ensures minimal added noise for heating, cooling, and ventilation.

The majority of ducting and plumbing is routed through dropped ceilings in selected rooms and a bulkhead above the kitchen cabinetry, which serves the purpose of avoiding visual exposure of the ducts, as well as preventing the need for dusting. Dropped ceilings are employed in the mechanical room and all of the bathrooms.

5.7 Maintenance

Occupants should follow the manufacturer guidelines for operation and maintenance for the RenewAire GR90 ERV and filter, Panasonic WhisperGreen vent fans, and WaterFurnace 5 series and filter. A pre-heating-season check for the heat pump should be performed. Additionally, check external pipes and fittings.

5.8 References

2013 ASHRAE Handbook -- Fundamentals. (2013).

Holladay, M. (2014, April 18). All About Radiant Floors. Green Building Advisor. Retrieved March 22, 2015, from http://greenbuildingadvisor.com/blogs/dept/musings/all-about-radiant-floors

6 ENERGY ANALYSIS

Two methods of computational energy analysis were used in the design of this home. Firstly, EneryPlus was used to determine best practices for this particular home design according to TMY3 weather data for Pittsburgh, PA. Secondly, REM/Rate was used to project total home energy use and the percent reduction in energy use from a home built to the standards of IECC 2006.

6.1 ENERGYPLUS PARAMETRICS

Our team chose to use energy modeling as an early-stage method for design decision support in addition to the REM/Rate model to confirm that we had met our goal of net zero. 95 different parametric simulations were run in EnergyPlus to show how different envelope design alternatives would affect both energy use and occupant comfort as defined by ASHRAE 55-2010. Many of the simulations were determined to show changes in energy use and comfort that were not significant enough to be valuable as design choices. Of the 95 initial simulations, 45 of are shown here, and were used as design decision support to determine envelope construction values and methods.

6.1.1 Base Design Case and Parametric Test Values

In order to have a basis for comparison, a base design case energy model was constructed based on inputs from various standardized energy modeling methods. Parametric simulations were then run, changing one value at a time in order to show the individual impact of each envelope element. These values can be seen below in Table 11.

		Base Design Case Input Value	Reference	Parametric Test Values
Roof Insulation		R-49	IECC 2015	R-55, R-60, R-65, R-70
Wall Insulation		R-20	IECC 2015	R-25, R-30, R-35, R-40, R-45
Floor Insulation		R-30	IECC 2015	R-35, R-40, R-45
Glazing U-factor		0.32	IECC 2015	U-0.2, U-0.125
Window Wall Ratio	**South**	28%	ASHRAE 90.1 2010	22%, 15%, 7%, 0%
	East	28%	ASHRAE 90.1 2010	22%, 15%, 7%, 0%
	North	28%	ASHRAE 90.1 2010	22%, 15%, 7%, 0%
	West	28%	ASHRAE 90.1 2010	22%, 15%, 7%, 0%
SHGC	**South**	0.4	ASHRAE 90.1 2010	0.6, 0.5, 0.3, 0.2
	East	0.4	ASHRAE 90.1 2010	0.6, 0.5, 0.3, 0.2
	North	0.4	ASHRAE 90.1 2010	0.6, 0.5, 0.3, 0.2
	West	0.4	ASHRAE 90.1 2010	0.6, 0.5, 0.3, 0.2
External Shading Depth (meters)	**South Solid Shading**	No shading		0.25, 0.5, 0.75, 1
	South Trellis Shading	No shading		0.3, 0.6, 0.9, 1.2

Table 11 – EnergyPlus parametric window inputs

6.1.2 Insulation

The overall effects of adding insulation were unsurprising. Additional insulation will always save some energy. With a goal of super-insulation already set, the question becomes "where is the most sensible place to put a new layer of insulation." Beginning with an energy model based on IECC 2015 guidelines for CZ5 insulation levels (Wall R-20, Roof R-49, Floor R-30), we then created a series of parametric simulations which incrementally increased the insulation of each of these layers by one inch of rigid XPS insulation (~R-5/inch). Roof, wall, and floor insulation layers were tested independently of one another, so as to test only one parameter at a time.

6.1.2.1 Bang for Buck - Where to Put More Insulation

The results of these simulations were normalized for the square footage of each material, giving us the ability to compare the effectiveness of the same 1'x1'x1" square of continuous insulation when placed on the roof, the wall, or the floor. The results are shown in Figure 37. The results shown are marginal, so that the decreasing effectiveness of each successive layer of insulation can be seen.

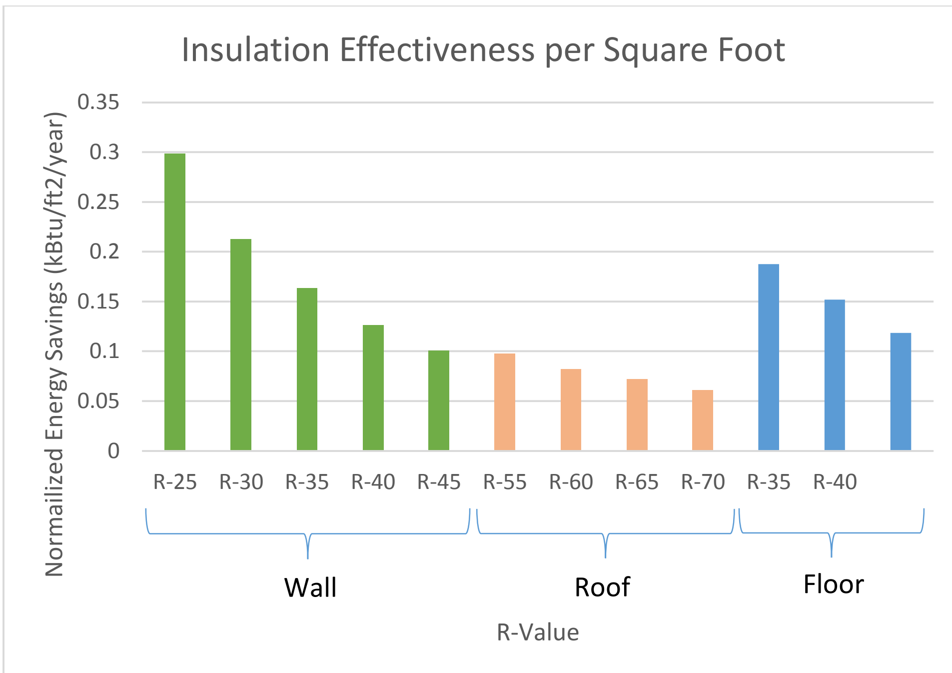


Figure 37 - Marginal energy savings per square foot of insulation

This graph shows us that adding a board foot of XPS insulation to code-insulated wall will reduce energy consumption by ~0.3 kBtu/year. Adding another square over top will decrease energy use by ~0.2 kBtu/year, and so on. This shows that adding a layer of insulation to the roof is the least effective option. Only after increasing the walls to R-30 does it make sense to think about adding to the floor. However, given that the walls take up a great deal more square footage than the floor, Figure 37 demonstrates that investment in wall insulation is still more effective than floor insulation until R-40 is reached. A decision was therefor made to invest primarily in added wall insulation.

Our initial choice was to insulate walls to R-48 and floors to R-30. When modeled in REM/Rate, this design yielded a HERS score of 37. However, after viewing Figure 38 we chose instead to reduce wall R-value to an R-37 Murus SIP. We also increased floor R-value to R-41 PermaTherm steel SIP, partly to deal with structural floor load issues. The REM/Rate analysis was performed again, and a HERS rating of 35 was achieved, with less overall insulation than before, and therefore lower cost.

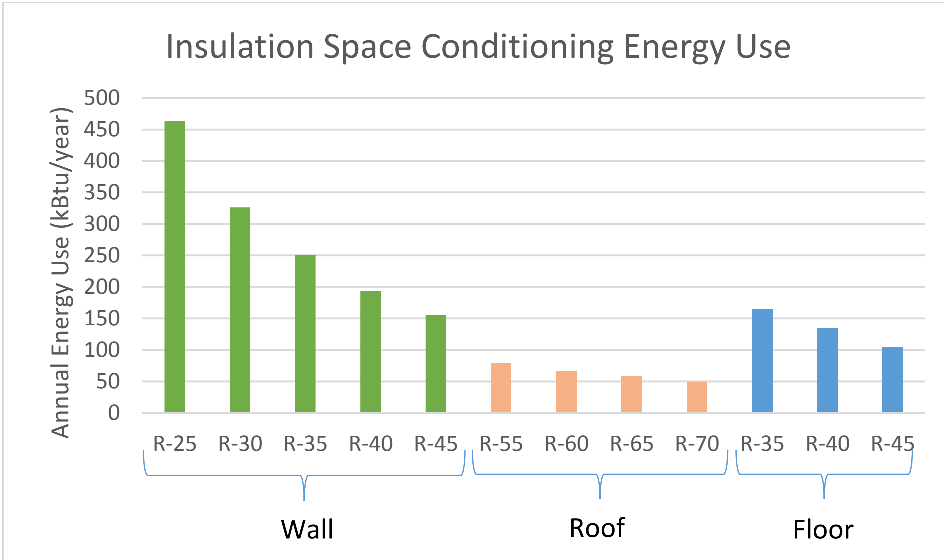


Figure 38 - Marginal energy savings of insulation

6.1.3 Glazing

Several parametrics were run to find optimal window characteristics for the home. These included U-factor, window-wall-ratio (WWR), solar heat gain coefficient (SHGC), and two types of external shading. The following window specifications were used in this design.

