# INFLUENCE OF DESIGN AND CLIMATE CHANGE ON THE ANNUAL ENERGY CONSUMPTION OF A PASSIVE SOLAR HOUSE

By

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# ABSTRACT

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This thesis describes a method that has been used to assess the annual energy consumption of an energy-efficient house based on the operating energy requirements over a one-year period. As heating and cooling consume the most energy, it was decided that the study would mainly focus on the heating and cooling of the house.

The object of this study is a virtual 2019 $ft^2$ home (referred to throughout this report as the Seahouse) originally modeled for Seattle, Washington. The Seahouse is a four bedroom single family house with a passive solar design and a heating, ventilating and air conditioning system composed of geothermal heat-pumps. The home was sized based on the average dimension of new homes built in the US at the end of year 2009 [3].

The first objective of this study was to assess the influence of design on annual energy consumption. In this regard, the passive solar design was compared to a typical current American house.

Subsequently, this paper evaluated the influence of climate change on annual energy consumption. Climate change weather files were generated with the CCWorldWeatherGen tool, implemented in DesignBuilder and simulations were conducted for 2010 and 2050.

Finally, $CO_2$ emissions of the Seahouse were assessed with state emission factors found in the eGRID 2006.

Results from the different simulations indicated the efficiency of the Seahouse, as it saved from 84% to 93% more energy than the standard design. This design was also found to consume 8% to 40% more energy during 2050 than it did during 2010. In addition, an increase of carbon dioxide emissions 8% to 40% depending on location was noticed for the Seahouse. This design, however, allowed savings in carbon dioxide emissions ranging from 76% to 97% during over the typical design.

It was concluded that the savings in energy made by the passive solar house were mostly due to its shape and HVAC system. Conversely, the impact of climate change was an increase energy consumption mostly generated by the variations of dry bulb temperature, solar radiation and relative humidity while wind speed seemed to have no influence.

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# CHAPTER I - INTRODUCTION

## I.1 Background

Residences represent an important sector of construction, a significant demand for resources, a major investment by individuals and families, and a major cause of pollution. With sustainability growing as a major concern in the residential sector, designers are concentrating their attention on reducing the influence of their buildings on the environment. [2]. However, unless a thorough impartial analysis is achieved, it is not possible to establish the impact that a particular building has on the environment.

With this concern in mind, interest in procedures to improve environmental performance increased over the past years. Many researchers are starting to adopt life-cycle assessment as a way to estimate natural resources consumption.[3],[4],[5].

The life cycle of a house encompasses three phases: manufacture or pre-use, use and disposal. The first phase includes the manufacturing as well as transportation of all building materials used, and the construction of the house [3]. The second one consists of all activities related to the use of the house over its lifespan (which is generally supposed to be 50 years). The intensive energy consuming activities during the use phase include heating, cooling, lighting and utilization of appliances. The last phase consists of the eventual demolishing of the residential building, in addition to its deconstruction and the transportation of waste to be recycled or become landfills.

Designers must take into account these three phases and their impacts on the environment in order to build sustainable. However, this focus of this study was confined to the use phase. A solution ,found by Olgyay [6], is to use the energy provided by the sun to implement passive solar designs. These designs can collect, store and redistribute solar energy. By proceeding accordingly, they can drastically lower the energy consumption of a home for heating and cooling.

Recent studies have emphasized the significance of both the embodied energy (inherent to pre-use and end-of life phases) and operational energy (related to the use-phase) of a residential building over its lifetime.[3] In this regard, low-embodied materials were chosen and applied to the main model. However, this paper does not conduct a Life Cycle Assessment (LCA) and consequently will not analyze the embodied energy of the building in depth, but rather focus on the energy use due to heating and cooling over a one-year period of time. A Seattle based case study will demonstrate the effect of design and climate change on the energy consumption of an energy efficient house with a passive solar design.

## I.2 Study Objectives

This research had three specific objectives:

1. Evaluate the influence of design on the annual energy consumption of the design ;
2. Investigate the influence of climate change on the annual energy consumption of the design; and
3. Assess the $CO_2$ emissions of the design.

## I.3 Previous research

Building sustainable habitations has been a growing concern over the past few years, time during which various studies on passive solar designs and their energy consumption have been conducted.

In 1963, Victor Olgyay published the extensive study of the impact of climate on design [6] that was used to design most of the Seahouse. He used a baseline design that he distorted and placed in different climates of the United States to determine the optimum orientation and shape of a building in relation with low energy consumption. He defined this shape as: "one with minimum heat loss in winter and minimum heat gain in summer". The results of the study indicated the optimum orientation to be within 20° of true south and the optimum shape in all climates to be a form elongated somewhere along an east-west direction due to the specific path of the sun throughout the year. It however also highlighted that this type of design was more sensitive to overheating during summer. Studies by Raeissi et al. 1998[12], Florides et al. 2002[13] and Cheung et al. 2004[14] describe the role of window and roof overhangs and their impact on energy consumption. It was found that when properly sized, they prevent the overheating effect and efficiently reduce energy requirements. These criteria conditioned the design of the Seahouse.

Regarding the influence of climate change on energy use, few in-depth analyses were encountered. This is due to the fact that most existing methods generating future weather data are too computationally intensive to be commonly used with building energy analysis. However, recently, a study on the impact of climate change on residential building heating and cooling energy requirement was realized in Australia by Wang et al. 2010[15]. Similarly to our case study, the Wang et al. paper studied the impact of climate change on both an energy-efficient[1] house and a typical house. While this study solely described the influence of temperature change on energy consumption, this paper will additionally tackle the influence of solar radiation, relative humidity and wind speed. The Wang study highlighted a general increase in heating and cooling (H/C) energy consumption between 2010 and 2050. It was also noticed that while the energy-efficient house experienced less absolute changes in energy use, it experienced higher percentage changes in the total H/C energy consumption.

Finally, a study made by Wilbanks et al.[16] in 2008 evaluated that, in the residential sector, the increase of air temperature will result in a decrease of heating energy requirements, an increase of cooling energy use and a general increase of total energy consumption. Nonetheless, no studies were found on the possible impact of the variation of other weather parameters (such as solar radiation, relative humidity or wind speed) on H/C energy consumption. Wilbanks also deduced that the increase of energy consumption would result in an increase of carbon dioxide emissions.

[1] Based on a star rating system

# CHAPTER II - INFLUENCE OF DESIGN AND CLIMATE CHANGE ON ANNUAL ENERGY CONSUMPTION OF A PASSIVE SOLAR HOUSE

## II.1 Methods

### II.1.1 Climate change weather files

The general consensus amongst scientists, indicated by the Intergovernmental Panel on Climate Change (IPCC) 2007 report [17], is that the Earth has been experiencing a gradual warming throughout the twentieth century and that it is mainly due to human emissions of greenhouse gases. What was at first considered as a theory has became a reality as more observations on climate change have been made and new expressions such as 'global warming', 'global weirding[2]' or 'greenify[3]' are surfacing, revealing the growing concern of society.

This climate change is relevant to architects and civil engineers as existing buildings should remain sturdy under future weather conditions and energy use kept to a minimum in order to ensure low carbon emissions and prevent negative environmental impacts such as heat waves for instance.

Therefore, climate change needs to be factored in when designing and modeling a new building. Consequently, it was decided to assess the influence of climate change on heating and cooling energy consumption. In order to do so, a building performance software (PBS) was utilized. While most performance building software [7][8][9][10] are suited for the analysis of building energy requirements under current weather, they do not natively allow to simulate for future weather conditions. This is mainly due to the fact that, at present, no approved climate-

[2] "*Global weirding: an increase in severe or unusual environmental activity often attributed to global warming (includes an increase in average temperatures, heat waves, cold spells, hurricanes, blizzards, plant and animal die-offs and population explosions, and new animal migration patterns).*"

[3] "*Greenify: to make less harmful to the environment*"

change weather files exist. Therefore a method had to be developed to generate climate change weather files which have the same format as present weather files.

In 2008, a convenient method was created by Jentsch et al.[11]. Developed by the University of Southampton, CCWorldWeatherGen is a Microsoft® Excel based tool which transforms present weather files, available from the US Department of Energy (US DOE) website [18], into climate change weather files. Subsequently, those files can be implemented in most energy use analysis software available in the market.

The following shows the CCWorldWeatherGen spreadsheet that was used to generate the climate change weather files.

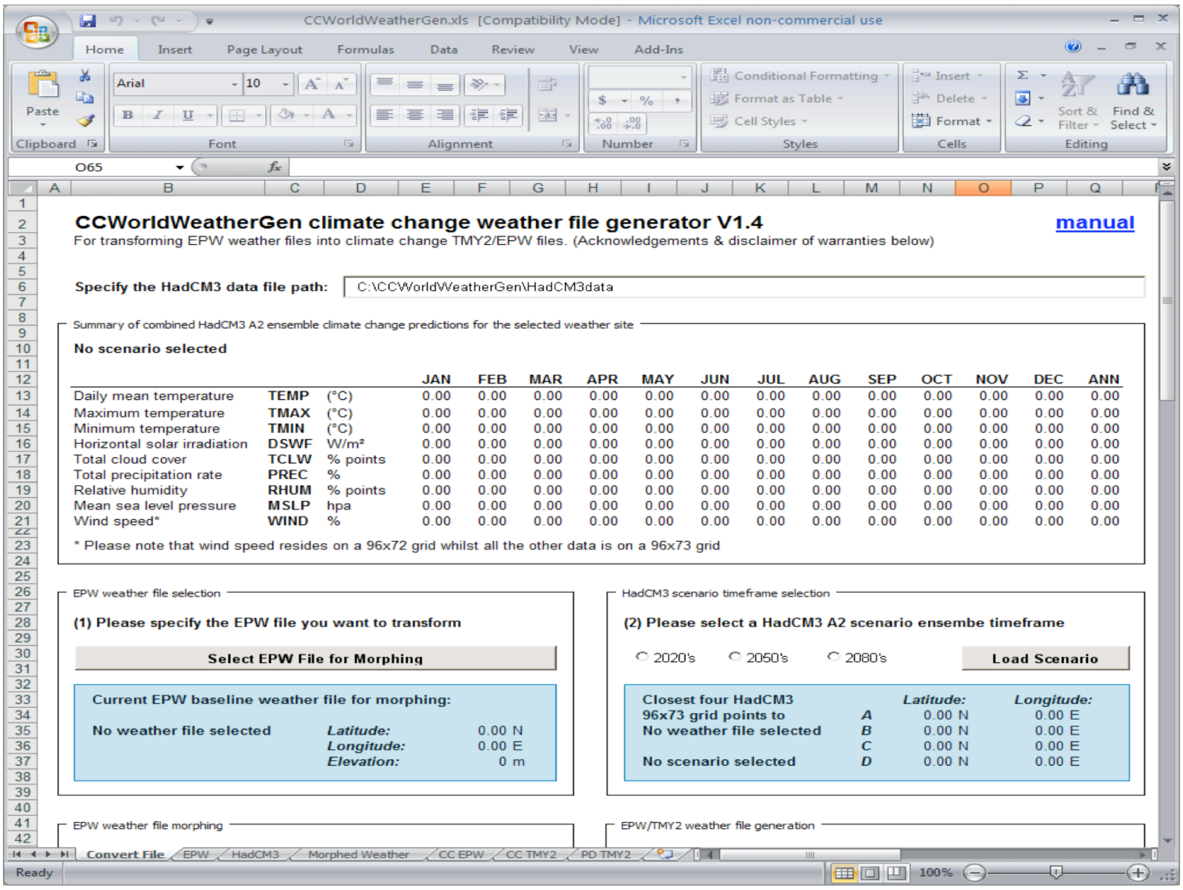



**Figure II.1.1 – CCWorldWeatherGen tool**

The present weather file is first implemented, a year is chosen (2020, 2050 and 2080) and a climate change weather file is issued. 2050 was chosen in our case study.

This tool uses algorithms based on present data from Belcher et al. [19] to obtain climate-change results. Both these papers describe this method as "meteorologically consistent" as it is based on reliable[4] weather data from present weather files. It was therefore considered appropriate for the analysis of the heating and cooling energy consumption of the Seahouse.

More information on the weather file format and variables that it encapsulates can be found in both the appendix and in a paper by Crawley et al.[20].

### II.1.2 Building performance & design software

Building energy consumption can be determined by taking measurements of the actual fuel and electricity consumed over an extended period of time, or by modeling simulations. Use of modeling software was selected for several reasons:

1) A whole year of measurements would be required to actually assess annual energy consumption while a software simulation typically takes several hours.

3) Using simulation software prevents from, measurement or calibration errors due to heating/cooling control equipment, untypical occupant behavior, irregularities from seasonal variations or abnormal weather conditions. This is relevant because it was decided to evaluate energy consumption of a 'typical' year.

4) Modeling with software provides an alternative to adjust and improve a design. For instance, various scenarios can be run to assess the energy use of different building envelope configurations in order to obtain a more energy efficient design.

[4] This data is reliable because measured at real location

Energy analysis is a major concern of residential design due to the large life cycle energy uses. Many building performance software are currently available on the market with EnergyPlus [7], DesignBuilder [8], Autodesk's Ecotect [9] and Integrated Environmental Solutions' Virtual Environment suite (IES VE) [10] being the major ones. Concerning the modeling of the residential building, countless software exists.

To provide a relevant analysis, it was decided to choose the industry standard in both categories. While Ecotect is currently gaining attention, EnergyPlus is still considered the industry standard software for assessment of energy consumption. This is partially due to the fact that EnergyPlus is based on more accurate weather files[5], which are of considerable significance for building simulation. EnergyPlus is the U.S. DOE building energy simulation program for modeling energy flows (such as heating, cooling and lighting, etc...). Although it provides accurate calculations and is free, it is not user-friendly and lacks graphical outputs. Consequently, it was decided to utilize DesignBuilder. DesignBuilder is a graphic engine for EnergyPlus which displays EnergyPlus results as graphs and tables to enable an easier understanding and assessment of the analysis. Another advantage of DesignBuilder is that, as its name indicates, it allows the user to create a design directly within the software in a very instinctive manner. A design can be created out of nothing, imported or extruded from floor plan files. The latter was chosen to model the standard home (then referred to as Minnhouse or MH) for reasons described in the section entitled 'Minnhouse framework' of the appendix, while the second option was selected to model the energy efficient house (later on alluded to as Seahouse or SH).

The energy efficient design created during the course of this thesis is based on the recommendations of the Olgyay study [6]. This initial design was modeled in Revit [25],

[5] The composition of these weather files are discussed in the second chapter of this thesis paper.

widely considered the industry standard software for modeling by architects and engineers, and it was therefore decided to modify it in Autodesk's Revit. The original design was already made to be sustainable in many but its gross floor area (GFA) was only 1500 $ft^2$ and for 2 occupants. The design was altered to reach a final GFA of 2019 $ft^2$, incorporates 4 bedrooms and 4 occupants and meet the requirements of section 704.3.1.1 of the National Green Building Standard (NGBS) rating system (including the R-values recommendations and windows criteria previously mentionned). The shape of the original design was the one of a passive solar house and the materials of the outer shell were judged in accordance with the NGBS code. Consequently, despite of the size of the building, the designs are extremely similar from the outside. This baseline house (BH) was built over summer 2010 and pictures were taken and added to the appendix to provide a close preview of the final design.

### II.1.3 Sustainable materials selection of the Seahouse

Utilizing materials efficiently, selecting them to be environmentally preferable and minimizing waste during construction substantially contributes to make a home sustainable. For this reason most of the points of the NGBS code [24] are awarded to Resource Efficiency.

Since the lower the embodied energy the more sustainable the material, any practice that can lower the embodied energy of a material should be factored in the decision making process. Therefore a certain material is judged sustainable if it is renewable, resource-efficient, reused or salvaged, durable, requires low maintenance or has a high recycled-content. All these criteria make the assessment of embodied energy and choice of materials an intricate process as some of them balance the other. For instance for wall siding, some metals (such as Aluminum or Copper) usually have high embodied energy when compared to wood grown locally but is more durable and requires less maintenance on the other hand.

While embodied energy of materials was not meticulously assessed in this case study, it was still considered in the choice of materials. However, materials that would substantially lower operational energy were generally used instead of materials of comparatively less embodied energy as the study focused mostly on heating and cooling. Materials with lowest possible embodied energy were chosen otherwise. Points awarded by the NGBS code for the choice of certain materials were also considered.

Subsequently, the following materials were chosen:

- Reclaimed oak wood for flooring;
- High recycled-content steel for wall;
- ENERGY STAR certified high recycled-content steel roofing with appropriate reflectance;
- Forest Stewardship Council (FSC) [26] certified wood for house framing; and
- Low-density spray foam-in-place polyurethane for insulation.

Note: While these materials were chosen in order to build a sustainable house, they do not play a role in the calculations of heating and cooling requirements and were solely included for potential future studies on embodied energy and cost calculations.

The interior finished walls for the Seahouse are composed of standard drywalls made from gypsum plasterboard. At present, more sustainable drywalls exist: the EcoRock [27] drywalls made by Serious Materials. They are essentially from recycled content and contain less embodied energy than gypsum. However, this product is still in the beta testing stage in select markets in North California and at this time its technology is still proprietary. Therefore, the lack of information on properties of this product did not allow for modeling in DesignBuilder. Nonetheless, this change would not have made an impact on the final results of this paper as EcoRock drywalls are not more energy energy-efficient than standard drywalls.

More details explaining the choice of these materials can be found in the appendix section of this thesis.

### II.1.4 The Passive Solar Design of the Seahouse

While the energy consumption of a residential building is dependent on the type of appliances that were used and the behavior of inhabitants, it is also contingent upon the design. A specific design will imply a specific consumption; therefore a part of this thesis was focused on choosing the most beneficial design for our particular case study. Since the concern of this case study is heating and cooling energy use, it was decided to implement a passive solar design. This type of design utilizes the sun's energy for the heating and cooling of living spaces in a way that allows to reduce energy consumption from appliances. This process is done by either introducing materials which will directly take advantage of the natural energy features produced by exposure to the sun or by the implementation of certain architectural elements. Another attractive criteria for choosing this alternative, is that passive solar design can be relatively simple[6] which in turn implies that they could be made as prefabs, sustainably relieving the cost of construction.

The choice of the NGBS code and passive solar design imposed restrictions. Following these restrictions, the passive solar design discussed in this paper is as follows:

- The long side of building faces within 20 degrees of true south
- Vertical glazing is ENERGY STAR compliant and represents:
    - **7** percent of gross conditioned floor area on **south face**

[6] The particular design of the Seahouse attests to it as it is box-like.

▪ **2** percent of the gross conditioned floor area on the **west face**

▪ **4** percent of the gross conditioned floor area on the **east face**

▪ **8** percent of the gross conditioned floor area on the **north face**

- The skylights are ENERGY STAR compliant and represent 1.5 percent of the finished ceiling area.

- The south facing overhangs were also designed using the NGBS recommendations following this table

| | Vertical distance between bottom of overhang and top of window sill | | | | |
|---|---|---|---|---|---|
| | **≤ 7’4’’** | **≤ 6’4’’** | **≤ 5’4’’** | **≤ 4’4’’** | **≤ 3’4’’** |
| For Seattle’s climate zone | **2’4’’** | **2’4’’** | **2’0’’** | **2’0’’** | **1’8’’** |

**Figure II.1.4.1 - NGBS criteria for south-facing window overhang depth**

The overhangs’ depth was set to 1’8’’ as the vertical between bottom of it overhang and top of window sill was inferior to 3’4’’.

The following shows where window overhangs and skylights were placed.

