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A Passive Solar Retrofit in a Gloomy Climate

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A Passive Solar Retrofit in a Gloomy Climate

By

James Russell Fugate

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF ARCHITECTURE

Department of Architecture
Golisano Institute for Sustainability
Rochester Institute of Technology

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Committee Approval

A Passive Solar Retrofit in a Gloomy Climate

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Abstract

A common perception with solar technologies is that they are practical only in sunny regions of the country. The sun is a source of clean and plentiful energy, but for regions of the country that experience frequent cloud cover, solar energy is typically not considered a worthwhile endeavor. In addition to the problem of limited sunshine, solar energy is often deemed to be too expensive for the average homeowner, particularly without significant government incentives. For solar technology to be adopted on a broad scale, it must make practical sense to the homeowner, not just economically, but also for an improved quality of life. Otherwise, solar technology in home construction will be limited to those who are especially motivated and can afford it.

Passive solar, in particular, is often dismissed as a relic of the 1970’s. The excessive amounts of glass can lead to too much heat loss or heat gain, and the home may experience wide temperature swings, making it uncomfortable. While the complaints do have merit, they are often a result of a poor design rather than an inherit failure of passive solar systems.

This thesis project attempts to demonstrate that passive solar technology can be effective in any region, even the gloomy climate of Western New York, and that it can be incorporated into an existing home cost-effectively. The project analyzed an existing single-family home and a rehabilitation proposal was developed that met the needs of the clients and incorporated passive solar technologies. A number of passive solar features were reviewed, and it was learned that the benefits of a passive solar feature often go beyond its mere cost-effectiveness. Intangibles, such as daylighting, a sense of place, plant growth, and improved market-value, contribute to the assessment of a passive solar feature.
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“We must begin by taking note of the countries and climates in which homes are to be built if our designs for them are to be correct. This is because one part of the Earth is directly under the sun’s course, another is far away from it, while another lies midway between these two. It is obvious that designs for homes ought to conform to diversities of climate.”

~ Vitruvius (Roman architect, first century B.C.E.)

Introduction

In this thesis project, there is an attempt to bring together different strategies of sustainability to rehabilitate an existing house to become a comfortable, inviting, and functional home for a family of four, in a climate that many would consider to be a “gloomy climate,” which is simply a place that experiences a combination of higher than average cloud cover and precipitation, along with colder than average temperatures. The family has many needs, including thermal comfort, fresh air, ample daylight, pleasant acoustics, satisfying views, and productive spaces. The home is to also be a place that inspires and invigorates the family members.

At its most primitive level, a house is a place that provides shelter and safety for its occupants. Max Jacobson expanded on this in Invitation toArchitecture when he described that “this experience can include the pleasant feeling of being safe inside during a storm, or gathering together with others in a space made for that purpose, or in the simple satisfaction of owning a space that one has created for oneself.” (Jacobson & Brock, 2014) A home is an intimately
personal space. Unlike buildings of commerce, education, or even worship, a home is a unique space that reaches deep into one’s soul. It is the place to which we yearn to come back after being away for some time. For many, their childhood home remains etched in memory as that one place where life was comfortable and simple.

A home is also a complex system. Swiss-French architect Le Corbusier famously referred to a house as “a machine for living in.” Like a machine, a house is an assembly of many interrelated parts. Charles Moore, et al., also observed this in The Place of Houses when he wrote that “a good house is a single thing, as well as a collection of many, and to make it requires a conceptual leap from the individual components to a vision of the whole.” (Moore, Allen, & Lyndon, 1974) The assembly includes physical components such as the foundation system; the structural skeleton; the fenestrations; the thermal and moisture protection layers; the mechanical, electrical, and plumbing systems; the myriad of finishes; and much more. The assembly also includes non-physical considerations such as daylighting, air and sound quality, and other qualities of space that influence one’s quality of life. American architect Louis Kahn referred to these frequently elusive qualities when he stated that “a great building must begin with the unmeasurable, must go through the measurable means when it is being designed and in the end must be unmeasurable.”

An interesting analogy is the symphony orchestra, which is comprised of a variety of musical instruments. Generally, there are four families of instruments, including strings, woodwinds,

Figure 1 Rochester Philharmonic Orchestra (Source: https://www.democratandchronicle.com)
brass, and percussion. However, within each family of instruments are numerous variations of instruments, each capable of producing a unique and purposeful sound, that when combined in harmony create a pleasing whole. Not every instrument is needed for every measure of every piece. Some instruments are used sparingly and some are used intensely. Some instruments may not be needed at all for a particular piece, but will be used extensively for another piece. How and when each instrument is used is dependent on the composer’s objectives. Likewise, a house is a complex system of many parts, that when they work together create a pleasing and stimulating home for its occupants. Not every component is required to function actively at every moment. Different activities and seasons call for varying assemblies of components to create a comfortable and functional indoor environment. A single element, such as a window, should not be viewed in isolation. Rather it must be viewed in concert with all of the other components as part of an effective system called a “house.”

**Thesis Objective**

The objective of this thesis project is to create a data-driven architectural design that brings together individual components and features into a holistic solution that is sustainable and meets the needs of the family who will call this project their home. Because this is an existing structure, a unique set of circumstances will impact the design process. At a high level, the challenges of this project include answering the following four questions:

- Can passive solar be effective in a “gloomy climate?”
- Can passive solar be retrofitted into an existing home?
- Can a passive solar retrofit be cost effective?
- Can passive solar be part of a solution that satisfies the programmatic desires of the client?
It should be noted that the clients are not an advocate for passive solar energy. In fact, the clients hold a general perception that a passive solar solution would be impracticable in the local climate given the limited sunshine. To be sure, the clients are not philosophically opposed to passive solar, but it will be the responsibility of the designer to present passive solar as a viable solution to a renovation plan that will enhance the quality of life for the client’s family.

As the individual components of a building cannot be considered in isolation, the building itself also cannot be separated from its surroundings. Architecture is not a thing that lives on a pedestal, like a sculpture. Though a house may be separated from its foundation and moved to a different location, the house in essence would become a wholly different structure in its new setting. The building and its individual parts are dependent on each other and their surroundings in order to achieve architecture. These challenges became the underlying considerations for the design of this thesis project.

**Project Description**

This particular property was selected for a number of reasons. First and foremost, the property simply became available at the right time and at the right price. Being an estate sale, the executor, who lives out of town, was anxious to sell. Secondly, the project was in need of extensive rehabilitation work, which lowered its price, making it feasible to perform wide-ranging upgrades. Thirdly, the site and the location of the dwelling on the site were deemed to be reasonable in order to incorporate passive solar strategies, which is an important objective for this project. Finally, the existing structure
presented multiple real-life challenges that will provide a significant learning opportunity for the author.

Located on Baker Road in the Town of Wheatland, the structure sits on a nearly five-acre lot in a rural district. The closest town is Mumford, which is a small hamlet located three miles to the south. The nearest city is Rochester, New York, which is located approximately sixteen miles northeast of the property. Baker Road is a quiet dead-end road that was severed by the New York State Thruway in 1954. The property was once part of a larger farm owned by the Baker family during the nineteenth century. According to the current neighbors, the Baker family ran into financial trouble stemming from a lawsuit as a result of an automobile accident in the early twentieth century. The farm was divided and sold to pay the debts.

The original portion of the present structure was built in 1900 as a small one-and-a-half story secondary farm house. The main Baker family farm house is today the neighbor’s house. No descendants of the Baker family live in the area today, though one of the neighbors claim to have met a descendent a few years ago. From what the neighbor learned, the house for this project was originally built as a place for the Baker family grandchildren to stay when they visited, thus it was apparently a guest house. The house was quite small with just over eight hundred square feet, a dirt floor basement, a fieldstone foundation, and a south-facing porch. The original structure also did not include any indoor plumbing.

Figure 3 Property boundary, 4.7 acres (Image source: Google Maps)
During the twentieth century, the property sold a few times, with the most recent occupants taking ownership in the late 1960’s. Every few years, it seemed, a new addition was constructed. While town records are incomplete, there seems to be five separate additions, with the most recent addition being the two-car garage completed in 2003. Some of the additions were built on a crawl space while others we built on a concrete slab. There apparently was no attempt to have the additions’ floor levels match adjacent floor levels. Thus there are five different floor levels for the main level. The majority of the dwelling is one story, with the exception being the original structure which includes a small upper level.

Clearly, there was little thought to architectural style when the additions we constructed. The architecture could be described as muddled with different roof slopes, floor elevations, and finish materials. Nevertheless, when reviewing the structure as a whole, it brought to mind the connected farm building that is a distinct vernacular architecture of New England. Architectural historian Thomas Hubka referred to this style as “Big House, Little House, Back House, Barn.” (Hubka, 1985) Though likely unintentional, there is a sense that the house mimics this regional historic architectural style. While New York is not actually part of New England, many of New England’s vernacular styles spread to New York State, including the Colonial and Cape Cod house styles, which are prevalent in the region.

Hubka’s description of the connected farm buildings aptly describes the present house:

First is the big house, the major farmhouse... usually faces the road and is the nearest structure to it. The big house is usually identified as the farmhouse by the farm family and contains the formal parlor room and the bedrooms or chambers on the second floor... Second is the little house, which was, and still is, the kitchen building and active living center for the farm family... Third is the back house, a building extending from the... little house to the major barn. It usually contained... multipurpose work and storage spaces for house and barn... Together, the little house and the back house buildings are commonly called the ell, which was a
term derived from the typical L-shaped plan relationship... It is, finally, the barn that terminates the connected building complex and, as on most American farms, is the functional center of the farming operation.” (Hubka, Big House, Little House, Back House, Barn, 1985, p. 6)

The arrangement also includes the creation of three separate yards: the front yard, located between the big house and the road, the work yard (or door yard) formed by the ell shape of the building, and the barn yard, located behind the barn. Each of these elements can be clearly identified in the illustration in Figure 4. To be sure, the description is not a perfect match. The “barn” is actually a two-car garage and the kitchen is located in the big house rather than the little house. Nevertheless, there is a uniqueness about this architectural layout and its (likely unintended) connection to a distinct regional architecture.

**Sustainable Architecture**

As previously mentioned, a challenge of this project is to use sustainability as a unifying objective to bring the many parts of the project together. It has been three decades since the United Nation’s Brundtland Report defined sustainable development as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.”
Today, sustainable architecture is a widely adopted concept, to one degree or another. Many people recognize, as architect Max Jacobson does, that “structures that waste energy through inefficient heating, ventilation, and lighting, and that embody exorbitant amounts of energy in their material extraction, manufacture, and construction, may be useful to us in the short run, but collectively they ruin us in the long term.” (Jacobson & Brock, 2014, p. 189) Sustainability is a world-wide concern that anyone can address at a local level, certainly with residential projects.

As the town’s name suggests, Wheatland’s community character is rural with many rolling farmlands. The town’s Comprehensive Plan makes a number of references to preserving the rural character. “The rural character of Wheatland is comprised of working fields, wooded hedgerows, new and old barns, and patches of wooded land surround the many natural topographical features that separate the many farms in the area… The community’s rural and historic character should be preserved.” (Committee, 2004, p. 87) The objectives of the community are entirely compatible with sustainable practices, and the objectives of this project are intended, in part, to satisfy the desires of the local community.

**Residential Energy Consumption**

In 1956, Victor Olgyay wrote in his influential book, *Design with Climate*, “The desirable procedure would be to work with, not against, the forces of nature and to make use of their
potentialities to create better living conditions.” (Olgyay, 1956) In essence, that is what this thesis is about: discovering how to rehabilitate an existing house in such a way that it works with the climate in which it exists. Furthermore, the objective of sustainable architecture is to consciously consume resources in such a way that is not detrimental to the future.

An important component of sustainable architecture is energy consumption. According to the US Department of Energy, residential buildings consume nearly fourteen percent of the total energy market worldwide. (EIA, 2017) Space heating accounts for forty-two percent of the residential energy. (EIA, 2013) Thus, nearly six percent of the entire world’s energy consumption is specifically for residential space heating. More than three quarters of homes in the United States use either electricity or natural gas. Most of the remaining homes use fuel oil, propane, kerosene, or wood. (Today in Energy, 2012) Solar energy accounts for a very small percentage of the energy consumption in the United States, only 0.39%, according to the U.S. Energy Information Administration for 2014. Yet, solar energy is abundant and freely available.

In the book, Mechanical and Electrical Equipment for Buildings (MEEB), a table is provided that compares the amount of solar energy received on the earth daily with energy
consumed by various human activities. Astonishingly, the amount of energy consumed by all of mankind in a year is only one-hundredth of the energy received from the sun each day!

Table 1 Daily arrival of solar energy on earth compared to other energy quantities (Brondzik & Kwok, 2014)

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Daily Arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar energy received each day</td>
<td>1</td>
</tr>
<tr>
<td>Melting of an average winter's snow during the spring</td>
<td>$\frac{1}{10}$</td>
</tr>
<tr>
<td>A monsoon's circulation between ocean and continent</td>
<td>$\frac{1}{100}$</td>
</tr>
<tr>
<td>Use of energy by all mankind in a year</td>
<td>$\frac{1}{100}$</td>
</tr>
<tr>
<td>A mid-latitude cyclone</td>
<td>$\frac{1}{1000}$</td>
</tr>
<tr>
<td>A tropical cyclone</td>
<td>$\frac{1}{1000}$</td>
</tr>
<tr>
<td>Kinetic energy of motion in Earth's general circulation</td>
<td>$\frac{1}{10000}$</td>
</tr>
<tr>
<td>The first hydrogen bomb</td>
<td>$\frac{1}{10000}$</td>
</tr>
<tr>
<td>A squall line containing severe thunderstorms</td>
<td>$\frac{1}{100000}$</td>
</tr>
<tr>
<td>A thunderstorm</td>
<td>$\frac{1}{100000}$.</td>
</tr>
<tr>
<td>The first atomic bomb</td>
<td>$\frac{1}{100000}$</td>
</tr>
<tr>
<td>The daily output of Boulder Dam</td>
<td>$\frac{1}{1000000}$</td>
</tr>
<tr>
<td>A typical local rain shower</td>
<td>$\frac{1}{1000000}$</td>
</tr>
<tr>
<td>A tornado</td>
<td>$\frac{1}{1000000}$</td>
</tr>
<tr>
<td>Lighting New York City for one night</td>
<td>$\frac{1}{100000000}$</td>
</tr>
</tbody>
</table>

Of course, a key challenge is the ability to collect and control solar energy. While dropping in price, photovoltaic systems remain costly. They are also inefficient at converting the energy that they capture into electricity, and batteries are not yet efficient enough to provide reliable power. (Integrating Renewable Electricity on the Grid, 2010)

In all the commotion regarding energy consumption, the availability and sustainability of different fuels, and the cost and efficiency of photovoltaic arrays, there remains one technology which is underutilized, cost efficient, low-tech, and quite straightforward to implement. It is also probably the oldest energy technology, having been used since antiquity. Two thousand, five hundred years ago in ancient Greece, Socrates explained that “In houses that look toward the south, the sun penetrates the portico in winter, while in summer that path of the sun is right over our heads and above the roof so that there is shade.” (Butti & Perlin, 1980) The technology to which Socrates was referring to was, of course, passive solar energy.
Passive Solar Overview

History of Passive Solar

Passive solar has a long and rich history. During the first millennia C.E., the Chinese adopted solar building designs enthusiastically. “Indeed, solar city planning reached greater heights in China than it had in ancient Greece.” (Butti & Perlin, 1980) The Chinese valued the southern exposure and associated it with warmth and healing. They were sure to orient any building of significance with its primary façade facing southward. During the same time period, the Spanish adopted the practice of building with thick walls of limestone and adobe in order to moderate the interior temperature throughout the year. Later, Italian architect Andrea Palladio followed Roman architect Vitruvius’ advice and oriented his buildings and room layouts according to the best practices of solar design. Nature often necessitates advances in technology. During the sixteenth to eighteenth centuries, the Little Ice Age in Europe encouraged the development of greenhouses to expand the growing season. In addition, active worldwide exploration fostered the desire to bring exotic plants and fruits to northern climates, which was enabled by the use of solar technology.

Perhaps one of the greatest feats of historic solar architecture was the grand

Figure 7 Attached greenhouse during the Little Ice Age
(Source: http://microfarmgardens.com/)

Figure 8 Crystal Palace of London, 1851 (Source: Wikipedia)
glass-enclosed Crystal Place of London, built for the Great Exhibition of 1851. “The Crystal Palace was an astonishing building… the five-aisled building was glazed throughout.” (Kostof, 1995)

German-American architect Mies van der Rohe applied principles of passive solar architecture in the Villa Tugendhat, a house built in 1930 in the Czech Republic. “All of the basic elements of passive solar architecture can be found in Villa Tugendhat, including building orientation, plan thermal zoning, shading elements, internal thermal mass, and the dimension and orientation of glazing.” (Maurerova & Hirs, 2014)

In 1933, American architect George F. Keck established his role in the Modernist era with his entries in Chicago’s Century of Progress Exposition, the House of Tomorrow, and the Crystal House. (Boyce, 1996) Both houses were revolutionary during their era, for their extensive use of glazing. Engineers apparently predicted that the heat loss for the glass would be too great for the heating system to overcome. On the contrary, the homes proved to require less mechanical heat due to the solar gain. Overheating did become a detriment, however, and the glass walls were later replaced with operable windows. (Boyce, 1996)
During the 1940’s, the solar design of homes declined dramatically. The housing market of the post-war era was very competitive and energy was cheap. Solar homes tended to be more expensive because of the expansive use of double-pane glass and the need for individualized design based on the site conditions. (Butti & Perlin, 1980) Homes needed to be built quickly with low-cost materials, and little concern was given to energy consumption and solar orientation.