Alpen 525 Series dual pane, 1 low SHGC film			
	East/West Single-Hung	North/South Picture	North/South Single-hung
U-value	0.21	0.18	0.22
SHGC	0.24	0.47	0.39
VT	0.44	0.62	0.51
Gas Fill	Krypton	Argon	Krypton

Table 12 - Window Specifications

6.1.3.1 U-Factor

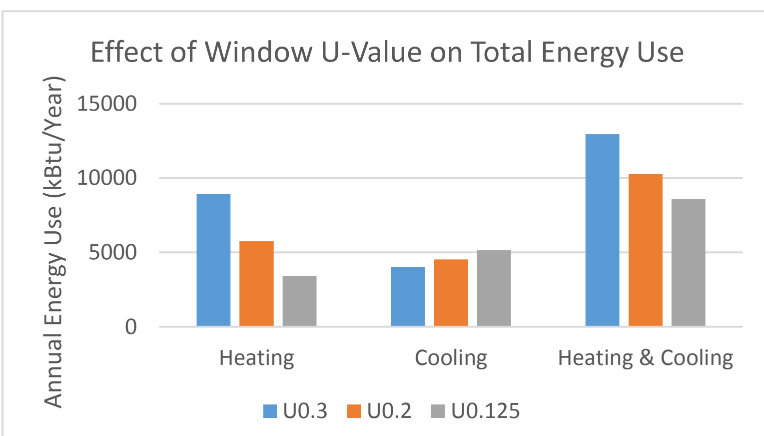


Figure 39 demonstrates the effectiveness of super-insulated windows. Significant savings are visible with both U-0.2 windows and U-0.125 windows. While U-0.125 windows still show energy savings, due to financial constraints, windows were chosen in the range of U-0.18 and U-0.22.

Figure 39 - Insulated glazing energy effectiveness

6.1.3.2 Window-Wall Ratio

Window-to-wall ratio (WWR) was examined for each orientation. Results of increased or decreased WWR vary broadly by orientation. Because of the role that windows play in determining the mean radiant temperature and operative temperature of the space, hours of time not comfortable based on the ASHRAE 55 comfort zone were overlapped with energy savings in order to provide for easier decision support for choosing levels of glazing in each orientation. Comfort is shown in orange and energy savings is shown in blue. For the purposes of these graphs, higher values are always better for both categories. Green arrows show the value that was ultimately chosen for the design. While other constraints, such as interior layout and need for egress windows also played a role in window placement, this analysis was used as a primary determining factor.

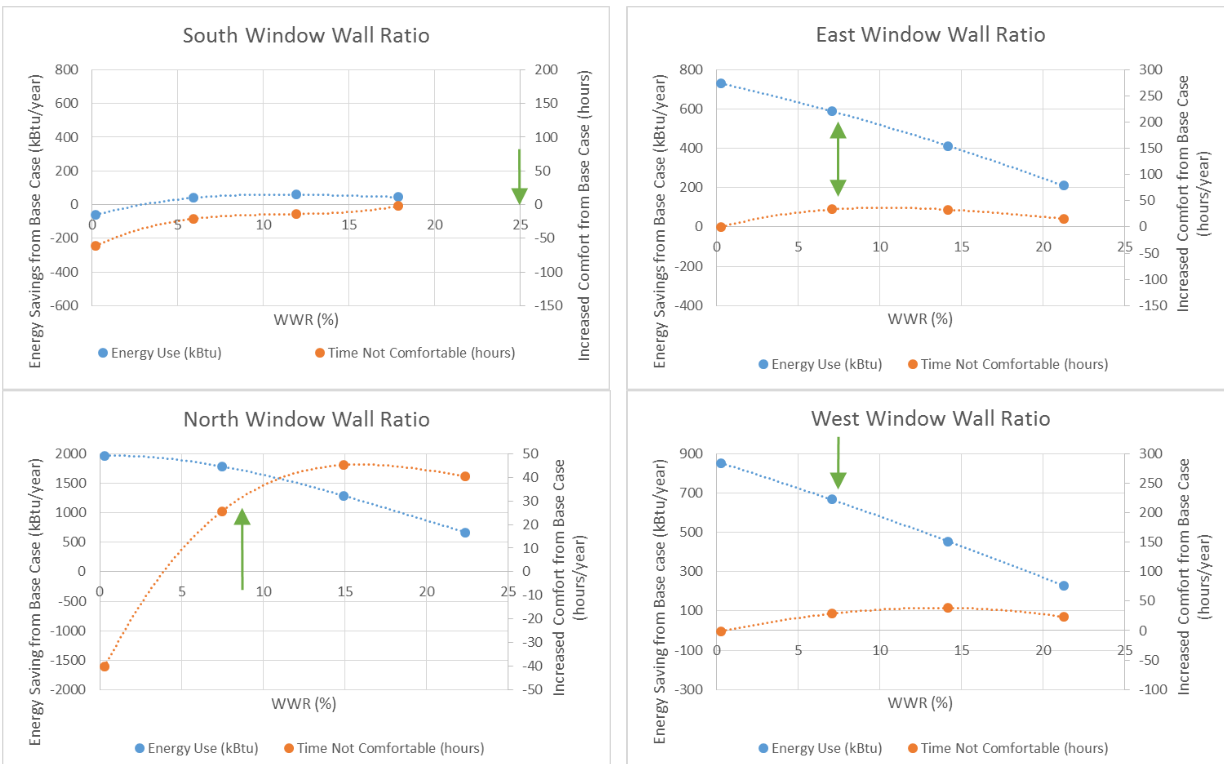


Figure 40 - Comfort by wall window ratio

6.1.3.3 Solar Heat Gain Coefficient

Solar heat gain coefficient was also simulated separately for each wall orientation. Strong inverse correlations between comfort and energy use are visible in each of these simulations, most dramatically so in the south and east orientations. A higher SHGC was ultimately chosen for the south wall in anticipation of the effects of external shading on the south side. Because SHGC on the north wall has little effect on comfort, for the sake of simplicity, the north and south walls both use the same type of window, and likewise the east and west walls.

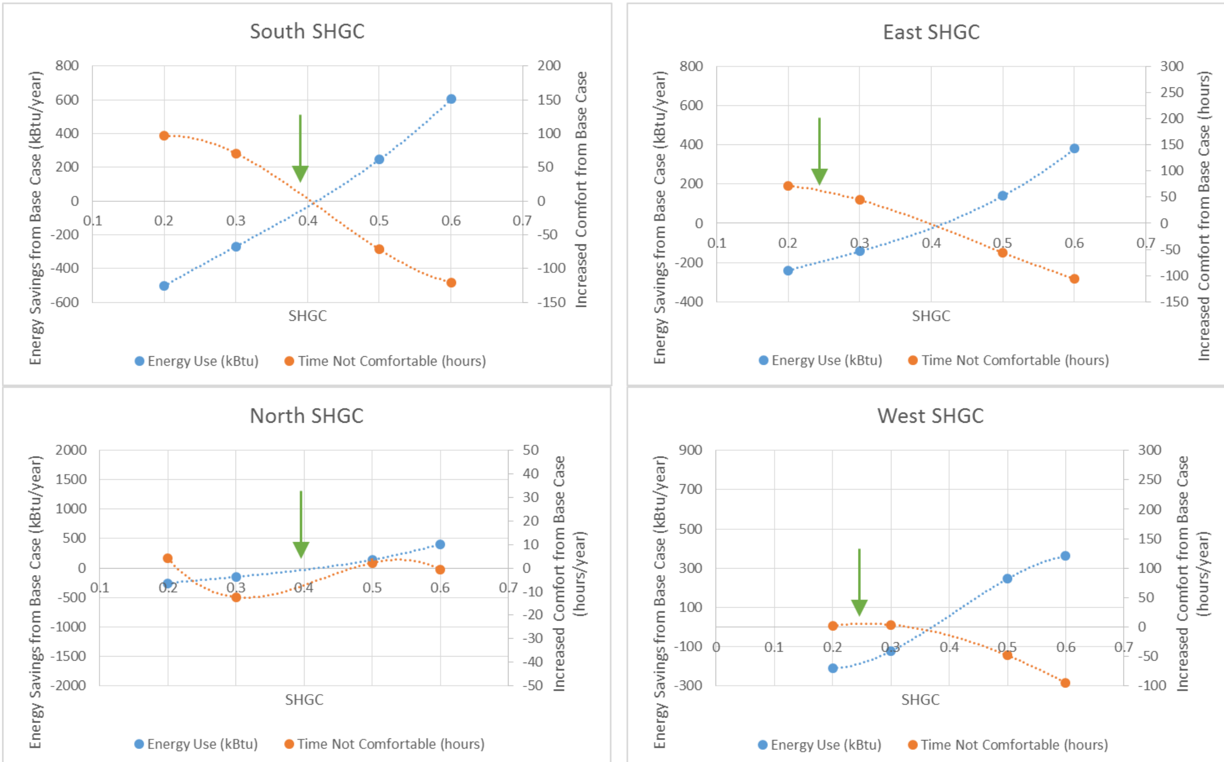


Figure 41 - SHGC by orientation

6.1.4 External Shading

Two different types of external shading were simulated for this analysis, a solid overhang and a slatted shade with fins at 30° to allow direct sunlight to penetrate the space in winter but not in summer. Both of these shading types were varied by depth of projection from the wall. Comfort shows a consistent upward trend whenever shading is increased. When solid shading is used, energy savings consistently decline (energy use increases) as depth increases. In order to avoid this inverse correlation translucent shading was modelled, and it was found that while this type of shading did yield significant comfort increases, the energy use penalty was relatively modest or non-existent. We therefor chose to include this strategy in our final design for the first floor southern windows, while a simple solid overhang was used for the second floor southern windows. Shading on the east and west walls showed little impact on either comfort or energy use, likely due to the low angle of the sun at these orientations. This model did not take shading from nearby trees into account. No nearby buildings shade the house.