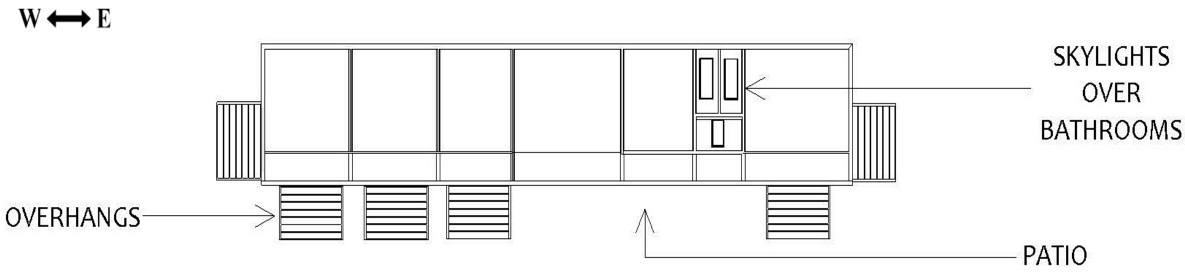



**Figure II.1.4.2 - Placement of window overhangs and skylights.**

The windows overhangs were sized to prevent overheating of the building of the building during summer and let light enter the building during winter. This is done by taking into account the altitude of the sun during both these seasons as shown in the next figure.

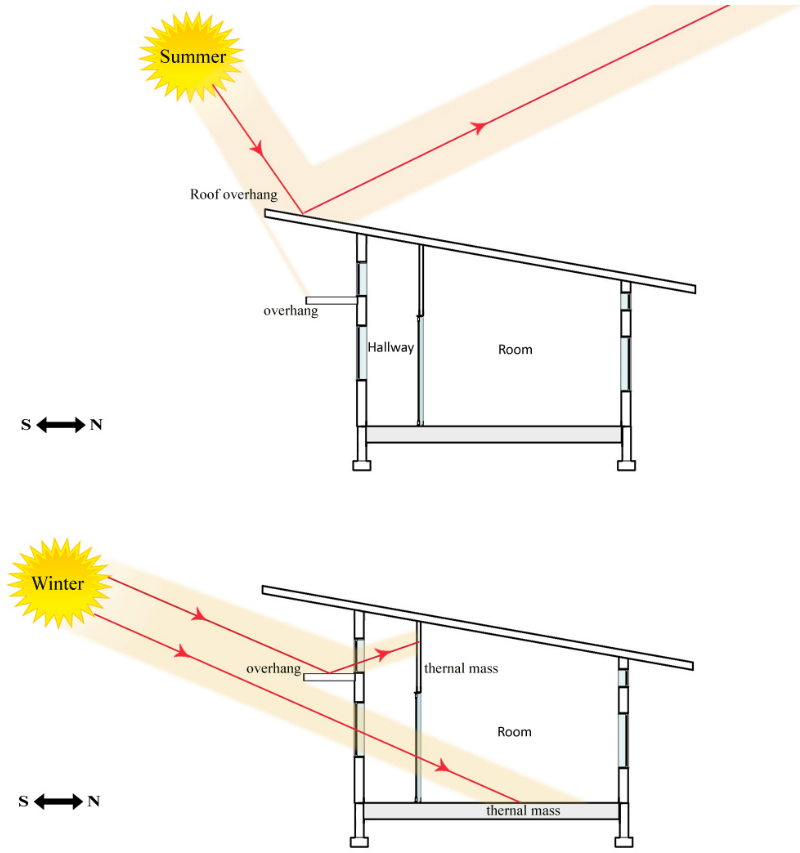



**Figure II.1.4.3 - Role of the overhangs of the Seahouse design**

During winter, the south facing wall of our design is going to act as a sun collector. As can be seen on figure II.1.5.3, the sun will be at an altitude that will allow it to reach the inside of the house. Some light will bounce off the top of the window overhang into the house, while most of the light will pass through glazing. The glazing is composed of energy efficient windows. These ENERY STAR windows [28] are filled with argon which allow for high insulation and therefore reduce heat loss through windows. The low-Emissivity (Low-E) coating will reflect infrared light, keeping heat outside during summer and inside during winter. Once the light passes though the first layer of glazing and hallway, it will either reach a wall or another window. This wall is composed of thermal mass and the window will let the light reach a floor that will also be made of thermal mass. This thermal mass is going to store heat energy for a prolonged period of time and prevent rapid variations of temperature. By this process, passive heating is achieved and floors and walls become functional parts of the house.

During summer, the sun is significantly higher than during the winter solstice. For this reason, the roof is going to play a major part in reducing energy cost from cooling. Both windows and roof overhangs are sized to let only a certain amount of sunlight enter the house. Additionally, the roof is ENERGY STAR certified. The ENERGY STAR criteria used to assess the energy efficiency of a roof is the solar reflectance index (SRI). This implies that the roof is made out of a surface that will reflect light keeping heat outside of the house.

More information on how this passive solar design was set can be found in the appendix.

### II.1.5 Comparison of Seahouse and Minnhouse

The Seahouse was modeled as an energy-efficient design to assess both the validity of the NGBS code recommendations and how this type of design would behave under future weather conditions. It is a one story high, passive solar house with a total floor area of 2,019 $ft^2$ and four bedrooms (which three are occupied and one is a guestroom) shared between four occupants. The design is very simple, box-like. That simplicity implies that the Seahouse could eventually be available as a prefab. While the Triple bottom line ("people, planet, profit") is at the heart of sustainability, the economy and social aspects are fulfilled by the green prefab design of the Seahouse, lowering the price and making it more accessible to people. In this regard, the design appears sustainable.

The standard house (referred to as the Minnhouse) was chosen because of exhaustive data availability and its size being close to the Seahouse's. It was originally found in a report from the Consortium for Research on Renewable Industrial Materials (CORRIM) [29] and was designed as a two-story building with a basement, representing a typical construction in the Minneapolis area. An unconditioned attic acts as the ceiling of the second story. A two car garage and a full unfinished basement are also part of this model. Wood-based composites (mostly plywood) were used as sheathing and pre-engineered roof trusses were used as a roof system. The total floor area of the structure was 2,062 $ft^2$. The foundation was designed as 12-in thick concrete masonry block walls.

One of the most important features is the insulation of the house as it directly affects the heating and cooling energy consumptions. The R-value is usually used to quantify the level of insulations of different house components. The following table compares the R-values of both designs. While the Minnhouse followed the recommendations of the Uniform Building Code 2000 for Minnesota, the Seahouse followed the NGBS' for the Seattle area.

| Location | R-values of Minnhouse | R-values of Seahouse |
|---|---|---|
| Roof (ceiling) | R-49 | R-44 |
| External Walls | R-21 | R-22 |
| Internal Walls | R-15 | R-15 |
| Crawl Space | No crawlspace | R-15 |
| Basement Walls | R-11 | No basement |
| Floors | R-30 | R-35 |

**Table II.1.5 - R-values of Minnhouse and Seahouse**

Focus was also brought upon the Heating, Ventilating and Air-conditioning (HVAC) system. While geothermal heat-pumps with a coefficient of performance [7](CoP) of 4.3 were used for both heating and cooling of the Seahouse, the Minnhouse used a central gas furnace system fueled by natural gas with a CoP of 0.65 for heating. For cooling, central air conditioner was assumed with a CoP of 2.5.

Renderings, floor plans and construction details of both designs can be found in the appendix section of this paper.

### II.1.6 Assumptions made for the simulation

Site-specific assumptions are required by the energy use software. The following lists the assumptions that were common for both buildings and the ones that were made for each building in order to provide a relevant energy analysis.

**For both models:**

- The orientation of each house faced south. It was assumed that there were no neighboring houses or large trees within 25 feet.
- The double pane, low-emission (low E), ENERGY STAR certified windows filled

[7] *The coefficient of performance is a measure of efficiency in the heating mode that represents the ratio of total heating capacity to electrical energy input.*

with argon were used in both models.

•The grid supplied 110 volt electricity.

•Heating and cooling were set-back/set-up set for between 11 p.m. and 7 a.m.

•Life span of home: 1 year.

•Under the 'environmental control' tab, for each model the temperature assumptions for heating and cooling were:

| | Temperature assumptions for heating and cooling (°C) | Temperature assumptions for heating and cooling (°F) |
|---|---|---|
| Heating—daytime | 20 | 68 |
| Heating—nighttime | 16.7 | 62 |
| Cooling—daytime | 25.6 | 78 |
| Cooling—nighttime | 26.7 | 80 |

**Table II.1.6 - Heating and cooling temperature assumptions**

•The climatic specifics of the various locations the model was simulated for were:

▪ **Seattle**, Washington, at the Seattle-Boeing field, Koppen classification[8] [30]: Cfb and climatic region: 4C.

▪ **Minneapolis**, Minnesota, at Minneapolis-St Paul International Airport, Koppen classification: Dfa and climatic region: 6A.

▪ **Denver**, Colorado, at Denver-Stapleton International Airport, Koppen classification: BSk and climatic region: 5B.

▪ and **Atlanta**, Georgia at the International Airport, Koppen classification: Cfa and

[8] *The Köppen climate classification is one of the most widely used climate classification systems. In this classification, climate zone boundaries are based on vegetation. It includes average annual and monthly temperatures and precipitation, and the seasonality of precipitation.*

climatic region: 4A.

While both designs could have been more efficient depending on the climate, they were remained unchanged through all simulations to assess the influence of design on annual energy consumption.

Regarding **occupancy**, both models are single family houses. In DesignBuilder, the occupancy of a house is a density set in people/$m^2$. The birth rate [31] being 2.1 in 2008, it was assessed that the typical American family is composed of 4 people (2 parents and 2 children). Therefore the density was of: 0.0208 people/$m^2$ (i.e. 4 people/191.566 $m^2$) for the Minnhouse and 0.0213 people/$m^2$ (i.e. 4 people/ 187.571$m^2$) for the Seahouse.

Periods of holidays, when family might leave the house were not taken into account for each model.

The daily hot water (DHW) consumption rate was set on the dwelling template for both models which gives: 0.53 liter/($m^2$.day).

Natural ventilation option was on, with outside air set to 3 AC/hr[9].

Regarding airtightness, the infiltration (which corresponds to unintentional ventilation) rate was set on a constant rate of 0.7 AC/h.

Finally, the 'auxiliary energy' HVAC tab in DesignBuilder (-which defines the energy consumption of fans, pumps and other auxiliary equipment-) is used to set up a constant annual auxiliary energy consumption. It was set to 0.40 kWh/$m^2$ for both houses.

Differences between both models include building code and year of construction. While the Minnhouse followed the 2000 Uniform Building Code (UBC), the Seahouse followed the

[9] Ventilation air change in Air Change / hour

NGBS code. A year of construction has to be entered in DesignBuilder in the model specifications. Since the Minnhouse was built in 2002 and the baseline house for the Seahouse in 2010, they were set accordingly. This, however, does not affect energy calculations.

### II.1.7 Processes and Factors not included

In order to solely focus on the design's direct influence on energy use, some components found in most homes and some other factors were not addressed. The following issues were not taken into account in this case study:

▪**Energy and material issues related to the house surrounding** (e.g., drive-way concrete, landscaping, irrigation),

▪ Furthermore anything in relation with **Site design, lot design and development** that would make the house more sustainable, including issues related to slope disturbance, soil disturbance and erosion, storm water management, landscape planning, wildlife habitat, operation and maintenance planning, existing buildings, existing and recycled materials, environmentally sensitive areas and mixed-use development, driveways and parking areas, cluster development, zoning, wetlands, mass transit and heat island mitigation.

▪**Embodied energy** was included in the choice of certain materials (such as for walls and floors), but operational was perceived as the priority of this case study. No attention was accorded to the deconstruction of the house. A life-cycle assessment (LCA) was not carried out.

▪**Indoor environmental quality (IEQ) and moisture** management related issues such as off-gassing from paint, cleaning materials and flooring; wall coverings, architectural coatings, adhesives and sealants, radon control, central vacuum systems, living space contaminants and moisture and humidity control measures.

▪**Energy used by common appliances** such as computer, TV, radio, microwave, toaster, computers,…**and the energy that could be saved by considering energy efficient appliances**, such as ENERGY STAR [23] refrigerators/freezers, dishwashers, clothes washers, clothes dryers,…

▪**The social factors** which include behavioral patterns of habitants in relation with food consumption, clothing, entertainment equipment, pet supplies or other items not requiring energy for operation.

▪ **Water consumption and energy consumption related to treating/supplying water** by showerheads, faucets, water closets, irrigation systems; and **rainwater collection and distribution**.

▪ **Renewable energy** that could have been brought by efficient recent technologies such as photovoltaics, solar water heaters or wind turbines for instance.

▪**Garage**: any standard house includes a garage; it was however decided not to implement one since the study exclusively focuses on heating and cooling energy requirements.

▪Other common components such as furniture and curtains which would have an incidence on daylighting, pipes excavation, meters, wiring and other utility or power hook-ups…

▪**Cost estimates**: due to the short timeframe of this thesis, no cost estimates were realized on the Seahouse and Minnhouse. Additional work on this thesis would cover a detailed cost analysis including the cost of materials, operational energy and payback periods for both models as this is would help further assess the sustainability of the Seahouse design since a sustainable design should be affordable.

## II.2 Results and discussion

The following results will focus on the influence of our passive solar design and climate change on annual heating and cooling energy consumption. Finally the carbon dioxide emissions of the Seahouse will be analyzed. Throughout this section the Seahouse will be referred to as SH and the Minnhouse as MH. All graphs were produced from simulations realized in the city the SH was originally located in: Seattle, Washington. The size difference between SH and MH led to a normalization of both designs in $kWh/m^2$. More results regarding the other locations can be found in the appendix section.

### II.2.1 Influence of Design on energy consumption

The first simulations were run for SH and MH located in different cities during current weather. As can be seen in table III.8.2, the passive solar design saved significantly more energy than the standard home from 84% to 93% depending on location. The SH was found to be most efficient in Seattle, which is characterized by an oceanic climate, and least in Atlanta, which can be depicted by a humid subtropical climate[10]. This is therefore coherent as the energy-efficiency of a building is climate dependent [6] and that the SH was originally modeled for Seattle area climate standards.

The following figure displays the influence of the design on total[11] annual energy consumption by comparing the consumption of both SH and MH.

[10] *More information on those climates and tables on site weather data are available in the appendix section of this document.*
[11] Heating & cooling energy consumption

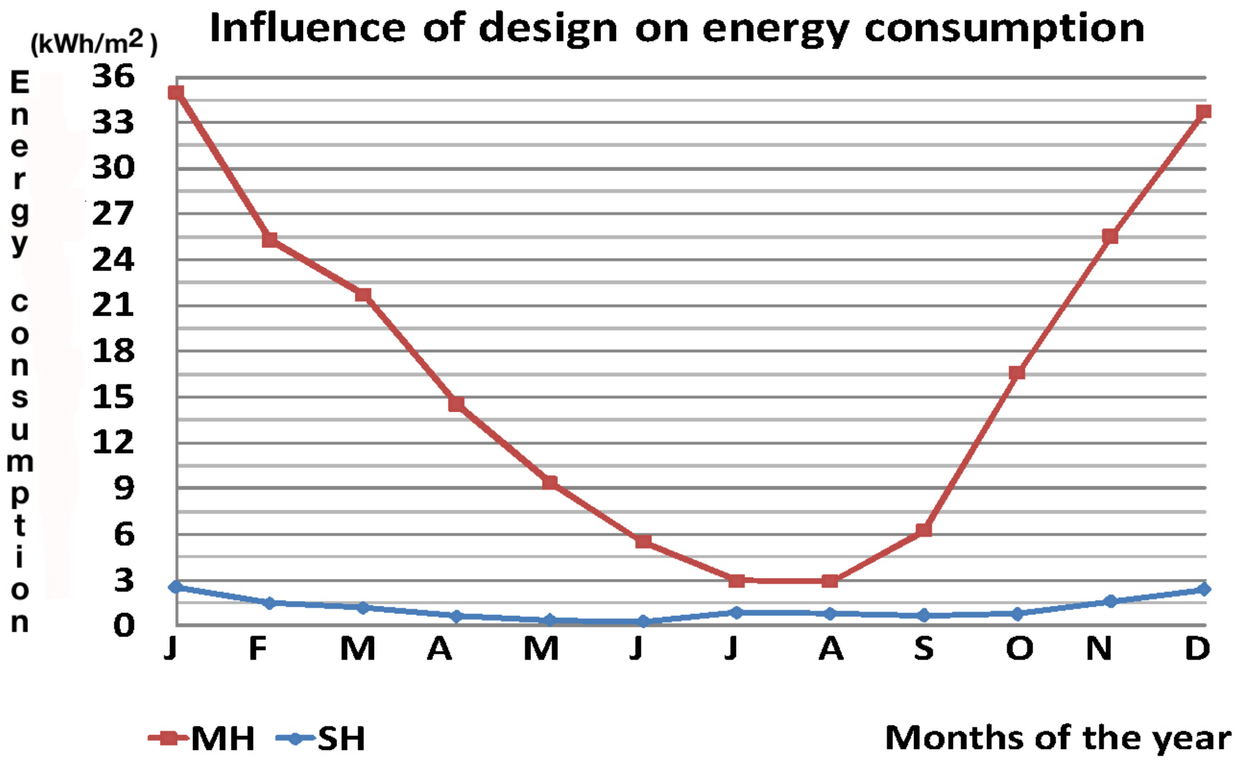



**Figure II.2.1 - Influence of design during current weather**

SH design consumes significantly less energy for heating and cooling than the MH design throughout the year. The graph shows that both designs consume the majority of their energy during winter season (from November to March) and that, when compared to the typical house, the efficiency of the passive solar design is optimum between September and June. Table III.8.2, available in the appendix, shows that most of the energy is generally used for heating for both designs[12]. In addition, table III.8.3.1 indicates that both buildings behave the same way during future weather and that the passive solar design is still considerably more efficient than the typical house during future weather (from 75% to 91% depending on location).

Three parts of the SH design were considered to explain those results. The next

[12] During present weather, the SH design consumes 1 to 4 times more energy for heating than cooling except in Atlanta and the MH design consumes 8 to 90 times more energy for heating depending on location

sections will focus on the influence of the shape of the SH, its HVAC system and finally of its insulation on annual energy consumption.

#### II.2.1.1 Influence of Shape on energy consumption

To assess the influence of the SH shape on energy consumption, a simulation comparing the energy requirements of both MH and a modified house was carried out. That modified house is characterized by the shape of SH but with all other components identical to the ones of MH and is referred to as SH1 in figure II.2.1.1.

This simulation, available in table III.8.2.1, shows that when compared to the squarish shape of the Minnhouse, the elongated shape saved from 52% to 63% on annual energy consumption. These results are in accordance with a study made by Olgyay in 1963[6]. In simulations realized upon several climates of the United States, it was noticed the followings:

- The square shape is not the optimum for any location;
- Buildings shaped without regard for the sun's impact need large amounts of energy for heating and cooling; and
- The optimum shape in all climates was found to be a form elongated somewhere along an east-west direction such as design of the Seahouse.

The fact that the design is elongated along the east-west axis means that its longest façade is facing south. This implies that it receives the most solar radiation [6] [32]. The study showed however that, while this orientation and shape is optimum (especially during winter months), this design is also the most sensitive to overheating during summer. As seen in the section regarding the passive solar design of the Seahouse, the issue was solved with the use of appropriately sized overhangs. While the specific influence of overhangs was not assessed in this case study, the efficiency of overhangs has been proven in several studies such as the ones made by Raeissi et al. 1998 [12], Florides et al. 2002 [13] and Cheung et al. 2004[14].