After World War II, the journal *Arts and Architecture* attempted to revive solar architecture with a program called “The Case Study House Program.” “The program was a central arena for thinking about and experimenting with how to build in the postwar future. It strove to provide models—for the architect, for the homeowner, and for the developer—that would allow technological innovation to lead to transformations in the broader culture and to produce new ways of living.” (Barber, 2014) While well received by some, the economics of the period was too great an obstacle for the more costly solar architecture to become mainstream.
In 1956, Victor Olgyay referred to a state of “climate balance” as that which, in a given environmental setting, reduces undesirable stresses, and at the same time utilizes all natural resources favorable to human comfort. Olgyay described utilizing a four-step process when designing a “climate balanced” house: 1) Discover and utilize climate data, including temperature, relative humidity, radiation, and wind effects; 2) Evaluate a process that analyzes the climate data in terms of the importance of its elements for human comfort; 3) Find methods to minimize the adverse elements of the climate and maximize the advantageous elements to strike the “balanced shelter;” 4) Design the architectural application of the technological solutions. (Olgyay, 1956)

After the OPEC energy embargo of 1973 set off an energy crisis, research and interest resumed in solar homes with particular fervor. In 1978, architect David Wright (with Dennis Andrejko and Jeffrey Cook) wrote the book, Natural Solar Architecture: A Passive Primer. In the book, Wright claimed that most regions on the earth received “the quality and quantity of solar energy […] sufficient for human life support.” (Wright, Andrejko and Cook 1978) During the energy crisis, passive solar made logical sense. “Passive space-conditioning applications are potentially the most cost effective, most efficient, and possibly most comfortable approach to world-wide solar energy use.” (Wright, Andrejko, & Cook, 1978)

In 1979, Edward Mazria wrote a definitive book called The Passive Solar Energy Book. In the introduction, Mazria declared that “perhaps the greatest advantage of a passive system is the simplicity of its design, operation, and maintenance. […] These systems are built with common construction materials and usually have a long life, low operating temperature, no fans, pumps,
compressors, pipes or ducts and few moving parts.” (Mazria, 1979) He also went on to explain that a passive solar system “not only affords large savings of energy for heating, but that it also can be included at little or no additional cost in the original design and construction of a building.” (Mazria, 1979)

David Wright and Dennis Andrejko continued their advocacy of passive solar in 1982 with their book, Passive Solar Architecture: Logic and Beauty. “Logic involves function, structure, economics, planning, and the myriad other aspects of the architectural arts. The beauty is truly in the eye of the beholder, whether owner, user, architect, builder, neighbor, community, or society. Inescapably, neither logic nor beauty is complete without the other.” (Wright & Andrejko, 1982) In this book, both authors describe passive solar as something more than a means to conserve energy: Passive solar is architecture. “The successful combination of art and engineering creates an environment that is both exciting and satisfying to the inhabitant. This is the essence of the beauty and logic in passive solar architecture.” (Wright & Andrejko, 1982)

During this time period, architect Darryl J. Strickler wrote several practical books on passive solar homes. “Through an appropriate combination of south-facing glazing, thermal storage mass, shading devices, ventilation and natural air movement, and proper site orientation and building configuration, passive solar structures become a system capable of heating and cooling the interior of a building.” (Strickler, 1982) For Strickler, this was not just theory, but reality. “In recent years, practical applications of passive solar for heating and cooling have been evaluated, analyzed, and documented, with this conclusion: it works!” (Strickler, 1982)

During the 1980’s, energy became cheap once again and interest in solar energy began to lose favor. Furthermore, insulation and window technology experienced remarkable advancement to the point that it became easier and more cost effective simply to reduce energy
demand through tighter and better insulated homes rather than designing how to capture, store, and distribute solar energy. In fact, a lively debate emerged between those that supported passive solar and advocates of super-insulated homes. Dr. Joseph Lstiburek, the founding principal of the Building Science Corporation (BSC) bluntly summed up his verdict in the great passive solar versus super-insulated debate:

*Don’t bother with the passive solar. Your house will overheat in the winter. Yes, you heard that right. Even in Chicago. Are you listening Passive House? You should go with very, very low SHGC’s [Solar Heat Gain Coefficient], around 0.2, in your glazing. If this sounds familiar to those of you who are as old as me it should. We were here in the late 1970’s when “mass and glass” took on “super-insulated”. Super-insulated won. And super-insulated won with lousy windows compared to what we have today. What are you folks thinking? Today’s ‘ultra-efficient’ crushes the old ‘super-insulated’ and you want to collect solar energy? Leave that to the PV.”* (Lstiburek, Zeroing In, 2014)

Martin Holladay is the editor of *Green Building Advisor* and was an associate editor at the *Journal of Light Construction* and editor of Energy Design Update. An active participant of the passive solar movement during the 1970’s, Holladay built his first passive solar home in Northern Vermont in 1974. He recently provided his assessment of the passive solar movement:

*Passive-solar buildings never worked all that well. They tend to be cold on winter mornings and hot on sunny afternoons. But most solar enthusiasts were so excited by the idea of “free heat” that we accepted uncomfortable conditions as a necessary part of the brave new solar future we were creating.*

*While large expanses of south-facing glass help heat up a home on a sunny day, the solar heat gain doesn’t always come when heat is needed. Most of the time, a passive solar home has either too much or too little solar heat gain, so much of it is wasted. Today’s houses are better insulated and a lot more airtight than they used to be. They require less energy to heat and cool than houses built in the 1970s. However, these improvements also make homes with lots of south-facing glazing even more susceptible to overheating, so it’s more important than ever to avoid*
excessive glazing areas. And of course, large expanses of south-facing glass lose significantly more heat at night and on cloudy days than insulated walls do. (Holladay, 2016)

For a contrary view in support of passive solar, architect Ken Haggard, coauthor of *Passive Solar Architecture*, continues to incorporate passive solar features in his projects. His perspective is that too many designers associate passive solar with just space heating, when it is actually much broader. “It’s important not to define passive design strictly on the basis of heating.” Haggard argues that passive solar must also include cooling, ventilation, and daylighting as well. (Wilson, 2012) Another proponent of passive solar is architect Mike Nicklas of Innovative Design in Raleigh, North Carolina. He argues that too many people simply turn to photovoltaics rather than taking the time to design an effective passive solar “skin” for homes and small commercial buildings. “People just do what they want to do and throw on a bunch of PV at the end,” he complained. (Wilson, Passive Solar Heating, 2012)

For the past two and one-half millennia, the adoption of passive solar in architectural design has ebbed and flowed. “The steady evolution of solar architecture and technology has been periodically interrupted by the discovery of apparently plentiful and cheap fuels such as new forests or deposits of coal, oil, natural gas and uranium.” (Butti & Perlin, 1980) Currently, advancements in insulation, glazing, and photovoltaic technology, along with relatively cheap energy is tempering the public’s enthusiasm for passive solar. Nevertheless, whether or not architects intentionally incorporate passive solar into their designs, the sun is always there, impacting the design of their buildings to one degree or another.
Benefits and Challenges of Passive Solar

In spite of the apparent decline in enthusiasm, passive solar still offers several advantages that ought to be considered. Dr. Robert Noyes, in *Solar Energy: Principles of Thermal Collection and Storage*, identified two critical benefits of solar energy. First, the sun continues to shine, providing free energy to anyone who so desires it, and its collection is possible virtually anywhere in the world. Second, solar energy is entirely nonpolluting and collecting it for energy is safe to the environment. (Sukhatme & Sukhatme, 1996) David Wright observed in 1978 that “Solar space-heating is less polluting, more economical, and healthier for our environment and economy than any other energy source.” (Wright, Andrejko, & Cook, 1978, p. 22)

The sun does present several challenges, though. First, solar energy is a dilute energy source. “Even in the hottest regions on earth, the solar radiation flux available rarely exceeds one kWh/m², and the total radiation over a day is at best about seven kWh/m².” (Sukhatme & Sukhatme, 1996, p. 22) Thus, collecting solar energy to convert to usable energy requires large areas, which are not always available. Second, solar energy’s availability is intermittent as it is not present during the night or during heavy cloud cover. The sun’s constantly changing availability requires the need to collect and store solar energy for later retrieval when the sun is not accessible.

Given the challenges with passive solar design, one may wonder why it is being considered for this project. Windows present a particular challenge, because even the best performing windows are still less energy efficient than a well-designed wall. Thus, it is often recommended that glazing areas should be minimized in order to improve the overall thermal performance of the wall. In fact, an ASHRAE Journal article recommended that window glazing be less than four percent of the total floor area of a well-insulated house. (Sander & Barakat, 1984) On the other hand, Bainbridge and Haggard, in *Passive Solar Architecture*, recommended...
an area of aperture per floor area percentage of fourteen to twenty percent for Rochester’s climate. That is four to five times the amount of glazing recommended by ASHRAE.

Daylighting provides a number of benefits beyond solar gain and natural light, reducing heating and electric loads, respectively. Another significant benefit of abundant daylighting is the psychological uplift the occupants will experience from both the natural sunlight and the visual connection to the outdoors. Many studies have shown the health benefits of daylighting. Worker productivity and student scores increase when coupled with sufficient daylight. (Wymelenberg, 2014) An “ample and pleasant view out of a window, that includes vegetation or human activity and objects in the far distance, support better outcomes of student learning.” (California Energy Commission, 2003) Also, Christoph Reinhart of Harvard University described a well-designed, day-lit space as a space that is “primarily lit with natural light and combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling.” (Reinhart, 2014)

To be sure, an abundance of daylight can become too much of a good thing. Glare and overheating will transform a space from one that is pleasant to a space that is uncomfortable. In a home, glare generally occurs when the sun is low, particularly in the morning and evening. Thus the east and west windows are more susceptible to sun glare and should be tinted and minimized. (Wilson, 2012) Solutions for controlling glare generally involve light diffusion and shading devices, including louvered shades, shutters, light shelves, roller blinds, and curtains. (Bainbridge & Haggard, 2011) Christoph Reinhart offered another solution for sun glare and that is occupant flexibility. “Allowing occupants to adapt to their environment by moving around the space is another design option to address visual comfort.” (Reinhart, 2014)
The prevention of overheating is a slightly more complex concern. While solar heat gain is generally a desirable outcome of a passive solar system, too much gain during the summer months or even during sunny cool days will make the home uncomfortable. Four strategies are used to control heat gain. First, thermal mass is an important component to absorb excess solar energy for release later when needed. Without thermal mass, the interior temperatures will fluctuate too much, rising too high during sunny days and falling too fast when the sun disappears. The great benefit of the thermal mass is its ability to moderate interior temperature swings. Second, shading devices are strategically located to block direct sunlight when it is not needed, particularly during the summer months. Manual shades, such as blinds and curtains, may also be used, although their effectiveness will be dependent on the user. Third, ventilation is used to move the hot air out of the dwelling. Installing vents at the roof level as well as on opposite walls, to provide cross ventilation, is an effective strategy. Finally, an isolated-gain system, such as an attached sunspace, may be used to control the timing and the amount of heat that is transferred to the living space. A sunspace acts as its own collector and storage of solar energy. Vents are opened or closed depending on the needs. “Heat can be transferred to the living spaces when desired, allowing more control and reducing the potential for overheating.” (Wright & Andrejko, 1982, p. 130)

It should be mentioned that passive solar energy will have certain side effects which the occupants ought to consider. The higher amounts of south-facing glazing may contribute to issues related to acoustics, privacy, and color fading. Glass is a hard surface, and a space with large amounts of glazing may experience higher levels of sound reverberation. Also, privacy ought to be reviewed before determining the glazing. If the south is facing a neighbor or a busy street, the amount of glazing may need to be adjusted to address the concerns of privacy.
Finally, fabrics exposed to sunlight, particularly ultraviolet light, will tend to fade. Using fabrics that are more resistant to fading such as polyester or acrylic, selecting lighter colors, and placing furniture strategically should be considered to minimize this side effect.

For this project, it has been determined that the benefits of passive solar outweigh its weaknesses. Nevertheless, passive solar is but one element in the design considerations for the project. In fact, it would be a mistake to refer to this project as a purely passive solar project. Certainly, elements of passive solar will be utilized, yet there is a sense of passive solar being restrained in order to maximize the benefits of passive solar while minimizing its risks.

Furthermore, there was concern that attempting to do too much would overwhelm the project and create a greater risk of falling short of the project goals. As Wright and Andrejko clearly warned in *Logic and Beauty*, “The key to the success of most passive solar architecture is simplicity. Adding unnecessary fans and exotic shades, or creating complex forms and intricate spatial relationships often creates design liabilities with more difficulties than the problems they attempt to solve.” (Wright & Andrejko, 1982, p. 29)

**Resiliency**

The Resilient Design Institute (www.resilientdesign.org) defines resilience as “the capacity to adapt to changing conditions and to maintain or regain functionality and vitality in the face of stress or disturbance.” (Wilson, 2013) Changing conditions can be caused by power outages, natural disasters, changing climate conditions, or simply the day-to-day fluctuations in the local climate. A building using resilient design principles is able to respond to changing conditions outdoors in order to maintain comfortable conditions indoors.

In the 1970’s, Edward Mazria recognized the resilient value of a passive solar design. By heating the surfaces of the space, the occupants experienced a higher level of satisfaction in spite
of the air temperature. “The inside air temperature for comfort in a passively heated space is usually somewhat lower, and frequently substantially lower than in a space heated by conventional (convective) means.” (Mazria, 1979) Mazria understood the positive impact of the radiant temperature and how it has a more recognizable effect on comfort than air temperature. Furthermore, the ability of passive homes to moderate the interior temperature swings in spite of the widely changing conditions of the outdoor environment provides a level of reassurance for the building occupants. Conversely, a conventional home is typically too dependent on functioning mechanical systems to control the indoor environment. “In a sense, we have become prisoners of complicated mechanical systems. A minor power or equipment failure can make these buildings uninhabitable.” (Mazria, 1979)

Bainbridge and Haggard also recognized the risk of living in a conventionally built home. “People are too often hot in summer, cold in winter, and face real danger if the power goes off.” (Bainbridge & Haggard, 2011) Because the systems in a passive solar home are dependent on natural resources and not the utility company, the home is far more resilient against changing conditions. “The benefits of sustainable design include comfort, health, economy, security, and safety during power outages.” (Bainbridge & Haggard, 2011)

The Resilient Design Institute provides a set of design principles to promote resiliency. The following principles were identified as applicable to the thesis project:

- Resilient systems should provide for basic human needs, including potable water, sanitation, energy, livable conditions (temperature and humidity), lighting, safe air, occupant health, and food.

- While sometimes in conflict with efficiency and green building priorities, redundant systems for such needs as electricity, water, and transportation improve resilience.
• Simple, passive, and flexible systems are more resilient than complex solutions that can break down and require ongoing maintenance. Flexible solutions are able to adapt to changing conditions both in the short- and long-term.

• Strategies that increase durability enhance resilience.

• Reliance on abundant local resources, such as solar energy, annually replenished groundwater, and local food provides greater resilience than dependence on nonrenewable resources or resources from far away.

• Recognize that incremental steps can be taken and that total resilience in the face of all situations is not possible. Implement what is feasible in the short term and work to achieve greater resilience in stages. (Wilson, 2013)

**Elements of Passive Solar**

Every passive solar strategy must include the following four fundamental and essential elements: collection, storage, distribution, and control. First, glazing (typically windows) is used to collect solar energy. In the northern hemisphere, the apertures should be south-facing, within thirty degrees of due south. (Energy.gov, 1999) East-facing and west-facing windows will also collect solar energy, but significantly less than south-facing windows.

Second, because not all of the solar energy is needed immediately, a means of storage for the solar energy is necessary for later use. Materials with a high thermal mass absorb heat from sunlight either by radiation when it is radiatively connected (i.e., in view of the sun) or by convection when it is not radiatively connected. Thermal mass is also useful for cooling during the summer because it will absorb excess heat from the warm air in the house.
Third, solar heat must be distributed from the areas where it is collected and stored to the areas of the home where it is needed. The heat may be desired in the immediate area, or it may be needed in a remote area. Either way, a means of distribution is required in order to promote a higher level of comfort throughout the building and to avoid excessive hot and cold spots. Heat will be transferred by either convection, conduction, or radiation. Convection moves heat by the movement of fluids, commonly air. This can be accomplished naturally via the natural movement of air, or it may receive assistance from a low-powered fan. Conduction moves heat by direct contact, such as walking on floors. Radiation is the warmth felt when facing a heated surface, such as a warm wall, a sunny window, or a wood stove.

Finally, a properly designed passive solar system must include a means of control. Wide indoor temperature swings are a common issue experienced by occupants of passive solar homes. Control devices, such as overhangs, awning, shutters, blinds, and shades, help to block the sun when temperatures rise too high. Other devices, such as exterior vents to allow overheated air to escape, and dampers on interior vents are used to provide convective control. Excessive heat loss during the night can be minimized with moveable insulating shutters.

In addition to the four fundamental elements, some resources will add one or two more elements to a passive solar design. For example, the U.S. Department of Energy identifies an “absorber” as a fifth element. (See Figure 14) While some consider the absorber as part of the storage element, the absorber is the intermediary between the solar radiation captured by the glazing and the thermal mass. The absorber should be a dark, matte colored surface in order to minimize losing solar radiation to reflectance. Another element identified by some resources, such as Passive Solar Architecture (Bainbridge & Haggard, 2011) is conservation, which initially may not seem to be a passive solar element. As explained in the upcoming section on
the building envelope, a passive solar strategy cannot succeed if the building is not first an energy-efficient building.

**Passive Solar Strategies**

Compared to active means of providing comfort and energy conservation, passive systems are quite straight-forward. As described in the previous section, the elements of the passive solar building are used to collect, store, distribute, and control solar energy. There are no complex mechanical systems to design. Once a good design is achieved, there is no reason why a passive system cannot function effectively for the life of the building. The key, though, is a good design. Unlike active systems, which can oftentimes be planned independently of the building design, a passive system is entirely dependent on the design of the building itself. Thus, it is imperative that a passive solar system be an intimate part of the early design stages of a project. The following is a review of the common strategies frequently considered when designing a passive solar system.

**Building Orientation and Layout**

Proper orientation of the building to the sun is a critical starting point for designing a passive solar building. The south-facing side of a building is the location where solar collection will occur in the northern hemisphere. South-facing windows will bring solar radiation to the interior for solar heat gain. Thermal mass within the building should be located in line with the solar collecting apertures so that it can receive direct solar radiation. Other passive solar features, such as sunspaces and Trombè walls, should also be located on the south side. Optimally, the shape of the building should be longer in the east-west direction to maximize the
south-facing surfaces of the building. The building could even be slightly curved like Frank Loyd Wright’s Solar Hemiscycle house in Madison, Wisconsin. The building forms a concave arc oriented towards the sun, which allows the building to collect the sun directly from thirty degrees of due south.

When working with an existing structure, which is the case with this thesis project, modifying the orientation is not generally practical. However, the layout of the building can be modified to optimize the southern exposure for spaces that need it the most. The windows can be resized and relocated. The decision for modifications to the roof and wall structures should be influenced by solar orientation. Finally, the layout of the interior spaces should be logically located based on solar access requirements. “The rooms where people will spend most of their time should be located on the south side of the house, while utility rooms, bathrooms, closets, stairways, and hallways should be located on the north side of the house.” (Holladay, 2015) Bedrooms can be located where it is cooler and more dimly lit, whereas the primary social spaces, including the kitchen, the dining room, and the living room, should be located for maximum solar access.

The Building Envelope

Bainbridge and Haggard make an unambiguous statement that before considering passive solar strategies, a “passive building must first be an energy-conserving building.” (Bainbridge & Haggard, 2011, p. 67) Passive house builder, Brian Knight, also bluntly states that “the most important detail of a passive solar design is an airtight, continuously insulated building envelope.
Free heat does us little good if we can’t control where it goes. A building envelope is the most important component of passive solar, energy efficient and high performance homes and buildings.” (Knight, 2011) The collection, storage, distribution, and control of solar energy are the essential elements of a passive solar structure. These elements, coupled with an energy-efficient building envelope, are critical in order to facilitate the effectiveness of the passive solar functions, whereas an inefficient envelope will work to defeat the objectives of passive solar. A building that suffers from too much energy loss will not be able effectively to store and distribute solar energy in a controlled manner in order to promote human comfort.