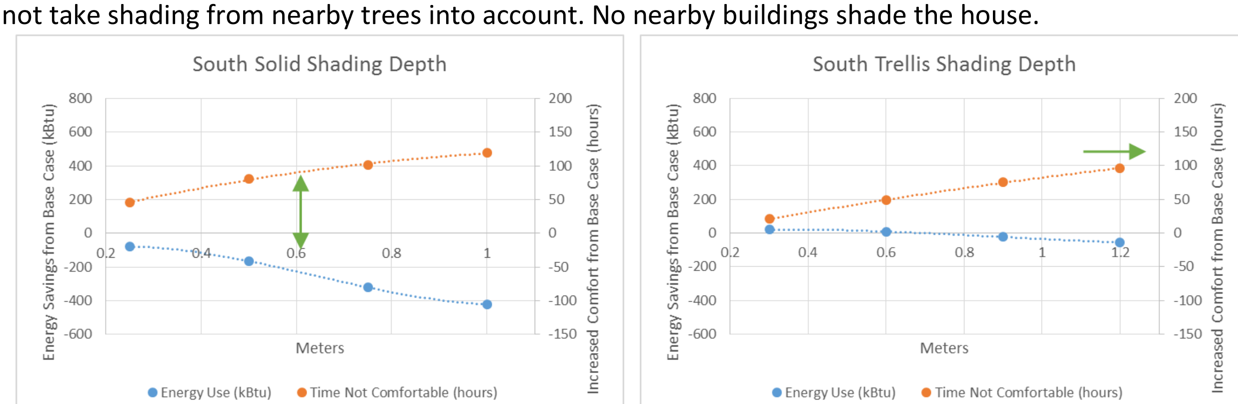


Figure 42 - External window shading

6.2 REM/Rate Energy Analysis

Inputs into REM/Rate were filled according to actual product data and performance whenever possible. Energy use predictions using these inputs are considered safe estimates for several reasons:

A. Infiltration rate was modeled as slightly higher than may be expected from the tight building design.
B. Lighting loads, because of the minimalist lighting design, are likely lower than REM/Rate's assumptions.
C. Hot water use might be slightly overestimated in REM/Rate because of not accounting for:
   a. The implemented water-efficient appliances and faucets, as well as efficient plumbing design.
   b. The hot-water set-point being 120°F instead of 140 F because of the dishwasher selection (discussed in *Domestic Hot Water, Lighting, and Appliances*)
D. Load and cost estimations for ventilation are likely overestimated, as the ERV is required to be on for 24 hours/day as per code, but given that it can also be controlled by a CO2 sensor (an option for RenewAire products where the CO2 sensor is located at the ERV itself), actual operation time will likely be far less than the 24 hours input into REM/Rate.

Assumptions:

A. Interior shading will be drawn on the east- and west-facing windows during the summer to prevent excess solar heat gain and discomfort.
B. Infiltration = 1.5 ACH50
C. Exhaust fans run at 45 cfm consistently.
D. Heating and cooling design temperatures were 99% worst-case: 8F design heating and 86F design cooling
E. Heating and cooling set-points were 68F for heating and 78F for cooling (although, for equipment sizing, peak cooling loads were calculated using 74F indoor design temperature, and peak heating loads were calculated using 72F indoor design temperature)

For the Zero-Energy Ready home without PV panels, annual loads are predicted as shown in Figure 43:

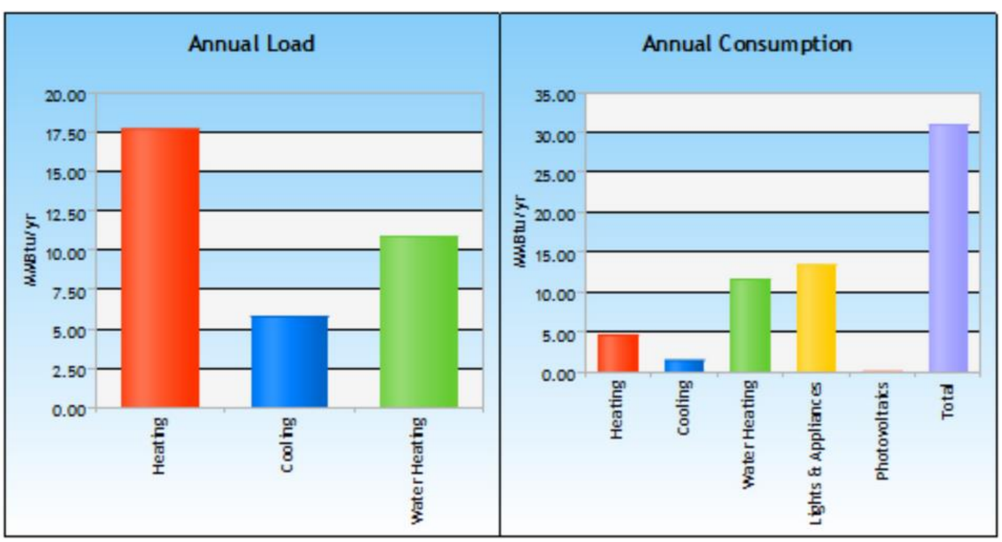


Figure 43 - Predicted annual load and energy consumption for Zero Energy Ready home without PV

Pittsburgh is a heating-dominated climate, so it makes sense that heating makes up most of the annual load in terms of space conditioning. It is important to note, however, that lighting and appliances make up a much larger proportion of annual energy use than is the case for standard homes, which is a sign that the building envelope is successfully designed.

As compared to the REM/Rate reference home, this home uses 85% less energy for heating, 54% less energy for cooling, 36% less energy for hot water, 38% less energy for lighting and appliances, for an overall estimate of 60% less energy use and a HERS score of 35. Estimated annual energy cost is $639 without PV panels.

It is interesting to note that when the building is oriented to the “worst case” orientation, according to REM/Rate, peak cooling loads increase by 1.3 kBTU/hr, and the HERS score is changed to 40. This demonstrates that the house was designed well within the context of its environment.

In terms of choosing renewable energy sources (in addition to the GSHP) to reach net-zero energy, although Pittsburgh is very cloudy, photovoltaics are still relatively common, and because cost of PV has decreased dramatically in recent years, an all-PV renewable system was the most logical choice. Local home builders suggested solar PV as the most promising option for energy production. While solar hot water could have directly reduced hot water energy demands, its exact energy contribution is difficult to track, and use of PV makes up more easily for source energy use. Addition of PV panels in Pennsylvania provides the opportunity for net metering, which means that, over the course of the year, energy produced and sent back to the grid will be credited at the same rate charged for electricity use. Pennsylvania is known to have one of the best net metering policies, considering array capacity and level of participation. Therefore, bills could be $0, or even net negative, if enough PV panels were installed. However, the aim of this project was to achieve net-zero source energy, not $0 utility bills, so the calculations below demonstrate PV sizing in order to achieve this goal.

6.3 Net Zero Balance

Pittsburgh													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Sun hours	1.7	2.5	3.5	4.6	5.5	6.1	5.9	5.2	4.2	3	1.8	1.4	
Days in month	31	28	31	30	31	30	31	31	30	31	30	31	
	52.7	70	108.5	138	170.5	183	182.9	161.2	126	93	54	43.4	**3.79**

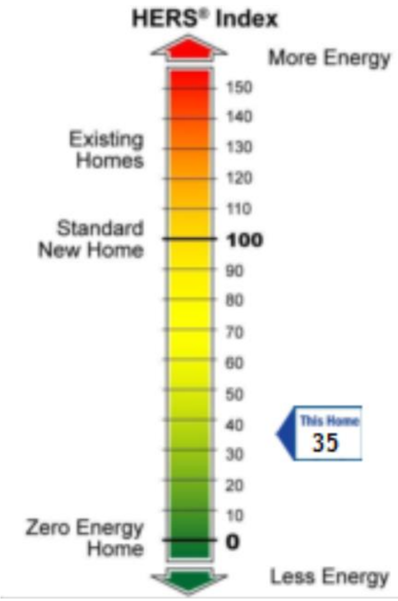


Figure 44 - HERS score

Calculating array size needed for net-zero source energy
Equation: Energy use (kWh/yr) / 365 / (sun hours/day) / .75 derate factor
7.01

Calculating kWh/yr generated by system		
Array size	6	7
kWh produced	6224.4	7261.8

Table 13 - PV panel sizing

It was estimated that, to achieve truly net-zero source energy, the house would need a 7-kW solar panel array. Although the house is energy-efficient, average sun hours per day in Pittsburgh, based on NREL's solar radiation data, is 3.8, which is low compared to sun-rich climates like the Southwestern US, which can receive between 6 to 8 sun hours per day on average. Still, the team felt it was appropriate to spec the house outfitted with a full 7-kW array on the roof because this would likely achieve the goal of net-zero source energy and would have the potential to pay back over time.

Annual Zero Energy Balance					
	Site Energy		**Source Energy**		**Carbon Emissions (lb) (based on source energy)**
Natural gas	**kBTUs**	**kWh**	**kBTUs**	**kWh**	
	11,600	3,399	12,180	3,569	5464
Electricity		**kWh**			
	21,000	6,153	65,940	19,320	29580
Total Energy Consumed/Emissions Generated	32600	**9,552**	78,120	**22,889**	35043
Renewable Energy	**kBTUs**	**kWh**	**kBTUs**	**kWh**	
Produced on site (7kW array)	24782	7,261	77,814	22,800	34906
Imported or derived from on-site processes		0			
Purchased		0			
Total Renewable Energy	24782	**7,261**	77,814	**22,800**	34906
Net Balance in kWh (Renewable Energy -Total Energy)		**-2,291**		**-90**	
Site EUI (kBTU/ft2/yr) [US Residential Avg EUI: 44 kBTU/ft2]	**19.88**	**Source EUI (kBTU/ft2/yr)**	**47.63**	**CO2 emissions EUI (Ramseur, 2014)**	**21.37**
Site EUI with renewables	**4.77**	**Source EUI with renewables**	**0.19**		**0.08**

Figure 45 - Annual zero energy balance sheet

Additional considerations for solar PV are the inverter type, the type of array, and its location. Because the house is oriented toward the top of the hill at the north side of the lot without obstructions, excess shading is not anticipated. The roof is inclined toward the south, so solar panels can face south and can be tilted at the optimum angle of 31° when raised slightly off the roof, which also allows them to be cleaned easily by rainfall and permits air to flow beneath the panels to cool them (Solmetric).