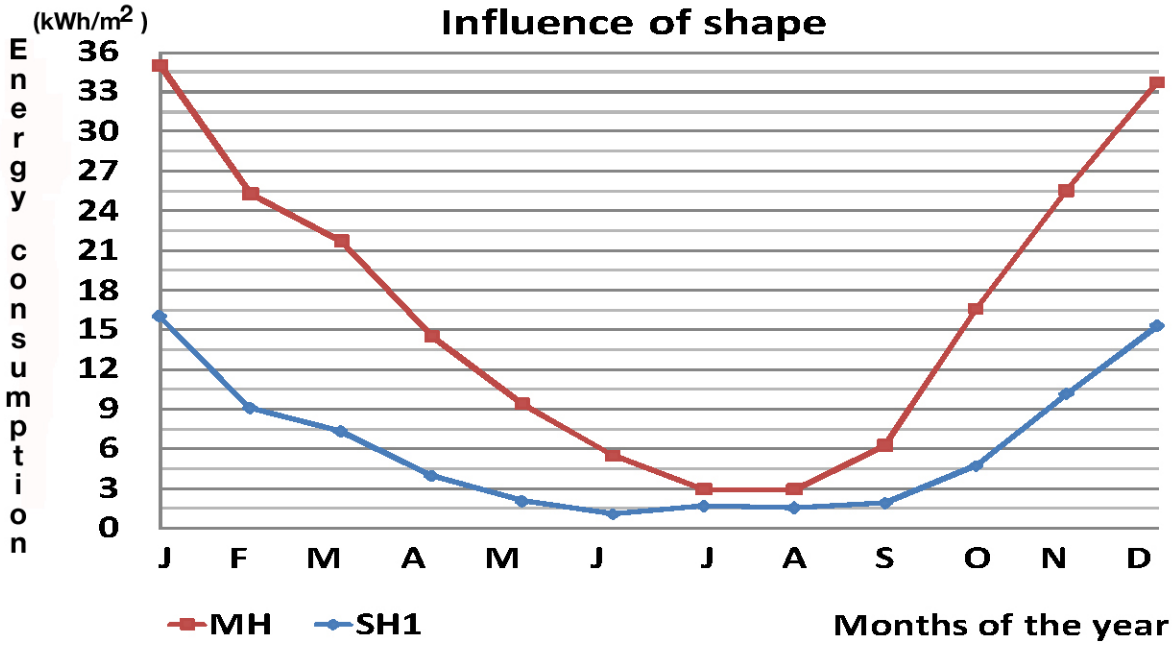



**Figure II.2.1.1 - Influence of shape during current weather**

Figure II.2.1.1 highlights that the significant savings in energy consumption generated by the elongated shape were mostly made between September and June. When compared to figure II.2.1, figure II.2.1.1 also indicates that while the change in shape plays a major role in the influence of design on energy consumption, it does not fully explain it. To that effect, it was decided to analyze in more details the roles played by insulation and HVAC system were assessed.

### II.2.1.2 Influence of Insulation on energy consumption

The R-values and construction materials of the SH design were implemented in the MH design to evaluate the influence of insulation on energy consumption. The resulting design is referred to as SH2 in figure II.2.1.2. The following graph compares the total energy consumption of the typical house with the one of the SH2.

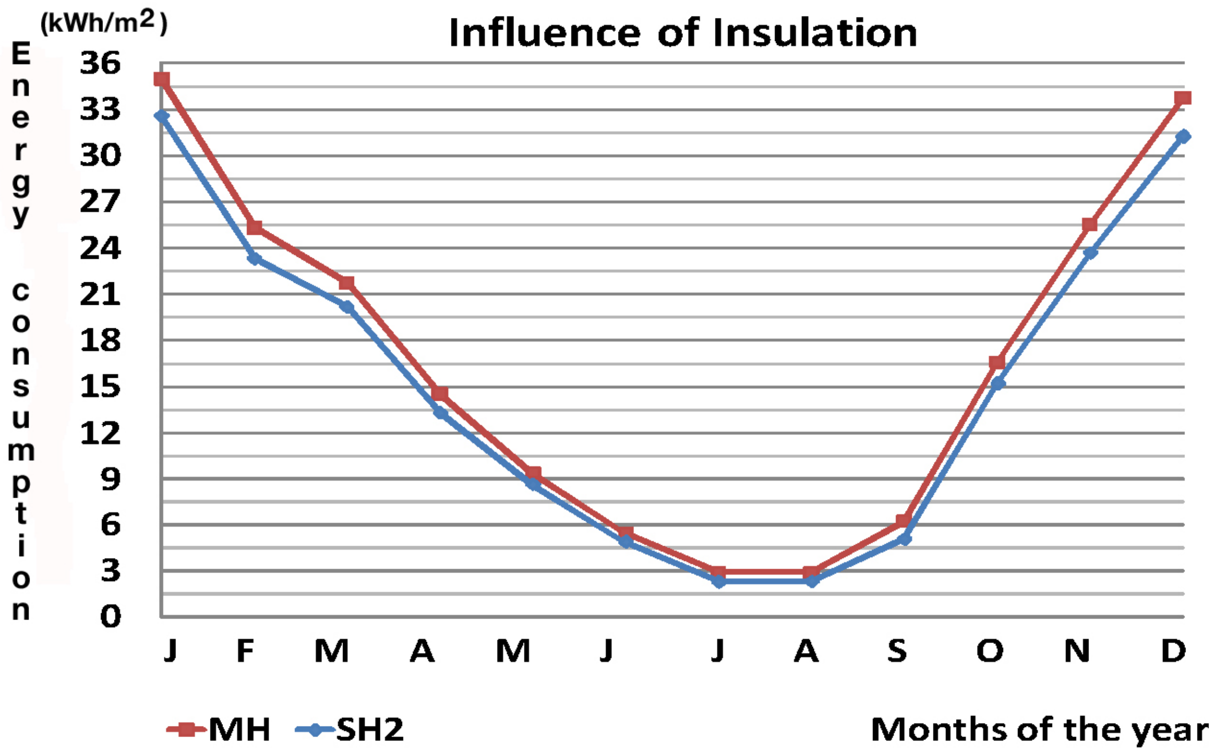



**Figure II.2.1.2 - Influence of insulation during current weather**

Figure II.2.1.2 shows that, relatively to the influence of shape, the changes made to the insulation of the typical house slightly improved its savings in energy consumption. Table III.8.2.2 indicates that these improvements were between 8% to 10% depending on location. As seen in table II.1.6, the R-values of SH are close to the ones of MH explaining the results of figure II.2.1.2. While the influence of insulation on energy consumption is known to be existent (Xiao et al. 2010) [33], the change in insulation is not significant enough in our case study to imply consequent savings. The difference of insulation values is small because both houses were designed for different climates using different building codes. Therefore, while MH was designed for a colder climate using a standard building code[13], SH was designed for

[13] UBC 2000

a slightly warmer climate[14] using a more stringent code reducing the gap in recommended R-values for both designs.

### II.2.1.3 Influence of HVAC system on energy consumption

For this simulation, the HVAC system of SH was implemented in the design of MH. The resulting design is referred to as SH3.

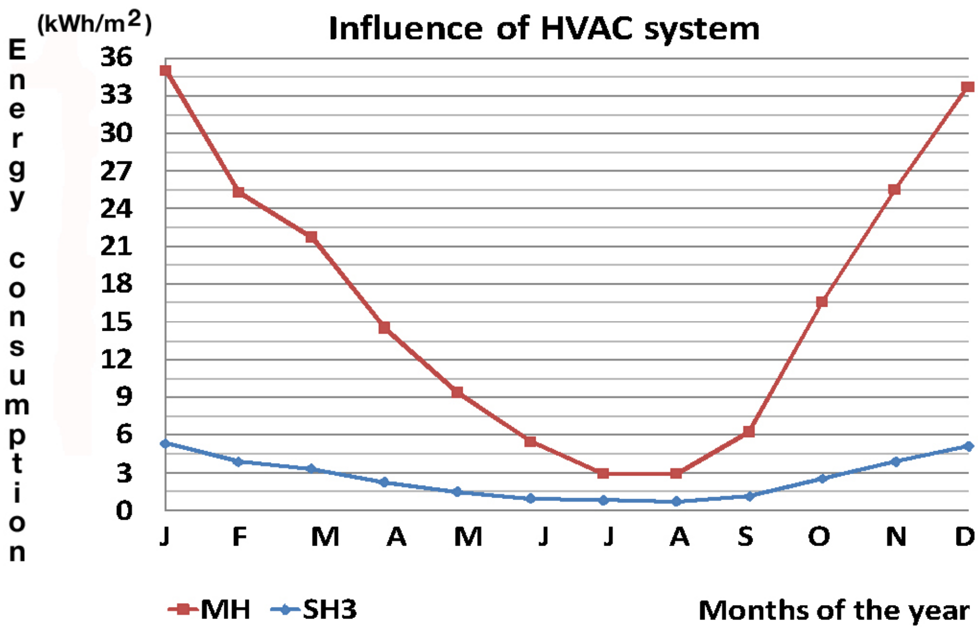



**Figure II.2.1.3 - Influence of HVAC system during current weather**

Figure II.2.1.3 indicates that the HVAC system plays an important role in the influence of the design on the annual energy consumption. This is correlated by the results found in table III.8.2.3 which expresses that, depending on location, the SH HVAC system allows to save from 81% to 84% on annual energy consumption. This high efficiency is explained by the difference in coefficients of performance (CoP) between both HVAC systems. The coefficient of performance is defined as the ratio of the desired effect from the heat pump (i.e. producing heat) to the power consumed by the compressor of the heat pump [34] Therefore, for the same amount of heat produced, less energy is consumed by a technology characterized

[14] As seen in the 'different climates' and 'site weather' section of the appendix.

by high CoP values instead of standard ones. In order to prove the importance of these CoP values, simulations where CoPs from the SH HVAC system were replaced in the MH HVAC system were run and summarized in table III.8.2.4 of the appendix. For all locations, a difference between tables III.8.2.3 and III.8.2.4's results of less than 1% was noticed. The influence of the HVAC system on energy consumption therefore coincides with the influence of its CoP values. Those results are in accordance with the study realized by Zogou et al. in 2007[35] on the optimization of thermal performance of a building with ground source heat pump system. In our case study, while SH uses a geothermal heat-pump system with a CoP of 4.3 for both heating and cooling, MH uses a central gas furnace with a CoP of 0.65 for heating and a traditional electric air conditioning system for cooling with a CoP of 2.5 explaining the results from figure II.2.1.3.

Consequently, the efficiency of the design is mostly due to its shape and the efficiency of its HVAC system, while in our case study the change in insulation values had a significantly lesser impact on energy consumption.

### II.2.2 Influence of Climate change on energy consumption

The following graph displays the influence of climate change on total energy consumption of the SH design placed in Seattle.

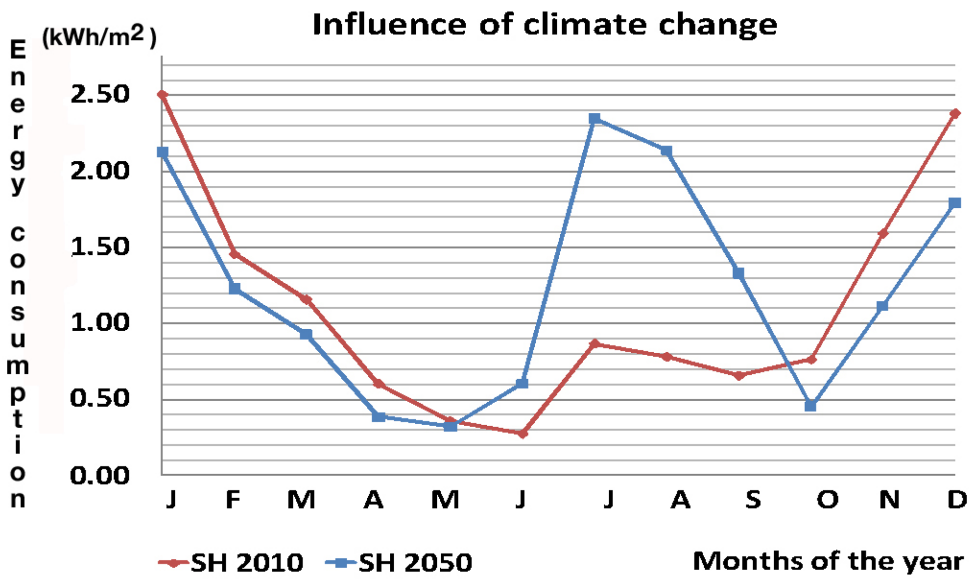



**Figure II.2.2 - Influence of climate change on total energy consumption**

During the year 2050, the SH design consumes considerably more energy between May and September than it did during the year 2010 and less during the rest of the year. Table III.8.3.1 indicates that, depending on location, SH consumes yearly from 8% to 39% more energy during future weather than present, and that while the design consumes more energy for cooling than it previously did, it also consumes less for heating. Those results are in accordance with the report made by Wilbanks et al. 2008[16].

To understand these results on the influence of climate change on the annual energy consumption, the analysis was divided in the assessment of four different weather parameters: dry bulb temperature, solar radiation, relative humidity and wind speed. Data relative to each of these parameters were extracted from the 2050 weather files and implemented in the 2010 weather files and four types of simulations were run.

### II.2.2.1 Influence of dry bulb temperature

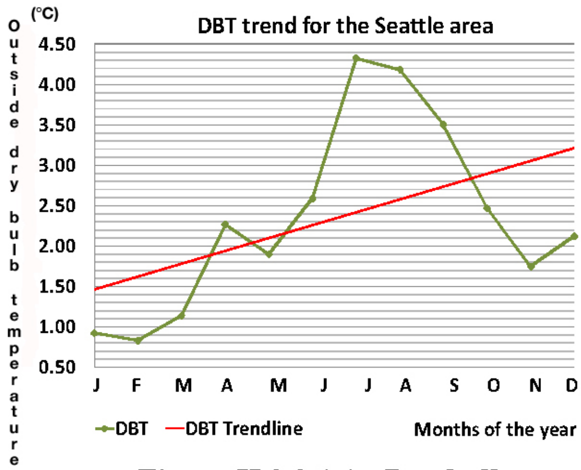



**Figure II.2.2.1.1 - Dry bulb temperature (DBT) trend**

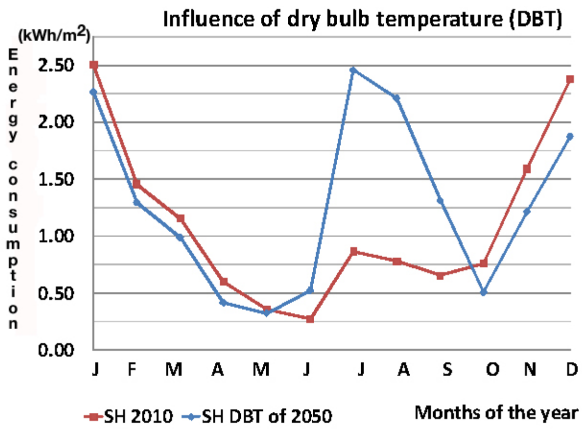



**Figure II.2.2.1.2 - Influence of dry bulb temperature**

The most obvious explanation to the increase in cooling needs and decrease in heating requirements would be an increase of temperature as also noticed by Houghton et al. 2001[36] and Wang et al. 2010[15]. For this reason, the influence of dry bulb temperature[15] on the energy consumption was undertaken. As displayed by table III.8.1.3 and figure II.2.2.1.1, the dry bulb temperature year average increased by 2.33°C for Seattle between 2010 and 2050, which represents an increase in temperature of almost 20 %. Figure II.2.2.1.2 shows a very similar graph to the previous one on the influence of climate change. This means that temperature is likely to be the most influential factor in the impact of climate change on energy consumption. As expected, the simulations on the influence of dry bulb temperature highlight that under these new temperatures, the building now consumes more energy to cool itself and less for heating than it did under a typical 2010 weather. These results were found to be in accordance with a report made by Wang et al. in 2010[15]. Table III.8.3.2 also indicates that the change in dry bulb temperature increased annual energy consumption from 9% to 44% depending on location. This is more than what was noticed for

[15] Dry bulb temperature is also referred to as Air temperature.

the influence of climate change on energy consumption, which means that other weather parameters should decrease the energy requirements during future climate.

### II.2.2.2 Influence of solar radiation on energy consumption

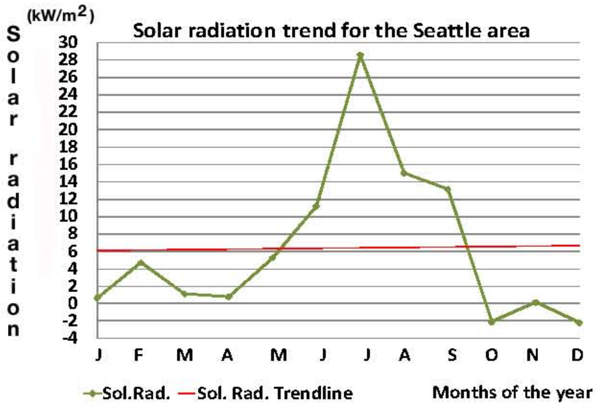



Figure II.2.2.2.1 - Solar radiation (Sol.Rad.) trend

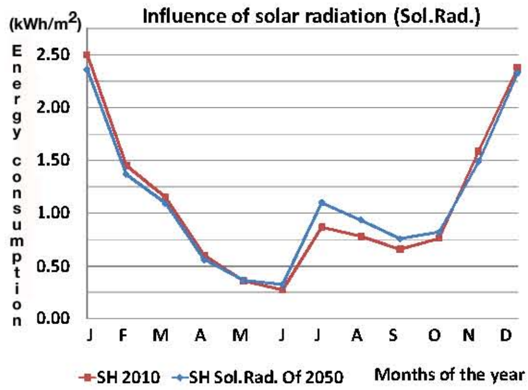



Figure II.2.2.2.2 - Influence of solar radiation

Figure II.2.2.2.1 shows a slight increase of solar radiation that table III.8.1.3 depicts as an annual increase of 6.5% between 2010 and 2050.That increase trend of solar radiation was found to be in accordance with simulations found in a report made by Wang et al. 2010[15]. On figure II.2.2.2.2, the influence of solar radiation on energy consumption is not as significant as the influence of dry bulb temperature and mostly takes effect between June and October. This is confirmed by table III.8.3.3 which shows that, as for dry bulb temperature, the increase of solar radiation provokes an increase of cooling requirements and a decrease of heating needs. Since the house is of passive solar type, it was designed to receive and store the heat produced by the sun with the help of thermal mass and appropriate glazing. Consequently, an increase of solar radiation logically results in a decrease of heating needs. SH was however designed, with NGBS guidelines, for the Seattle area under current weather assumptions instead of future ones. In our case study, the increase of solar radiation also resulted in an increase of cooling requirements. When compared to the 2010 weather, the solar radiation increase produced an increase in energy consumption of 1%[16] to 4% depending on location[17].