**Figure 16 Features of an Effective Building Envelope. Source: Autodesk Sustainability Workshop**

**Thermal Conductance**

Insulation is largely intended to address the conductive characteristic of the building’s skin. The higher the quality of the insulation, the less heat will be lost via heat transfer through the building envelope. Conductive heat loss is measured via the U-factor, the inverse of the more familiar R-value. Lower U-factors (or higher R-values) mean that insulation (or any building material) is better able to resist the transfer of heat energy. In cold weather, the objective is to keep the heat inside, while in hot weather the heat should be kept outside. In a passive solar home, the heat that has been collected and stored in thermal mass will be released as the indoor temperature begins to cool during the night. If the conductive value of the exterior
walls and roof are too high, then the heat being released by the thermal mass will be lost to the outdoors too rapidly, resulting in indoor discomfort. Thus, conserving the indoor heat energy is critical for an effective passive solar design. There will be little chance of success with collecting solar energy in a poorly insulated building. “For passive design, the motto should be ‘Insulate before you insolate.’” (Brondzik & Kwok, 2014)

Glazing is also a primary concern for heat loss because even the most energy-efficient windows suffer from much more heat loss than even code-minimum insulated walls. Yet, glazing is an essential part of any building for transmitting daylight and, depending on the orientation, solar heat energy. Along with other building materials, window technology has experienced significant advancement in the past twenty years. Windows are now available with double and triple panes, Low-E metallic coatings on the glass to reduce radiant heat flow, gas-filled spaces between the panes to lower conductive heat transfer, and improved frame designs to control thermal bridging and leakage. The designer must carefully consider the type of windows that are selected for each location in the project.

**Thermal Bridging**

In addition to insulation and glazing, thermal bridging is another important issue that impacts the conductance of the thermal envelope. While different insulating materials may have R-values ranging from R-3 to R-8 per inch, depending on the type of insulating material, wood has an R-value of only about R-1.25 per inch. Thus a light wood-framed wall assembly with insulation installed in the cavity between the framing members will suffer from heat loss through the wood frame in spite of the presence of the insulation. The image shown in Figure 17 is a classic illustration of the impact of thermal bridging. The frost clearly shows the location of the roof rafters.

![Figure 17 Effect of thermal bridging (Lstiburek, 2012)](image)
even though high R-value closed-cell spray foam insulation was installed in the cavities between the rafters. To counter the detrimental impact of thermal bridging, the “bridge” created by the framing members must be interrupted by a low-conductance material. Most often, this is accomplished with a layer of continuous insulation on the exterior of the wall sheathing or on top of the roof sheathing. Any heat that attempts to transfer through a high-conductance material, such as wood framing, will be slowed by the presence of the continuous insulation. There are other solutions, including the Bonfig Wall assembly that includes a one-inch layer of rigid insulation on the interior edge of the wall studs or rafters which resists the transfer of heat energy before it reaches the wood framing members. (Bonfiglioli, 2015) Arresting the impact of thermal bridging is critical to improving the overall performance of the building envelope.

**Air Infiltration**

Air infiltration is another critical topic in creating an energy-efficient building. The Green Building Advisor (GBA) explained that “Stopping air leaks is just as important as — maybe more important than — adding insulation. Unless builders prevent air from leaking through walls and ceilings, insulation alone won't do much good. Not only are drafts uncomfortable, but air moving through insulated cavities can cut the efficiency of the insulation by as much as 50%.” (Insulation Overview, 2012) To further emphasize the point, the Building Science Corporation (BSC) declared that “All wall assemblies experience a loss in thermal performance due to air movement through the assembly. This is true … regardless of the type of insulation material used.” (Holladay, 2012) So, it is important to stop the air leakage, and the clearest way to accomplish this is with an air barrier.

Different methods are utilized for creating an air barrier. The low-cost method is to carefully inspect every area of the building envelope and seal any cracks and penetrations with sealant, tape, or canned spray foam. This task must be performed while the structure is open and
accessible, before insulation and finishes are installed. A second option for creating an air barrier is to select an insulation material that can also act as an air barrier. Spray foam and taped rigid foam insulation, if properly installed, can be used to create an air-tight structure. (Holladay, 2012) However, some designers advocate against using materials to perform more than one function as doing so can increase complexity and the chance for failure. (Baczek, 2013) The third method for creating an air barrier is to install a membrane specifically designed to be an air barrier. Traditionally, a weather resistant barrier (WRB) such as Tyvek house wrap, is stapled to the outside of the wall sheathing. If the product is taped and carefully installed, it is a cost-effective means to creating an air and water barrier, while allowing water vapor to escape to help keep the walls dry. (Dupont Tyvek Building Envelope Solutions, 2017) More recently, a variety of new products have appeared on the market, many from Europe, with promises of creating a super air-tight home. (https://foursevenfive.com/)

Indoor Air Quality

A consequence of creating a super air-tight home is that the home may suffer from poor indoor air quality. The lack of fresh air can create an unhealthy environment for the occupants, because of the off-gassing of contaminants and harmful particulates from building materials and human activity. (EPA, 2017) There needs to be a way to exhaust and replace the stale indoor air with fresh outdoor air. A leaky building will naturally ventilate with fresh air, but the ventilation will be uneven and the air leakage will cause excessive convective heat loss, leading to discomfort and high energy consumption. Windows could simply be opened, but that would not be practical during cold seasons. A passive solution for ventilation is the creation of a solar chimney, in which the air inside the chimney is heated by the sun, which will cause the air to become buoyant and rise through a vent at the top of the building. This process will create
negative pressure inside the house and fresh air will be drawn into the interior from strategically located inlet ports. (Wilson, 2014) Ideally, the inlet ports should not simply be located on exterior walls, which will bring in cold air. Instead, the inlet ports should be piped through the ground so that the earth can temper the cold outdoor air before it enters the home (see Figure 18). The difficulty, though, with solar chimneys is that the sun is not always available to warm the air within the chimney, thus making the system intermittent in its performance and effectiveness.

A more reliable solution is a controlled mechanical ventilation system with an air-to-air heat exchanger. A heat recovery ventilator (HRV) includes inlet and outlet ports at key locations in the house. Stale indoor air is withdrawn from the house and exhausted to the outdoors, while fresh outdoor air is supplied to the indoor spaces. Before the stale indoor air is exhausted, it passes through a heat exchanger where much of the heat is captured and passed to the incoming fresh air. The exchanger is a key component to prevent excessive heat loss with the ventilation system. While the system is an added cost and requires an electric fan to move the air, the energy consumption is minimal and the value of having high-quality indoor air is significant.
**Direct-Gain Systems**

Direct-gain systems are probably the most familiar passive solar feature, with south-facing windows allowing sunlight to shine directly into living spaces, providing warmth and daylight. “Simply stated, in a direct-gain system, heat is collected or dissipated directly within the living space; thermal collection and storage are integral with the building’s interior.” (Wright & Andrejko, 1982) Windows are the primary means of thermal collection, and interior materials of thermal mass are used for thermal storage.

![Figure 20 Direct-Gain Systems](image)

**Solar Collectors**

Glazing is the medium with which solar radiation is collected for a passive solar house. The objective for passive solar design is to *optimize*, not just increase, the amount of south-facing glazing. As mentioned in the previous section, window technology has grown tremendously since the height of the passive solar movement during the 1970’s. Window selection is critical to the success of a passive solar design. An incorrect window selection may result in too much heat loss or too little solar radiation collected. Today, every window sold in the United States must include a National Fenestration Rating Council (NFRC) rating. (NFRC, 2017) These ratings, affixed to every new window, include four rating numbers, three of which
are particularly relevant to passive solar space heating. These numbers include the U-factor, the Solar Heat Gain Coefficient (SHGC), and the Air Leakage.

The U-factor determines the conductance of the window, the inverse of which is the R-value. Higher performing windows will have a lower U-factor, which is generally achieved by adding panes of glass, applying a low-emissivity metallic film to one or more surfaces of the panes, replacing the air in the space between the panes with a low conductance gas, such as argon, and by reducing the thermal bridge impact of the frame and the glass spacers. More specifically, the U-factor measures the amount of energy of British thermal units (Btu) that is conducted through a material per hour (h), per square foot (ft²), per degree Fahrenheit (°F), or Btu/h·ft²·°F. U-factor values typically range from 0.25 (best) to 1.25 (worst). (energystar.gov)

The SHGC measures the transmittance of solar radiation. The SHGC is somewhat controversial, because many resources recommend windows with low SHGC for high performance homes because solar heat gain will lead to higher cooling costs during the summer. However, the solar collecting windows for a passive solar house need the solar radiation, which means the SHGC measure should be fairly high. The ideal window for passive solar collection is one with a high SHGC and a low U-factor, which is a combination not always readily available. It should be noted that this discussion is about the south-facing solar collecting windows only. The east-, west-, and north-facing windows should all have low measures for both the U-factor and the SHGC.

Figure 21 Typical NFRC Label
The third rating, Air Leakage, measures how much air will pass (or leak) through the window. Obviously, a leaky window is not desirable, and, like the U-factor, the number should be as low as possible. What is interesting with this rating is that different types of operable windows will impact this measure. A fixed window would be expected to have the lowest air leakage value. Among operable windows, those that close by compression rather than sliding are more efficient. Thus, casement and awning windows would naturally be expected to have a lower air leakage number than double-hung or sliding windows.

Another way to think about the relationship between SHGC, U-factor, and Air Leakage is that SHGC is the means by which the window will collect heat, and the U-factor and Air Leakage are the measures of how quickly a window will lose heat. Heat will be collected on a sunny day as the sun’s radiation shines through the windows, heating the interior space. During the night and on cloudy days, though, heat will be lost through the window. One’s ideal objective, then, is to collect a greater amount of heat than is lost for a net gain over a period of time. Interestingly, a south-facing, high-performing, triple-glazed window with a high SHGC and very low U-factor and air leakage values may gather more heat than is lost, in effect making them higher performing than the high R-value wall in which the window resides. (Holladay, 2015)

The fourth rating on the NRSC label is the Visible Transmittance (VT) which measures how much visible light is transmitted through the glazing. The higher the number, the more visible light will enter the space. While this rating does not have a significant impact on energy calculations for the passive solar house, it is still worth noting. It was mentioned earlier that daylight is an important component for this project, and sun glare is an issue that should be addressed. The east and west windows are most susceptible to glare when the sun is rising or
setting. Tinting the window can help reduce the discomfort experienced from glare, thus a window with a lower VT measure will be better for the east and west windows. (Holladay, 2016)

In terms of cost effectiveness of expensive windows, the research does not support investing in the most expensive windows available. To be sure, inexpensive windows that are leaky and have a high U-factor are a significant drain on the home’s energy-efficiency. Gary Proskiw, a mechanical engineer from Winnipeg, Manitoba, researched this issue in the paper, “Identifying Affordable Net Zero Energy Housing Solutions.” At issue is the fact that windows, even average-performing windows, are more costly per area than the same area of wall, but the thermal performance of the window is significantly lower than the wall. Also, there is a wide price-range among the high-performing windows. The question then becomes: when does the incremental cost increase of the window begin to diminish its return on investment? Proskiw found that even though extra high-performing windows may lower energy consumption due to increased solar heat gain, the reduction of energy consumption does not justify the significant increase in the window costs. In one example, Proskiw calculated that switching a one square meter, conventional, triple-glazed window to a more expensive argon-gas filled triple-glazed window having low-e coatings and insulated spacers saved a mere eight kWh per year (less than $2.00), yet it cost an additional one hundred twenty-eight dollars, plus additional installation costs.

Proskiw explained that when a house is energy-tight, the energy consumption is already fairly low, and that an incremental increase in window performance will not have a significant impact since windows are a relatively low percent of the overall wall surface area. Proskiw argues that condensation control is a more critical issue. The window’s U-factor should be low enough to resist condensation, but the thermal performance beyond that is not a significant factor
in the building’s overall performance. In summary, Proskiw’s recommendation is to “Select a window which meets the minimum condensation resistance requirements of the National Building Code [of Canada]. This will mean complying with either the maximum U-factor requirements or the minimum Temperature Index requirements [of the code]. Further, restrict the south-facing window area to no more than 6% of the floor area of the house.” (Proskiw, 2010)

*Thermal Mass*

After solar collection, thermal storage is the next essential element of an effective passive solar strategy, and this is accomplished through thermal mass. All materials have thermal mass of varying capacities. To be effective as a heat storage component in a passive solar building, the material must have adequate heat capacity in order to store enough heat, and it must release the heat at an optimal rate in order to moderate indoor temperature flux. Many metals have high heat capacity, but they are ineffective as passive solar thermal mass because of their high rate of conductance – heat is absorbed and released too fast. On the other hand, wood also has decent heat capacity, but its rate of conductance is too low. Water has excellent thermal capacity, and many passive solar designers have incorporated water walls or tanks into their plans. Using water requires special design considerations and watertight containers would become an important concern. Novel building products use phase change materials (PCMs), offering the potential for lightweight solutions for thermal mass. National Gypsum experimented with the production of PCM gypsum wallboard, but its implementation has not yet reached the end user, likely due to costs or flammability concerns. (Mathews, 2013)

By far, the most common form of thermal mass is concrete, masonry, and stone. For a direct-gain system, the thermal mass must be coordinated with the solar collecting glass in order to receive solar radiation directly. Usually, this is accomplished with a concrete floor and/or a
masonry wall on the north side of the space, opposite the south-facing windows. As the sun moves along its path, the solar radiation will be absorbed by the thermal mass. The amount of thermal mass is an important consideration in order to be able to store enough heat, and it is equally important to not lose the heat to the wrong side of the thermal mass. For instance, the concrete slab must have insulation under it. Otherwise, much of the heat energy absorbed by the concrete will be lost to the earth below since the earth is consistently cooler than the indoor temperature and heat moves from warm to cold.

Thermal mass, if properly implemented, can have a positive impact on the Mean Radiant Temperature (MRT) of a space. Simply put, the MRT is the average temperature of all of the surfaces in a space, including floors, ceilings, walls, doors, and windows. The radiant temperature of the surfaces may have a greater impact on the perceived comfort of a space than the ambient air temperature. When facing cold surfaces, radiant heat will be drawn from one’s body through emissivity. Conversely, when facing warm surfaces, one’s body will absorb radiant heat regardless of the air temperature. “As a matter of fact, warm surfaces may cause a person to feel warmer than the surrounding air temperature would indicate and likewise cold walls or windows may make one feel cold even though the surrounding air may be at a comfortable level.” (Alfano, Dell'Iola, Palella, Riccio, & Russi, 2013)

Thermal mass seems to be a rather controversial topic with those weighing the benefits of passive solar versus super-insulated construction. Thermal mass is generally more costly and, if not designed properly, can be more harmful than helpful. A house with a lot of thermal mass on both the interior and exterior is most effective if it is located in a diurnal climate, which is a climate that experiences wide daytime and nighttime temperature swings. When it becomes hot during the day, the thermal mass will absorb much of the heat keeping the indoor temperature
from becoming too hot. Then, during the cool night, the thermal mass will slowly release its stored heat keeping the indoor temperature from becoming too cold. In other words, the thermal mass is useful to moderate the indoor temperature swings. In a cold climate, however, the outdoor temperature may never reach above comfort level. Thus, the thermal mass never gets an opportunity to absorb very much heat energy. In fact, the conductance of the thermal will constantly draw heat away from the interior to the exterior. In this case, insulation is needed more than thermal mass because the mass will be working against the thermal comfort of the occupants. (Holladay, 2013)

Another concern when relying on thermal mass for space heating is its lag affect. It takes a while for the mass to warm up and then the heat will be released at a fairly slow rate. The result of this is a wide indoor temperature swing that many users find uncomfortable. Building performance researcher, Peter Yost, stated that “during the winter, I’ve concluded that it is best to expand your thermal comfort zone quite a bit in the early mornings until the sun catches up on that mass.” (Holladay, 2013) The solution for this is to include a supplemental heating system that can quickly warm up the house in the early morning.

Martin Holladay of Green Building Advisor provides the following rules of thumb for including thermal mass in a direct-gain passive solar building (Holladay, 2013):

- The area of the thermal mass should be about three to six times the area of south-facing glazing for direct-gain systems.
- The maximum thickness of the thermal mass (usually concrete) should be about 4 inches. Thicker concrete won’t absorb heat quickly enough for the extra thickness to be useful for direct-gain systems.
- Dark-colored concrete floors work better than light-colored floors.
- Concrete floors should be bare — not covered with carpets.
While four inches of concrete slab appears to be a common recommendation as a starting point, the final effective sizing is based on system type and material type. Concrete is common, but earth, brick, water, stone, and other mass materials may be used, each of which have their own guidelines. Furthermore, whether or not the thermal mass is directly exposed to the sun also impacts the design of the component.

Bare concrete is not particularly attractive and can be industrial looking. However, there are options to improve the appearance of exposed concrete. “Stained and polished concrete floors are increasingly recognized as one of the most aesthetic, low-maintenance, high-performance floor finishes available.” (Knight, 2011) Another option to dress up a concrete slab without losing its thermal mass benefits is to cover the concrete with a hard-surface material, such as slate or granite. Regardless, if a concrete slab is to be used within a space with south-facing windows, it makes logical sense to tap into its passive solar potential.

Another topic of contention with using concrete for thermal mass that should be mentioned is the environmental impact of producing Portland cement, a key ingredient in a concrete mix. “Producing the Portland cement that binds concrete together is energy intensive and emits enormous amounts of carbon dioxide (CO₂) as well as numerous other pollutants.” (Ehrlich, 2010) Producing Portland cement requires 1.6 tons of raw materials, mainly limestone, silicon, aluminum, and iron, to produce one ton of Portland cement, and then the mined materials need to be heated in a kiln to an astounding two thousand, seven hundred degrees Fahrenheit. The production of Portland cement alone accounts for about five percent of the total anthropogenic carbon dioxide emissions worldwide. (Ehrlich, 2010) Substitute materials for Portland cement will help reduce its environmental impact. The most common substitute is fly ash, which is a byproduct of coal-fired power plants. Fly ash can replace up to forty percent of
Portland cement in standard applications, although fly ash has its own environmental concerns, with some considering fly ash to be a hazardous material. “More research needs to be done, but if we can reduce concrete’s carbon footprint using fly ash in a way that locks up contaminants and keeps them out of landfills—where leaching is much more likely—then concrete should remain a key material for creating durable, green buildings, at least until something better comes along.” (Ehrlich, 2010)

Shading Devices

Inevitably, too much sun radiation will lead to overheating, particularly during the warm season when there is little conductance of heat through the building envelope. Heat from the solar radiation will build up and simply have no place to go. David Wright, et al., explained that the most effective method to address this problem is to prevent too much solar radiation from reaching the dwelling in the first place. “Shading the exterior, interior, and surrounding areas of a structure is the first line of action to reduce the temperature buildup due to ambient air or solar incidence. By limiting the amount of heat buildup in the thermal mass of a building, the job of cooling is reduced.” (Wright, Andrejko, & Cook, 1978, p. 164) Trees are often cited as effective shading devices that prevent excessive solar radiation from reaching the building. For this project, mature deciduous trees are located to the southwest and west of the house, and provide late-day shading when the home is more vulnerable to overheating. (See Figure 22)

In addition to vegetation, there are other approaches to providing shading. The two general categories for shading strategies include exterior and interior devices. An exterior shading device is deemed to
be more effective because it blocks solar radiation from reaching the window. Interior shading device, such as curtains, roller shades, blinds, or interior shutters, permits the radiation to enter the window, but then attempts to block it from going any further. However, once the solar energy has entered the building envelope, a portion of the energy will pass around the device and enter the interior space. (Bainbridge & Haggard, 2011)

For the exterior, special shading devices include louvered shades, blinds, or operable shutters. A more common exterior shading feature is a type of fixed overhanging device, including an awning, a sun shade, or the roof overhang. Because of the movement of the sun at different times of year, the precise design of the overhanging device can be problematic. For example, in early April, the outdoor temperature is still quite cold and thus collecting solar radiation for warmth is desirable. However, in early September, the outdoor temperatures may still be rather warm and the solar radiation may be unwanted. Yet, the sun is following the same path in both instances. Adjustable overhangs are one possible solution to this dilemma, although they are more expensive, prone to failure, and require the engagement of the user, which is typically unreliable. Fortunately, computer modeling allows the designer to configure the overhang in a way that is a reasonable compromise. (Wilson, 2012) The sun shading scenarios illustrated in Figure 23 show the challenges of designing an effective shading system.
One passive solar designer takes a contrarian view on using shading devices. Architect Peter Powell specializes in passive solar homes in the Maryland and Pennsylvania area and has lived in seven of them. Powell states bluntly that overhangs and shading devices are “ugly, unnecessary, and counterproductive.” (Powell, 2010) He explained:

In my experience, these overhangs are not really needed. Because of the high solar altitude in the summer, over half of the solar radiation striking the glass is simply reflected away; another significant fraction of the solar radiation is rejected by the glass coatings.