Monocrystalline panels are chosen, as they are the most efficient and take up the least amount of space. Integrated PV was compared but not chosen because of high expenses and lower performance. Similarly, sun-tracking PV allows for optimal power production, but moving parts were determined to be too much of a liability if they were to break. As mentioned before, shading is expected to be minimal on site, so string-level inverters are specified to balance responsiveness and cost-effectiveness. Supplemental equipment needed includes the circuit breaker panel and the electrical meter.

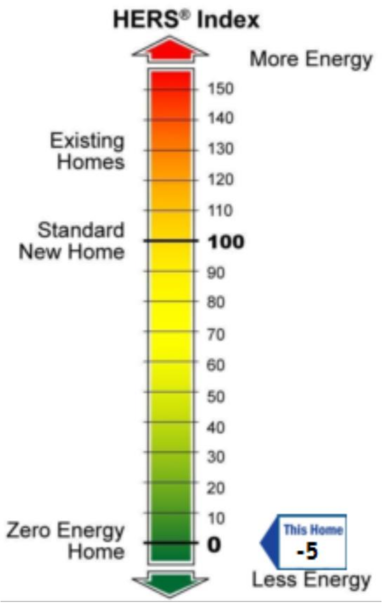


Figure 47 - HERS score with PV

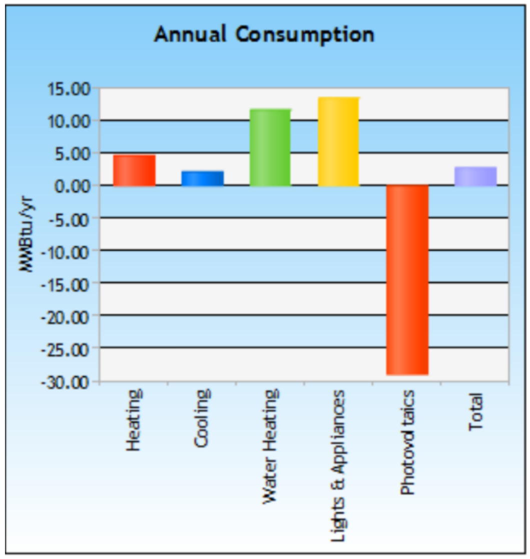


Figure 46 - Annual energy consumption with PV

With a 7-kW array, the HERS score becomes -5, and calculations show that net source energy becomes effectively zero. CO2 emissions also net out to zero through this method.

We also find that the estimated annual energy bills not only net to $0, but the occupant actually achieves a net income of $18/yr from the 7-kW array.

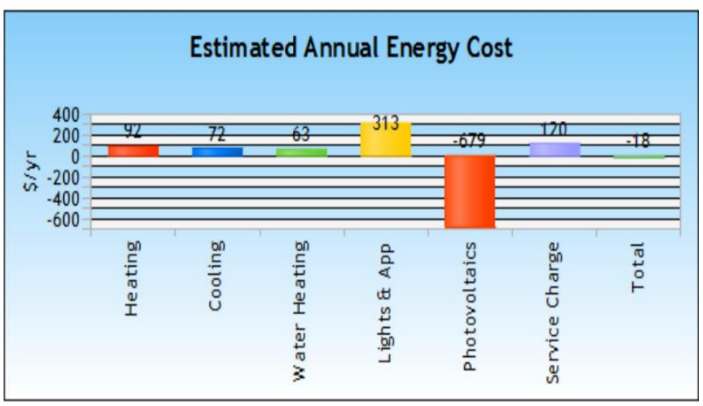


Figure 48 - Annual energy cost with PV

6.3.1 Maintenance and Lifetime

PV panels come with a 25-year warranty and are expected to last about 30 years. Inverters come with a warranty of 10 to 12 years. Replacement after this time may be required. Maintenance is minimal, especially with frequent rain at the specified tilt; however, in infrequent heavy snow events, panels may be cleaned. Inverter maintenance includes annual inverter inspections.

6.4 References

NREL. (n.d.). Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors. Retrieved March 20, 2015, from http://rredc.nrel.gov/solar/pubs/redbook/

Solmetric, Annual Insolation as a Function of Panel Orientation. www1.solmetric.com/cgi/insolation_lookup/match.cgi?state=PA&city=PITTSBURGH%20INTERNATION

State CO2 Emission Rate Goals in EPA's Proposed Rule for Existing Power Plants, http://fas.org/sgp/crs/misc/R43652.pdf

7 FINANCIAL ANALYSIS

7.1 ASSUMPTIONS

1. The costs for most components has been sourced from RS Means 2014 editions – they are assumed to reflect accurate market costs
2. The national average costs obtained from RS means is converted to Pittsburgh costs by using a city cost index parameter listed in the reference section of RS means – these costs are assumed to reflect actual city costs.
3. The soft costs are estimated based on a percentage value of total construction cost obtained from the national construction cost survey data generated by the National Association of Homebuilders.
4. The principle for the loan is assumed to be 90% of the sale price of the house, so the down-payment for the loan is 10% of the sales price.
5. The property taxes are estimated based on the local tax rates assuming the property value to be $200,000
6. For comparing the cost between a conventional home and 3 Rivers House, a sensitivity analysis of the inflation rates is done using 3 values for inflation which are based on historic low, high and average rate of inflation of USA from year 2001-14.
7. The building energy management system service bill of $5.99 per month is added to the annual utility bills.

7.2 CONSTRUCTION COST ESTIMATE

In this section the construction costs of 3 Rivers House is broken down into different components to give an in-depth understanding into the selection of high performance components, which not only make 3 Rivers House extremely energy efficient but also give it a unique characteristic designed to cater to clients from all demographic segments by virtue of being cost efficient, aesthetically pleasing, easy to maintain and by essentially being a smart home equipped with the latest technology like building automation systems, smart thermostats, ground source heat pumps and active solar power.

The pie chart below summarizes the construction cost breakdown. As is observable at first glance from the pie chart, that we have spent a significant amount of money in the prefabricated walls, flooring and Roof, by using high quality materials such as Cross Laminated Timber which was used in the floors, a thick layer of rigid expanded polystyrene insulation was used in the walls, floors and the roof, the use of commercial grade vapor barriers etc. Considerable financial resources were also spent in high performance windows and doors. This investment is in line with our strategy to minimize consumption by passive techniques which ensures that the outer façade was durable, reliable and extremely high performing. The construction cost target for our property was set to be around $ 150. The actual construction cost obtained after taking into account 5.6% of the cost to go towards site-work like obtaining building permits, inspection and other soft costs and another 3.1% contingency cost, is $140 which is well within the target thereby providing us the opportunity to be able to market this product to a wide variety of buyers.

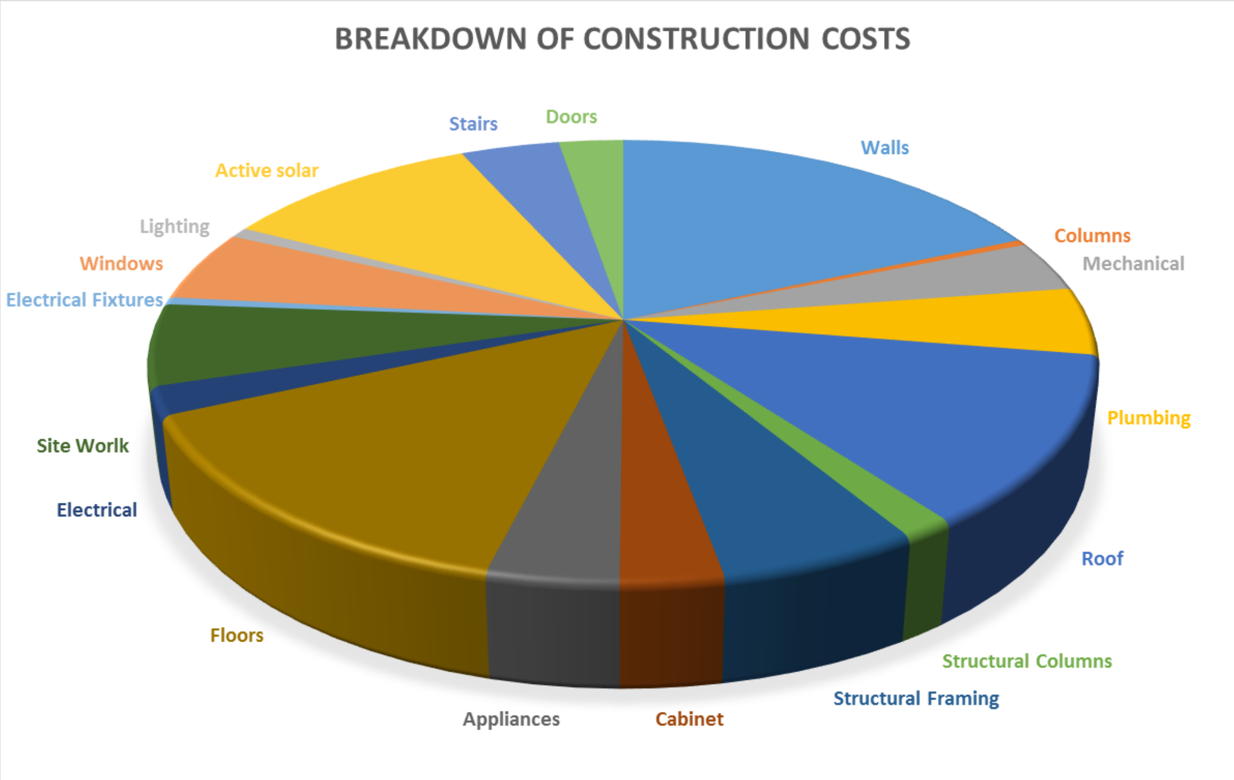


Figure 49 - Construction cost breakdown

7.3 DETAILED COST BREAKDOWN BY COMPONENTS:

7.3.1 1. Structural Columns

Structural Column					
Component	RS Means Code	Material	Labor	Total	Total O&P
Pipe-Column	05 12 23.17.1700	$ 1,834	$ 529	$ 2,644	$ 3,229
Brick Column	04 21 13.18.0800	$ 227	$ 538	$ 765	$ 1,075
Reduction in labor cost due to prefabrication			$ 266.56		
Wastage cost		$ 82.44			
Total cost		$ 2,143.39	$ 799.69	$ 2,943.08	$ 3,716.14
			Total		$ 3,716.1