### II.2.2.3 Influence of relative humidity on energy consumption

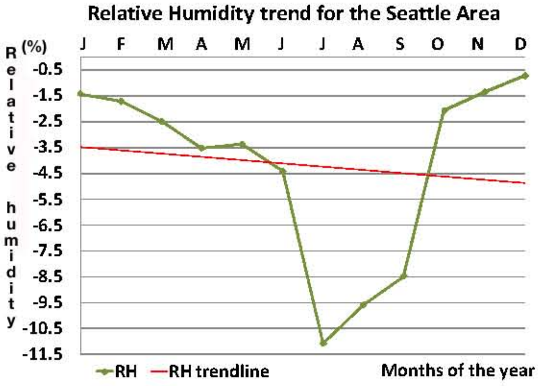



**Figure II.2.2.3.1 - Relative humidity (RH) trend**

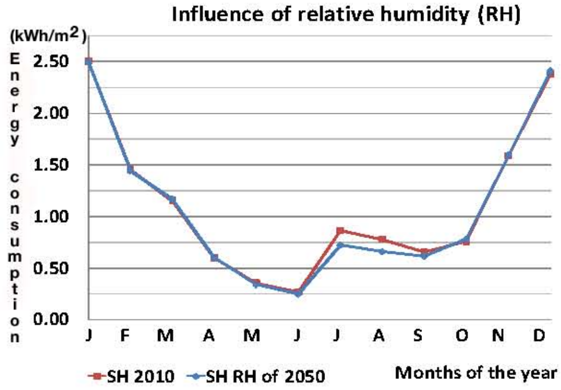
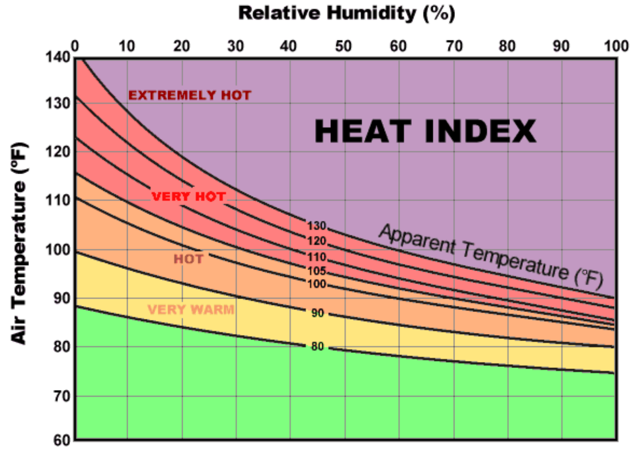



**Figure II.2.2.3.2 - Influence of relative humidity**

While other weather parameters increased during future weather, relative humidity decreases. This trend was found to be in accordance with a recent paper on the impact of climate change on residential heating and cooling by Wang et al 2010[15]. According to table III.8.1.3, this decrease is of 5.6% for Seattle. Figure II.2.2.3.2 stresses that, for the SH design, the decrease in relative humidity contributes to a decrease in energy requirements and that most of its influence on energy consumption occurs between June and October. The decrease in total energy consumption ranges between 2% and 7% depending on location[18]. This counterbalances the increase of energy consumption due to both the increase of dry bulb temperature and solar radiation in the final count of the influence of climate change on the annual energy consumption of SH.

[16] For Seattle
[17] See table III.8.3.3
[18] See table III.8.3.4




Source: www.noaa.gov

**Figure II.2.2.3.3 Apparent temperature in function of relative humidity**

Figure II.2.2.3.3 indicates that for a certain air temperature (or dry bulb temperature), a decrease of relative humidity is correlated to a decrease of apparent temperature. The apparent temperature, or heat index, is the temperature that is felt by the human body in relation to the actual air temperature and relative humidity.

A study realized by Winslow et al. in 1937 [37] explains the reaction of the human body in relation to varying temperatures. It describes that the human body cools itself by the processes of perspiration and sweating which evaporate heat away from the body. It also shows that, for instance, under a scenario of high temperature and high relative humidity[19], the evaporation of water is slow explaining that the body retains more heat than it would in dry air. In an opposite scenario where relative humidity is low, the evaporation rate of water is fast and the body can cool itself easily, therefore the temperature appears lower than it actually is.

As DesignBuilder [38] takes human behavior and apparent temperature into account in its calculations of energy consumption, that decrease of relative humidity translated into a decrease of apparent temperature which in turn translated into a decrease of annual energy consumption. Consequently, relative humidity was found to be the weather parameter that

[19] i.e. where the air is considerably moist

counterbalanced the influence of dry bulb temperature and solar radiation on energy consumption.

#### II.2.2.4 Influence of wind speed on energy consumption

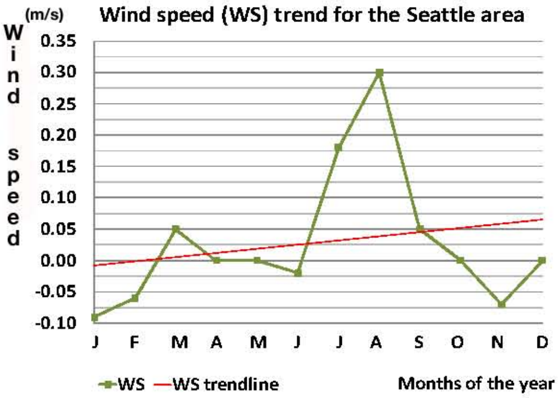



Figure II.2.2.4.1 - Wind speed (WS) trend

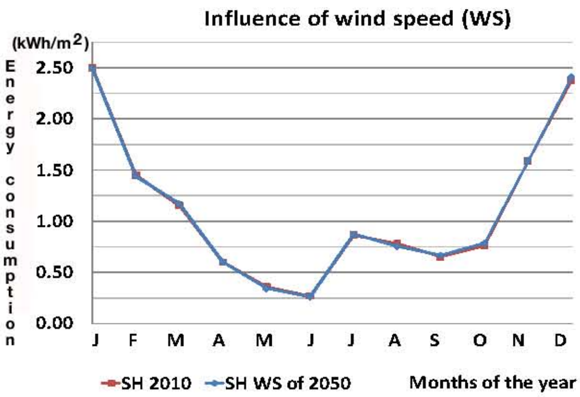



Figure II.2.2.4.2 - Influence of wind speed

As far as wind speed is concerned, while figure II.2.2.4.1 shows an increase of wind speed values from 2010 to 2050 for Seattle, table III.8.1.3 quantifies this increase of only being 1% for all locations. Figure II.2.2.4.2 accentuates that no difference in energy consumption can be noticed[20]. Consequently the slight change in wind speed values had very little to no effect on the influence of climate change on annual energy consumption and can therefore be neglected.

### II.2.3 $CO_2$ emissions of the Seahouse

This section will discuss the carbon dioxide emissions of SH and MH coming from heating and cooling fuel consumption. The emission values were obtained by multiplying $CO_2$ emission coefficients (in kg $CO_2$/kWh) to the heating and cooling energy consumption results of tables III.8.2 and III.8.3.1. Regarding the emissions of the MH central gas furnace, the $CO_2$ emission coefficient was found in a report made by the International Energy Agency

[20] As also highlighted by table III.8.3.5

(IEA) [39]. Concerning emissions from electricity use, state $CO_2$ emissions coefficients were found in the eGRID 2006[40] from the US Environmental Protection Agency (US EPA). The difference between these state coefficients resides in the way electricity was generated in these different states. For instance, as seen in table II.2.3.1, electricity generated in Washington is much cleaner than in other states. This is due to the fact that, while in this state electricity is mostly generated by hydropower, it is created by the burning of coal in the others [41].

| $CO_2$ emissions coefficients in kg $CO_2$/kWh | | | | | | | |
|---|---|---|---|---|---|---|---|
| SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| Natural Gas | Electricity | Natural Gas | Electricity | Natural Gas | Electricity | Natural Gas | Electricity |
| 0.370 | 0.163 | 0.370 | 0.706 | 0.370 | 0.901 | 0.370 | 0.607 |

**Table II.2.3.1 – $CO_2$ emissions coefficients**

The following figures were established for SH and MH placed in Seattle, WA during 2010 and 2050.

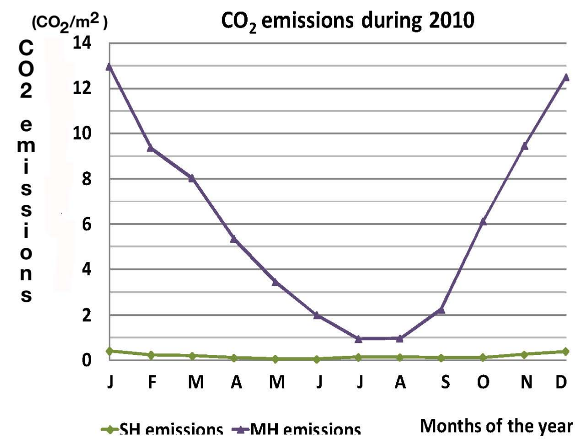



**Figure II.2.3.2 - $CO_2$ emissions during 2010**

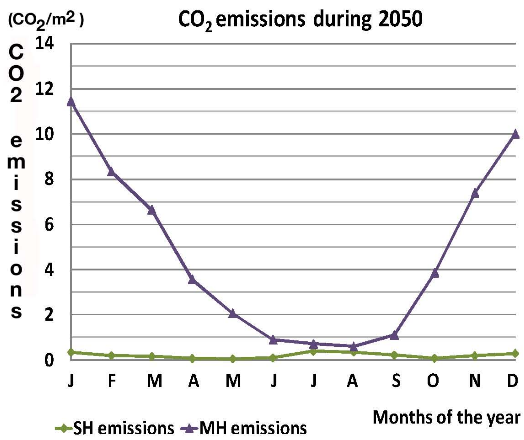



**Figure II.2.3.3 - $CO_2$ emissions during 2050**

As seen in the previous section, the SH design was found to be much more efficient than the MH design as it consumed considerably less energy for heating and cooling. This translated to figure II.2.3.2 and figure II.2.3.3 which highlight the low emissions of the SH design during both present and future weather when compared to MH.

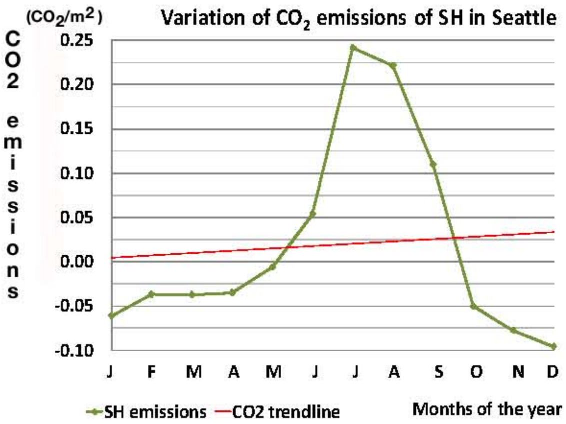



Figure II.2.3.4 - Variation of $CO_2$ emissions

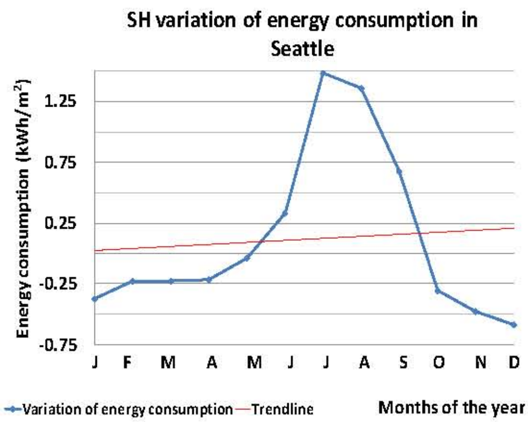



Figure II.2.3.5 - Variation of energy consumption

Additionally, figure II.2.3.4 shows an increase of $CO_2$ emissions for SH explained by the increase of energy consumption from figure II.2.3.5. As noticed and explained in section II.2.2, SH was noticed to consume less energy during winter months and more during summer months than it previously did; which in turn signifies that the design emitted less carbon dioxide during winter and more during summer. The general increase of carbon dioxide emissions throughout the whole year and the variations noticed during summer and winter seasons were found to be in accordance with the predictions made by Wilbanks et al. 2008 [16]. Table III.8.4.1.2 informs that this increase in $CO_2$ emissions is of 10% for Seattle and in the range of 8% to 40% for the other locations. As emissions are proportional to energy needs, the increase of $CO_2$ emissions is inherent to the increase of energy consumption caused by climate change. Regardless of this increase, the SH design was however considered noticeably more sustainable than the MH design by examination of figures II.2.3.2 and II.2.3.3 and tables III.8.4.1.1 and III.8.4.1.2. These tables indicate that choosing the SH design over the MH design saves from 76% to 97% on carbon dioxide emissions during 2010 and from 65% to 96% during 2050. The proportional relationship between energy consumption and $CO_2$ emissions explains that these results come from the energy-efficiency of the SH design.

# II.3 Conclusion

## II.3.1 Summary

This study investigated both the influence of design and climate change on the annual consumption of an energy-efficient design.

It was decided to design a passive solar building originally located in Seattle, Washington: the Seahouse. This design was modeled in Revit in accordance with guidelines given by the National Green Building Standard code and its energy consumption was analyzed in DesignBuilder. Another building was built to represent typical current American houses and was compared to the Seahouse in order to evaluate its energy-efficiency and the influence of design on energy consumption. Due to data availability from the CORRIM papers, this design was originally built for Minneapolis, Minnesota resulting in a design referred to as the Minnhouse.

On the one hand, to determine the influence of design on annual energy consumption the effects of the following variables were investigated: shape, insulation and Heating, Ventilating and Air Conditioning system (of HVAC system).

On the other hand, to assess the influence of climate change on the annual energy consumption the impact of the following variables was analyzed: dry bulb temperature, solar radiation, relative humidity and wind speed. Future weather files were created using the Climate Change World Weather File Generator tool (CCWorldWeatherGen) and implemented in DesignBuilder to evaluate the influence of climate change on heating and cooling energy consumption.

### II.3.2 Conclusions

Based on the results of this research, the following conclusions were reached:

- **the energy-efficiency of the design:** the study showed that regardless of location and year of simulation the Seahouse proved to be significantly more efficient than the Minnhouse. Depending on location, this design saved from 84% to 93% more energy for heating and cooling than the standard home during current weather and between 75% and 91% during future weather.

- **the influence of the design on annual energy consumption:** the results on the energy-efficiency of the Seahouse design led to the investigation of the influence of several design factors. The study showed that the influence of the design on annual energy consumption was mostly driven by the efficiency of the shape and HVAC system of the Seahouse while insulation had a lesser impact. While the savings in energy consumption realized by the efficient HVAC system were between 81% and 84% depending on location, the savings due to the shape of the SH were between 52% and 63%.

- **the influence of climate change on annual energy consumption:** the study indicated that the building consumed 8% to 40% more energy for its heating and cooling that it did during current weather. The analysis revealed that the increase in temperature played the lead role in the increase of energy consumption. This increase was found to be between 9% and 44% depending on location. The increase of solar radiation was also noticed to imply an increase of energy consumption. This increase was however less significant as it implied an increase of energy consumption of 1% to 4% depending on location. Relative humidity was noticed to both decrease and imply a decrease in energy consumption of 2% to 7% depending on location which help counterbalancing the influence of both dry bulb temperature and solar radiation on annual energy consumption. The increase in wind speed was of less than 1% for all location and did not significantly affect the energy consumption.

- **the emissions of the energy-efficient design:** the results on the heating and cooling emissions of the Seahouse demonstrated that it was more sustainable than the typical house. By choosing this design over the Minnhouse, savings in carbon dioxide emissions ranging from 76% to 97% during 2010 and from 65% to 96% during 2050 were noticed. As the emission values were obtained by multiplying emission factors to energy needs, these results can be explained by the superior energy-efficiency of the Seahouse. It was also observed that the increase of energy consumption, due to the influence of climate change, implied an increase of carbon dioxide emissions ranging from 8% to 40% depending on location.

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# CHAPTER III - APPENDIX

The following section provides further information on the choices made during this thesis and on the results found in chapter II.

## III.1 Climate change data

### III.1.1 The emission scenarios

In order to establish how climate might evolve, we need to identify and make assumptions on the drivers of the change. As formerly mentioned, climate change is mostly characterized by an increase of greenhouse gases which in turn provoke a rise in the general temperature of the Earth. That increase in greenhouse gases in mainly due to human activities. Historically, the inception of climate change can be traced to the industrial revolution which generated a substantial increment of greenhouse gases concentrations in the atmosphere.

Since these emissions are for the most part human-induced, the assumptions have to be made on population growth, land use, economic activity and energy use.

For this reason, the IPCC lists four main emissions scenarios relating giving four different levels of emission: low (B1), medium-low (A1), medium-high (B2) and high (A2); all given by the IPCC Special Report on Emission Scenarios (SRES). The low emission scenario is seen as sustainable because it has less carbon emissions than current climate, while the high emission scenario contain three times more emissions that the Earth is experiencing at present. In the SRES, the A1 scenario is divided in three groups based on the prominence of technology: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B).

The following table given by the the Fourth Assessment Report of the IPCC made in 2007 gives projected temperature change and sea level rise at the end of the 21st century for each of the scenarios:

| Case | Temperature Change (°C at 2090-2099 relative to 1980-1999)[a] | | Sea Level Rise (m at 2090-2099 relative to 1980-1999) |
|---|---|---|---|
| | Best estimate | *Likely* range | Model-based range excluding future rapid dynamical changes in ice flow |
| Constant Year 2000 concentrations[b] | 0.6 | 0.3 – 0.9 | NA |
| B1 scenario | 1.8 | 1.1 – 2.9 | 0.18 – 0.38 |
| A1T scenario | 2.4 | 1.4 – 3.8 | 0.20 – 0.45 |
| B2 scenario | 2.4 | 1.4 – 3.8 | 0.20 – 0.43 |
| A1B scenario | 2.8 | 1.7 – 4.4 | 0.21 – 0.48 |
| A2 scenario | 3.4 | 2.0 – 5.4 | 0.23 – 0.51 |
| A1FI scenario | 4.0 | 2.4 – 6.4 | 0.26 – 0.59 |

Table notes:
[a] These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth System Models of Intermediate Complexity and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs).
[b] Year 2000 constant composition is derived from AOGCMs only.

**Table III.1.1 - Projected temperature change and sea level rise at the end of 21$^{st}$ century**

*Source: IPCC 2007's Summary for Policymakers [42]*

These scenarios were created to help understanding potential future developments of complex physical and social systems (IPCC 2007).

Consequently, they are only hypothetical and all as likely to occur. The IPCC SRES A2 scenario was chosen mostly due to data availability concerning the making of climate change weather file. However, as is highlighted by the above table, this scenario generates the second most emissions and changes in temperature when compared to the other ones. Therefore, in a need to produce a conservative study, this climate scenario is appropriate for our analysis since it is one of the worst projected global environments amongst all the scenario families (Nakicenovic et al., 2000). [43]

The A2 scenario as described by IPCC 2007:

"The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines". [42]

### III.1.2 Climate change weather files

While most performance building software are suited for the analysis of building energy requirements under current weather, they do not allow to simulate for future weather conditions. This is mainly due to the fact that, at present, no approved climate-change weather files exist. This imposed the method used in chapter II. Therefore climate change weather files have the same format as present weather files.

Most building performance software which analyze energy use at specific location use text input files as weather files. These files are generally found as hourly datasets in different formats; the most operated one in the U.S. being the Typical Meteorological Year (TMY3) format. Created by the U.S. National Renewable Energy Laboratory (NREL) in the early 1990s, the TMY3 files provide annual averages of weather variables calculated from weather data that was measured over a 14 year period (1991-2005). The data is fractioned into hourly values for a 'typical' one year duration.