Most overheating problems in the summer are due to east and west windows — windows which can’t easily be shaded and which obviously should be minimized in the design.

The easy solution to most summer overheating is to open windows. The major cause of summer thermal discomfort is caused not by excess solar gain but by high ambient temperatures and humidity. We shouldn’t throw out the baby with the bathwater by installing overhangs which are counterproductive most of the year and only marginally helpful in August (at least in my climate).
Solar gain in the spring and fall should generally be maximized and the heat stored to minimize any overheating. Overhangs, which by design will be shading as much as half of the glass in these seasons, should be avoided. (Powell, 2010)

In spite of Powell’s admonition, there are no plans to completely disregard shading design for this thesis project. Powell’s comments are thought provoking and will influence the design of shading strategies. Below is a list of general recommendations for shading control (compiled from various sources):

• Accept that fixed outdoor shading will not be perfect
• Design shading for summer, but not the swing seasons
• Moveable shading is a possible solution
• Ventilation is more a effective cooling strategy
• Keep windows vertical and avoid skylights
• Locate deciduous shade trees along the west, not the south

In summary, designing a shading device that will block all unwanted sun while permitting all wanted sun is not a realistic goal. Instead, minimal shading should be provided only to block the extreme of solar heat gain during the peak of summer. Beyond that, flexible devices, such as interior shades and blinds, should be provided to allow for user adjustability.

**Indirect-Gain Systems**

In the direct-gain system described above, the solar energy is passed through the wall via glazed apertures directly into the living space. An indirect-gain system works differently in that the south-facing exterior wall becomes the collection and storage feature of the passive solar system. “Heat is accepted or dissipated at the weather skin of the building. Typically, collection is separated from the living space but storage is thermally linked.” (Wright & Andrejko, 1982)
Thermal Walls

In an indirect-gain system, the south-facing exterior wall is a thermal wall consisting of a layer of glass that collects and traps solar radiation, a layer of thermal mass used to absorb and store the radiation, and an air space separating the two layers. The air within the airspace is heated by the trapped solar radiation, which causes it to rise and enter the living space via vents near the top of the thermal wall. Simultaneously, the cooler interior air flows into the air space via vents near the base of the thermal wall. In turn, the cool air is warmed by the solar radiation, rises, and returns to the living space creating a natural convective loop delivering warm air to the living space. After the sun sets and the convective current has paused, dampers on the vents will close in order to prevent a reverse thermosiphon event where the warm air within the living space is inadvertently drawn out. In addition to the convective current, the sun will shine on the thermal mass, which will absorb the solar radiation. As the indoor temperature begins to fall, the heat stored in the thermal mass will be released to provide warmth to the living space.
The most familiar type of thermal wall is the Trombè wall, named after French scientist, Felix Trombè. The Trombè wall consists of a mass wall, typically concrete or masonry, in varying thicknesses depending on the material used. The mass wall creates a lag so that the stored heat will radiate to the space at night. (Bainbridge & Haggard, 2011) The Trombè wall is also painted black or some other dark color to aid with absorption of the solar energy. While Trombè walls have been demonstrated to work (Torcellini & Pless, 2004), perhaps the biggest drawbacks with thermal walls are that they are costly, they block the southern view, and they reduce daylight to the living space. (Kosmer, 2011)

Water walls are similar to Trombè walls in that glazing is used to trap solar radiation within an air space between the glazing and the mass wall. In this case, water is used for the thermal mass material. Water has a higher heat storage capacity than concrete or masonry, and heat will transfer through the medium faster due to the natural convective currents that will occur within the water container. While black-painted metal drums are traditionally used for passive solar water containers, translucent tubes may be used to allow daylight to enter the living space. Also, color dyes may be added to the water to create an attractive architectural feature.

[Figure 25 Trombè Wall System Source: Autodesk Sustainability Workshop]
Isolated-Gain Systems

An isolated-gain system is similar to an indirect-gain system except that the solar radiation is captured and stored outside the building envelope. “Collection or dissipation is adjacent to or apart from the weather skin and remote from the primary living spaces.” (Wright & Andrejko, 1982) Like a ducted furnace operating in a basement or utility closet, an isolated-gain system functions independently of the living space. Heat is collected and distributed only when it is needed. Two common isolated systems include a sunspace and a thermosiphon system.

Figure 26 Water Walls Source: Autodesk Sustainability Workshop and Solar Components Corporation

Figure 27 Isolated-Gain Systems Sketches by Phill Cooper (Wright & Andrejko, 1982)
Sunspaces

Sunspaces are the most common feature for an isolated-gain system. Solar radiation is collected through the sunspace glazing and then either distributed to the living space or stored in thermal mass within the sunspace. A low-thermal mass sunspace will be able to distribute higher amounts of heat to the living space during the day, but then the space will become cold and may even freeze during the night. A high-thermal mass sunspace will have less heat available for distribution because the mass will absorb much of the heat, but the thermal mass will help to moderate the temperature extremes of the sunspace, which will make the sunspace more useful for growing plants or as an extended living space. Thermal mass is often provided as a concrete or masonry floor, or metal drums filled with water. A convective loop is created as the air in the sunspace is warmed and circulated within the living space through a door, a window, or upper and lower vents in the wall separating the spaces, similar to the thermal wall vents described in the previous section. The presence of the openings allows the occupants to control the convective flow. On a cool day with the sun shining, the door can be opened to circulate warm air into the living space. During the summer, on the other hand, the door can be closed to prevent overheating in the living space.

Figure 28 Sunspace System  Source: Autodesk Sustainability Workshop
Another benefit of sunspaces is that they can act as a greenhouse for growing plants. The temperatures will vary greatly, however, so the plants must be able to tolerate wide temperature swings. (Strickler, 1983) One should understand, however, that using the sunspace for growing plants will involve heat loss penalty. Through a process called transpiration, water is absorbed by plants and then released through their leaves as water vapor. (USGS, 2016) This process of evaporation absorbs heat from the sunspace. (Jones & McFarland, 1984, p. 140) Though this may be desirable during the warm season to help with cooling, the sunspace will be unable to produce as much heat as it could during the cold season if the sunspace was devoid of vegetation. Thus, one must weigh the benefits of being able to grow plants in the sunspace versus maximizing its heat production during the cold season.

A sunspace can also be a very pleasant extension of the home’s living space - a place where one may retreat that is quite different from the other spaces in the home. As already mentioned, a sunspace is susceptible to wide temperature swings. To become a more comfortable living space, strategies will need to be in place to moderate the extreme temperature swings typically experienced in unconditioned sunspaces. Thermal mass should be used to absorb and release solar radiation. The sunspace should consist of no more glazing than necessary, and sloped or roof glazing should be avoided since they are prone to significant heat loss. All unglazed walls should be airtight and insulated, similar to the house’s exterior walls. Finally, exterior vents should be provided to exhaust hot air when the space overheats. (DOE, 2000)

Figure 29 Sunspace Living  Source: DOE
One must be very careful when considering installing a sunspace. Research has shown that the heat energy produced by the sunspace does not justify its construction costs. Thus, including a sunspace as part of a passive solar strategy should be based on more than just having it be an isolated-gain component. A sunspace is often considered a “thermal flux zone,” similar to an air lock space or a buffer zone. The temperature swings in this type of space will be expected to vary beyond the comfort zone, yet the space may offer benefits other than energy conservation.

Martin Holladay elaborated on this topic in a blogpost on Green Building Advisor:

There are very, very few hours during a year when these spaces are comfortable. They are almost always too hot or too cold, so you won’t see many people sitting in their sunspaces with a smile on their face. [Designed appropriately], they can add a little bit of heat to a house. That said, homeowners who invest in this type of room should be aware that the investment won’t be a cost-effective way to lower their energy bills. It’s simply another room -- one that may be delightful and worth the investment (because of the pleasure it provides), but not one that can be considered an energy feature. (Holladay, 2015)

The United States Department of Energy (DOE) also cautioned against investing in a sunspace simply for generating heat. “In practice, sunspaces are rarely built to serve only as heaters, because there are less expensive ways to provide solar heat.” (energy.gov, 2000) That is not to say that the DOE is against sunspaces. Beyond generating heat, they have value for providing space for growing plants, for extending the additional living space, and for increasing the market-value of the home.
Thermosiphon Features

As air warms, it becomes less dense, which means it will begin to rise. This fact of physics is the basis of a thermosiphon system. A glass panel collects and traps solar radiation which warms the air beneath the glass. The heated air will rise and draw in cooler air from below, thus creating a convective current. The heated air is either delivered to an indoor space, or the heat is transferred to a thermal mass storage system such as a rock bed.

Thermosiphon Air Panels (TAPS) can vary in size to service an entire house or just a single window. A variation of this system uses water instead of air in order to provide for domestic hot water.

Ventilation and Passive Cooling

As mentioned in the previous discussion on indoor air quality, ventilation is a critical component for healthy indoor air. Ventilation is also a key strategy for passive cooling. When the temperature becomes uncomfortably high, human comfort is assisted by air movement. Thus, a summer breeze can feel cool and refreshing, even if the temperature remains above the comfort level. There are two general approaches to natural ventilation: cross ventilation and stack ventilation. (Bainbridge & Haggard, 2011)

Cross ventilation occurs when two or more openings are located on opposite sides of a space. An analysis is done in both plan view and section view to determine the natural patterns of air flow. In addition to sketching air flows, the window openings should be roughly equal on the opposite sides to avoid creating a funnel effect on one side or the other. Outdoor
landscaping, wing walls, and overhangs will impact flow direction. Finally, certain window types, such as casement windows, are effective at capturing and directing air flow to the interior. (Bainbridge & Haggard, 2011) A limitation of relying on open windows and doors for a ventilation strategy is that they are only practical during warm seasons. A different strategy should be in place for ventilation during cooler seasons.

The second strategy for natural ventilation is stack ventilation, which again is based on the fact that warm air is lighter than cool air, causing it to rise, creating natural air movement. For a building, warm air will flow out of high vents creating negative pressure, which will draw cool air in through low vents. (Bainbridge & Haggard, 2011) This principle is the same principle that caused open fireplaces to fall out of favor. The fire heated the air in the chimney flue, which caused the system to siphon warm air right out of the house, resulting in high heat loss in spite of the fire. In the summer, though, the stack effect is a useful strategy to move hot air out. As previously discussed with solar chimneys, this system is most effective if the makeup air can be piped through the earth in order to provide for natural cooling. The earth would also be useful to moderate incoming cold-air temperature if the stack ventilation strategy was to be employed for year-round ventilation.
**Solar Savings Fraction**

When designing passive solar systems, it would be useful to know the amount of energy that would be offset with the various passive solar strategies. While it can be challenging to predict, estimating the amount of energy savings from passive solar will help determine the cost effectiveness of different strategies. Historically, the Solar Heating Fraction (SHF) was calculated to describe the percentage of the building’s heating load being offset with solar energy. Today, the more common measure is the Solar Savings Fraction (SSF).

While SSF and SHF are similar, they are not the same. SHF is the percentage of the total energy load provided by solar energy, ranging from 0% (no solar load) to 100% (full solar load). To be sure, some researchers defined SHF differently including one that described the SHF as being the percentage of solar energy collected compared to the potential solar energy available. This definition will always result in a low percentage as current technologies for collecting solar energy are inefficient. Most researchers, though, describe SHF as simply the percentage of the building's energy load being served by solar energy.

SSF is similar except that it compares the solar energy to the energy load of the same building of traditional construction methods using conventional sources for energy. In other words, it describes the savings realized when a typical building is converted to use solar energy. The building’s total energy load will likely increase when converting to solar, largely because more south-facing windows will result in more heat loss during the winter and increased cooling loads during the summer. However, the solar gains will outweigh the losses (hopefully), resulting in a solar savings.

Ideally, one would attempt to achieve the highest SSF (or SHF) percentage as possible. The higher the SSF percent, the less conventional energy sources will be required, thus saving costs as well as being better for the environment. A “sweet spot” should be achievable where the
balance between the SSF percentage and the cost of the passive solar system becomes optimal and in balance. Some climates will naturally be able to produce higher SSF values than others. Nevertheless, even if the percentage is relatively small, the clean solar energy will still be offsetting a certain amount of fossil fuel, which will contribute to a cleaner and more sustainable future for everyone.

**Climate Analysis**

In the Rochester region, in western New York State, the average daily temperature during the cold months of October through April is a mere thirty-five degrees Fahrenheit, and the region receives an annual average of ninety-nine inches of snowfall. The sun shines fully for only sixty-one days during an average year. One hundred four days have partial sunshine, and two hundred days are mostly cloudy or overcast every year on average. Another way of describing how much sunshine the region receives is that during the time period between sunrise and sunset, the sunshine actually reaches the ground only fifty-one percent of the time. (U.S. Climate Data, 2016) Table 2 ranks the major United States metropolitan areas with the number of days that experience at least twenty-five percent cloud cover. Rochester, New York ranks as the fourth cloudiest city with a stunning eighty-three percent partial cloudy or overcast skies.

A key challenge for this thesis project is to apply passive solar principles in a relatively cold climate that receives very

<table>
<thead>
<tr>
<th>City</th>
<th>Cloudy Days a Year % of Days</th>
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</thead>
<tbody>
<tr>
<td>Buffalo, New York</td>
<td>311 85</td>
</tr>
<tr>
<td>Seattle, Washington</td>
<td>308 84</td>
</tr>
<tr>
<td>Pittsburgh, Pennsylvania</td>
<td>306 84</td>
</tr>
<tr>
<td><strong>Rochester, New York</strong></td>
<td>304 83</td>
</tr>
<tr>
<td>Cleveland, Ohio</td>
<td>299 82</td>
</tr>
<tr>
<td>Portland, Oregon</td>
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</tr>
<tr>
<td>Columbus, Ohio</td>
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</tr>
<tr>
<td>Detroit, Michigan</td>
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<tr>
<td>Miami, Florida</td>
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<tr>
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<tr>
<td>Milwaukee, Wisconsin</td>
<td>275 75</td>
</tr>
<tr>
<td>Houston, Texas</td>
<td>275 75</td>
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</table>
limited sunshine. In 1994, Burke Thayer referred to this climate area as the “gloom belt” because of its frequent cloud cover and cold temperatures. For many people, the assumption would be that the “gloom belt” would not be considered an area where passive solar design strategies can succeed. As an architect and passive solar advocate, Dennis Andrejko demonstrated that this perception should not be the case. In Thayer’s article, Andrejko’s home addition is described as a passive solar addition in the suburbs of Buffalo. “In Buffalo’s climate, it makes most sense to design solar features for optimal performance during the ‘swing seasons’ of September to November and March to May rather than for the dead of winter.” (Thayer, 1994) Andrejko also explained that incorporating passive solar heating added very little to the construction cost of the project. “His approach to solar energy not only saves money but adds to the livability and beauty of a home. [...] Andrejko’s addition shows that passive solar design is not just for new construction, and that it can make sense anywhere in the country, even in the ‘gloom belt’ of western New York.” (Thayer, 1994)

Rochester is located in the International Energy Conservation Code Climate Zone 5 (IECC, 2009) as shown in Figure 33. The temperature range of Rochester is tempered by Lake Ontario, which is why the region south of Rochester is in the colder Climate Zone 6. The U.S. Department of Energy (DOE) identifies the Rochester as being a “Cold” climate (DOE EERE, 2015) because the number of heating degree days (65°F basis) is over five thousand, four hundred (See Figure 32).
Figure 33 IECC Climate Zone map of the United States (Source: https://basc.pnnl.gov/images/iecc-climate-zone-map)

Figure 32 Hygrothermal regions of North America (Source: https://buildingscience.com/)

All of Alaska is in Zone 7 except for the following boroughs in Zone 8:
Bethel, Northwest Arctic, Dillingham, Southeast Fairbanks, Fairbanks N. Star, Wade Hampton, Nome, Yukon-Koyukuk, North Slope

Zone 1 includes Hawaii, Guam, Puerto Rico, and the Virgin Islands
Table 3 below lists relevant climate data that will be required for analysis of the proposal.

Table 3 Table of climate data for energy modeling analysis (Source: https://www.nyserda.ny.gov/)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Project Geo-coordinates</td>
<td>43° 03’ N Latitude; 77° 85’ W Longitude</td>
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<tr>
<td>Elevation</td>
<td>642’ above sea level</td>
</tr>
<tr>
<td>Heating Degree Days (65° F basis)</td>
<td>6,748 (30-year average for 1971-2000)</td>
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<tr>
<td>Cooling Degree Days (65° F basis)</td>
<td>664 (30-year average for 1971-2000)</td>
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<td>Design Temperature, Winter</td>
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<tr>
<td>Design Temperature, Summer Dry Bulb</td>
<td>88° F</td>
</tr>
<tr>
<td>Design Temperature, Summer Wet Bulb</td>
<td>73° F</td>
</tr>
<tr>
<td>Snow Load</td>
<td>40 PSF</td>
</tr>
</tbody>
</table>
Climate Charts

The chart in Figure 34 shows the annual temperature range for the Rochester region, along with the noontime sun altitude angle. An important observation is that the temperate range lags the sun altitude, which is key to remember when making design decisions regarding solar collection and sun shading.
The chart in Figure 35 shows the monthly average cloud cover experienced in the Rochester region. As expected, the least average coverage occurs in July (forty-eight percent) and the highest average coverage occurs in December (eighty-three percent). On average for the year, the Rochester region experiences almost sixty-five percent cloud coverage. As also indicated in Table 2, the project location is an area that experiences a much higher than average amount of cloud cover, making it a challenging area for passive solar strategies.