Table 14 - Structural column estimated costs

7.3.2 2. Structural Framing

Structural Framing					
Component	RS Means Code	Material	Labor	Total	Total O&P
Glue Laminated Beams - western species	06 18 13.20.6500	$ 376.5	$ 38.0	$ 414.5	$ 472.2
Shop Fabricated structural wood	06 17 33.10.1500	$ 7,605.0	$ 1,212.1	$ 8,817.1	$ 11,730.0
Reduction in labor cost due to prefabrication			$ 312.53		
Wastage cost		$ 319.26			
Total cost		$ 8,300.68	$ 937.59	$ 9,238.3	$12,286.91
			Total		$ 12,286.9

Table 15 - Structural framing estimated costs

7.3.3 3. Walls

Walls					
Component	RS Means Code	Material	Labor	Total	Total O&P
Hardie Lap Siding	07 46 29.2500	$ 1,896.66	$ 2,521.17	$ 4,417.83	$ 5,967.54
Rigid Insulation - Expanded polystyrene 12"	07 21 13.10.2140	$ 5,691.60	$ 3,952.50	$ 9,644.10	$12,410.85
Plasterboard	09 29 10.30.0150	$ 808.48	$ 964.96	$ 1,773.44	$ 2,373.28
Tyvek					$ 2,562.74
White pine, rough sawn, natural siding	07 46 23.5400	$ 692.04	$ 350.76	$ 1,042.80	$ 1,305.08
Wood - Sheathing - Chipboard	06 16 36.10.4610	$ 3,929.50	$ 4,793.99	$ 8,723.49	$11,709.91
Wood - Stud Layer	09 21 16.33.7200	$ 2,183.80	$ 3,806.40	$ 5,990.20	$ 7,564.00
Reduction in labor cost due to prefabrication			$ 4,097.45		
Wastage cost		$ 608.08			
Total cost		$15,810.16	$12,292.34	$ 28,102.5	$39,045.32

Table 16 - Wall estimated costs

7.3.4 4. Floors

Floors					
Component	RS Means Code	Material	Labor	Total	Total O&P
Rigid Insulation - Expanded polystyrene 12"	07 21 13.10.2120	$ 2,637.60	$ 2,747.50	$ 5,385.10	$ 7,198.45
Metal - Steel flashing	07 65 10.10.9328	$ 1,351.02	$ 3,955.16	$ 5,306.18	$ 8,223.60
Plasterboard	09 29 10.30.0150	$ 1,351.02	$ 3,955.16	$ 5,306.18	$ 8,223.60
Structure - Timber Joist/Rafter Layer	06 17 33.10.1500	$ 1,645.47	$ 262.26	$ 1,907.73	$ 2,220.75
Wood - Deck Floor	06 16 23.10.0100	$ 401.82	$ 293.22	$ 695.04	$ 901.38
Floor: Cross Laminated Timber Interior Floor					$11,443.20
Wood - Flooring	06 16 23.10.0011	$ 587.40	$ 479.71	$ 1,067.11	$ 1,370.60
Wood - Sheathing - Chipboard	06 16 36.10.4610	$ 483.00	$ 589.26	$ 1,072.26	$ 1,439.34
Reduction in labor cost due to prefabrication			$ 2,092.88		
Wastage cost		$ 285.74			
Total cost		$ 7,429.25	$ 6,278.63	$ 13,707.9	$29,471.07

Table 17 - Floor estimated costs

7.3.5 5. Roof

Roof					
Component	RS Means Code	Material	Labor	Total	Total O&P
Rigid Insulation - Expanded polystyrene 12"	07 21 13.10.2140	$ 4,167.4	$ 2,894.0	$ 7,061.4	$ 9,087.2
Aluminum Flashing 0.05" thick	07 65 10.10.0300	$ 7,032.4	$ 6,251.0	$ 13,283.5	$ 18,376.9
Gypsum Board 0.5" thick	09 29 10.30.0300	$ 434.10	$ 535.39	$ 969.49	$ 1,302.30
Reduction in labor cost due to prefabrication			$2,420.11		
Wastage cost		$ 465.36			
Total cost		$12,099.24	$7,260.32	$19,359.56	$26,128.17
			Total		$ 26,128.2

Table 18 - Roof estimated costs

7.3.6 6. Stairs

Stairs					
Component	RS Means Code	Material	Labor	Total	Total O&P
Concrete Stairs	03 30 53.40.7050	$ 814.20	$1,076.16	$ 1,906.88	$ 2,560.60
Porch Stairs (2'X4')	06 11 10.28.0930	$ 860.31	$1,244.25	$ 2,104.56	$ 2,867.70
Prefabricated wood stairs	06 43 13.20.1100	$ 1,041.25	$ 263.20	$ 1,096.20	$ 1,323.00
Prefabricated handrail with balusters	06 43 13.20.1550	$ 1,332.00	$ 220.50	$ 1,552.50	$ 1,800.00
			Total		$ 8,551.3

Table 19 - Stairs estimated costs

7.3.7 7. Windows

Window											
Window areas											
	Great room				Kids bed (1st floor)	1st floor bathroom	Bed2	Bath2	Master bath	Master bed	
	S	E	N	W	S	N	W	N	N	S	E
Area (ft2)	74	18	23.6	9.5	20	6	19	8	8	32	27
								Total area in SF	Unit costs		Total costs
								245.1	$45/sq ft		$11,029.5

Table 20 - Windows estimated costs

7.3.8 8. Doors

Doors						
Component	RS Means Code	Units	Material	Labor	Total	Total O&P
Bifold-4 Panel	08 14 16.09.2200	2	$ 278.00	$ 122.00	$ 440.00	$ 496.00
M_Single-Flush: 24" x 80" Closet Door	08 14 33.20.7720	3	$ 127.50	$ 123.00	$ 250.50	$ 330.00
M_Single-Flush: 0915 x 2134mm	08 14 33.20.7780	4	$ 208.00	$ 172.00	$ 380.00	$ 496.00
Single-Decorative 2: 36" x 84"	08 16 13.10.0140	5	$ 2,560.00	$ 196.00	$ 2,756.00	$ 3,100.00
Single-Glass 2: 36" x 80"	08 16 13.10.0120	2	$ 930.00	$ 98.00	$ 1,028.00	$ 1,170.00
					Total Cost	$ 5,592.00

Table 21 - Doors estimated costs

7.3.9 9. Columns

Columns					
Component	RS Means Code	Material	Labor	Total	Total O&P
M_Rectangular Column: 610 x 610mm	04 21 13.18.0800	$ 227.21	$ 537.49	$ 764.70	$ 1,074.98
Reduction in labor cost due to prefabrication			$ 134.37		
Wastage cost		$ 9.09			
Total cost		$ 236.3	$ 403.12	$ 639.4	$ 898.86

Table 22 - Columns estimated costs

7.3.10 10. Lighting Fixtures

Lighting Fixtures				
Component	Model	Unit Cost	Total units	Total Costs
Pendant lights	Progress Lighting P5011-09	98	7	686
Wall lamps	Progress Lighting P2959-09	40	8	320
Outdoor Lights	Progress Lighting P5742-84	51	2	102
Bulbs	INSTEON 2672-222	30	17	510
		Total		$ 1,618.0

Table 23 - Lighting fixtures estimated costs

7.3.11 11. Casework

Case Work					
Component	RS Means Code	Unit	Unit Cost	Total	Total O&P
Base Cabinet-4 Drawers	12 32 23.10.1040	4	$ 380.00	$ 1,318.00	$ 1,520.00
Base Cabinet-Double Door & 2 Drawer	12 32 23.10.1200	2	$ 465.00	$ 817.00	$ 930.00
Base Cabinet-Corner Unit-Angled	12 32 23.10.6100	1	$ 520.00	$ 454.50	$ 520.00
Tall Cabinet-Double Door(4)	12 32 23.15.5100	2	$ 335.00	$ 547.00	$ 670.00
Upper Cabinet-Corner Unit Tall 1-Wall	12 23 23.15.6000	1	$ 440.00	$ 381.00	$ 440.00
Upper Cabinet-Single Door-Wall	12 32 23.15.5040	3	$ 335.00	$ 867.00	$ 1,005.00
Upper Cabinet-Single Door-Wall	12 32 23.15.5060	1	$ 380.00	$ 332.00	$ 380.00
Cabinet Handles	12 32 23.35.2000	12	$ 17.10	$ 149.40	$ 205.20
Counter Tops	12 36 61.16.0100	6	$ 99.50	$ 477.00	$ 597.00
			Total		$ 6,267.20

Table 24 - Casework estimated costs

7.3.12 12. Plumbing

Plumbing						
Component	RS Means Code	Units	Material	Labor	Total	Total O&P
Faucets	22 41 39.10.0150	14	$ 1,211.0	$ 805.0	$ 2,016.0	$ 2,548.0
PEX pipe 0.5 inch	22 11 13.74.7360	380 feet	$ 220.4	$ -	$ -	$ 243.2
Elbows	23 83 16.10.7142	17	$ 113.1	$ 295.0	$ 369.1	$ 527.0
Couplings	23 83 16.10.7120	26	$ 174.2	$ 451.1	$ 625.3	$ 871.0
T Fittings	23 83 16.10.7132	5	$ 21.8	$ 86.8	$ 108.6	$ 155.0
Showerheads	22 41 39.10.4000	2	$ 137.0	$ 51.0	$ 188.0	$ 228.0
Sinks	22 41 16.30.2000+4000	4	$ 1,560.0	$ 592.0	$ 2,152.0	$ 2,610.0
Sink steel	22 41 16.30.2000	1	$ 275.0	$ 148.0	$ 423.0	$ 525.0
Bathtubs	22 41 19.10.4100	2	$ 1,150.0	$ 166.0	$ 1,316.0	$ 1,525.0
Toilet bowl	22 41 16.10.1040	2	$ 412.0	$ 260.0	$ 672.0	$ 850.0
	Total Costs Fixtures		$ 4,745.0	$ 2,022.0	$ 6,767.0	$ 8,286.0
	Other Cost		$ 529.5	$ 832.8	$ 1,102.9	$ 1,796.2
	Total Costs		$ 5,274.5	$ 2,854.8	$ 7,869.9	$ 10,082.2