As mentioned in the chapter II, the decision was made to use DesignBuilder (DB). DB is a user-friendly interface for EnergyPlus therefore DesignBuilder's weather files are EnergyPlus'. They come under the EPW filename extension (for EnergyPlus Weather) and are derived from the TMY3 files described above. EPW files are, in effect, TMY3 files that have been modified in structure to be reduced in size and able to integrate sub-hourly data. This last feature is necessary when a meticulous evaluation of diurnal cycles is sought.

These files were used for current weather energy analysis and morphed into future weather files for climate-change analysis by a process described later on in this chapter.

More information on the EPW file format and weather variables that it encapsulates can be found in a paper by Crawley et al.1999 [20].

### III.1.3 Dynamical downscaling vs. morphing technique

Two methods were initially considered to generate climate change weather files : dynamical downscaling and the morphing technique.

Downscaling is a method for acquiring high-resolution climate or climate change data from relatively coarse-resolution global climate models (GCMs). GCMs usually have a resolution of 150-300 km by 150-300 km. Many impacts models require information at scales of 50 km or less, so some method is needed to estimate the smaller-scale information. Dynamical downscaling uses a limited-area, high-resolution model (a regional climate model, or RCM) driven by boundary conditions from a GCM to derive smaller-scale information. RCMs generally have resolutions of 20 to 60 km.

The morphing technique is a downscaling method that creates climate-change weather data by shifting and stretching the variables of the current weather using the climate prediction changes made by GCM and RCM under a certain greenhouse gas emission scenario.

Mostly due to data availability, the morphing technique was selected. Other reasons that led to the choice of the morphing technique are indicated the following overview of the advantages and inconvenient of both methods.

| The morphing technique | | Dynamical downscaling | |
|---|---|---|---|
| Advantages | Inconvenients | Advantages | Inconvenients |
| ▪Computationally cheap, simple and flexible, can be applied to a broad range of climate change scenarios | ▪Uses GCM data instead of RCM data: uncertainty of data due to resolution of the grid being too large. | ▪Uses RCM data: provide more accurate predictions. | ▪Computationally expensive |
| ▪Uses present-day weather data measured at real locations: reliable present weather data | | | ▪Does not use measured data for present-day weather data. |
| ▪Spatial and temporal downscaling is reliable because of previous reason. | | | |
| ▪Data availability : data available the 12 months of the year at 1042 locations in the U.S. | | | ▪Data availability (Only March through November) |
| ▪Meteorologically consistent | | | |
| ▪Averages datasets: appropriate for calculating averages of building heating and cooling energy requirements. | ▪Averages data based on present-day weather: interannual variabilities (such as heat waves) of predicted future are very close to the present ones. | ▪Provides potential interannual variabilities of future weather | |
| ▪Available as EPW format : compatible with most building performance software | | | ▪Data generally not available in convenient format for implementation in building performance software |
| **<u>Conclusion:</u> Practical for building simulation.** | | **<u>Conclusion:</u> Impractical for building simulation.** | |

**Table II.1.3 - Advantages and inconvenient of morphing and dynamical downscaling.**

### III.1.4 Limitations of the morphing technique

The main inconvenient of the morphing technique used in this paper is that it is based on GCM data instead of RCM data. Since the simulations are realized in specific cities, it would be more appropriate and accurate to base the morphing technique on the data provided by the finer resolution RCMs. However, at this time, no practical tools using the morphing technique and RCM data for building analysis use is available.

Integrating GCM data directly into building simulation weather files is not easy to achieve as GCM data is not generally available in the correct format and temporal resolution. Both Belcher et al. 2005 [19] and Jentsch et al. 2008 [11] give some indication of the advantages of the morphing methodology compared to other methods such as dynamical downscaling. The main advantage of using real weather station data as baseline is that spatial and temporal downscaling are achieved with the real data and that a comparison with measured values is possible. However, the main drawback of this method is that the morphing methodology essentially assumes the future weather to be analogous to the current weather which does not necessarily have to be the case. Morphing of existing weather data by using GCM outputs adds a further uncertainty in comparison to using regional climate model data as GCM grid scales are usually rather large. Ideally climate change adapted simulation weather data would be derived from multiple runs of detailed regional climate models at hourly resolution that have been benchmarked against historic weather profiles. However, this would require an intensive computational effort. In addition, such an approach will still contain uncertainties related to the underlying modeling approach. The morphing methodology relies on standard scaling and shifting techniques which permit generation of future weather data series with relatively low computational requirements. Nonetheless, users need to be aware of the uncertainties inherent in the method as pointed out above.

At present, it is not possible to use any other data than the HadCM3 A2 data (i.e. GCM data) with the CCWorldWeatherGen tool, simply because the other datasets of the HadCM3 family or other climate models do not contain all the parameters required for producing building simulation weather data in standard formats. Furthermore, many models only provide one simulation run.

More information on the morphing technique and underlying formulas can be found in both Belcher et al. 2005 [19] and Jentsch et al. 2008 [11].

## III.2 Green rating systems & R-values recommendations

### III.2.1 Compliance method of available green codes

The compliance method used by most of green codes is point allocation. They are rating systems which award a certain number of points according to the respect of specific sustainable practices. While for each of its sections, LEED for Homes has prerequisite points which correspond to the minimum mandatory measures to be undertaken for a house to be LEED certified, NGBS rarely does. Instead, NGBS gives a list of recommendations that are called ‘performance level points’. Both rating systems have different levels of certifications according to the number of points accumulated.  The performance levels are Bronze, Silver, Gold and Emerald for the NGBS code and Certified, Silver, Gold and Platinum for LEED for Homes. Although chapter titles and number of points attributed differ in each code, they both share very similar content and a large amount of points awarded are in accordance with ENERGY STAR guidelines or the use of ENERGY STAR products.

The following table displays the distribution of those performance points for the NGBS code.

Table 303
Threshold Point Ratings for Green Buildings

| Green Building Categories | | | Performance Level Points | | | |
|---|---|---|---|---|---|---|
| | | | BRONZE | SILVER | GOLD | EMERALD |
| 1. | Chapter 5 | Lot Design, Preparation, and Development | 39 | 66 | 93 | 119 |
| 2. | Chapter 6 | Resource Efficiency | 45 | 79 | 113 | 146 |
| 3. | Chapter 7 | Energy Efficiency | 30 | 60 | 100 | 120 |
| 4. | Chapter 8 | Water Efficiency | 14 | 26 | 41 | 60 |
| 5. | Chapter 9 | Indoor Environmental Quality | 36 | 65 | 100 | 140 |
| 6. | Chapter 10 | Operation, Maintenance, and Building Owner Education | 8 | 10 | 11 | 12 |
| 7. | | Additional Points from any category | 50 | 100 | 100 | 100 |
| | | Total Points: | 222 | 406 | 558 | 697 |

**Figure III.2.1 - NGBS Threshold Point Ratings table for Green Buildings**

As can be seen on this table, most points are allocated for Resource Efficiency, Energy Efficiency and Indoor Environmental Quality. Since this case study solely focuses on the heating and cooling requirements of the house, the attention was primarily turned to the energy efficiency requirements and secondarily to resource efficiency requirements that would affect the design.

### III.2.2 R-values recommendations and windows criteria for the Seattle area

It was decided to build a model using green standards and to keep the design unchanged during the diverse simulations to assess the influence of design on annual energy consumption. The original location of the house was arbitrarily chosen as being Seattle, WA. Because a 'green' design is climate dependent, each code had different standards depending on the location of the design.

The following table summarizes the different recommendations regarding the insulation of the house (i.e. R-values recommendations and windows U-factors) for the Seattle area:

| R-values recommendations and Windows criteria for Seattle area | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Part of the house | LEED 1pt | LEED 2 pts | LEED >2pts | ENERGY -STAR | US-DOE | IECC 2006 | NGBS Performance Path | IECC 2009 |
| **Insulation** | | | | | | | | |
| Roof (ceiling) | R-38 | R-40 | None | R-38 to R-60 | R-38 | R-38 | R-44 | R-38 |
| External walls | R-21 | R-22 | None | Add R-5 insulative sheating before installing new siding | R-15 | R-19 | R-22 | R-20 |
| Internal walls | R-13 | R-14 | None | ? | ? | R-13 | R-15 | R-17 |
| Crawl space | R-13 | R-14 | None | ? | R-25 | R-13 | R-15 | R-13 |
| Slab | R-10 | R-11 | None | ? | R-8 | R-10 | R-12 | R-10 |
| Basement Walls | R-13 | R-14 | None | Add R-5... | R-8 | R-13 | R-15 | R-13 |
| Floors | R-30 | R-32 | None | R-25 to R-30 | R-25 | R-30 | R-35 | R-30 |
| **Windows** | | | | | | | | |
| U-factor | ≤0.35 | ≤0.31 | ≤0.28 | ≤0.30 | ? | ? | ≤0.35 | ≤0.35 |
| SHGC | Any | Any | Any | Any | ? | ? | Any | ≤0.6 |

**Table III.2.2 - R-values recommendations and windows criteria for the Seattle area**

The comparison was set between the LEED for Homes, IECC 2006, IECC 2009, NGBS codebooks and the ENERGY STAR and US D.O.E guidelines. In this table, “?” corresponds to: “Not addressed”.

To measure how insulating the parts of the building envelope (i.e. walls, floors or ceilings) are, the R-value is usually used. It is a measure of thermal resistance, in (ft²·°F·h)/Btu, where the bigger the number, the more insulating the house component. As a general rule, increasing the thickness of an insulating layer also increases the R-value. Additionally, to compute heat loss from windows, the U-factor is generally used. The U-factor is in fact the inverse of the R-value (U=1/R) and consequently depicts the thermal conductivity of a window.

The first three columns of this table index the recommendations of the LEED for Homes codebook for to get a certain number of points. The first one gives the R-values to get the LEED prerequisite point and actually corresponds to the IECC 2004 R-values recommendations, while the second and third column gives recommendations for a better performance to acquire a higher LEED rating. Note that to get the maximum number of points (usually three points) in LEED for Homes, the recommendations are the no different than to get two points except for the U-factor of the windows. On the other hand, ENERGY STAR set his own R-values but is not as prescriptive on the matter as crawl space, slab and internal walls insulations are not addressed. R-values recommendations from the US DOE were obtained using their evaluation tool. This tool, available online[21], sets these recommendations based on three major criteria: house status (new or existing), fuel type (natural gas furnace, oil furnace, electric furnace, electric baseboard, heat pump or LPG[22] furnace) and house location (with three first digit of the ZIP code).

While LEED for Homes guidelines are based on the IECC 2004, NGBS' are based on the IECC 2006. This, amongst other reasons mentioned in the previous section, conditioned the choice of this codebook. The NGBS minimum performance path R-values recommendations are reported in this table and correspond to an increase of 15% on the IECC 2006 recommendations. A certain number of points are granted depending on the increase that it realized on the IECC 2006. The maximum amount of points granted is given for a 60% increase. It was however decided to build the house to be green according to minimum recommendation.

Although at present no green building code is based on the IECC 2009, it can be assumed that future codes will. Therefore, the last column was added informatively.

[21] *http://www.ornl.gov/sci/roofs+walls/insulation/ins_16.html*

[22] Liquefied Petroleum Gas

## III.3 The choice of sustainable materials

Reclaimed oak wood was chosen for flooring as it contains the least amount of embodied energy when compared to other flooring options.

High recycled-content steel was chosen for wall and roof siding as it was found to be one of the metals with the least amount of embodied energy. While metal siding is made from recycled metal, it can be re-recycled instead of being thrown away. Besides comparatively to wood siding, steel is particularly fire resistant, lightweight, very low maintenance and extremely durable. Therefore, in addition to being an eco-friendly solution, it is also an economical alternative when considering the whole life span of the building. Another sustainable advantage of metal roofing over other materials is its physical properties regarding rainwater harvesting. When compared to other roofing materials such as asphalt shingles, metal is relatively toxin free, allowing a cleaner water to be caught and reused. Finally, metal roofing provides an advantage over other materials in climates with heavy snow falls (such as Minneapolis[23]), as snow slides away from the roof area more easily due to the non-adherence of the surface, reducing the final snow load on the roof. Following NGBS recommendations, an ENERGY STAR certified roofing was selected. The roof of the Seahouse has a slope of 5:12 which is considered as a steep roof by ENERGY STAR. The ENERGY STAR criteria [23] regarding this type of roof is that, to be certified, "the roof's initial solar reflectance[24] must be greater than or equal to 0.25 and to 0.15 three years after installation under normal conditions".

Regarding renewable materials, the NGBS code suggests the use of bio-based products such as certified solid wood, engineered wood, bamboo, cotton, cork  straw and natural fiber

[23] Minneapolis snowfall data: *http://climate.umn.edu/doc/twin_cities/twin_cities_snow.htm*

[24] *ENERGY STAR defines the solar reflectance as "The fraction of solar flux reflected by a surface expressed as a percent or within the range of 0.00 and 1.00 ".*

products made from crops (soy or corn-based). Certified wood had to be certified by one of the following product programs: the American Forest Foundation's American Tree Farm System (ATFS), Canadian Standards Association's Sustainable Forest Management System Standards (CSA Z809), the Forest Stewardship Council (FSC) and Sustainable Forestry Initiative (SFI). These organizations each promote responsible forest management. It therefore was decided to use FSC [26]certified wood was used for the house framing.

Out of all different types of sustainable materials that can be chosen from to build a residential building, reused and salvaged materials offered the most point in the NGBS code. This is due to the fact that using reclaimed materials represents the lowest embodied energy solution comparatively to other processes. For this reason, it was first decided to use reclaimed wood for both wall-siding and flooring. However, the demand for reclaimed wood usually allows the availability of a limited quantity and this process ends up solely being used for flooring[25]. It was subsequently decided to choose reclaimed oak flooring.

Low-density sprayed foam or foam-in-place polyurethane insulation was chosen. While this material does not have the very low embodied energy of a straw bale wall for instance, it has the highest R-value insulation comparatively to all other products available on the market. This allows for less material to be used and a substantial cut in annual energy consumption and cost[26]. It was considered the most energy-efficient insulating material and relevant choice for our specific case study.

[25] To have enough wood for both wall siding and flooring, it would have to be transported from further locations which would higher the embody energy of the material for transportation.
[26] Reportedly yearly energy cost is cut by 35%: *http://www.goodtobegreen.com/res_buildingguide_insulation.aspx?material=foam*

# III.4 The choice of a solar passive design

Roof and window overhangs, energy efficient windows and thermal mass (either in walls and/or floors) are frequent elements found in passive design. The orientation of the building is also a key factor in generating low energy costs. Since the sun's path is specific to the tilt of the earth and the way it rotates, the house will perceive the sun differently according to its location. In the United States, most of the sun will hit the south facing wall of a building. Additionally, to successfully collect solar energy, a sun collector should be oriented within twenty degrees of true south.  Although the passive solar design of our case study does not include any solar panels, the south facing wall acts as a sun collector. Therefore, the long side of a sun-tempered building should face within 20 degrees of true south as it will allow to store gather the most energy.

This sun path will also differ with seasons. For instance, the sun will appear substantially higher during summer solstice than during winter solstice. Taking this main factor into account, passive heating and cooling as described in the Passive Solar Design section of our thesis.

Regarding thermal mass, a factor corresponding to the presence of thermal mass of certain components was set within DesignBuilder for the Seahouse design and not for the Minnhouse. This thermal mass will absorb the heat produced by sunlight to radiate it at night. By this process, passive heating is achieved in our model and floors and walls become functional parts of the house. Our case study is the one of a direct gain system; therefore heat will mostly be transferred by radiation (from the thermal mass wall and floor to the air inside the room) and conduction (i.e. direct contact to the living space, being objects of the house or inhabitants). Note that on figure II.1.1.5.3 is shown a section of the hallway and one of the bedroom. While this section of the building would be the same for each room, it would be different for the living room, bathrooms and kitchen. The section view of the living room would not have shown any partition walls. The sunlight would only travel one layer of glazing to strike the thermal mass contained in the floor. Regarding the bathrooms and kitchen section views, it would be observed that the south facing partition walls do not contain glazing, but are instead fully composed of thermal mass.

# III.5 Specifics of Seahouse and Minnhouse

## III.5.1 Seahouse framework

### III.5.1.1 Seahouse: floor plans and 3D views.

As previously mentioned, the Seahouse was first modeled in Revit before it was imported in DesignBuilder. While it could have been directly modeled and simulated in DesignBuilder, it was decided to use Revit because a baseline passive solar house was provided in this format. While this initial house was satisfying in most features it was however decided to modify it to follow the NGBS code and correspond to a future typical American single-family home. Here is the simplified[27] floor plan of this 1500sf baseline house followed by the floor plan of the final model.

[27] The original building had an additional studio room and a two-car garage.

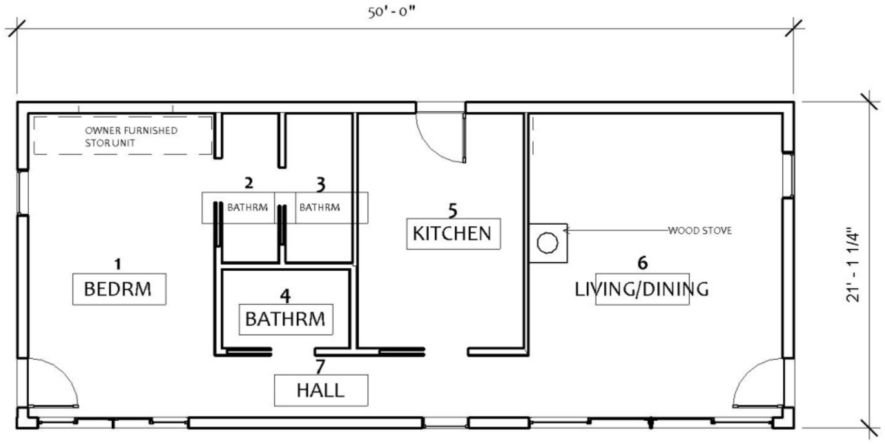


**Figure III.5.1.1.1 - Revit floor plan of baseline model.**

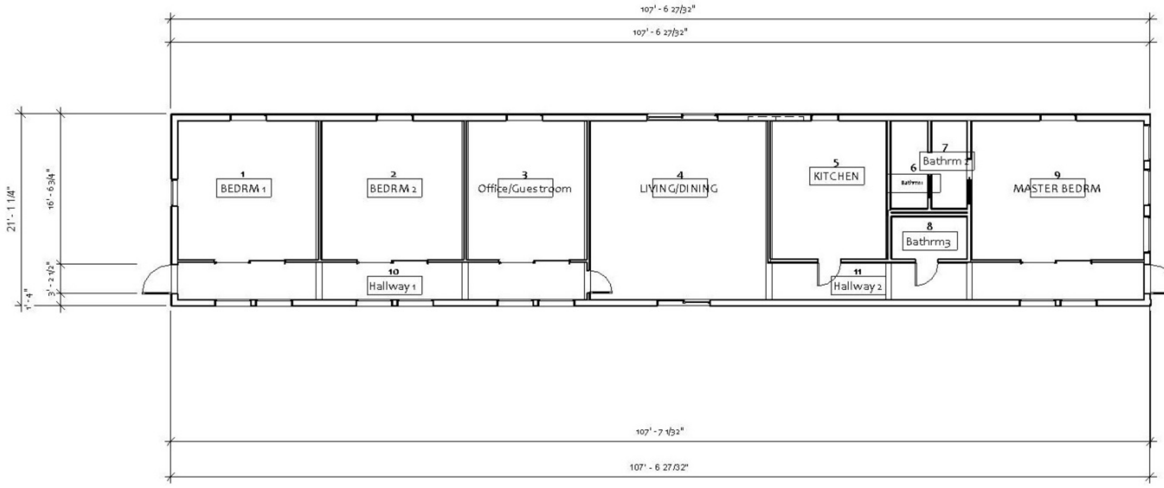


**Figure III.5.1.1.2 - Revit floor plan of Seahouse**

The Seahouse has a GFA of 2019sf and 4 bedrooms (3 occupied and a space one) shared in between 4 occupants instead of only 1500sf, 1 bedroom and 2 occupants for the baseline. Most of the design of the baseline house was however kept. This is due to two reasons. The first one is because it represents the design of a passive solar house which is widely regarded as one of the most energy efficient design alternative concerning heating and cooling requirements. The second reason is that the design is very simple, box-like. That simplicity implies that the Seahouse could eventually be available as a prefab. While the Triple bottom line ("people, planet, profit") is at the heart of sustainability, the economy and social aspects are fulfilled by the green prefab design of the Seahouse, lowering the price and making it more accessible to people. In this regard, the design appears sustainable.