Figure 35 Annual average cloud cover percentage (Source: Climate Consultant 5.5)
The chart in Figure 36 shows the relative humidity for the Rochester region. The comfort range for relative humidity is from forty to sixty percent. The Rochester region experiences a relative humidity higher than the comfort range during eighty-three percent of the year. As shown on the IECC Climate Zone map (Figure 33), the project location is within a “moist” region of the United States. As such, dehumidification will likely be a desirable cooling strategy for summertime comfort.

*Figure 36 Annual average relative humidity range (Source: Climate Consultant 5.5)*
Psychrometric Analysis

Figure 37 is the Psychrometric Chart for Rochester, New York. Every hour during an average year is plotted as a point in the chart according to the hour’s dry-bulb and wet-bulb temperatures and the relative humidity. Indoor comfort is dependent on a combination of factors including temperature and relative humidity. Two areas are outlined in blue, with the one on the right representing the comfort zone for winter and the left outline representing the comfort zone for summer. These comfort zones indicate the times of the year when climate conditions naturally fall within the comfort level and no additional strategy would be needed. Only nine percent of the hourly data fell naturally within the comfort range. Ninety-one percent of the time, an adjustment to the indoor climate will be required to achieve a comfortable environment.
for the occupants. The adjustment can be achieved via either passive or active (mechanical) means. According to the chart, fifty-seven percent of the time will require an active means of supplemental heating, ten percent will require supplemental cooling and/or dehumidification, and about twenty percent of the year can achieve comfort with only passive solar or natural ventilation. As a result, about one third of the year, or about four months, can be made to be comfortable without any supplemental heating, cooling, or dehumidification.

As previously mentioned, the optimal time for designing a passive solar system in Rochester’s climate is the swing seasons of September to November and March to May. It is important to note, however, that the sun paths will be different during the two seasons. The sun is significantly lower in the sky in the autumn when the sun is moving towards the winter solstice than it is during the spring when the sun is moving towards the summer solstice. This fact makes designing a perfect shading system impossible. However, according to the Psychrometric Chart, shading only accounts for less than six percent of comfort design.

**Solar Exposure**

A solar site selector was used to determine the path of the sun for the south-facing side of the dwelling. For most of the year, the southern exposure is reasonably clear. From September to March, however, the sun will be shaded by deciduous trees beginning around three o’clock in the afternoon. Fortunately, the trees will still have leaves in September when the late afternoon shade will be welcome, but in March the trees will be bare, allowing for filtered sunlight to reach the dwelling and thus providing much desired solar energy. Therefore, shading from the trees to the southwest and west will not have a detrimental impact on the project.
Figure 38 Sun path charted using a solar selector at the thesis project sight (neighbor’s home and barn is shown)

Figure 39 Sun angles from winter solstice to summer solstice. (Source: http://suncalc.net)
Figure 40 shows a computer model of the solar potential of the existing structure. Note that the only portion of the structure that currently receives high solar potential is the eastern half of the steep-slope roof. The western half of that roof is affected by the tree shading. When considering options for restructuring the roof, it was logical that expanding the steep-sloped roof eastward would provide significant benefits for solar potential. In fact, this was
demonstrated in the model. By simply expanding the steep-pitched roof, one can see the positive impact that would have on the solar potential of the building. The kilowatt hours potential increased from 39,600 kWh for the existing building to 98,000 kWh for the expanded roof, an increase of almost two and one-half times. Also, the steep-sloped roof receives the highest level of solar intensity because the forty-five degree pitch is nearly optimal for photovoltaic panels.

**Prevailing Winds**

The final chart describing the regional climate, Figure 44, is the annual wind rose, which shows the direction of the prevailing winds. The majority of the winds come from the southwest and westerly directions. This is important information when considering ventilation strategies for passive cooling during the summertime. Knowing the direction of the prevailing winds, the home’s layout can be designed to allow for effective cross ventilation with the windows opened. In addition, casement windows can be designed to help capture the winds and direct them into the house.
Figure 44 Annual wind rose chart (Source: Autodesk Revit Energy Analysis)

Figure 43 Prevailing winds across the project site (Image source: Google Maps)
**Existing Conditions**

**Site Analysis**

While the grade at the property is relatively level overall, the dwelling does sit upon a small knoll, which allows water to drain away from the house. Inspecting the basement confirmed that there is no evidence of water seeping in through the fieldstone foundation. There is no sump pit in the basement, and the executor, whose parents owned the property since the 1960’s, stated that the basement has never experienced flooding.

The basement does smell of mustiness, however, which indicates a high level of moisture and a lack of ventilation. The floor is cementitious dirt and the stone foundation walls do not have any damp proofing. There is only one basement window, which has been boarded up. All of these things contribute to a cold, dark, and damp basement. Presently, only mechanicals and services, including the furnace, water heater, electrical panel, well-water pump, water softener, and pressure tank, are located in the basement. Converting the basement to finished space is not

![Figure 45 Existing site plan (Image created using Autodesk Revit)](image-url)
a reasonable option for this project because of the insufficient head height, which is only about five feet and nine inches.

Mature poplar and maple trees lining the street to the west and southwest of the dwelling provide shade from late afternoon to sunset. To the east and southeast are a mix of coniferous and deciduous trees, but their distance has minimal shading effect on the dwelling. The neighbor’s barn is located southeast of the house, but it is downhill and has no impact on shading. Most of the trees appear to be in reasonable health, though they are in need of pruning. One significant tree that ought to be removed is a large maple tree located within the ell of the home and near the main entrance. The tree overhangs the house’s roof and it is located a few feet from the septic tank. Though there are no signs of damage to the tank from the roots, the septic system inspector strongly urged the tree’s removal. Also, the insurance company required the tree’s removal due to its close proximity to the house.

In general, the property’s landscaping is rather chaotic, suffering from years of neglect. Large shrubs flank the house along the west and south sides, and there are a few remnants of flower beds scattered around. The soil is average with a wide range of gravel, cobbles, and fines, including silt and clay. The piles of fieldstone and old stone walls in the area are evidence that the soil is rocky.

**Plans and Elevations**

Figure 46 on the following page shows the existing floor plans for the dwelling. The current layout is the result of numerous renovations and additions since the original structure was built in 1900. Initially, the dwelling consisted of only two bedrooms, both of which were located on the upper level. An addition was added north of the family room and the kitchen, and a new master bedroom and bathroom were created. On the south side of the main level was an open-air
porch and the dwelling’s main entrance. The porch was later enclosed and converted into a fourth bedroom. The sunroom at the southeast corner is on a slab-on-grade without frost-depth footings. The two-car garage at the north end was the most recent addition, added in 2003.

The highlighted area shows the conditioned space, totaling a little over one thousand, nine hundred square feet (1,900 SF). There is no natural gas service or water service available at this property. The current heating system is a forced-air furnace consuming heating oil. However, the duct work does not extend to the small bathroom and laundry room north of the main entrance. In-wall electric resistance heaters provide supplemental heat for these spaces. The remaining spaces, including the old garage (now just storage), the workshop, and sunroom, are all unconditioned spaces.
Most of the finishes in these spaces have not been updated for several decades. About a third of the walls is finished with plaster-and-lath, a third is finished with gypsum wallboard, and a third is finished with thin wood paneling fastened directly to the wood studs without any backer boards. The floors are mostly carpeted, though the dining and living areas are finished with vinyl tile. In the kitchen, the floor under the carpet is tiled, and likely contains asbestos. The floors in the entryway, and the bathroom and laundry room north of the entrance, are concrete floors finished with either paint or indoor/outdoor carpet.

Regarding electrical services, most of the electric outlets are two-pronged outlets connected to two-wire cables from the early twentieth century. A few receptacles have three-pronged connections, though they do not appear to be grounded. The electric panel box is one of the few items that has been updated with circuit breakers and two-hundred amp service. There is an electric subpanel located in the workshop. The main electric line from where the utility reaches the house to where it connects to the service panel is extremely frayed and presents a potential hazard.

Most of the plumbing supply and waste lines appear to be copper piping. A few waste lines are PVC. The waste lines connect to a cast iron pipe in the old cellar steps area and exit the house to the septic system. The plumbing fixtures are all very dated with some fixtures damaged and poorly functioning. As already mentioned, the water supply is from a well. The water pump is located in the basement and looks to be quite old though it is still functioning. Of concern is the fact that both the water well and the septic system are located in the front yard. The septic system was inspected and passed, but the inspector noted that the well is located approximately fifty feet from the leech field, which would be a code violation. The well should be located at least one hundred feet from the leech field in order to avoid potential contamination. Although
the Town of Wheatland’s building inspector is not requiring a change, strong consideration will be given to relocating the well.

The original house did not have indoor plumbing. When a bathroom was later added, the cellar steps were floored over for a new bathroom and the cellar step space was used to locate the waste lines connected to the septic system. Although the waste lines take up a lot of space, the concrete cellar steps are still present and could potentially be brought back to use for access to the basement. This detail is an important part of the renovation plan.

In further analyzing the existing structure, it is important to note the different foundation systems in this project, which are shown in Figure 47. As stated previously, the current structure is the result of multiple additions, each of which used its own type of foundation. The original house was built on a fieldstone foundation with a basement and a cementitious dirt floor. Adjacent additions include crawlspaces and pier foundations. The more recent additions used slab-on-grade foundations and stem walls. It is important to note that the sunroom’s slab does not have frost depth footings. Also worth noting is that the two-car garage is built as a pole barn. Another critical detail shown in Figure 47 is the different floor levels. While traversing the existing structure, it is noticeably uncomfortable having to frequently step up or step down to a different level when navigating from one space to another. Remedying the floor levels is an important issue that will be addressed with the proposed renovation plan.
Figure 47 Main floor levels and foundation types (Base image produced with Autodesk Revit)
Figure 48 to Figure 50 on the following pages show section views of the existing structure. There are a number of details worth noting as one considers design options for a passive solar retrofit. In Section 1, the important detail shown is the ample head room. This head room provides potential flexibility to adjust the floor level, in order to mitigate the excessive number of level changes on the main level. The floor is a concrete slab-on-grade. Also note the two-foot overhangs and the relatively low-sloping roof.

Section 2 shows a longitudinal section through the original house, the dining and living room addition, and the sunroom. Again, notice how each floor is at a different level. Also note the long, low-sloping roof over the dining and living room and sunroom. This low-slope roof is covered with a rolled membrane with welded seams. While there are no signs of roof leakage anywhere in the house, the condition of the roof is poor and it needs to be replaced. The long, low-sloping roof is also awkward in appearance and does a poor job of architecturally connecting the adjacent roofs. This situation presents an opportunity to engage in a significant restructuring of the roof in order to create a more architecturally-connected roof system and to improve water shedding. Furthermore, note that the wall separating the dining and living rooms and the sunroom is on a crawl space stem wall, which indicates that it is a load-bearing wall. This will be a very helpful fact when considering roof restructuring options.

The upper level roof pitch in Section 3 is twelve in twelve (forty-five degrees), while the roofs on either side are a much shallower three in twelve (about fourteen degrees). The forty-five-degree slope has a south-facing side; thus, the angle is nearly optimal for future photovoltaic panels. It is noticeably dark on the upper level, as each bedroom has only one small window on its gable end wall. Options to consider for bringing in additional daylight to the upper level include skylights or, preferably, dormers.
As previously noted, the bedroom on the south side on the main level was originally a porch and the space is rather narrow. It is also on a pier foundation, which means that the underside of the floor is exposed. It should also be noted that the roof over this bedroom is a hip roof making it noticeably different from the other roofs. Finally, notice the line of the abandoned cellar stairs in the basement.

Figure 48 Section 1 – Cross section view

Figure 49 Section 2 – Longitudinal section view
Figure 50 Section 3 – Cross section view
Energy Assessment

Obviously, the existing home is poorly insulated and very leaky. The comfort level in this home is quite low and the air quality is not good. Even a cursory inspection will indicate that the home needs a significant energy upgrade. Regardless, it is worthwhile to collect some numbers on the existing conditions in order to help determine the optimal strategy for upgrading.

Blower Door Test

A local home energy firm, Airtight Services, Inc., performed a blower door test. The purpose of this test was to measure the airtightness of the structure. The test procedure is pretty straightforward. An exterior door is selected and a fan and panel apparatus is sealed within the door frame. All other exterior doors are shut tight, and any windows or other openings are closed and locked. The power fan pulls air out of the house, and a pressure gauge measures the air pressure difference between the outdoors and the indoors. The fan speed is increased until it creates an air pressure difference of fifty Pascal, which has become the standard for home energy audits. Once the air pressure differential has been reached, a manometer will measure the amount of airflow.

When Airtight Services attempted the blower door test, they were unable to run the fan fast enough to reach the target air pressure differential of fifty pascals because, although they came close at forty-six pascals, the structure was too leaky. Nevertheless, the airflow rate was measured at a little over five thousand, one hundred cubic feet per minute (CFM).
According to the 2012 International Energy Conservation Code (IECC), the airtightness of a new construction should be at most three air changes per hour (ACH). To convert CFM to ACH, one must determine the volume of the conditioned space, which in this case is about fourteen thousand, five hundred cubic feet, and then use the following formula:

\[ \text{ACH} = \frac{\text{CFM} \times 60 \text{ min/hr}}{\text{space volume in cubic feet}} \]

\[ \text{ACH} = \frac{5,133 \text{ CFM} \times 60 \text{ min/hr}}{14,500 \text{ CF}} \]

\[ \text{ACH} = 21 \text{ ACH} \]

Twenty one air changes per hour is severely leaky. That is seven times the minimum allowed per the energy code! For an even more stark comparison, the airtightness standard for a Passive House is a mere 0.6 ACH at fifty pascals.

Just to further emphasize the importance of this issue, it is useful to ponder what these measurements mean. The interior air contains latent heat, which is what we consider the temperature of the air. A large portion of that latent heat was generated by the oil-burning furnace. For every cubic feet of air that leaks out of the house, it carries with it latent heat that had been generated, and the heat is wasted to the outdoors. A home that suffers from an ACH rate of twenty-one means that the entire volume of air of the house is lost multiple times every hour! Obviously, one does not normally have a powerful fan forcing that much air out. Nevertheless, the wasted energy lost from air leakage is palpable. Clearly, improving the airtightness of this home is of the utmost importance.

*Insulation*

Airtight Services also performed a thermal camera test and created some holes to determine the current level of insulation. Like the airtightness test, the insulation level was found to be either missing or poorly installed. There was only a thin layer of fiberglass batt insulation in the attics, and the walls of the original house were found to have no insulation. The
walls of the additions did have R-11 fiberglass batt insulation, but they were poorly installed with many gaps and compressed areas. Fiberglass batt insulation is an effective, low-cost insulation, but if it is not installed properly, its performance degrades rapidly.

Energy Consumption

While it would be helpful to have historical data for this property’s energy consumption, that data does not appear to be available. The house was unoccupied briefly prior to taking possession and it has remained unoccupied for all of the year 2017. The previous owner was moved to a nursing home, and the grandson was living in the home. There are no records kept, though even if they were available, it would likely be misleading due to the sporadic occupancy. The executor of the estate did comment that he recalled the electric bill always declaring that the property had very high energy consumption for its size and location, which is not surprising. From December 2016 to May 2017, the temperature at the unoccupied property was kept at forty-eight degrees to keep the water pipes from freezing. Even at this low thermostat setting, the furnace still consumed three hundred fifty-seven gallons of heating oil. Extrapolating this figure to the remaining cold months and estimating the increased consumption to maintain sixty-eight degrees, it was calculated that the property would consume between nine hundred and twelve hundred gallons of heating oil. At three dollars per gallon, that would require an investment of between two thousand, seven hundred and three thousand, six hundred dollars for heating oil. That is twice the national average for single family heating oil consumption. (EIA U. , 2017)
Daylighting

Most people, when they first enter the home, generally comment about how dark it feels inside. The home is divided into many rooms, which tend to be small with low ceilings. Also, many of the finish materials are dark, from wood paneling to dark carpets. The biggest reason for the dark feeling, though, is the small windows, which do not permit sufficient daylight into the space. On the main level, there are twelve windows in the conditioned spaces, for a total of one hundred fourteen square feet. There is also a large sliding glass door with sixty square feet of glazing. That is a total of one hundred seventy-four square feet of glazing. With one thousand, four hundred fifty-five square feet of floor area on the main level, that is a glass-to-floor ratio of twelve percent. On the upper level, there is twenty square feet of glazing for three hundred ninety square feet of floor, resulting in a glass-to-floor ratio of only five percent.

At first glance, the glass-to-floor ratio for the main level is low, but not excessively low. However, when you analyze only the south-facing windows, the total glazing area is thirty-four square feet, which is a glass-to-floor ratio of only two percent - a very low figure. Much of the glazing on the main level is on the other three facades, including a large picture window on the north wall. A daylighting analysis is shown in Figure 54. The well-lit areas shown by the yellow and green colors encompass very little of the floor area. The dark areas cover a significant portion of the plans, especially for the upper level.
Figure 54 Lighting Analysis - Existing main and upper levels (Source: Autodesk Insight)
An energy model, Figure 55, was created for the existing conditions. This energy model is more useful to establish a baseline for comparing results of different proposals, rather than for attaching true meaning to the results. The energy model results for the existing dwelling will be revisited in the following section on the proposed solution.

*Figure 55 Energy model of existing dwelling (Produced with Autodesk Revit Energy Analysis)*
Proposed Solution

The proposed design was guided by several precepts in addition to the main theme of the thesis, a passive solar retrofit. The first precept is that this home must first and foremost satisfy the desires of the clients. There is little in life that is innately more personal than one’s home, and the house is the container that encompasses the home. A home is “a diffuse and complex condition that integrates memories and images, desires and fears, the past and the present.” (Moore, Allen, & Lyndon, 1974) The clients provided the author with an initial program and many discussions ensued regarding the desired features of the home. In summary, the clients are a family of four, with two school-aged children. The children are educated at home, thus the mother and children are home most of the time, while the father works away from the home during regular work hours. The clients stressed that natural light is of the utmost importance for the living and school spaces. The family plans to engage in homesteading activities, including gardening and small-animal husbandry. Space must also be provided for overnight guests, especially for the couple’s elderly parents. The home will be active daily, so it needs to be comfortable, warm, bright, and inviting.

Full Demolition?

Another important precept for this project is that the solution ought to work with the existing structure as much as reasonably possible. To be clear, there is no historic preservation goal with this project. As explained earlier, the present dwelling evolved with a number of modifications and additions during its almost one-hundred twenty-year life. Architectural design was evidently not an important concern when the home or its additions were built. Presumably, the previous owners were primarily focused on practicality and economics. There are very few
features worth preserving for their architectural value, other than perhaps the fieldstone foundation and the steeply pitched roof of the original structure.