Table 25 - Plumbing estimated costs

7.3.13 13. Mechanical (HVAC) and Appliances

Mechanical Cost Estimation	
Component	Cost
Duct Work	$ 1,743.4
ERV	$620
Ground Source heat pump (total cost including installation)	$ 5,600.00
Total Cost	$ 7,963.38

Table 26 - Mechanical estimated costs

Appliance Cost Estimation			
Appliance	Model Name	Unit	Cost
Fridge/freezer	Whirlpool WRT541SZDM		$ 944.10
Washer	Whirlpool Duet WFW72HEDW		$ 648.00
Condensing dryer	LG DLEC855W		$ 899.10
Instantaneous gas condensing hot water heate	Reliance TS-240-GIH		$914.00
Bathroom fan	Panasonic WhisperGreen		$104.89
Dishwasher	Bosch SHE68E05UC or SHE8ER5#UC		$ 1,100.00
Thermostat	7-Day Wiser Programmabl	2	$ 480.00
Building Automtation System			$ 430.00
Smoke Detector	28 31 46.50.5200	5	$ 1,115.00
CO2 Sensor	Vernier Carbon Dioxide Sensor CO2 Ser		$ 75.00
Oven/stove	Whirlpool WFE710H0AS		$ 697.50
Range hood	Whirlpool Gold Convertible Wall-Moun		$ 539.00
Bathroom fan	Panasonic WhisperGreen		$ 104.89
		Total Cost	$ 8,051.48

Table 27 - Appliance estimated costs

7.4 Sales Cost Estimate

7.4.1 Affordability Analysis

The sales price target for the house is based on an affordability analysis for residents in the city of Pittsburgh. The affordability analysis is based on a conventional assumption of the lending industry that a family can afford to spend 28% of its gross income after deducting property taxes and home insurance on housing. By running some basic financial calculations which is listed in Table below in detail, we targeted the sales price to be $280,500, costing around $170 per square foot to purchase.

Pittsburgh median household income year 2014 [1]	$51,291	Source: Department of Numbers Pittsburgh Pennsylvania
Property taxes	$4,484	Assuming property value to be $200,000
Home insurance [2]	$700	Source: Henshaw
Estimating annual mortgage	$12,910	=28% of Median household income less property taxes and home insurance
Monthly mortgage	$1,076	Annual mortgage/12
Sales price based on monthly mortgage for a 30 year loan	$280,500	Interest rate is 3% and after taking into account a 10% down-payment a total loan principal of around $255,000

Table 28 - Affordability analysis

The Table below shows the breakdown of the sales costs.

	3 Rivers House		
		3 Rivers House	**Share of Price**
A.	Finished Lot Costs	$ 2,500.00	0.89%
B.	Total Construction costs	$ 229,764.81	81.91%
C.	Financing Costs	$ 3,927.00	1.40%
D.	Overhead and General expenses	$ 12,061.50	4.30%
E.	Marketing Cost	$ 3,085.50	1.10%
F.	Sales Commissions	$ 10,098.00	3.60%
G.	Profit	$ 19,063.19	6.80%
	Total Sales Price	$ 280,500.00	

Table 29 - Sales costs

7.5 Cost Comparison with a National Average House

Below is a table which compares the cost differences between a national average single family house as per the results of a construction cost survey conducted by National Association of Home Builders in the year 2013 and the 3 Rivers House.

		National Average Single Family house		3 Rivers House	
I.	Sale Price Breakdown	National Average	Share of Price	3 Rivers House	Share of Price
A.	Finished Lot Costs	$74,509	18.60%	$ 2,500.00	0.89%
B.	Total Construction costs	$246,453	61.70%	$ 229,764.81	81.91%
C.	Financing Costs	$5,479	1.40%	$ 3,927.00	1.40%
D.	Overhead and General expenses	$17,340	4.30%	$ 12,061.50	4.30%
E.	Marketing Cost	$4,260	1.10%	$ 3,085.50	1.10%
F.	Sales Commissions	$14,235	3.60%	$ 10,098.00	3.60%
G.	Profit	$37,255	9.30%	$ 19,063.19	6.80%
	Total Sales Price	$399,532	100%	$ 280,500.00	

II.	Construction Cost Breakdown	National Average	Share of Constructi	3 Rivers House	Share of Price
I.	Site Work(sum of A to E)	$ 16,824	7%	$ 12,637.06	5.50%
A.	Building Permit fees	$ 3,647	1.50%	$ 3,446	1.50%
B.	Impact Fee	$ 3,312	1.30%	$ 2,987	1.30%
C.	Water & Sewer fees inspection	$ 4,346	1.80%	$ 2,298	1.00%
D.	Architecture, Engineering	$ 3,721	1.50%	$ 3,446	1.50%
E.	Other	$ 1,799	0.70%	$ 460	0.20%
II.	Foundations (sum of F to G)	$ 23,401	10%	$ 2,922	1.27%
F.	Excavation, foundation, conctrete, retaining walls and backf	$ 23,028	9.30%	$ 2,922	1.27%
G.	Other	$ 373	0.20%	$ -	0.00%
III.	Framing (sum of H to L)	$ 47,035	19%	$ 38,646	16.82%
H.	Framing (including roof)	$ 36,438	14.80%	$ 19,466	8.47%
I.	Trusses (if not included above)	$ 5,461	2.20%	$ -	0.00%
J.	Sheathing (if not included above)	$ 2,332	0.90%	$ 12,406	5.40%
K.	General Metal, steel	$ 1,604	0.70%	$ 6,775	2.95%
L.	Other	$ 1,201	0.50%	$ -	0.00%
IV.	Exterior Finishes (sum of M to P)	$ 35,474	14%	$ 47,876	20.84%
M.	Exterior wall finish	$ 16,867	6.80%	$ 6,449	2.81%
N.	Roofing	$ 7,932	3.20%	$ 26,128	11.37%
O.	Windows and doors	$ 10,117	4.10%	$ 15,300	6.66%
P.	Other	$ 557	0.20%	$ -	
V.	Major systems rough-ins(sum of Q to T)	$ 32,959	13%	$ 36,927	16.07%
Q.	Plumbing (excluding fixtures)	$ 11,823	4.80%	$ 1,796	0.78%
R.	Electrical (excluding fixtures)	$ 9,967	4.00%	$ 4,595	2.00%
S.	HVAC	$ 10,980	4.50%	$ 7,963	3.47%
T.	Other	$ 189	0.10%	$ 22,572	9.82%
VI.	Interior finishes (Sum of U to AE)	$ 72,241	29%	$ 79,986	34.81%
U.	Insulation	$ 4,786	1.90%	$ 17,854	7.77%
V.	Drywall	$ 9,376	3.80%	$ 11,598	5.05%
W.	Interior trims, doors and mirrors	$ 10,536	4.30%	$ 1,322	0.58%
X.	Painting	$ 8,355	3.40%	$ 4,595	2.00%
Y.	Lighting	$ 3,008	1.20%	$ 1,618	0.70%
Z.	Cabinets, countertops	$ 12,785	5.20%	$ 6,267	2.73%
AA.	Appliances	$ 4,189	1.70%	$ 8,051	3.50%
AB.	Flooring	$ 12,378	5.00%	$ 19,970	8.69%
AC.	Plumbing fixtures	$ 4,265	1.70%	$ 8,711	3.79%
AD.	Fireplace	$ 2,057	0.80%	$ -	0.00%
AE.	Other	$ 506	0.20%	$ -	0.00%
VII.	Final steps (sum of AF to AJ)	$ 16,254	7%	$ 3,676	1.60%
AF.	Landscaping	$ 5,744	2.30%	$ 2,298	1.00%
AG.	Outdoor structures	$ 2,891	1.20%	$ -	0.00%
AH.	Driveway	$ 3,741	1.50%	$ -	0.00%
AI.	Clean up	$ 2,261	0.90%	$ 1,379	0.60%
AJ.	Other	$ 1,617	0.70%	$ -	0.00%
VIII.	Other	$ 2,265	0.90%	$ -	
	Contingency			$ 7,100	3.09%
	Total	$ 246,453	100%	$ 229,765	100.00%

Table 30 - Sales price comparison

7.6 High Performance Features

We further compare specifically the construction cost differences of high performance components utilized in the 3 Rivers house with the national average house.

Considering inflation rate of 2.4%, which is the average rate for the last 15 years, we calculate the savings in terms of utility cost generated by 3 Rivers House as compared to a conventional house.

High Performance Features			
Component	3 Rivers House	Conventional	Difference
Structural Framing	$ 19,466	$ 36,438	$ (16,972)
Walls	$ 39,045.32	$ 26,243	$ 12,802
Roof	$ 26,128	$ 7,932	$ 18,196
Appliances	$ 8,051.48	$ 4,189.00	$ 3,862
Windows and Doors	$ 15,300	$ 10,117	$ 5,183
HVAC	$ 7,963	$ 10,980	$ (3,017)
Plumbing	$ 1,796	$ 11,823	$ (10,027)
Flooring	$ 19,970	$ 12,378	$ 7,592
Lighting	$ 1,618.00	$ 3,008.00	$ (1,390)
Total	$ 139,337	$ 123,108	$ 16,229

Table 31 - Cost of high performance features

7.7 Annual Utility Bills Comparison

The cost difference for the high performance features in the 3 Rivers House and a conventional home is $38,801 which is a 15.7% increase in the first costs for construction of the 3 rivers house. But within the first year itself the cost savings generated by the 3 Rivers House is substantial, nearing 97.5%.