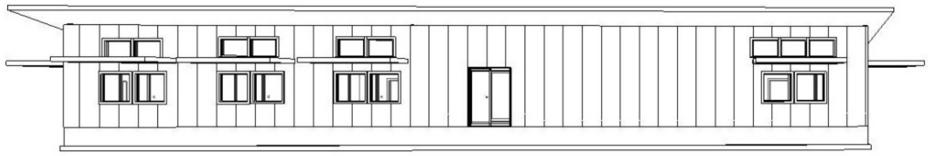

**Figure III.5.1.1.3 - Revit 3D view of south facing wall of building**

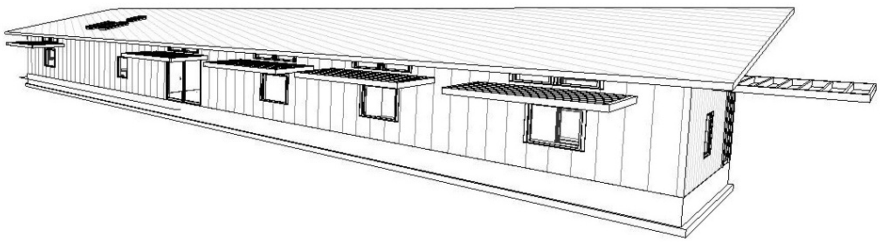

**Figure III.5.1.1.4 - Revit 3D angled view of north facing wall of building**

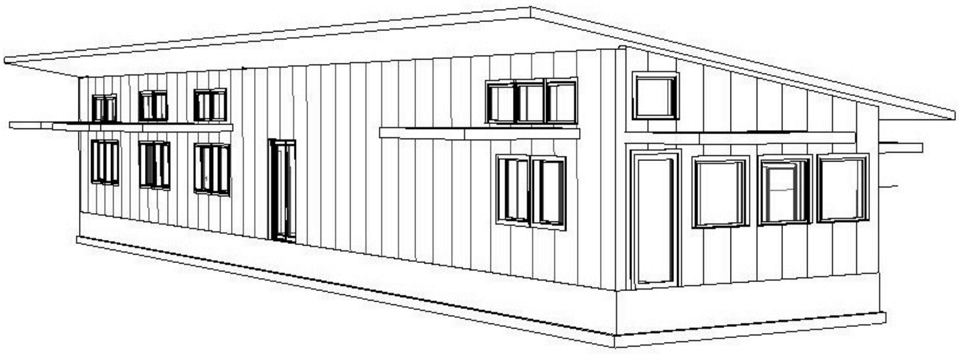

**Figure III.5.1.1.5 - Revit 3D view of south facing wall of building**

### III.5.1.2 Seahouse: gross floor area

The Seahouse total gross floor area (GFA) is 2019sf. It was decided to model a house that would comfortably fit a 4 occupants with an extra guestroom with the restriction of a

GFA under 2100sf and a conditioned floor area (CFA) under 2000 sf. The CFA of the Seahouse is 1900sf. The CFA restriction was decided based on a condition given in the NGBS code found in the following table:

| | |
|---|---|
| **601.1 Conditioned floor area.** Conditioned floor area, as defined by ICC IRC and calculated in accordance with NAHBRC Z765, is limited. Dwelling unit size is to be calculated in accordance with NAHBRC Z765. Only the conditioned floor area for stories above grade plane is to be included in the calculation. | 15 max |
| **(1)** less than or equal to 1,000 square feet (93 $m^2$) | **15** |
| **(2)** less than or equal to 1,500 square feet (139 $m^2$) | **12** |
| **(3)** less than or equal to 2,000 square feet (186 $m^2$) | **9** |
| **(4)** less than or equal to 2,500 square feet (232 $m^2$) | **6** |
| **(5)** greater than 4,000 square feet (372 $m^2$) **(For every 100 square feet (9.29 $m^2$) over 4,000 square feet (372 $m^2$), one point is to be added in Table 303, Category 7 for each performance level.)** | **Mandatory** |

**Figure III.5.1.2 - NGBS Conditioned Floor Area criteria**

This criterion can be found in the Resource Efficiency chapter (chapter 6) of the NGBS code. It states that a certain amount of point is given depending on the CFA. The smaller the CFA the more points given. This measure is coherent as a building with a smaller CFA implies a smaller carbon footprint. Since the Seahouse is supposed to host a typical American family (generally composed by 4 members), a CFA of under 1500 or 1000 sf was judged inappropriate. The restriction of the GFA being under 2100sf was made by observing the GFA of a typical American home of 2009. From a recent study led by the U.S Census Bureau, it was noticed a shrinking trend of US homes 0. Although this shrinking trend might mostly be due to the recent economic crisis and that the size of the typical American home of year 2050 cannot be assessed with ease, an assumption had to be made. Since "energy-efficient Mc Mansion" strikes as an oxymoron, the assumption was based on the fact that for a house to be sustainable it would need to be large enough to be livable for a family and small enough to reduce its carbon footprint (partially caused by installation).

### III.5.1.3 Seahouse: construction details

The different components of the Seahouse were modeled as follows:

**SEATTLE STRUCTURE:**

**Ceiling/Roof Systems:**

- type: Shed roof with 3:12 slope
- ½ inch gypsum plasterboard
- 6 mil polyethylene sheet
- Wood engineered trusses 24 in. off center (o.c.)[28]
- Spray foam insulation (R-44)
- ½ inch Oriented Strand Board (OSB)

sheathing

- Tyvek®[29] tarp paper
- ¾ inch recycled steel roofing

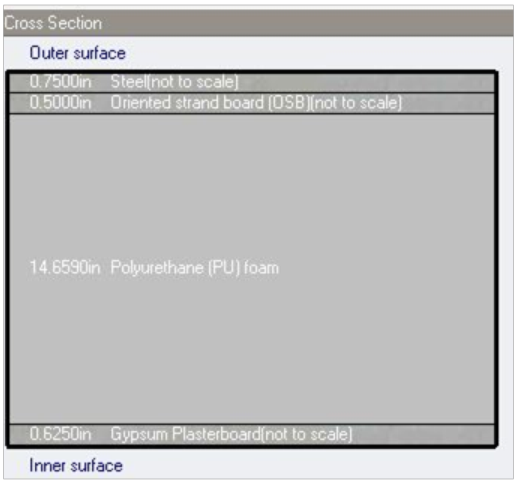


**Figure III.5.1.3.1 - DesignBuilder cross section of SH roof.**

**Crawl space walls:**

- 15.5 inches fly ash concrete slab
- Vapor retarder installed on block wall

(*Typically 6 mil poly*)

- 6 mil flame retardant poly vapor retarder


**Figure III.5.1.3.2 - Cross section of SH crawlspace walls.**

[28] *not shown in the cross section but was bridged to the air gap layer in DB.*
[29] http://www.materialconcepts.com/products/tyvek/

**Floor:**

• ¾ inch reclaimed hardwood flooring

• ¾ inch OSB sheathing

• 11" spray foam insulation (R-35) bridged to I-joist equivalent to 2x10" FSC solid wood joists 16" o.c.

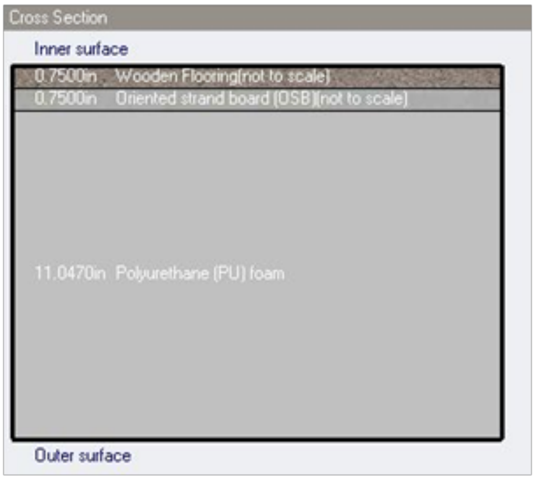


**Figure III.5.1.3.3 - Cross section of SH floor.**

**Exterior Walls:**

• ½ inch sheetrock plasterboard

• 6 mil poly vapor retarder

• 2x6 inch FSC wood stud, 16 o.c.

(*Bridged to insulating layer*)

• Spray foam insulation (R-22)

• Tyvek® tarp paper (not shown in cross section)

• ¾ inch recycled steel siding

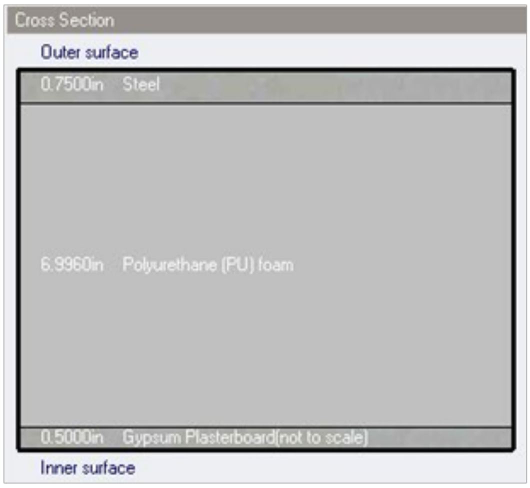


**Figure III.5.1.3.4 - Cross section of SH exterior walls.**

**Partition walls:** *(Same as Minnhouse)*

• ½ inch gypsum sheetrock both sides

• 3.6 inches air gap (R-15)

• 2x4 FSC wood studs, 16 inches o.c, (*bridged to the air layer*)

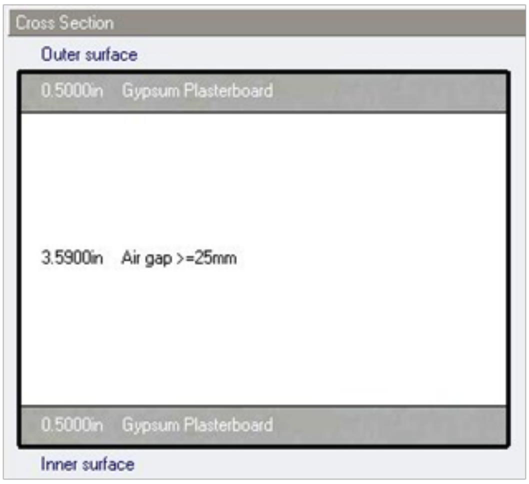

**Figure III.5.1.3.5 - Cross section of SH partition walls.**

**Windows:**

• ENERGY STAR certified, double glaze, low E, argon filled, vinyl frame

These windows were selected because recommended by the NGBS code. Low-E stands for Low Emissivity in reference to the coating which prevents from heat loss winter months. The windows frames should be made out of reclaimed wood for its very low embodied energy. Besides the layers of argon greatly increase the insulation value of the windows making them more energy efficient which in turn reduces heating and cooling costs.

The insulation of each component was based on the R-values recommendations of the NGBS recommendations from figure III.2.2 of the appendix of this paper.

### III.5.1.4 Characteristics of the SH Passive Solar Design.

The choice for the NGBS code and passive solar design imposed restrictions. These NGBS restrictions regard the orientation of the building, the type of windows chosen the sizing of the overhangs and horizontal and vertical glazing, as can be seen on this next figure:

**704.3.1.1 Sun-tempered design.** Building orientation, sizing of glazing, and design of overhangs are in accordance with all of the following:

**(1)** The long side (or one side if of equal length) of the building faces within 20 degrees of true south.

**(2)** Vertical glazing area is between 5 and 7 percent of the gross conditioned floor area on the south face [also see Section 704.3.1.1(8)].

**(3)** Vertical glazing area is less than 2 percent of the gross conditioned floor area on the west face, and glazing is ENERGY STAR compliant or equivalent.

**(4)** Vertical glazing area is less than 4 percent of the gross conditioned floor area on the east face, and glazing is ENERGY STAR compliant or equivalent.

**(5)** Vertical glazing area is less than 8 percent of the gross conditioned floor area on the north face, and glazing is ENERGY STAR compliant or equivalent.

**(6)** Skylights, where installed, are in accordance with the following:
- **(a)** shades and insulated wells are used, and all glazing is ENERGY STAR compliant or equivalent
- **(b)** horizontal skylights are less than 0.5 percent of finished ceiling area
- **(c)** sloped skylights on slopes facing within 45 degrees of true south, east or west are less than 1.5 percent of the finished ceiling area

**(7)** Overhangs or adjustable canopies or awnings or trellises provide shading on south-facing glass for the appropriate climate zone in accordance with Table 704.3.1.1:

**Table 704.3.1.1**
**South-Facing Window Overhang Depth**

| | | Vertical distance between bottom of overhang and top of window sill | | | | |
|---|---|---|---|---|---|---|
| | | ≤ 7' 4" | ≤ 6' 4" | ≤ 5' 4" | ≤ 4' 4" | ≤ 3' 4" |
| Climate Zone | 1 & 2 & 3 | 2' 8" | 2' 8" | 2' 4" | 2' 0" | 2' 0" |
| | 4 & 5 & 6 | 2' 4" | 2' 4" | 2' 0" | 2' 0" | 1' 8" |
| | 7 & 8 | 2' 0" | 1' 8" | 1' 8" | 1' 4" | 1' 0" |

For SI: 1 inch = 25.4 mm

**Figure III.5.1.4 - NGBS criteria for a passive solar design.**

Requirement 1 was satisfied as the building was directed straight towards South for all the simulations. Concerning glazing, all windows and skylights were ENERGY STAR as previously mentioned and glazing area was calculated from a gross conditioned floor area of 1900 sf.

Therefore, to respect requirements 2,3,4 and 5, the total vertical glazing of the south face at 228sf, north face at 152sf, west face at 38sf and east face at 76sf, setting the total vertical glazing at 494 sf.

Since the design is composed by a shed roof and a finished ceiling area of 2019sf, it implied a total horizontal glazing area of 30 sf. It was decided to place them above bathrooms to increase natural lighting of these rooms.

Regarding the overhangs, they were sized at 1'8'' as the vertical between bottom of it overhang and top of window sill was inferior to 3'4'' and Seattle belongs to climatic zone 4.

### III.5.1.5 Seahouse: HVAC system.

Since the case study is the assessment of heating and cooling, the choice of the Heating, Ventilating and Air Conditioning (HVAC) system was made carefully.

The SH HVAC system is ENERGY STAR certified geothermal heat-pumps. The system chosen satisfies both the NGBS code and ENERGY STAR guidelines. NGBS states that closed-loop water-to-air ground source heat pumps should have an Energy Efficient Ratio[30] (EER) and Coefficient of Performance[31] (CoP) of at least 14.1 and 3.3 respectively. ENERGY STAR [34] requires the EER and CoP to respectively exceed 16.1 and 3.5. The selected heat-pump system is the 50PT AQUAZONE®[32] closed loop geothermal heat-pump system made by the Carrier Corporation® for its acute performance (EER of 25.3 and CoP of 4.3).

Geothermal heat pumps not being available in DesignBuilder as a template yet, the HVAC system was set as follows:

- The fan-coil unit template was chosen and modified to correspond to geothermal heat-pumps.

---

[30] **EER**: *a measure of efficiency in the cooling mode that represents the ratio of total cooling capacity to electrical energy input.*
[31] **CoP**: *a measure of efficiency in the heating mode that represents the ratio of total heating capacity to electrical energy input. For the purpose of this specification,*
[32] 50 PT Aquazone HVAC system: *http://www.floridageothermal.com/5701.html*

• Both heating and cooling were fueled by electricity since geothermal heat pumps are electricity needs compressors which function with electricity.

• CoP was set to 4.3, no EER option was offered.

### III.5.1.6 Seahouse: renderings.

The followings renderings of the Seahouse were obtain in Revit Architecture 2011.

**Figure III.5.1.6.1- Rendering - Axonometric front view of SH.**

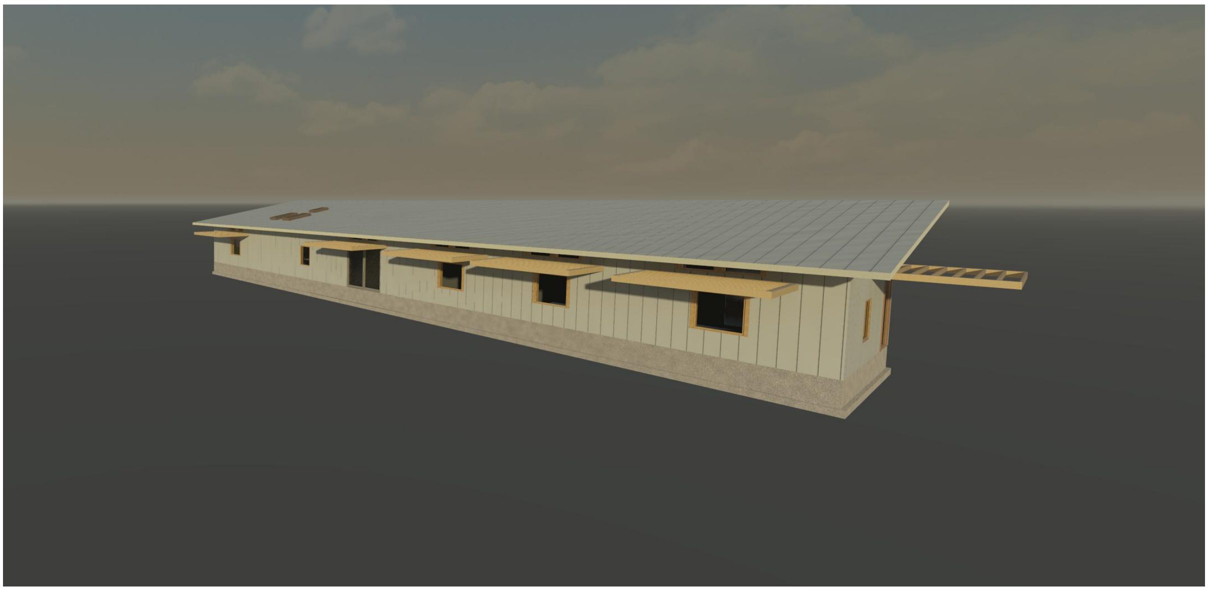

**Figure III.5.1.6.2 – Rendering - Axonometric rear view of SH.**

### III.5.2 Minnhouse framework

In keeping with the objective to assess the energy efficiency of the Seahouse, it was decided to compare it with another design. This second design is the one of a typical American colonial style[33] originally based in Minnesota and will be referred to as 'the Minnhouse' throughout this paper. This specific house has been chosen for several reasons. The first reason was the data availability. The Minnhouse was originally analyzed by the Consortium for Research on Renewable Industrial Materials (CORRIM) [29]. This nonprofit consortium of 15 research institutions had studied both the embodied energy and the energy consumption of this wooden frame house for a year period. This was convenient as it would provide baseline data for comparison. However, their analysis of the house was realized under different assumptions (discussed in the next section) than the ones found useful for a relevant comparison with the Seahouse. Nonetheless, the CORRIM organization was of

[33] Also referred to as cape cod style house

assistance and supplied accurate DXF[34] format blue-prints of that typical house which allowed for detailed measurement of the building and examination of area-specific construction methods. After a meticulous study of the blue prints, the Minnhouse was modeled with DesignBuilder and finally analyzed and compared to the Seahouse.