After reviewing the poor state of the existing house, a number of acquaintances have commented to the author that it should simply be torn down and rebuilt. Indeed, the existing house has numerous problems that many observers would use to justify razing the home rather than salvaging it. However, a structural engineer reviewed the house and determined that the structure is largely intact and does not need to be abandoned and demolished. Furthermore, much of the embodied energy contained in the existing home would become lost in a full-scale demolition. (Pfaehler, 2008) This sacrifice may be justified if the energy required to continue operating and maintaining the existing home remained extraordinarily wasteful. However, if the process of renovation resulted in an energy-efficient structure, then it would be difficult to justify the costs, in both energy and financial terms, of tearing down and removing the existing structure to a landfill, and constructing a new house in its place.

This author strongly believes that every option to salvage an existing structure should be explored and that demolishing the structure should only occur once all other options prove to be impractical. A competent designer ought to be able to demonstrate quality design, even within difficult limitations. In this case, the author determined that there are a few feasible options available to rehabilitate and renovate the house, taking advantage of the existing structure and foundation systems. Thus, simply engaging in a full demolition was eliminated as an option.

**General Layout**

The layout for this project can be divided into three general zones: the social, the private, and the utility zones. The social zone consists of those spaces where social interaction occurs, both within the family and with invited guests. This space, which includes the living room, the
kitchen, and the dining room, is also where the occupants will spend the majority of their time during the daytime hours. The clients desire this space to have an abundance of natural light and that it be a mostly open space to facilitate social interaction and natural heat distribution. The private zone consists of the bedrooms and bathrooms, which should be clearly separated from the social zone. This space is characterized by private rooms, and natural light should be moderated to facilitate a sense of privacy, peace and restfulness. Finally, the utility zone includes the laundry room, the mechanical space, the coat room, the pantry, and storage. The utility zone should involve spaces that are easily accessible, but they should not occupy the prime locations that receive optimal natural daylight.

A practical result of identifying the three zones is that doing so prioritizes locations that will receive the most benefits of passive solar features. Retrofitting the entire house into a passive solar structure was determined to be not only impractical, but also undesirable. The capture, storage, distribution, and control of passive solar energy is most effective in the areas that have southern exposure. Logically, the space that desires the most solar energy is the social zone. Consequently, this zone should be located in the southeast part of the house in order to capture not only the noon time peak solar energy, but also the morning sun in order to begin the warming process earlier in the day.

The private zone are ideally located on the western side of the home so that the spaces will be warmed by the late-day sun in order to provide comfort as the occupants prepare for sleep. In addition, deciduous trees along the western façade will provide afternoon shade during the cooling season to help prevent overheating. The clients also want the bedrooms to be located on the western side in order to block the morning sun, preventing an early-morning interruption to sleep. Finally, the utility zone should occupy the least desirable locations since these spaces
receive the smallest amount of direct occupant activity. Maintaining comfortable conditions and significant natural light is not as important for these spaces. The dark basement and the northwest area of the main level adjacent to the garage are the logical locations for the utility zone. Figure 56 below illustrates the location for the three zones overlaid on the existing floor plan.

Figure 56 Zone locations: social, private, and utility overlay the existing floor plan
Proposed Main Level Plan

Figure 57 below shows the schematic design proposal for the main level floor plan.
Figure 58 below shows the same floor plan overlaid with the three zones: social, private, and utility.
The following are highlights of the proposed modifications to the floor plan.

- The best outdoor view is towards the east, overlooking a meadow and the woods beyond. Thus, the living room, breakfast room, kitchen, and homeschool rooms are all located with east-facing windows to take advantage of the best view. The east-facing windows will also receive the morning sun for an early-day warm up.

- The space for the breakfast and living room is a new addition, replacing the old sunroom, which was in poor condition and was built on a concrete slab without frost-depth footings. The over five hundred square foot addition will be built with a stem wall foundation and an insulated concrete slab. This space is also the primary direct-gain passive solar space. See the following section, Passive Solar Analysis, for more details.

- While south-facing windows are critical for passive solar heating, the south view is not the most desired view. Thus, a sunspace was provided both to create an isolated–gain passive solar feature and to create a visual buffer for the dining room while still admitting natural light. The south windows in the living room are not buffered because they provide direct-gain solar energy. However, the expanse of glazing on the east wall will direct the occupants view to the more desired view.

- The issue of the multiple levels was addressed, not by attempting to eliminate the multiple levels, but by consolidating them and using them to define distinct areas. Attempting to raise all floor levels to the highest common level would have created complications with ceiling heights and added a significant cost to the project. Thus, the existing living/dining room space was deemed to be the main
level and the additional living spaces were designed to match that level. A six-inch step at the library leads to the private zone, and two steps at the entry create a defined entry space, as well as place the entry at the same level as the laundry and homeschool rooms.

- Though the main entrance has not been relocated, the entry is a much grander space with a nine-foot ceiling and a wide view towards the living spaces. A significant amount of natural light from the living spaces will spill over into the entry area, drawing the visitor to the brightly-lit living spaces.

- The library is used to create a buffer between the social and the private zones. The clients own hundreds of books and reading is an important part of their lifestyle. The library provides a quiet space for reading that is removed from the main social spaces.

- The original central stairway to the upper level was moved to create an improved circulation flow, to allow for better heat flow to the upper level, and to provide space for the main bathroom next to the master bedroom. The stairway to the basement was also relocated to the original cellar stair location. A new basement stairway will be built around the waste plumbing lines currently occupying cellar stair space. An analysis was completed to determine that this option is, indeed, feasible. Access will be provided in the stairway for plumbing maintenance.

- The main bathroom is strategically located to connect the toilet waste line to the existing waste line more efficiently. The toilet is also aligned with the new toilet on the upper level in order to share the same waste stack vent.
• The kitchen is relocated to the east side. The clients specifically requested that the sink be located at a window that overlooks the rear yard. The floor of the kitchen is a false floor, raised to match the living and dining room floors. The false floor also provides plenum space below for plumbing lines. While the kitchen is part of the social spaces, it clearly has its own defined space separate from the living room and dining room.

• The homeschool room is essentially a classroom. Located on the eastern side of the home with two large windows, it will receive abundant morning sunshine, which studies have shown improves student performance. (Plympton, Conway, & Epstein, 2000) The classroom is also located to be somewhat separated from the other social spaces, which minimizes disturbances for the children working on their lessons. The separation also reduces the chance that visitors will accidentally wander into the space.

• The south bedroom, which was the original porch, has been removed from the thermal envelope and returned to being a three-season porch. With five exterior surfaces, this space would be difficult to make comfortable. Rather than engaging in a major reconstruction of this space, simply returning it to its original purpose made logical sense. After all, a screened-in porch was a desired amenity requested by the clients.
Proposed Upper Level Plan

Figure 59 below shows the schematic design proposal for the upper level floor plan.

Figure 59 Proposed Upper Level Plan (Produced with Autodesk Revit)
The following are highlights of the upper level floor plan:

- The east bedroom is an expansion of the upper level with the east exterior wall aligned with the existing load-bearing wall below. The expansion not only provides additional floor space for the upper level, but also provides optimal roof space for photovoltaic panels.

- A north-facing shed dormer will provide additional daylight, more headroom, and a second means of emergency egress for the bedrooms and bathroom. The north side was selected for the dormer for four reasons. First, the north side faces the front of the house where the main entrance it located; second, the daylight is more diffused on the north side, which is appropriate for bedrooms; third, the north side has lower solar heat gain during the summer, which will reduce cooling loads; and finally, as already mentioned, the south-facing roof is being reserved for future photovoltaic panels.

- The shed dormer also includes a ventilated window in the stairwell. This elevated aperture will provide daylight for the stairs, for safety. During the summer, this opening will become a stack vent that will allow for the exhaust of excessive heated air.

- As mentioned previously, the bathroom is aligned with the bathroom on the main level, simplifying the plumbing design and eliminating the need for a second stack vent.

- The common area between the bedrooms provides space for built-in cabinets for linen storage.
The following three-dimensional images provide for additional clarity on the proposed renovation.

*Figure 60 Existing Northwest 3D View*

*Figure 61 Proposed Northwest 3D View*
Figure 62 Existing Southeast 3D View

Figure 63 Proposed Southeast 3D View
Proposed Phase Options

The clients originally requested that the project be presented with options so that the budget for the renovation could be phased in over a period of a few years, depending on the availability of funds. It was decided that the options would be presented in three roughly equal phases. Yet, each phase will result in a fully functioning home in which the family can live and thrive. This strategy gives the clients flexibility as they will be able to proceed with the project as their time and finances warrant. It also allows for the clients to make adjustments to the plans as they proceed, similar to a design-build process in commercial construction. When retrofitting an existing home, it is not possible to know the condition of every aspect of the home. Discoveries, both good and bad, will be learned as the home is opened up, repaired, and lived in. The climate conditions will be better understood as the family lives in the home through the changing seasons. It is anticipated that the clients will likely want to make modifications to the final project design. By separating the project into phases, the clients will have more opportunities to make adjustments, rather than committing to the final project design now. In addition, each phase is designed to be approximately equal in cost, with each phase costing roughly fifty thousand dollars, assuming the clients perform a lot of the work themselves, which is their expressed desire.

To briefly summarize the phases, phase one keeps the building’s existing envelope intact, with no expansion required. The interior space is modified, but most of the costs will involve insulation, air sealing, and windows, as well as electrical and plumbing services. Improving the existing thermal envelope is the first step in a passive solar retrofit. These tasks are considered the highest priority to make the existing home livable.

Phase two expands the upper level, adds a shed dormer, relocates the stairway, and adds two new bathrooms. The sunspace will also be constructed and will serve as the primary passive
solar feature in this phase. Phase three removes the existing sunroom and expands the building’s footprint by adding the new direct-gain living space.

Figure 64 Phase 2: Expand the Upper Level and Add Sunspace

Figure 65 Phase 3: Add Direct-Gain Living Area
Passive Solar Analysis

The explicit passive solar features in this project are concentrated in the southeast area of the social zone as shown in Figure 66 and the section views Figure 67, Figure 68, and Figure 69. The living and breakfast rooms are designed to receive direct-gain solar radiation from east- and south-facing glazing, with the energy stored primarily in the insulated concrete slab. The slab will be stained and left uncovered, optimizing its passive solar storage potential. The masonry heater will also provide thermal mass for solar energy storage. During the swing seasons between winter and summer, the passive solar design is expected to provide sufficient warmth.
with the assistance of an efficient mini-split heat pump for remote spaces. During the winter months, the masonry heater will provide supplemental radiant heat.

The sunspace is designed to provide isolated-gain solar heat for the dining room. During cool sunny days, the vents, the window, or the door between the dining room and the sunspace may be opened to allow for the solar heat in the sunspace to enter the dining room. At night and during cloudy days, the openings to the sunspace shall be closed to prevent heat loss. In addition, the cool air returning to the sunspace will return via the sealed and insulated crawlspace below the dining room. Floor vents will be supplied at the side of the room opposite of the sunspace. The purpose for this is to encourage the warm air supplied from the sunspace to distribute through the living space more effectively before circulating back to the sunspace. Otherwise, if both the upper and lower vents were located in the dining room, there would be a

Figure 67 Section 1: Passive solar analysis section @ entry, dining room, and sunspace
greater chance that the warmed air supplied via the upper vents will be short-circuited with the convection current and returned to the sunspace before having a chance to be circulated deep into the living space. This circulation path will also enable improved conditioning of the crawlspace, in order to reduce the potential for moisture problems. (Holladay, 2011)

Section 2 (Figure 68) shows a cross-section through the living space and the kitchen, along with the noontime sun angle at different times during the year. As mentioned previously, the insulated concrete slab will absorb solar radiation during the winter and the swing seasons while the summer sun will be shaded by the overhang and interior shades. Admittedly, the southern sun does not penetrate the space deeply enough to reach the kitchen. Skylights in the vaulted ceiling of the living space were considered, which would allow for a much deeper penetration of the sun during the heating season. However, the idea was rejected for three reasons. First, even high-performing skylights are only a fraction of the thermal performance of the R-49 roof, resulting in greater heat loss. Second, the cooling load would increase

Figure 68 Section 2: Passive solar analysis section @ kitchen and living room at noon
significantly during the summer, though the skylights can be shaded. Third, the roof pitch is a shallow four in twelve, which would make the skylight vulnerable to leakage. Nevertheless, the kitchen may be equipped with high-efficient solar tubes which will provide natural daylight with less heat-loss penalty than skylights.

Section 3 (Figure 69) shows an east-west section through the living space and the dining room. Also shown in this section are the approximate morning sun angles at 9:00 AM in the morning. It should be noted that only the summer solstice line represents the true angle as the sun is normal to the glass. Both the equinox and the winter solstice lines represent angles of incidence as the sun will be south of due east at this time. Thus, the morning sun will enter the living space in a northwesterly direction. The deep penetration of the morning sun is desirable for most of the year, even for some of the summer months. The thermal capacities of the
insulated slab and the masonry heater provide ample opportunity to capture the morning sun, and provide comfortable radiant heat during the morning hours.

**Alternative Roof Design Option - Rejected**

An alternate roof design option was presented to the clients for consideration. The option locates a line of clerestory windows along the ridge of the addition. While adding a significant cost increase to the project, the clerestory windows would provide two main benefits. First, the southern sun will be able to penetrate much deeper into the space, reaching the kitchen on the opposite side of the living space. Not only would this provide a greater distribution of natural light into the space, but it would improve the impact of the direct-gain passive solar collection. The second benefit for the clerestory windows is that they could be opened during the summer to allow for the excess heat to escape. To further prevent overheating, an overhang would block the summer sun during peak hours, and flexible indoor shading could also be used to block unwanted solar radiation. Perhaps the greatest risk with this design is that the clerestory windows would permit too much heat loss during the heating season. It would be important to purchase high-performance windows with low U-factors (and high SHGC for direct-gain solar). Also, insulated flexible shades could minimize heat loss during the heating season while minimizing overheating during the cooling season.

Though this option is presented in this documentation, it must be noted that the clients rejected this option, mostly on the basis of aesthetics. The roof configuration created a contemporary addition on a traditional home, which seemed out of place. Also, the clerestory windows were determined to be too difficult to clean because of their height.

The images on the following page show a section view at the same location as Section 2. A southeast 3D view is also provided with the green areas identifying new construction.
Figure 70 Section 2 showing alternative clerestory windows (See key floor plan on page 96)

Figure 71 Southeast 3D View showing alternative clerestory windows

Note: This option was rejected by the clients.
Heating Load Calculations

Performing heating loads and heat-loss calculations are a necessary part of a project design. Traditional projects need this information to determine the type and size of mechanical equipment for heating, ventilation, and air conditioning (HVAC). The Air Conditioning Contractors of America (ACCA) developed a series of manuals on performing accurate load calculations and sizing equipment and ducts. The 2012 IRC adopted the ACCA method in the building code and specified the ACCA Manual J or similar method for performing load calculations (Section M1401.3). The Manual J method is a room-by-room method with fairly sophisticated formulas that would be time consuming without the use of specialized software. In spite of the code requirement, most HVAC contractors do not use the Manual J method. (Holladay, 2017) Rather, they use simplified “rules of thumb” to save a lot of time, which generally results in oversized equipment. “In almost all cases, the contractor wants to sell you a heating or cooling appliance with more capacity than you need.” (Holladay, 2017)

Because the thesis project is a schematic design of a retrofit proposal, performing a thorough Manual J heating load calculation was not realistic, since too many variables remain unknown at this time. Instead, four methods of estimating the heating loads of the structure were used. The four methods include: the net load coefficient (NLC) method, the transmission plus exfiltration method, a “Simplified Building Heat Loss Calculation” spreadsheet, and an energy modeling analysis using Autodesk Revit. All four methods require the designer to make assumptions about a variety of conditions for the structure, including the final U-factors for the walls, doors, windows, roof, and floor. As expected, each of the four methods resulted in different heating load calculations. Nevertheless, the results provide a general idea of what to expect for the energy loads of this project.
**NLC Method**

Perhaps the quickest load calculation method is simply multiplying the square footage of the house by the heating degree days by the net load coefficient as per the following formula.

\[
\text{Annual Heating Load} = A \times \text{HDD} \times \text{NLC}
\]

A is the area of the conditioned space of the house, HDD is the heating degree-days for the region, and the NLC is a coefficient number based on the airtight description of the house. The NLC factors are listed in a table available in different resources. In this case, the table provided in *The Sunspace Primer* was used. (Jones & McFarland, 1984) The table below shows the results of the NLC method for both the existing and proposed project.

*Table 4 Summary of Heating Load Calculations using the NLC method*

<table>
<thead>
<tr>
<th></th>
<th>Existing</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (A)</td>
<td>1,974 SF</td>
<td>2,926 SF</td>
</tr>
<tr>
<td>Heating Degree Days (HDD)</td>
<td>6,748</td>
<td>6,748</td>
</tr>
<tr>
<td>Net Load Coefficient (NLC)</td>
<td>28 Btu/SF (poorly insulated and leaky)</td>
<td>4 Btu/SF (well insulated and airtight)</td>
</tr>
<tr>
<td>Annual Heating Load</td>
<td>372,975,456 Btu</td>
<td>78,978,592 Btu</td>
</tr>
<tr>
<td>In million Btu (MMBtu)</td>
<td>373 MMBtu</td>
<td>79 MMBtu</td>
</tr>
</tbody>
</table>

**Transmission plus Exfiltration Method**

This method is more detailed than the NLC Method, but it is also more time consuming because it must be calculated on a room by room basis. The method is divided into two parts, which are then added together. First, the transmission of heat loss through the building envelope is calculated. The envelope includes exterior walls, roof, and floor (commonly referred to as “all six sides”) and all openings, including windows, doors, and skylights. The more information one has about the R-value (or U-factor) characteristics of the envelope components, the more
accurate this calculation will be. Because the thesis project is a schematic design, assumptions will be made regarding these conductance values.

Second, the exfiltration is calculated to determine the convective heat loss via cracks and openings in the building envelope. Again, assumptions are required for the amount of air leakage which will determine the building’s air changes per hour (ACH). The ACH can be accurately measured using a blower door test, which was done for the thesis project as previously described. While the measurement is very useful, it only determines the air leakage when there is a pressure difference of fifty pascals between the interior and exterior. For determining heat lost calculations, an attempt is made to determine the ACH under natural circumstances. Unfortunately, this value is elusive since the pressure difference between the indoors and outdoors is always changing. Nevertheless, coefficient tables have been created that will provide a reasonable estimate of the heat loss from exfiltration.

Table 5 lists the components of the building envelope and the calculated heat losses. The heat loss for each component is calculated using the following formula:

\[
\text{Heat Loss} = A \times U\text{-factor} \times \Delta T
\]

\(A\) is the area in square feet, the \(U\)-factor is the inverse of the \(R\)-value of the component, and \(\Delta T\) is the indoor temperature (70°F) minus the design temperature for the region (5°F). Thus, the \(\Delta T\) is 65°F.
Tables 5 and 6 are used to calculate the transmission heat loss for building envelope components and the air infiltration rate, respectively. The calculations assume that the existing building is in good condition and that the proposed building will be tight. The tables below show the heat loss and infiltration rates for different components of the building envelope.