End of Year	3 Rivers House Utility Bills cost	Utility Bills Average National house	Difference
1	$ 30.00	$ 1,191.00	$ 1,161.00
2	$ 30.72	$ 1,219.58	$ 1,188.86
3	$ 31.46	$ 1,248.85	$ 1,217.40
4	$ 32.21	$ 1,278.83	$ 1,246.61
5	$ 32.99	$ 1,309.52	$ 1,276.53
6	$ 33.78	$ 1,340.95	$ 1,307.17
7	$ 34.59	$ 1,373.13	$ 1,338.54
8	$ 35.42	$ 1,406.08	$ 1,370.67
9	$ 36.27	$ 1,439.83	$ 1,403.56
10	$ 37.14	$ 1,474.39	$ 1,437.25
11	$ 38.03	$ 1,509.77	$ 1,471.74
12	$ 38.94	$ 1,546.01	$ 1,507.06
13	$ 39.88	$ 1,583.11	$ 1,543.23
14	$ 40.83	$ 1,621.11	$ 1,580.27
15	$ 41.81	$ 1,660.01	$ 1,618.20
16	$ 42.82	$ 1,699.85	$ 1,657.03
17	$ 43.85	$ 1,740.65	$ 1,696.80
18	$ 44.90	$ 1,782.42	$ 1,737.53
19	$ 45.97	$ 1,825.20	$ 1,779.23
20	$ 47.08	$ 1,869.01	$ 1,821.93
21	$ 48.21	$ 1,913.86	$ 1,865.66
22	$ 49.37	$ 1,959.80	$ 1,910.43
23	$ 50.55	$ 2,006.83	$ 1,956.28
24	$ 51.76	$ 2,054.99	$ 2,003.23
25	$ 53.01	$ 2,104.31	$ 2,051.31
26	$ 54.28	$ 2,154.82	$ 2,100.54
27	$ 55.58	$ 2,206.53	$ 2,150.95
28	$ 56.91	$ 2,259.49	$ 2,202.58
29	$ 58.28	$ 2,313.72	$ 2,255.44
30	$ 59.68	$ 2,369.25	$ 2,309.57
	Sum		$ 50,166.62

Table 32 - Payback period calculation

Considering a discount rate of 5% the **payback period** for an investment of $16,229 with yearly returns in the form of savings as listed in the column “Difference” in the table above is calculated to be around **12.5 years**.

7.8 Utility Bills Sensitivity Analysis

From the table below we can see the variation in total savings generated from 3 Rivers House for a 30 year long period. The savings range from $31,076 to $158,253.

Inflation %	Energy Costs			
	3	5	8	10
1	$ 47,100	$ 65,115	$ 109,669	$ 158,253
2.4	$ 38,037	$ 51,791	$ 85,575	$ 122,250
3.8	$ 31,076	$ 41,628	$ 67,333	$ 95,083

Table 33 - Energy cost savings sensitivity analysis

7.9 CASH-OUTFLOW COMPARISON WITH AND WITHOUT THE PV

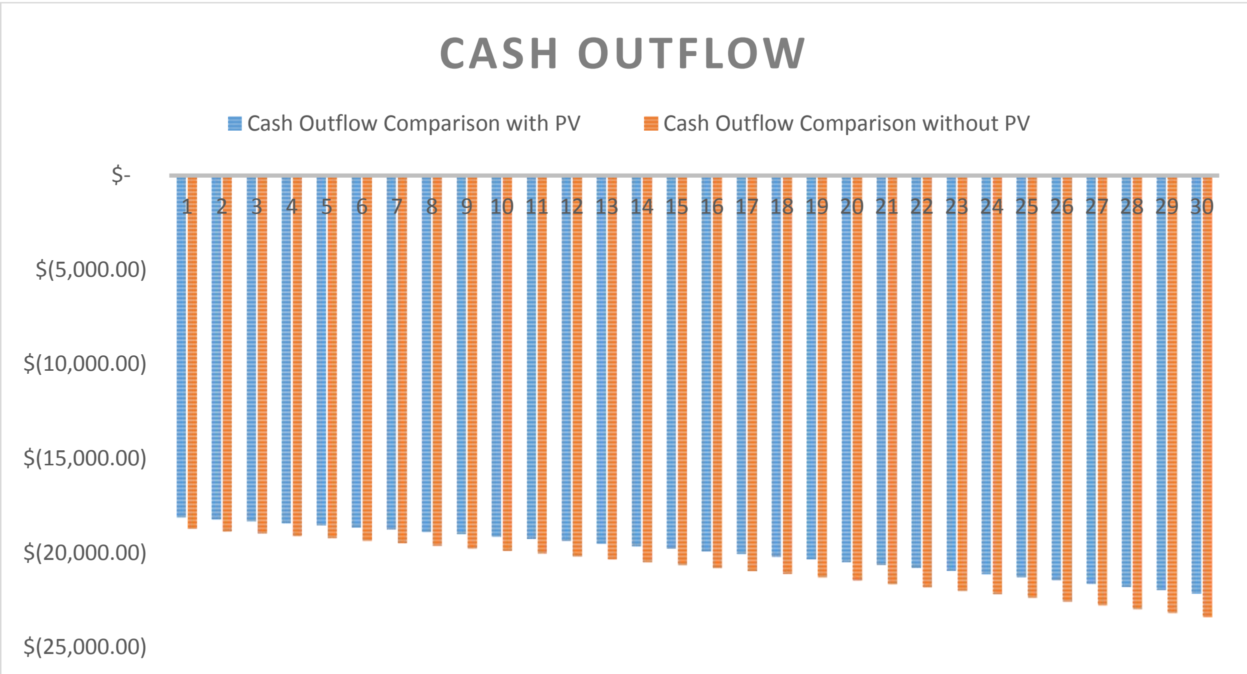


Figure 50 - Cash-outflow comparison with and without PV

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8 Domestic Hot Water, Lighting, and Appliances

8.1 Appliances

All appliances chosen are high-performance and Energy Star wherever possible. Zero Energy Ready Homes specification dictates that washers, refrigerators, vent fans, and dishwashers be Energy Star qualified, but we have also specified an Energy Star ERV and range hood. 100% of the lighting is LED because of LED's recent strides in both performance and visual quality that make it longer-lasting and less chemically harmful than all other alternatives. First-costs on most of these items are higher than for standard alternatives, but their payback is worth the investment. The following chart depicts standard household appliance energy use. Considering that lighting, appliances, and plug loads now account for most of the house's energy use, it is important to include energy-efficient appliances in the design.

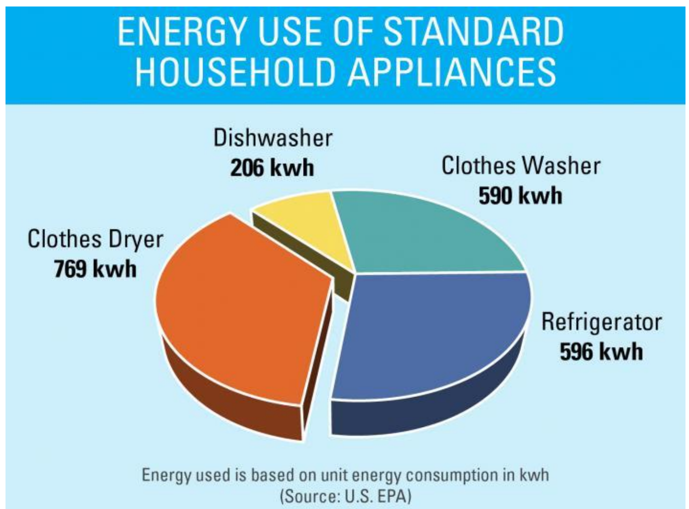

Figure 51 - Standard household energy consumption

Washers, dryers, and refrigerators can be huge contributors to annual loads. Thus, selection of these appliances was done thoroughly with the Energy Star catalog. Condensing dryers are not Energy Star rated, but one was chosen for this purpose because of the desire to avoid combustion appliances for indoor air quality purposes, and because another vent to the outside would mean less air-tightness. An LG ventless electric dryer was thus selected.

Refrigerator selection can also be tricky in terms of sizing, orientation, and energy management. For a family of four, a Whirlpool 21.3-cubic-foot fridge with top-mount freezer was chosen for its superior energy efficiency and generous space.

A Whirlpool front-load washer was also selected for its high energy efficiency, its matching capacity with the dryer, and its superior water factor rating, meaning lower energy use due to lower electricity and hot water use. This also fulfills EPA's Watersense requirements.

The dishwasher has a heater within it to further heat incoming water so that the house's hot water need not be maintained at 140°. Normally, water is heated to 140° for all hot-water uses, but with the dishwasher's water-heater, household water can be heated to only 120°, which saves huge amounts of energy on hot water.