The second reason, which explains why this home was selected, is because its size. In a previous section it was explained how the Seahouse was sized. It seemed more relevant to compare it to a typical American home with a similar size rather than to a Mc Mansion.

#### III.5.2.1 Minnhouse: blue prints.

Since the source of information were blue prints and that DesignBuilder has a DXF import function, it was decided to build the model directly in DesignBuilder instead going through Revit.

The floor plans of the Minnhouse allowed the modeling of the house by setting the floor plans in DesignBuilder and extruding the walls out of them. These floor plans are available in the CORRIM Report [29].

Here are the floor plans of each story as displayed within DesignBuilder:

[34] **AutoCAD DXF** *(Drawing Interchange Format, or Drawing Exchange Format) is a CAD data file format developed by Autodesk for enabling data interoperability between AutoCAD and other programs.*

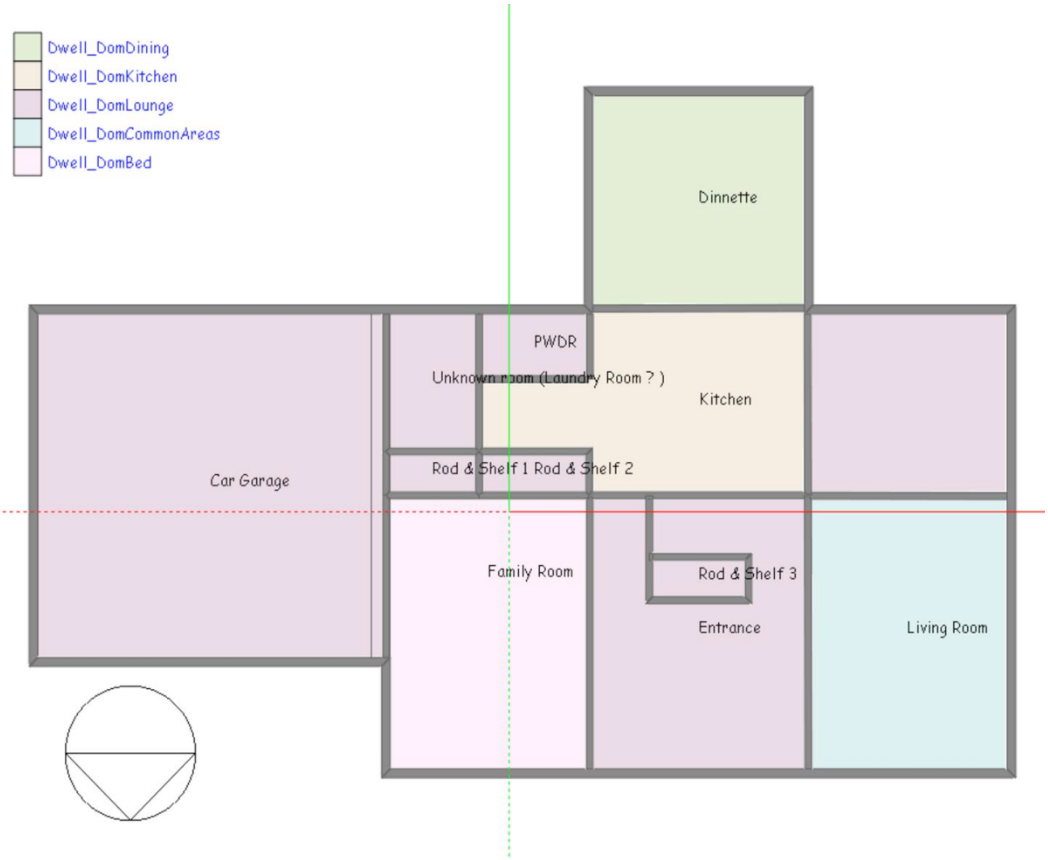


**Figure III.5.2.1.1 - DesignBuilder layout - Floor plan of first floor of MH**

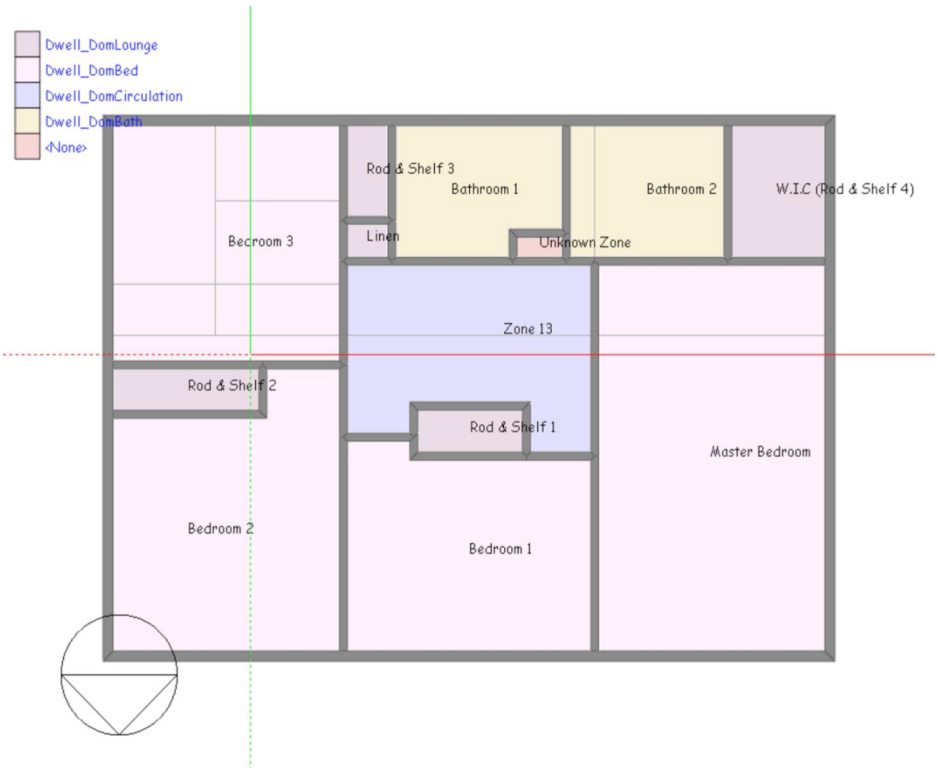


**Figure III.5.2.1.2 - DesignBuilder layout - Floor plan of second floor of MH.**

The following A-A section helped to understand the configuration of the external walls, the internal walls and the stairs; and therefore enabled picturing and modeling the 3D model. It also provided important construction details.

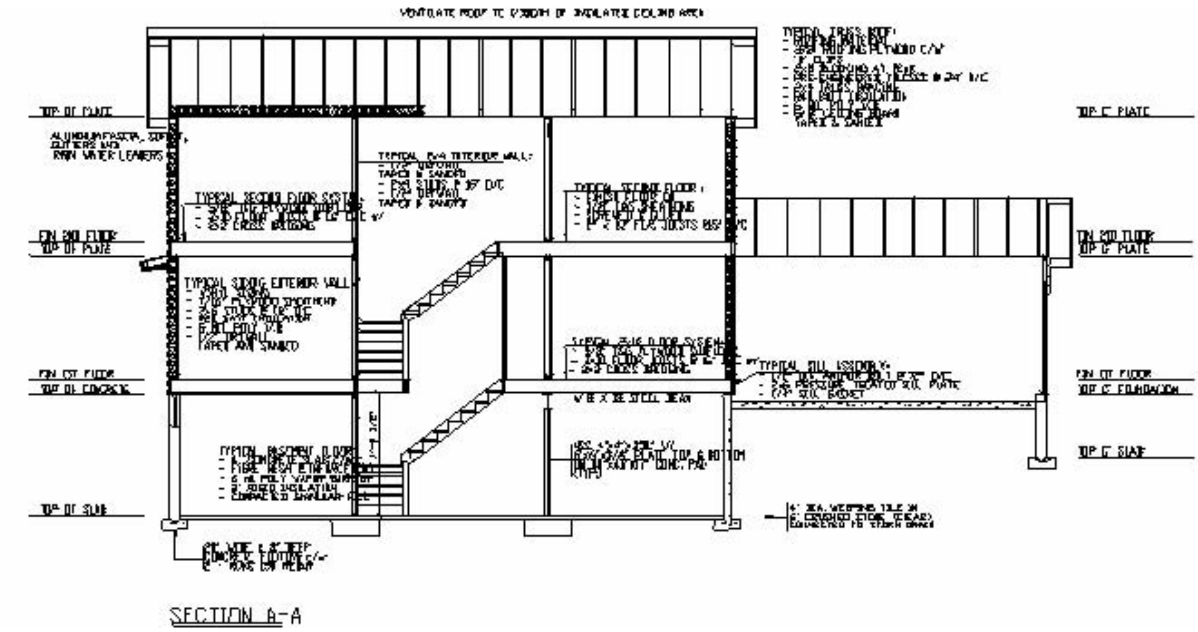


**Figure III.5.2.1.3 - Blue print - section A-A of MH.**

The first floor wall-framing diagram plan was used to model the internal and external wall of the first floor and evaluate the distances in between the studs.

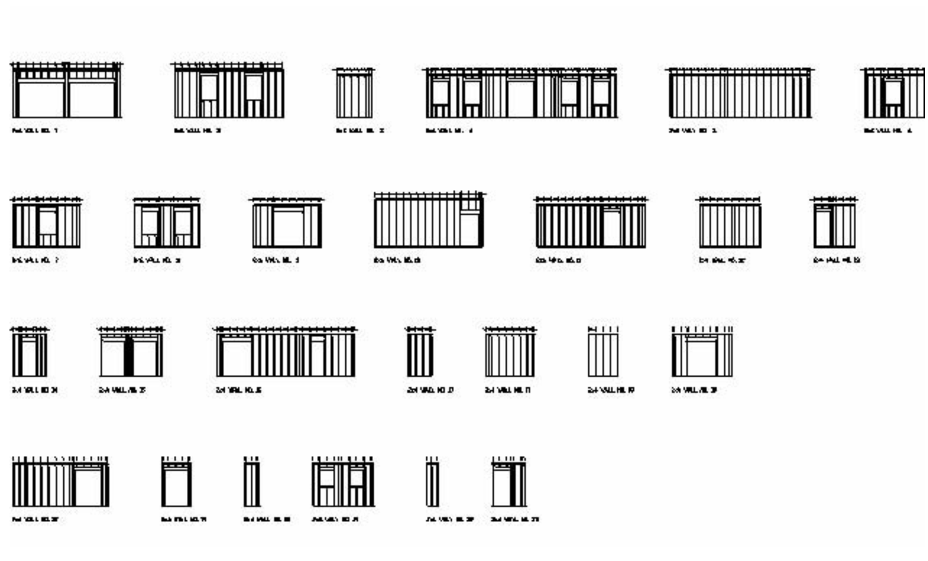

**Figure III.5.2.1.4 - Blue print - wall-framing plans for the first of MH.**

A zoom of this wall-framing plan gives two typical wall framing (a more extended zoom would give the distance in between the studs). The 2x6 stud walls were external walls whereas the 2x4 were internal walls (referred to as partition walls in the DesignBuilder).

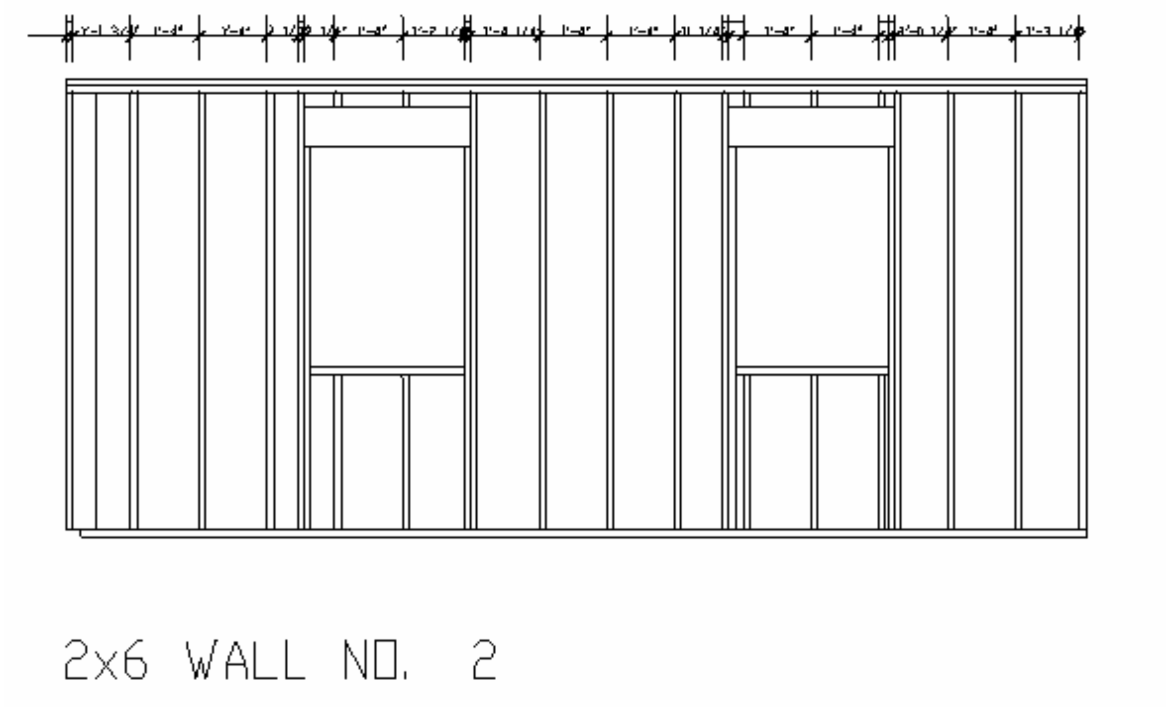


**Figure III.5.2.1.5 - 2x6 typical wall framing of MH.**

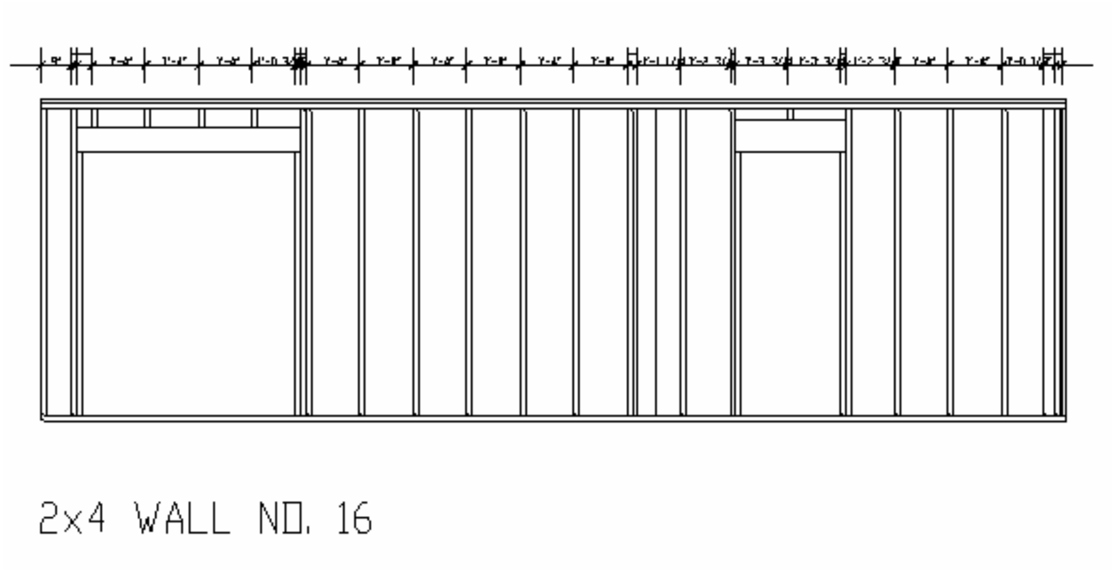


**Figure III.5.2.1.6 - 2x4 typical wall framing of MH.**

When the walls, floors and ceiling were modeled, their compositions and insulations had to be set up in DesignBuilder. The next section discusses that process.

### III.5.2.2 Minnhouse: construction details.

According to the information from the CORRIM report used to build the house, “the Minnhouse was designed as a two-story building with a basement, representing a typical construction in the Minneapolis area. An unconditioned attic acts as the ceiling of the second story. A two car garage and a full unfinished basement are also part of this model. All framing members were solid wood with a nominal thickness of 2 in., with the exception of floor joists which were composite I-joists. Wood-based composites (mostly plywood) were used as sheathing and pre-engineered roof trusses were used as a roof system. The total floor area of the structure was 2,062 sq. ft. The foundation was designed as 12-in thick concrete masonry block walls."

The other parts of the Minnhouse are described in this detailed list of the design specifics found in the CORRIM reports:

**MINNHOUSE STRUCTURE:**

**Ceiling/Roof Systems:**

- Type: pitched roof with 5:12 slope
- ½ inch plasterboard
- 6 mil polyethylene sheet
- Wood engineered trusses 24 in. o.c.[35]
- Glass wool insulation (R-49)
- 240# asphalt shingles

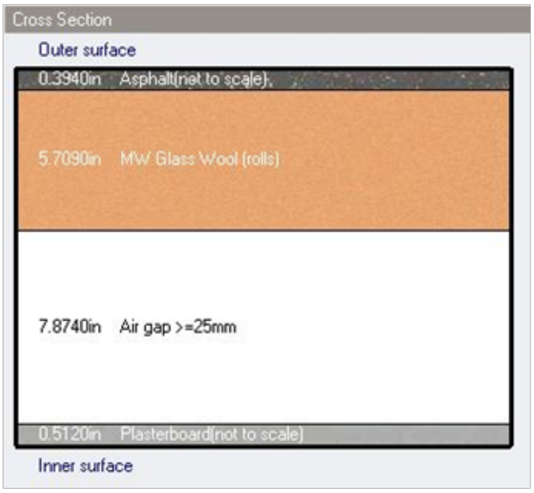


**Figure III.5.2.2.1 - Cross section of MH roof.**

[35] *Not shown in the cross section but was bridged to the air gap layer in DB.*

**Basement walls:**

• 8 inches x 20 inches cast concrete footings

• 12 inches concrete masonry block walls

• Vapor retarder installed on block wall

(*Typically 6 mil poly*)

• 2x4 in wood stud frame wall (24 o.c.)

on treated plate

• 6 mil flame retardant poly vapor retarder

• 2.5 in EPS Expanded Polystylene

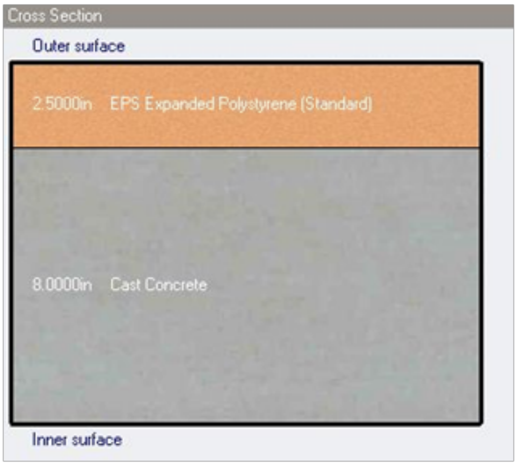


**Figure III.5.2.2.2 - Cross section of MH walls.**

**1st and 2nd Floor:**

• 19/32 inch plywood decking

• Air gap (R-30) bridged with I-joist equivalent

to 2x10 inch solid wood joists 1 inch o.c.