### Table 5 Transmission heat loss for building envelope components

<table>
<thead>
<tr>
<th>Component</th>
<th>Existing Building</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (SF)</td>
<td>U-factor</td>
</tr>
<tr>
<td>Windows</td>
<td>171</td>
<td>0.50</td>
</tr>
<tr>
<td>Doors</td>
<td>74</td>
<td>0.50</td>
</tr>
<tr>
<td>Walls</td>
<td>2,078</td>
<td>0.13</td>
</tr>
<tr>
<td>Ceiling/Roof</td>
<td>1,974</td>
<td>0.09</td>
</tr>
<tr>
<td>Foundation Walls</td>
<td>552</td>
<td>0.20</td>
</tr>
<tr>
<td>Basement Floor</td>
<td>409</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Next, the air exfiltration is calculated. Once again, assumptions must be made. Table 6, below, is an example of using a room by room estimate of air infiltration.

### Table 6 Infiltration factors (Holladay, 2012)

<table>
<thead>
<tr>
<th>Component</th>
<th>Infiltration factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rooms with windows or exterior doors on only 1 side of the room</td>
<td>0.012</td>
</tr>
<tr>
<td>Rooms with windows or exterior doors on 2 sides of the room</td>
<td>0.018</td>
</tr>
<tr>
<td>Rooms with windows or exterior doors on 3 sides of the room</td>
<td>0.027</td>
</tr>
<tr>
<td>Entrance halls</td>
<td>0.027</td>
</tr>
<tr>
<td>Sun rooms with many windows on 3 sides</td>
<td>0.036</td>
</tr>
</tbody>
</table>

Once the Infiltration factor has been determined, Table 7 converts the factor to estimate the natural air changes per hour, or ACH(nat).
Using the previous information, the heat loss through air exfiltration can be calculated using the following formula:

\[
\text{Heat Loss} = V \times \Delta T \times \text{IF} \times \text{ACH(nat)}
\]

\(V\) is the volume of the room in cubic feet, \(\Delta T\) is the difference between the indoor temperature and the design temperature (65°F), \(\text{IF}\) is the infiltration factor from Table 6, and \(\text{ACH(nat)}\) is the natural air changes per hour from Table 7. Table 8 and Table 9 lists the results of the exfiltration heat loss formula for each space in the existing and proposed dwelling.

**Table 8 Exfiltration heat loss from the existing building**

<table>
<thead>
<tr>
<th>Existing Room</th>
<th>Volume</th>
<th>Infiltration Factor</th>
<th>ACH</th>
<th>Exfiltration Heat Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living room</td>
<td>1,474</td>
<td>0.027</td>
<td>1.5</td>
<td>3,880</td>
</tr>
<tr>
<td>Bedroom East</td>
<td>1,190</td>
<td>0.018</td>
<td>1</td>
<td>1,392</td>
</tr>
<tr>
<td>Dining Room</td>
<td>893</td>
<td>0.018</td>
<td>1</td>
<td>1,045</td>
</tr>
<tr>
<td>Entrance</td>
<td>800</td>
<td>0.036</td>
<td>2</td>
<td>3,744</td>
</tr>
<tr>
<td>Bathroom</td>
<td>262</td>
<td>0.018</td>
<td>1</td>
<td>307</td>
</tr>
<tr>
<td>Laundry</td>
<td>1,554</td>
<td>0.018</td>
<td>1</td>
<td>1,818</td>
</tr>
<tr>
<td>Master Bedroom</td>
<td>946</td>
<td>0.027</td>
<td>1.5</td>
<td>2,490</td>
</tr>
<tr>
<td>Family Room</td>
<td>1,148</td>
<td>0.018</td>
<td>1</td>
<td>1,343</td>
</tr>
<tr>
<td>Bedroom West</td>
<td>1,179</td>
<td>0.018</td>
<td>1</td>
<td>1,379</td>
</tr>
<tr>
<td>Guest Room</td>
<td>878</td>
<td>0.036</td>
<td>2</td>
<td>4,109</td>
</tr>
<tr>
<td>Kitchen</td>
<td>1,159</td>
<td>0.018</td>
<td>1</td>
<td>1,356</td>
</tr>
<tr>
<td>Music Room</td>
<td>498</td>
<td>0.018</td>
<td>1</td>
<td>583</td>
</tr>
<tr>
<td>Bathroom</td>
<td>362</td>
<td>0.018</td>
<td>1</td>
<td>424</td>
</tr>
<tr>
<td><strong>Total Exfiltration Heat Loss</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>23,870</strong></td>
</tr>
</tbody>
</table>
Finally, the rate of heat loss for the entire house is estimated by adding the transmission heat loss to the exfiltration heat loss. Note that the result is the rate of heat loss in \textit{Btus per hour.} These values are useful when sizing HVAC equipment.

\begin{align*}
\text{Existing Building Heat Loss} & = 52,545 \text{ Btu/h} + 23,870 \text{ Btu/h} = \textbf{76,415 Btu/h} \\
\text{Proposed Building Heat Loss} & = 30,082 \text{ Btu/h} + 21,915 \text{ Btu/h} = \textbf{51,997 Btu/h}
\end{align*}
The previous heat loss values can be converted to the annual heating load by replacing
the $T$ with the heating degree-days (HDD) and by multiplying by twenty-four hours per day.

The results are as follows in million Btu:

Existing Building Heating Load = 190 MBtu

Proposed Building Heating Load = 130 MBtu
Simplified Building Heat Loss Spreadsheet

In September 2017, the author attended a workshop led by Bill Labine, a certified Passive House designer with Airtight Services, Inc. Mr. Labine provided attendees with a spreadsheet that he developed, which is intended to provide a quick means for estimating the heat loss of a building. The functions in the spreadsheet are similar to the transmission plus exfiltration method. The biggest difference is in how the exfiltration is calculated. Instead of a room-by-room analysis, the volume of the whole structure is calculated with the natural air change per hour and a coefficient called the LBL factor. LBL, which stands for Lawrence Berkley Laboratory (where the LBL method was developed), creates a coefficient value to determine the natural infiltration. The LBL factor takes into account the climate, the building height, how well the building is sheltered, and the average crack size. (Reysa, 2013) Table 10 below shows the results of the spreadsheet after inputting all of the data for component areas, estimated U-factors, and ACH assumptions. The UxA in the table refers to the U-factor multiplied by the area of the component.

Table 10 Simplified building heat loss calculation spreadsheet

<table>
<thead>
<tr>
<th></th>
<th>Existing Building</th>
<th>Proposed Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Conductive UxA</td>
<td>935 Btu/h</td>
<td>555 Btu/h</td>
</tr>
<tr>
<td>Ventilation UxA</td>
<td>280 Btu/h</td>
<td>73 Btu/h</td>
</tr>
<tr>
<td>Total Building UxA</td>
<td>1,215 Btu/h</td>
<td>628 Btu/h</td>
</tr>
<tr>
<td>Design Heating Load</td>
<td>78,966 Btu/h</td>
<td>40,806 Btu/h</td>
</tr>
<tr>
<td>Annual Heating Load</td>
<td>197 MBtu/yr</td>
<td>102 MBtu/yr</td>
</tr>
</tbody>
</table>
Energy Modeling Analysis

The software used for the energy modeling analysis was Autodesk Revit 2017 and Autodesk’s online tool, Green Building Studio (GBS). A mass object was created in Revit that accurately represented the shape of both the existing dwelling and the proposed renovated project. A series of parameters were set to describe the envelope conditions as well as the percent glazing. Some of the parameters are shown in Table 11 and Table 12 below:

**Table 11 Energy modeling parameters for the existing dwelling (Source: Autodesk Revit)**

<table>
<thead>
<tr>
<th>Conceptual Types</th>
<th>Mass Model</th>
<th>Constructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Exterior Wall</td>
<td>Lightweight Construction - Low Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass interior Wall</td>
<td>Lightweight Construction - No Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass Exterior Wall - Underground</td>
<td>High Mass Construction - No Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass Roof</td>
<td>Low Insulation - Dark Roof</td>
<td></td>
</tr>
<tr>
<td>Mass Floor</td>
<td>Lightweight Construction - No Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass Slab</td>
<td>High Mass Construction - No Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass Glazing</td>
<td>Single Pane Clear - No Coating</td>
<td></td>
</tr>
<tr>
<td>Mass Skylight</td>
<td>Double Pane Clear - No Coating</td>
<td></td>
</tr>
<tr>
<td>Mass Shade</td>
<td>Basic Shade</td>
<td></td>
</tr>
<tr>
<td>Mass Opening</td>
<td>Air</td>
<td></td>
</tr>
</tbody>
</table>

**Table 12 Energy modeling parameters for proposed renovation (Source: Autodesk Revit)**

<table>
<thead>
<tr>
<th>Conceptual Types</th>
<th>Mass Model</th>
<th>Constructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Exterior Wall</td>
<td>Lightweight Construction - High Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass interior Wall</td>
<td>Lightweight Construction - No Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass Exterior Wall - Underground</td>
<td>High Mass Construction - No Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass Roof</td>
<td>High Insulation - Dark Roof</td>
<td></td>
</tr>
<tr>
<td>Mass Floor</td>
<td>Lightweight Construction - No Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass Slab</td>
<td>High Mass Construction - Cold Climate Slab Insulation</td>
<td></td>
</tr>
<tr>
<td>Mass Glazing</td>
<td>Double Pane Clear - LowE Cold Climate, High SHGC</td>
<td></td>
</tr>
<tr>
<td>Mass Skylight</td>
<td>Double Pane Clear - No Coating</td>
<td></td>
</tr>
<tr>
<td>Mass Shade</td>
<td>Basic Shade</td>
<td></td>
</tr>
<tr>
<td>Mass Opening</td>
<td>Air</td>
<td></td>
</tr>
</tbody>
</table>

Once the parameters are set, an energy model is created from the mass objects, and the energy model is then uploaded to GBS where it is analyzed. Approximately thirty minutes later, GBS returned a seven-page report detailing a number of energy analyses, areas of potential energy
savings, and regional climate data. In order to compare the results to the other heating load calculations, the following is the annual heating loads for the existing and proposed structures.

Heating load for the existing dwelling: **107 MBtu/yr**

Heating load for the proposed project: **78 MMBtu/yr**

*Heating Load Summary*

Table 13 summarizes the heating load calculations using the four methods along with the average of the methods.

Table 13 Summary of heating load calculations in million Btu (MMBtu)

<table>
<thead>
<tr>
<th>Heating Load Calculation Method</th>
<th>Annual Heating Load (MMBtu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Existing</td>
</tr>
<tr>
<td>NLC Method</td>
<td>373</td>
</tr>
<tr>
<td>Transmission plus Exfiltration</td>
<td>190</td>
</tr>
<tr>
<td>Simplified Building Heat Loss Calculations Spreadsheet</td>
<td>197</td>
</tr>
<tr>
<td>Energy Model Analysis</td>
<td>107</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>217</strong></td>
</tr>
</tbody>
</table>

As is evident from the data, the discrepancy of the results is fairly widespread. Martin Holladay of Green Building Advisor explained that these methods are only a guess, based on a wide range of assumptions. He described several points of inaccuracy with the methods in the following points:

- *Since no one knows what the “natural” air changes per hour on a cold winter night will be for any particular house design, any ACH(nat) figure is no more than a guess.*

- *The simple one-dimensional heat flow equation used by this calculation method is a gross simplification of the way heat flows actually occur in a three-dimensional building.*
• This heat loss calculation method does not account for thermal mass effects.

• This heat loss calculation method does not account for losses due to mechanical ventilation.

• This heat loss calculation method ignores internal gains from occupants, pets, refrigerators, lighting, and electronic appliances.

• Large errors can be introduced when a designer is uncertain of a building assembly’s U-factor.

• This heat loss calculation method ignores most thermal bridges. (Holladay, 2012)

**Energy Use Intensity**

The summary of the building heating load in the previous section provides an incomplete picture of the improved design. The proposal involves an addition and an expansion of the upper level. The square footage of conditioned space increased from 1,924 SF to 2,926 SF, a fifty-two percent increase. When reviewing the total heating loads for the existing and proposed structures, it is unclear how much improvement occurred since the areas of the two structures are so different. A key metric used by most energy analysis software is the energy use intensity, or EUI. This metric weighs the energy load of the building based on the building size, thus providing a clearer comparison.

Table 14 summarizes the heating loads using the EUI metric. This data provides a much clearer picture of the improvements made with the design.
Table 14 Summary of energy use intensity (EUI) for heating loads

<table>
<thead>
<tr>
<th>Heating Load Calculation Method</th>
<th>Energy Use Intensity (kBtu/SF/yr)</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Existing</td>
<td>Proposed</td>
</tr>
<tr>
<td>NLC Method</td>
<td>194</td>
<td>32</td>
</tr>
<tr>
<td>Transmission plus Exfiltration</td>
<td>99</td>
<td>44</td>
</tr>
<tr>
<td>Simplified Building Heat Loss Calculations Spreadsheet</td>
<td>102</td>
<td>35</td>
</tr>
<tr>
<td>Energy Model Analysis</td>
<td>56</td>
<td>27</td>
</tr>
<tr>
<td>Average</td>
<td>113</td>
<td>35</td>
</tr>
</tbody>
</table>

**Phase Comparisons for EUI**

The heating load calculations were applied to all three phases of the project, to determine the area of greatest impact. Recall that the first phase does not involve any expansion, but focuses primarily on insulation and air sealing. In addition, the electrical and plumbing services will be updated, the layout will be modified, and the finishes will be replaced. Tightening of the thermal envelope is considered the first critical step in a passive solar retrofit. The second phase involves expanding the upper level and adding a sunspace, which is the primary passive solar retrofit in this phase. The third and final phase is building a direct-gain addition to expand the living space. Since each phase is intentionally designed to cost approximately fifty thousand dollars. Thus, the clients may proceed with the project at a pace that is financially affordable and practical.

Table 15 shows the comparison of the energy loads for each of the phases. The key data that stands out the most from this table is the impact that air sealing and insulation will have on the energy consumption. The Energy Use Intensity drops from 113 kBtu/sf/yr to a mere 23 kBtu/sf/yr. That is an eighty percent drop! Clearly, this step will be the most cost-effective task for this project.
Table 15 Summary of Annual Heating Loads

<table>
<thead>
<tr>
<th>Heating Load Calculation Method</th>
<th>Existing MMBtu</th>
<th>MMBtu kBtuh/sf*yr</th>
<th>Phase 1 Air Seal &amp; Insulate MMBtu kBtuh/sf*yr</th>
<th>Phase 2 Expand Upper Level &amp; Sunspace MMBtu kBtuh/sf*yr</th>
<th>Phase 3 Direct-Gain Addition MMBtu kBtuh/sf*yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLC Method</td>
<td>373</td>
<td>194</td>
<td>60</td>
<td>21</td>
<td>67</td>
</tr>
<tr>
<td>Transmission plus Exfiltration</td>
<td>190</td>
<td>99</td>
<td>69</td>
<td>31</td>
<td>86</td>
</tr>
<tr>
<td>“Simplified Building Heat Loss” Spreadsheet</td>
<td>197</td>
<td>102</td>
<td>31</td>
<td>14</td>
<td>49</td>
</tr>
<tr>
<td>Energy Model Analysis</td>
<td>107</td>
<td>56</td>
<td>56</td>
<td>25</td>
<td>64</td>
</tr>
<tr>
<td>Average</td>
<td>101</td>
<td>113</td>
<td>54</td>
<td>23</td>
<td>67</td>
</tr>
</tbody>
</table>

For the purposes of this thesis research, it will be important to determine the Solar Savings Fraction for each of the phases. In the sections that follow, an in-depth analysis will be performed on the two primary passive solar features, the sunspace and the direct-gain addition, and the Solar Savings Fraction will be calculated.

**Sunspace Solar Savings**

Like the house, the heating performance of the sunspace must involve several assumptions regarding the effectiveness of the sunspace’s design and the quality of its construction. For example, the sunspace was intentionally designed with an insulated opaque roof, rather than a glazed roof. This was done to help lessen nighttime heat loss and to minimize summertime overheating. Also, the glazing on the south-facing wall of the sunspace is to be vertical, not sloped as seen on many sunspaces of the past. In addition to easing the installation
process and reducing the opportunities for leakage, the vertical glass will reflect much of the high-noon summer sun, further minimizing the chance of overheating. The glass will be double paned clear glass salvaged from the sliding glass doors of the existing sunroom.

Before evaluating the heating performance of the sunspace, one must gain clarity of the evaluation terminology. The sunspace will collect a certain amount of solar heat when the sun is shining. Some of the heat will be absorbed by the thermal mass materials in the sunspace, some of the heat will be lost via conduction and convection of the exterior sunspace walls, and some of the heat will be available to be delivered to the building. The latter is referred to as the sunspace’s delivered heat. Also, the main building will have heating load requirements. On cold winter days, the heating load of the building may be quite high. On cool spring or autumn days, the heating load will be considerable less, and during the summer the building may not need any heat at all and in fact, may likely have a cooling load. The difference between the heating load and the delivered heat is referred to as the solar savings. (Jones & McFarland, 1984) If the delivered heat is greater than the building’s heating load, then the sunspace can meet all of the heating needs of the building, but some of the delivered heat will be wasted. If the delivered heat is less than the heating load, then the solar savings will simply reduce the supplemental heating needs of the building.

There is an important caveat that needs to be realized when determining the heating performance of the sunspace. For example, on an average spring or fall day when the sun is shining, the sunspace may likely produce all of the heat that would be needed for the adjoining space, or perhaps the whole building. However, most of the solar heat will be collected in a relatively short period of time, peaking in the early to midafternoon. The heat collected during this time will be in excess of the immediate heating load of the building, thus wasting much of
the solar heat that was collected. Later, during the evening and nighttime, the sunspace will collect very little heat or none at all, and, ironically, this is also the time of day when the heating load of the building is higher. The variable nature of the delivered heat versus the heating load complicates the calculation of the solar savings.

A possible solution to this problem is to provide more thermal mass in the sunspace. The additional thermal mass will store the excess heat produced during the day and then deliver the stored heat later in the day when the sun is no longer available. This strategy would lessen the amount of solar heat simply wasted when it cannot be used immediately. The difficulty with this strategy, though, is that the thermal mass will radiate its stored heat too slowly to be effective at producing deliverable heat to the building. (Babaee, Fayaz, & Sarshar, 2016) More likely, the thermal mass will simply moderate the temperature swings of the sunspace. To be sure, this can be very desirable when maintaining plants or providing a more comfortable sunspace for the occupants. Nevertheless, the sunspace does have important limitations in providing for the heating loads of the building.

Following the guidelines of Los Alamos National Laboratory researchers, Robert Jones and Robert McFarland, in their book, *The Sunspace Primer*, one can approximate the potential solar savings of proposed sunspace. The steps below are a summary of the procedure as outlined by the authors:

1. Building floor area, $A_f = 1,200$ SF, which includes the dining room, living room, breakfast area, kitchen, entry, and library. Rather than using the area of the entire building, 2,926 SF, it is reasonable to evaluate the sunspace performance for only the spaces to which it is directly serving.
2. Net load coefficient per square foot of building area, \( \text{NLC}/\text{Af} = 8 \text{ Btu/}^\circ\text{F/day/SF} \).
   