Appliance	Cost	Specs	Attributes	Energy Star (Y/N)	Warranty
Electrolux IQ Touch condensing dryer	$899.10	EFF estimated 2.55; 4 ft3 capacity	Moisture sensor, quiet, front-load	Y	1-year al parts; 10-year motor
Whirlpool Duet Washer	$648	MEF: 3.2; WF: 3.5, less than 6gpm; 4.2 ft3	MEF: 3.2; water factor (WF): 3.5; EPA Watersense qualified; front-load	Y	Limited 1-year
Whirlpool fridge/freezer	$944.10	399 kWh/yr	21.3 ft3; top-mount	Y	Limited 1-year
Whirlpool oven/stove	$697.50	30 in	Convection oven; electric stove	N/A	Limited 1-year
Whirlpool Gold Convertible Wall-Mounted Range Hood	$539	36 in; 300 cfm max	Variable speed; dishwasher-safe filters	Y	1-year
Reliance TS-240-GIH instantaneous gas condensing hot water heater	$1,020.50	EF: 0.95; 6.6 gpm	Ultra-low NOx	Y	5-year all parts; 15-year heat exchanger
Bosch dishwasher	$1,649	EF: 1.19; 180 kWh/yr; 2.22 gal/cycle	Standard size	Y	2-year limited
Water Furnace 5 Series Model 012 GSHP, water loop	$2,625	COP: 5.1; EER: 15.7; pump: 4 gal/min	MERV-11 filter compatible	Y	
RenewAire GR90 ERV	$620	40-110 cfm; 4.0 cfm/watt	Quiet, uses < 1W standby power	Y	10-year
Panasonic WhisperGreen bathroom	$104.89	15.1 cfm/watt at 50 cfm	Pick-a-Flow speed selector; Multi-Speed with Time Delay option	Y	6-year DC motor; 3-year parts
7-Day Wiser Smart Programmable Thermostat	$240 ea.	7-Day, 4-schedule programmable	Wireless; easy to use; integrated with HEMS	N/A	1-year

Table 34 - Appliances

8.2 Plumbing

While a plumbing system often comes as an afterthought in a house, optimization of the system is crucial to simplifying the system, reducing water use, and creating comfort by lessening hot-water wait time.

PEX tubing is used in this house because of its flexibility, fast and easy installation, and noise reduction. PEX is also almost 66% cheaper than copper. PEX requires less soldering and connections, which also saves on labor costs to a great extent. It does not corrode like copper, which means it has a longer life.

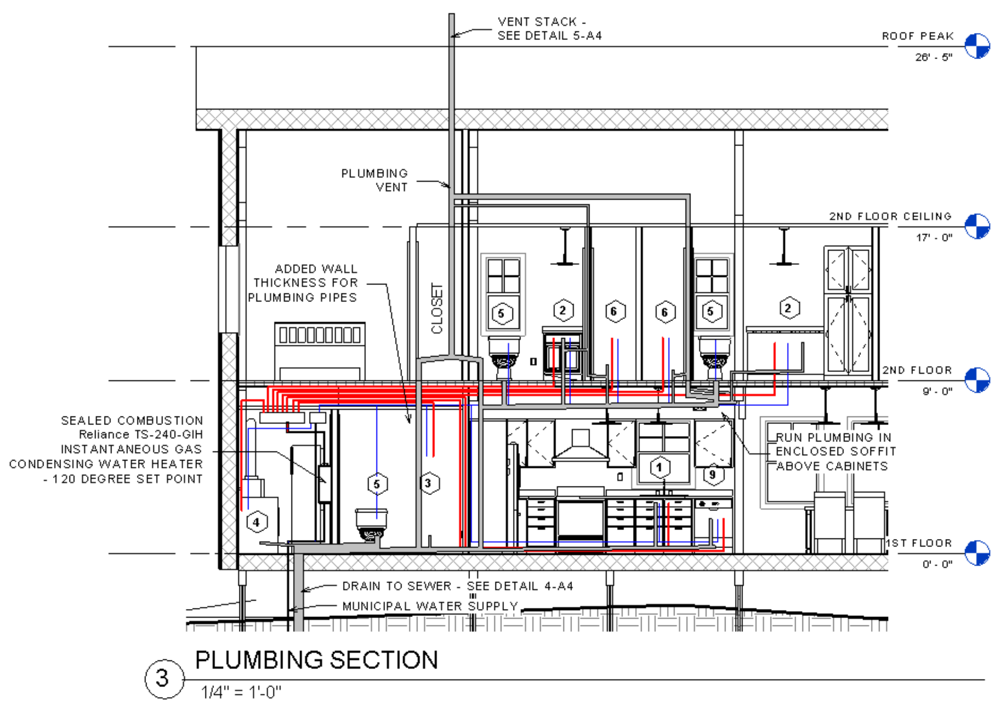

Figure 52 - Plumbing section

The cold water pipes in the Three Rivers house are laid in a trunk-and-branch system, while the hot water pipes run independently for each outlet. This helps in maintaining ideal pressure and temperature. If hot water pipes were put conventionally in a trunk-and-branch system, it would waste energy and water by allowing a lot of water would go down the drain before the hot water even reached faucet. Using a home-run manifold system for hot water means that the faucet need not run for too long before hot water reaches the sink because of using smaller pipes for individual faucets. It is slightly more expensive upfront, but it pays for itself in the long run. See the *Detail 4-A5* in Appendix A for water supply pipe path to the house.

We have designed a central vertical vent to connect to all the vents in order to create only one vent penetration through the envelope.

The hot water heater was chosen to be an instantaneous condensing combustion gas water heater with an energy factor of 0.95. This is the only combustion appliance in the house, and the combustion air is released directly to the outside, so there is no interior threat of combustion gases.
The instantaneous water heater heats water only when it is required, eliminating the need for a storage tank. This was chosen over demand hot water because demand hot water systems often lead to water heating even when it is not needed, therefore wasting energy. Our plumbing design using short distribution lines ensures that hot water reaches each necessary fixture in a short time without using a demand hot water system. Table 35 - Hot water wait time calculationTable 35 shows that no manifold holds more than 0.35 gallons of water, which is below the EPA Watersense requirement of a maximum of 0.5 gallons.

Fixture	Pipe diameter	Water capacity (oz/ft)	Pipe length (ft)	Water volume (gal)	Flow rate (gpm)	Hot-water wait time (s)
Kitchen sink	1/2"	1.18	30	0.28	1.5	11.06
1st floor bathroom sink	1/2"	1.18	8	0.07	1.5	2.95
1st floor shower	1/2"	1.18	10	0.09	2	2.77
Washing machine	1/2"	1.18	6	0.06	2	1.66
2nd floor bathroom sink	1/2"	1.18	17	0.16	1.5	6.27
2nd floor bathroom shower	1/2"	1.18	30	0.28	2	8.30
Master bath sink	1/2"	1.18	38	0.35	1.5	14.01
Master bath shower	1/2"	1.18	35	0.32	2	9.68
Dishwasher	1/2"	1.18	38	0.35	1	21.02

Table 35 - Hot water wait time calculation

Assumption: Water in pipes has completely cooled between uses.

An important note here is that the choice of water-efficient fixtures means slightly longer wait times for hot water because of a lower flow rate.

8.3 LIGHTING

All lighting fixtures are LED-compatible and are placed with consideration for where a task is located and the base light level needed for a task. The design goal was to be simplistic and provide sufficient electric lighting as is necessary and allow for task lighting to supplement additional needs at the occupants' demand. Much of the Three Rivers house will be naturally lit during the day, with most glazing on the south façade. Glare is avoided with carefully calculated overhangs.

The layout was also planned so that rooms would receive natural daylight and solar radiation when in most use. The mechanical room and bathrooms hardly need any sun for most hours, so they are oriented throughout the length of the north side of the house. Because of the house's open layout, the kitchen, living room, and dining area receive natural light from the morning throughout the afternoon.

Lighting control specification is very important here in addressing occupant behavior. Dimming switches are necessary to provide options for different light levels and thus allow for lower energy use when full light levels are not needed; however, simply including dimming switches is not enough. Occupant behavior must be factored in with the insight that, when an occupant is not required to change the level of lighting in order to turn on a light, he is likely to leave the dimming switch where it is. Providing switches with smaller binary on-off options than the dimmer itself, as is the case with the Leviton SureSlide, makes responsible behavior intuitive with no added effort.

Figure 53 - Leviton SureSlide dimmer switch

8.4 HOME ENERGY MANAGEMENT SYSTEM (HEMS)

As the saying goes, you can't manage what you can't measure. In order for residents to actually interact with their intelligently built home, they need to receive feedback on how the home is performing, in more ways and with higher frequency than a monthly net-metering bill. A home energy management system by Schneider Electric accomplishes remote energy management, including the incorporation of utility bills and net metering, to allow the homeowners to see clearly how their home is operating and how close to net-zero they really are. Then they can alter their behavior or appliance settings to match their goals. This is the last step to making net-zero a reality: real-time metering and working with the house to achieve net-zero energy.

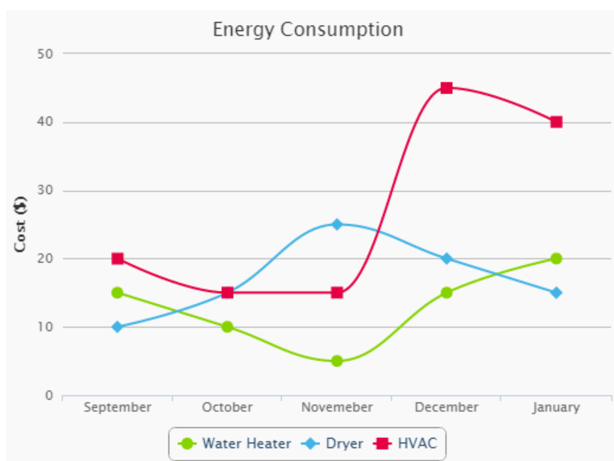

Figure 54 - Sample energy consumption of various devices

The Wiser Home Management system is integrated into this home to provide the following features:

- Integration with thermostat (7-Day Wiser Smart Programmable Thermostat)
- Each day can have 4 different event types
- Remote control of thermostat, lights, and other appliances through a mobile app or internet
- Provides alerts to users

- Energy tracking and management based on energy use and projected bills
- Real-time net metering information
- Compatibility with geothermal heat pump

Specified products:

- 7-Day Wiser Smart Programmable Thermostat ($240 each, included in appliance budget)
- Jetlun JIM Wireless Panel Meter ($197)
- Wiser Zigbee Gateway Coordinator ($120)
- Wiser Smart Plug ($113)
- Premium plan to allow for automated control, remote scheduling, and solar support ($5.99/mo)

→Total extra hard-cost: $430

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9 CONSTRUCTION DOCUMENTS

Complete construction documentation is included in Volume 2, Appendix A - Construction Documentation

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