   This value is arguably where the greatest error may occur. The value comes from a table with general descriptions of the building’s airtight and insulation qualities. While the building is expected to exceed the minimal energy code requirements, it likely will fall short of “superinsulated” standards. The value selected is considered a conservative estimate.

3. Heating degree-days base temperature = 65°F

4. Projected area of the sunspace glazing, \( A_p = 96 \text{ SF} \).

5. Ratio of the projected area to building floor area, \( A_p/\text{Af} = 96/1200 = 0.08 \)

6. Load collector ratio, \( \text{LCR} = (\text{NLC}/\text{Af})/(A_p/\text{Af}) = 8/0.08 = 100 \text{ Btu/HDD/SF} \)

7. Sunspace type is vertical glazing with night insulation and an opaque roof, which is type ‘C2,’ which will inform what charts to use in the proceeding steps.

8. Heat delivered per square foot of projected area = 74,000 Btu/SF. This figure was provided by a map of the United States for sunspace type ‘C2’.

9. Heating degree-days (HDD) for Rochester, NY = 6,748

10. Net heating load per square foot of projected area, \( L/A_p = \text{LCR} \times \text{HDD} = 100 \times 6748 = 674,800 \text{ Btu/SF} \)

11. Ratio of delivered heat to net heating load, \( D/L = (D/A_p)/(L/A_p) = 74,000/674,800 = .11 \)

12. Ratio of solar savings to delivered heat, \( S/D = 0.85 \), according to a chart provided by the authors.

13. Solar savings per square foot of projected area, \( S/A_p = (S/D) \times (D/A_p) = 0.85 \times 74,000 \text{ Btu/SF} = 62,900 \text{ Btu/SF} \)
14. Total solar savings, \( S = \left( \frac{S}{A_p} \right) \times A_p = 62,900 \text{ Btu/SF} \times 96 \text{ SF} = 6,038,400 \text{ Btu} \), or about 6 million Btus per year.

It is useful now to compare the solar savings from the sunspace to the heating load of the living area being served by the sunspace. Using the average energy use intensity (EUI) value from Table 14, the estimated heating load of the living area is 42 million Btu/year. Therefore, the solar savings represents \( 6 \text{ MBtu/yr} / 42 \text{ MBtu/yr} \) for a SSF of fourteen percent. When compared to the heating load for the entire building, the SSF drops to less than six percent.

Regarding the above calculations, one must pause on the description of the sunspace in Step 7. The delivered heat is based on a sunspace design that includes night insulation, which is movable insulation used to reduce heat loss during the heating season or overheating during the cooling season. Many types of moveable insulation are available, but the most common types are interior shades or shutters with sealed edges. (Jones & McFarland, 1984) The disadvantages of movable insulation is that it requires daily operation by the occupants and it adds to the cost of the sunspace. According to The Sunspace Primer, the penalty for not including movable insulation is significant. The delivered heat for a sunspace without movable insulation drops to eighteen thousand Btus per square foot of project glazing area. Using this information in the above calculation, the solar savings declines to less than two million Btus, a seventy-two percent reduction!

**Sunspace Consideration**

The heating load calculations in the previous sections clearly demonstrate the benefits of creating a tighter, well-insulated home with passive solar features. The sunspace, however, was shown to be of limited value in terms of the heating load. More specifically, the cost-benefit is not in favor of the sunspace. Furthermore, the sunspace requires active involvement on the part
of the homeowner for the sunspace to function properly, especially if the sunspace includes moveable insulation. The interior vents need to be opened when the sunspace temperature rises above the living space on cool days, but then need to be closed when the sunspace temperature drops. Also, the exterior vents for the sunspace need to opened during the summer to prevent the sunspace from excessively overheating. If the homeowner is not reliable, then the full benefits of the sunspace will not be realized.

On the other hand, the sunspace does provide benefits in addition to providing heat. As mentioned previously, the sunspace provides space for growing plants. The clients stated that gardening will be an important part of the family’s lifestyle, and the sunspace could prove to be a useful part of the process. In addition, the sunspace is also an attractive and relaxing space to which one can retreat that is unique from the other spaces in the home. Brightly lit and filled with plants, this space may become a favored space for certain members of the family, in spite of the temperature swings. Finally, a sunspace will improve the market value of the dwelling. Thus, the clients may recoup a significant portion of their investment should they decide to sell.

Nevertheless, the clients were presented with three alternatives to the sunspace, all utilizing passive solar technology in different ways. The first alternative was to create a direct-gain strategy. (See Figure 72) The walls will be well-insulated and sealed, and it was calculated that fifty-four square feet of glazing will be needed to provide the same amount of BTU that the sunspace would have provided. It should be understood that the dining room space is currently a low-mass space. Therefore, the heat gain from the windows will be experienced immediately, and likewise, when the sun becomes unavailable, the heat-gain will disappear suddenly. This may be partially remedied with a flooring material that provides some thermal mass, such as tiles. Still, this system is much more cost-effective with an estimated return on investment of
about twelve years. Not needing to add a foundation system or to extend the roof for the sunspace will save about ten thousand dollars. The drawback, of course, is the loss of a convenient place for plants and a unique extension of the living space.

Figure 72 Direct-Gain Option with Solar Windows

The second option is to create an indirect-gain system with a Trombé wall, which will provide an efficient means of providing solar heat. (See Figure 73) The clients immediately rejected this proposal, mostly due to the loss of daylight for the dining room. The rejection led to the third option, which is to create a water wall with translucent water tubes, which will permit daylight to enter the living space. (See Figure 74) The southern view will be obscured with the solar tubes, but that is acceptable since the southern view, overlooking the neighbor’s house, is not highly desired. Thus, the solar tubes provide the unique combination of ample daylight and privacy. Furthermore, the colored dyes in the tubes will create a very interesting architectural feature in the dining room. The solar gain from the tubes will be modest, providing a return on investment of about twenty years.
As of this writing, the clients are favorably inclined to include the sunspace based on the benefits discussed. Gardening is important to the clients. Careful design considerations will be made to include sufficient thermal mass in order to moderate the interior temperature.
Direct-Gain Analysis

The living area is the primary recipient of the direct-gain passive solar feature in this home. Solar radiation is collected via the south-facing windows. A portion of the solar radiation directly warms the interior space, with the remainder of the solar radiation absorbed by the thermal mass. A sufficient area of glazing is needed to provide enough solar radiation to be effective, yet the glazing area needs to be limited in order to prevent the heat loss from canceling the heat gains. There are many resources that provide “rules of thumb” to determine the proper glazing area. Table 16 presents a summary of recommendations from a variety of sources.

Table 16 Recommendations for south-facing window areas

<table>
<thead>
<tr>
<th>Source</th>
<th>Recommendation</th>
<th>Recommended Window Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Solar Energy Book by Edward Mazria (1979)</td>
<td>24% to 38% of window area per floor area</td>
<td>124 SF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>198 SF</td>
</tr>
<tr>
<td>Climate Building Design by Donald Watson (1983)</td>
<td>17% to 35% of the floor area</td>
<td>88 SF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>182 SF</td>
</tr>
<tr>
<td>Passive Solar Architecture by Bainbridge and Haggard (2011)</td>
<td>14% to 20% of aperture per floor area</td>
<td>72 SF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>104 SF</td>
</tr>
<tr>
<td>Green Building Advisor by Brian Knight (2011)</td>
<td>9% to 12% of the home’s conditioned floor area</td>
<td>94 SF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>126 SF</td>
</tr>
<tr>
<td>Daylighting Handbook I by Christoph Reinhart (2014)</td>
<td>40% to 60% of the south-facing wall area</td>
<td>79 SF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>119 SF</td>
</tr>
<tr>
<td>Average recommended south-facing window area</td>
<td>91 SF</td>
<td>146 SF</td>
</tr>
</tbody>
</table>

One may notice that the older resources tend to have higher recommendations than the more recent resources. That is likely because more has been learned about the impact of heat loss on the overall efficiency of the glazing. Also, numerous other factors will impact the effectiveness of the south-facing glass, including the SHGC, the U-factor of the glass and the frame, the air-leakage, and shading devices. The sizing of the glass is also a function of system type and climate. Dennis Andrejko, who as mentioned before, built a passive solar addition to his house in Buffalo, New York, stated that his experience “in colder, more ‘gloomy’ climates is
to use small solar apertures in favor of increased investment in efficiency (load reduction). For glazing, select the smaller end of the scale in our ‘gloomy’ climate.” For this thesis project, a south-facing glass area of about one-hundred square feet was selected for the initial schematic design. Further analysis on the heat gain versus heat loss will likely suggest an adjustment to the glass area.

The chart in Figure 75 shows the expected heat gain, in Btu per square foot, provided for south-facing windows annually in Rochester, New York. The calculations are based on windows with a high solar heat gain coefficient (0.75) and a low U-factor (0.2) to minimize heat loss.

While the chart shows the total annual heat gain, shading devices should block much of the heat gain during the cooling months to prevent overheating. When calculating heat gain potential during the heating months, only the heat gain potential for September to May will be considered. Thus, the total seasonal heat gain is 145,000 Btu per square foot.

<table>
<thead>
<tr>
<th></th>
<th>MORNING</th>
<th>AFTERNOON</th>
<th>MONTHLY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4:00</td>
<td>5:00</td>
<td>6:00</td>
</tr>
<tr>
<td>Jan</td>
<td>2</td>
<td>460</td>
<td>1,400</td>
</tr>
<tr>
<td>Feb</td>
<td>110</td>
<td>820</td>
<td>1,500</td>
</tr>
<tr>
<td>Mar</td>
<td>7</td>
<td>300</td>
<td>1,100</td>
</tr>
<tr>
<td>Apr</td>
<td>1</td>
<td>61</td>
<td>270</td>
</tr>
<tr>
<td>May</td>
<td>21</td>
<td>160</td>
<td>310</td>
</tr>
<tr>
<td>Jun</td>
<td>56</td>
<td>220</td>
<td>380</td>
</tr>
<tr>
<td>Jul</td>
<td>45</td>
<td>220</td>
<td>400</td>
</tr>
<tr>
<td>Aug</td>
<td>6</td>
<td>130</td>
<td>340</td>
</tr>
<tr>
<td>Sep</td>
<td>25</td>
<td>330</td>
<td>1,000</td>
</tr>
<tr>
<td>Oct</td>
<td>210</td>
<td>1,100</td>
<td>1,900</td>
</tr>
<tr>
<td>Nov</td>
<td>13</td>
<td>480</td>
<td>1,200</td>
</tr>
<tr>
<td>Dec</td>
<td>290</td>
<td>1,100</td>
<td>1,700</td>
</tr>
</tbody>
</table>

Figure 75 Window heat gain chart, Btu/SF for Rochester, New York (Source: http://susdesign.com/windowheatgain/index.php)
As previously determined, the south-facing glass area will be about one hundred square feet. Therefore, the total seasonal heat gain for the living space from the south-facing windows will be about 14,500,000 Btu. Calculating the heating load for the living area, the EUI was used to multiply by the area of the space, which calculated to about 42,000,000 Btu. Thus, the south-facing windows could provide about thirty-five percent of the heating load for the living space. In addition, the east-facing glass will also provide additional heat gain. However, because the heat gain from the east-facing glass will be less than from the south-facing glass, the heat loss through conduction will likely be greater than the heat gain. Again, one must realize the purpose for the east-facing glass. It will provide an early morning boost to the indoor temperature on sunny mornings and will provide an extensive view of the eastern landscape, which is the best view on the property. These factors provide justification for the expanse of east-facing glass, even though the amount of heat gain may be minimal.

The following is a summary of the calculations for the direct-gain addition:

- The south-facing windows will provide about fourteen and a half MMBtu per heating season.
- The east-facing windows will provide about five MMBtu per heating season.
- The total heating load for the living space is about forty-two MMBtu per heating season.
- The Solar Savings Fraction of the living space is about forty-six percent.
  - \( \frac{(14.5 \text{ MMBtu} + 5 \text{ MMBtu})}{42 \text{ MMBtu}} = 0.46 \text{ or } 46\% \)
- The above calculations are based on the following assumptions:
  - Very low U-value (0.2) and high SHGC (0.75)
○ Moveable insulation is used to cover windows at night to minimize heat loss.

○ Insulated concrete slab is left uncovered.

Summary of Solar Savings Fraction

As mentioned before, the high-efficiency masonry heater will provide a cost-effective and low-impact source of supplementary heat. If fired twice daily during the heating season, it is estimated that masonry heater will provide about twenty-four MMBtu. Incidentally, the masonry heater is a very efficient source of heat, burning the wood at a very high temperature which produces very little particulate pollution. Furthermore, the project’s rural location and the plentiful availability of wood on the property makes utilizing wood heat an ideal choice for the home’s supplemental heat.

Combining the energy provided from the masonry heater with the energy provided from the passive solar systems, the sunspace and the direct-gain addition, the total energy provided is about forty-nine MMBtu. As mentioned previously, the heating load of the living space is about forty-two MMBtu per heating season. Thus, the masonry heater and passive solar systems are anticipated to provide for all of the heating needs of the main living areas. When considered as part of the whole house, the combination of solar and wood heat provides for forty-eight percent (49 MMBtu / 101 MMBtu) of the heating load. The solar heat alone will provide a SSF of 25%. Still, that is a significant amount of fossil fuel energy being offset by wood heat and clean, renewable solar energy.
Addition Cost Estimate

As stated before, the addition is anticipated to cost about fifty thousand dollars, assuming the clients contribute a significant amount of labor. A breakdown of the cost estimate is as follows:

*Table 17 Summary Cost Estimate of Addition*

<table>
<thead>
<tr>
<th>Summary</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>200</td>
</tr>
<tr>
<td>Sitework</td>
<td>1,440</td>
</tr>
<tr>
<td>Foundation and Slab</td>
<td>8,870</td>
</tr>
<tr>
<td>Wood; Structural</td>
<td>9,040</td>
</tr>
<tr>
<td>Doors &amp; Windows</td>
<td>8,715</td>
</tr>
<tr>
<td>Thermal &amp; Moisture Protection (Siding &amp; Roofing)</td>
<td>10,096</td>
</tr>
<tr>
<td>Mechanical, Electrical, &amp; Plumbing</td>
<td>6,500</td>
</tr>
<tr>
<td>Finishes</td>
<td>4,630</td>
</tr>
<tr>
<td><strong>TOTAL (All Categories)</strong></td>
<td>$49,491</td>
</tr>
</tbody>
</table>

Given the energy savings from the passive solar features, as well as the energy contribution from the masonry heater, it is anticipated that the return on investment for the direct-gain addition will be about thirty years. While that may seem to be a long time, the increase in market-value of the property and the quality of life improvements for the occupants will be significant. The psychological uplift from the ample daylight, the radiant warmth of passive solar and the masonry heater, and visual connection to the outdoors is impossible to measure in terms of dollars and return on investment. It is believed that the design presented to the clients achieves all of the valuable benefits at a relatively affordable price.
Conclusion

To say that the thesis project went through an intense evolutionary process from conception through schematic design would be an understatement. The initial concept of creating a purely passive solar retrofit residence proved to be unrealistic. Instead, there was a realization that the entire structure did not need to be passive solar, but that passive solar features could be effectively incorporated into portions of the design. The southeast corner was determined to be the ideal location for a passive solar strategy, and the remainder of the project incorporated concepts from a super-insulated, super-tight passive house strategy. The end result is a house redesign which takes advantage of both worlds. Recall that Dr. Joseph Lstiburek declared that “mass-and-glass” took on “super-insulated,” and super-insulated won. Upon further reflection, neither strategy needs to be declared the winner or the loser. Passive solar has much to offer that can and ought to be coupled with the benefits and efficiency of a super-insulated strategy.

To bring the thesis document to a conclusion, it is worthwhile to return to the original four questions raised in the introduction. Each of the questions are listed below, along with the answers as determined by the thesis research:

1. Can passive solar be effective in a “gloomy climate?”

   Answer: Yes, passive solar can be effectively implemented in any climate. However, the expectations of passive solar need to be realistic for the climate. Gloomy climates experience very limited sunshine, so it would be unrealistic to expect passive solar to provide for all of the annual heating (or cooling) needs. Instead, the designer should determine what passive solar can contribute and let that become the focus. Also,
designing a passive solar system for the swing seasons will be more effective in a gloomy climate.

2. *Can passive solar be retrofitted into an existing home?*

Answer: Without question, passive solar can be retrofitted in nearly any home. The home selected for this project contained a lot of challenges that could have made passive solar an impractical choice. For instance, the home is oriented north-south and it is spread out on mostly one level. Ideally, a passive solar home should be oriented east-west with a compact, multistory layout. Yet, a passive solar solution was still successfully designed for this dwelling.

3. *Can a passive solar retrofit be cost effective?*

Answer: Yes, but the most important step is to first reduce the energy load. Any passive solar system will be ineffective if the building’s heating load is too high. Creating an air-tight and well-insulated thermal envelope is the critical first step. Once this is accomplished, then several of the passive solar systems become feasible. This research project demonstrated that a direct-gain system is the system most likely to be cost-effective. An isolated-gain system, such as a sunspace, is more difficult to justify in terms of cost-effectiveness, but other benefits must be considered that may make the system worthwhile.

4. *Can passive solar be part of a solution that satisfies the programmatic desires of the client*

Answer: Absolutely. As explained in the introduction, the clients were not advocates of passive solar energy, and in fact, were rather skeptical of the concept in a gloomy climate. After reviewing the proposals and hearing an explanation of the benefits of
passive solar, the clients have become quite receptive to the idea of tapping into the natural resource that is freely available. Interestingly, energy savings and cost-effectiveness were not the issues that persuaded the clients. Rather, the intangible benefits or natural light and a highly visual connection to the outdoors were the significant issues. In other words, passive solar promised to have a positive impact on the family’s quality of life.

Designing a successful passive solar system is not something that can be done lightly. A passive solar system that is poorly considered can become a real detriment to the occupants. “To develop the idea of a solar project from little more than a gleam in one’s eye to a well-conceived & engineered reality is an involved process, requiring an amazing number of decisions. Each step along the way should be made carefully and in proper sequence.” (Wright, Andrejko, & Cook, 1978) The effort will be worth it, however. “Passive solar architecture has proven to be highly efficient, cost effective, and creatively stimulating.” (Wright & Andrejko, 1982) Indeed, history has shown that passive solar is a strategy that can dramatically enhance a project, or if poorly designed, it can become a serious detriment to a project.

The design process for this project offered an opportunity to bring together a number of goals, which were sometimes conflicting. The countless iterations of the design attempted to combine the themes of architecture that the Roman architect Vitruvius referred to as firmitas (strength), utilitas (functionality), and venustas (beauty). Architecture is the rare discipline that touches nearly every aspect of human life – childhood and the elderly, husband and wife, education and work, health and sickness, entertainment and faith – what Kahn referred to as the “unmeasurable” qualities. Ultimately, the most important objective of the thesis project is to
provide a home for the clients that is comfortable and functional and within the family’s budget. As stated in the introduction, the home should be a place that inspires and reinvigorates the family members. After all, when the project is complete and the family has moved in, the hard labor of researching, analyzing, drawing, and construction will be worth the effort if the clients are happy with their new home for years to come.
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