• ½ inch gypsum sheetrock plasterboard

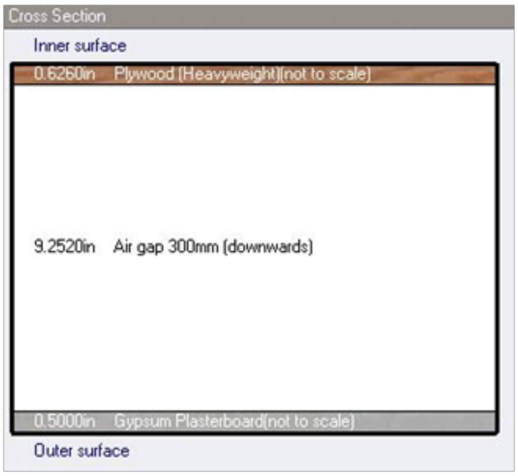


**Figure III.5.2.2.3 - Cross section of MH floor.**

**Walls (above grade):**

• ½ inch gypsum sheetrock

• 6 mil poly vapor retarder

• 2x6 inch stud, 16 o.c.

• Glass wool insulation (R-21)

•15# rolled asphalt impregnated paper

• Plywood siding

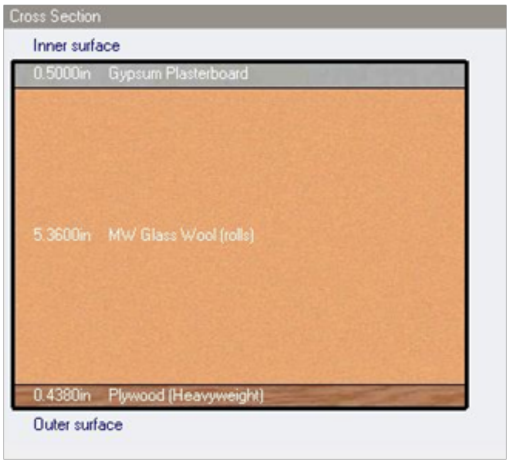


**Figure III.5.2.2.4 - Cross section of MH External walls.**

**Partition Walls:** *(Same as Seahouse)*

• ½ inch gypsum sheetrock both sides

• 3.6 inches air gap (R-15)

• 2x4 FSC wood studs, 16 inches o.c (*bridged to the air layer*)

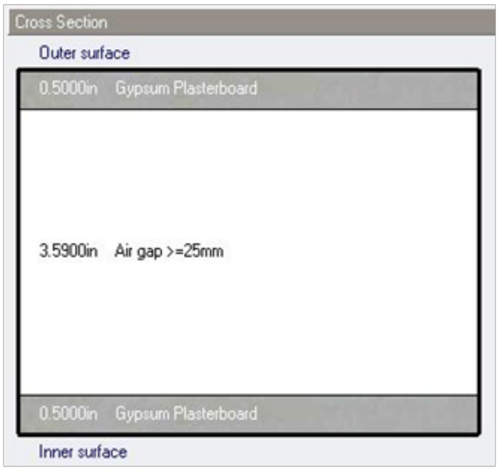


**Figure III.5.2.2.5 - Cross section of MH partition walls.**

**Windows:**

• Double glaze, low E argon filled, vinyl frame.

Therefore, the insulation of the envelope of the building was realized by setting 'glass wool rolls' as the insulating layer for both roof and external walls.

Once the materials for walls and floors are set, R-values must be addressed. When the R-value is set to the insulating layer of the wall within DesignBuilder, the thickness of that layer changes to adjust itself with the R-value.

Regarding windows high R-values can be achieved by replacing air with argon when practical (such as between sealed double-glazed windows). This and the fact that ENERGY STAR [28] recommends this type of windows, is why double-pane, low-emission (low E) windows filled with argon were selected for both models.

#### III.5.2.3 Minnhouse: HVAC system.

From the information found in the CORRIM report, the HVAC system was set in DesignBuilder as follows:

Heating was realized by a central gas furnace, which was fueled by natural gas. Central furnaces were connected to duct systems that distribute hot air around the house. Use of a central air conditioner was assumed; the system uses indoor coils to drive cool air to the duct system of the house, and has an outdoor unit exhausting system. A single central air conditioner was sized to cool the complete living areas of the Minnhouse.

The heating and cooling system coefficients of performance (CoPs) were based on the "Heating and ventilation ducted supply + extract" template. This template sets the heating system's CoP at 0.65, the heating type to 'convective'[36], the cooling system's CoP at 2.5, supply air temperature at 12 °C and supply air humidity ratio at 0.009 g/g.

#### III.5.2.4 Minnhouse: renderings.

The following renderings of the Minnhouse were obtained in DesignBuilder.

[36] In this type of heating system, the space is heated by an air system and controlled to the air temperature set point.

**Figure III.5.2.4.1 – Rendering - Axonometric view of MH.**

**Figure III.5.2.4.2 – Rendering - Front elevation view of MH.**

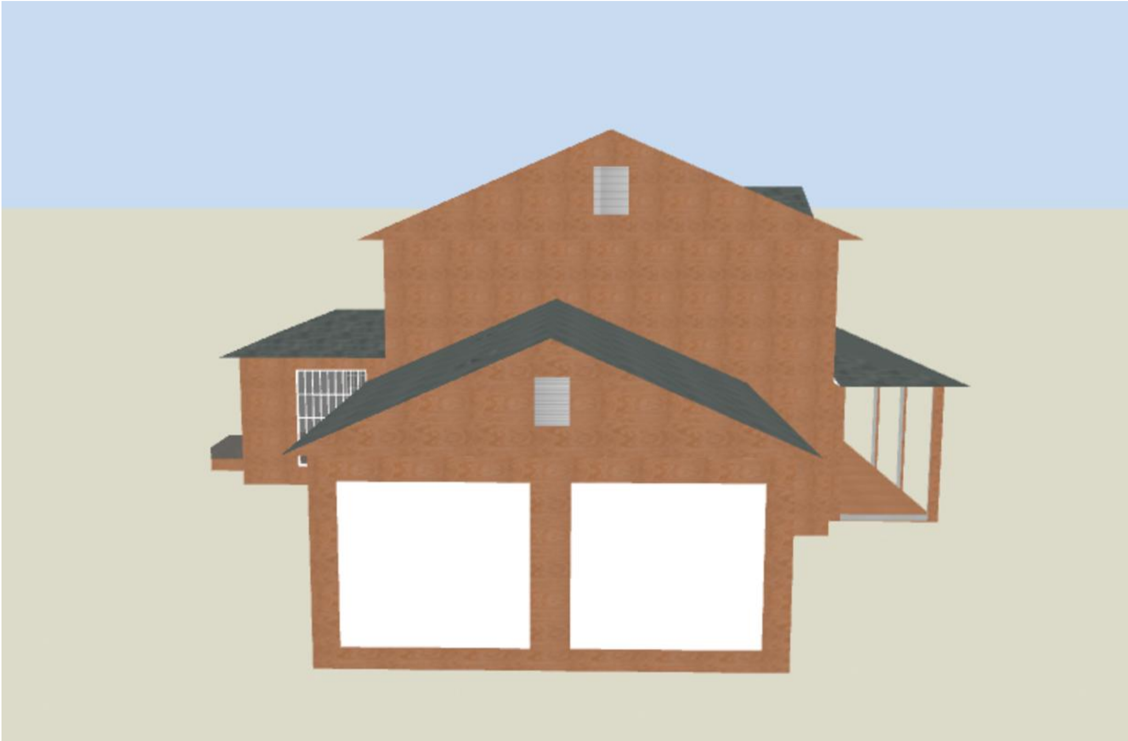

**Figure III.5.2.4.3 – Rendering - Left elevation view of MH.**

**Figure III.5.2.4.4 – Rendering - Rear elevation view of MH.**

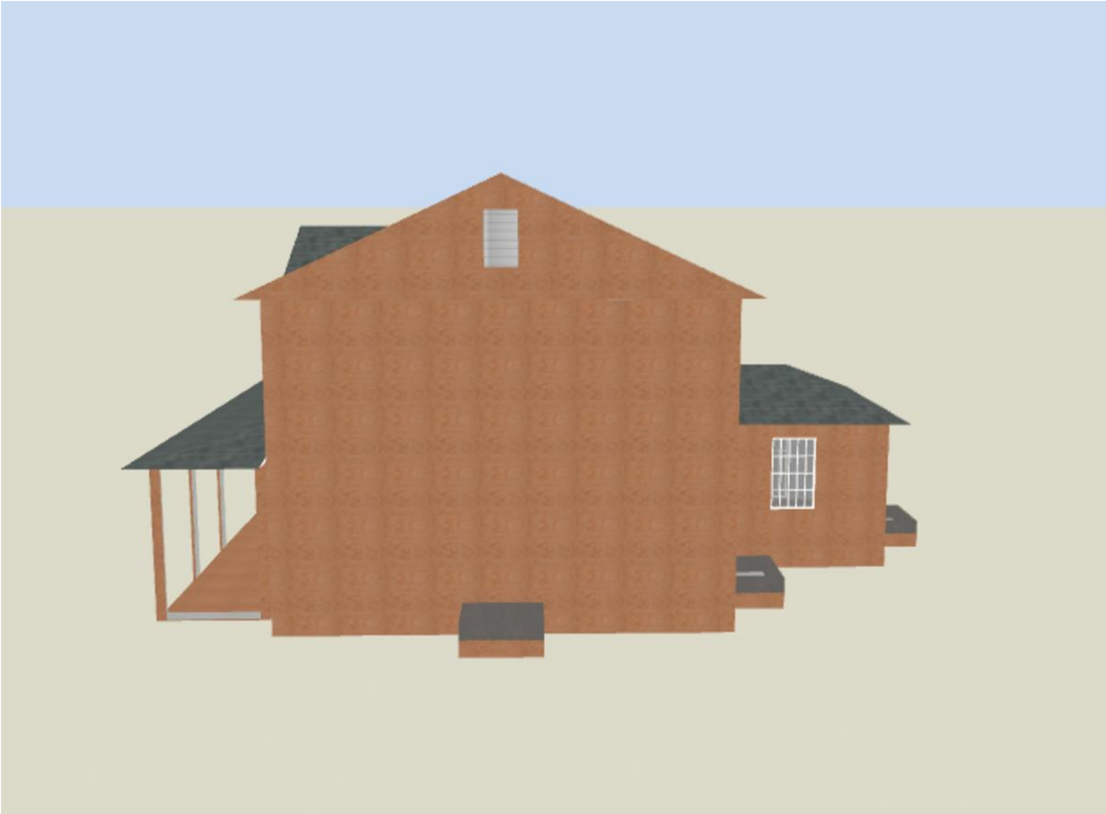

**Figure III.5.2.4.5 – Rendering - Right elevation view of MH.**

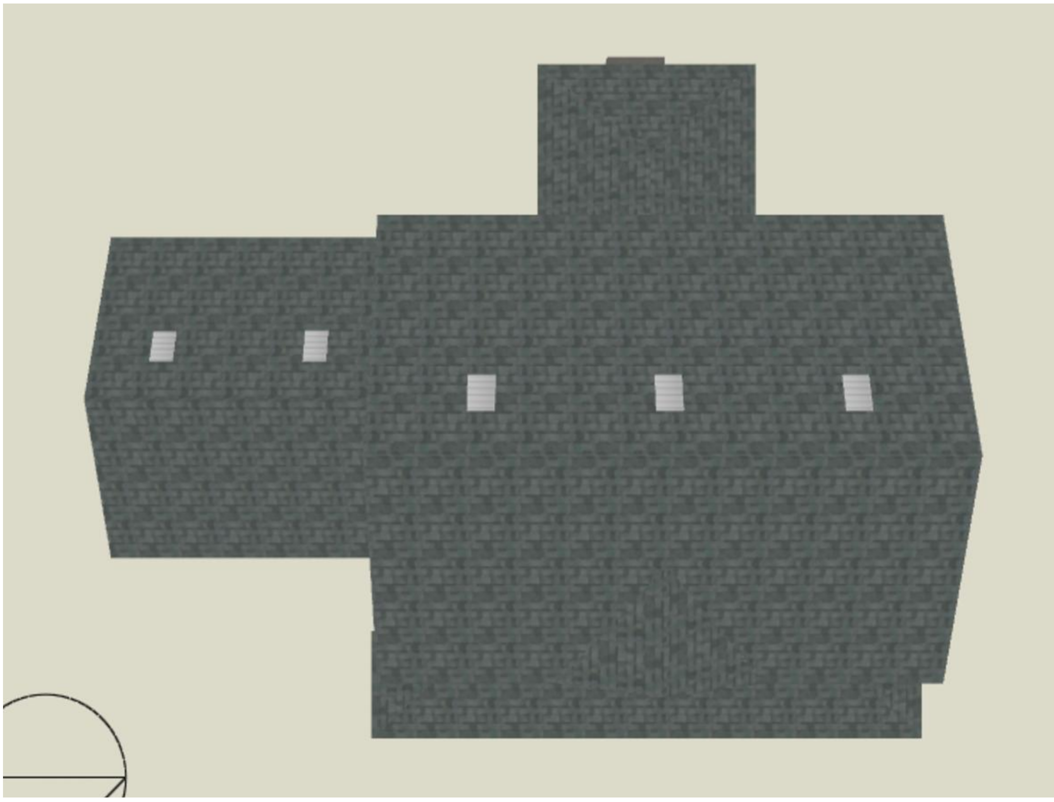

**Figure III.5.2.4.6 – Rendering - Roof plan of MH.**

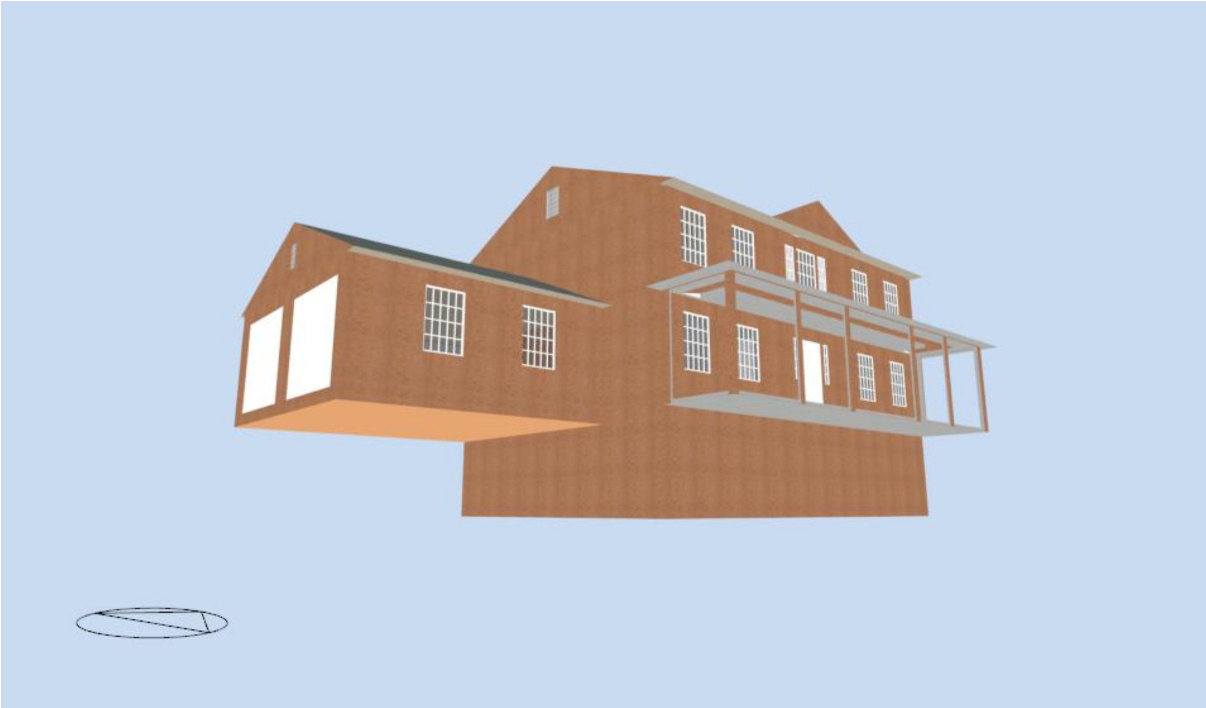

**Figure III.5.2.4.7 – Rendering - View showing the basement of MH.**

## III.6 Pictures of the SH Baseline house

The Seahouse was based on a house built in Pullman, WA in 2010 by MC & T Construction Inc[37]. While the proportions of that baseline house (referred to as BH in this section) were changed; the location of overhangs, shape, wall siding and roofing materials were conserved. Therefore the envelope of the Seahouse and baseline-house are similar and the intent of the following pictures is to provide a preview of what the Seahouse would look like if built. *(These pictures were provided by MC & T Construction Inc.[38]).*

[37] MC&T Construction Inc.: http://www.mctconstructioninc.com/
[38]

**Figure III.6.1 - Location of overhangs on BH**

**Figure III.6.2 - Closer view of BH overhang**

**Figure III.6.3 - BH Glass door**

**Figure III.6.4 - BH Wall siding**

# III.7 The different climates

Some features of an energy efficient house are dependent on the climate zone that it belongs to. These features are not only dependent on climate but also location - since, for instance, solar radiation varies with latitude. For these reasons, along with the choice of materials, overhangs and insulation values were conditioned by the International Energy Conservation Code 2006 (IECC 2006) climate zone that the house belonged to. The decision was made to build the house according to green standards and to keep it the same way for all simulations, in order to evaluate the influence of design on energy consumption. Since the design choices are inherent to location, this house might be efficient in Seattle (as it was originally designed for this city) but not in Denver or Atlanta. Some parameters in the design of the house would vary to make it more climate-dependent. For instance, while houses in cold climate should have more insulation, those in very hot climate should have white painted roofs. A report made by Miller et al., 2004, entitled “Painted metal roofs are energy-efficient, durable and sustainable”, and highlights the efficiency of this passive cooling technique for a house located in Florida. To assess how our model would react in several locations, cities with different climates were considered.

The following cities were selected:


**Figure III.7 - Map of simulated locations**[39]

### III.7.1 Seattle, WA

The house was originally modeled for Seattle, WA, following the NGBS code book guidelines. Therefore, the first analysis should be realized in Seattle where the lowest values for $CO_2$ and energy requirements are to be expected.

Seattle is classified as Cfb in the Koppen[Error! Reference source not found.]classification. This corresponds to a temperature oceanic climate usually representative of European countries (with the exception of Spain, Portugal and Italy). However Seattle's mild climate can sometimes be classified as Mediterranean because of its wet-winter/dry-summer patterns. Temperature extremes are regulated by the contiguous Puget Sound. Winters are usually cool and wet with average lows around 35–40 °F (2–4 °C) during nights. Summers are dry and warm, with average daytime highs around 73–80 °F (22.2–26.7 °C).

[39] Source : http://www.westpenhil-p.schools.nsw.edu.au/SoldierSam.htm

### III.7.2 Minneapolis, MN

Because the Seahouse was originally built in Seattle, WA and followed the NGBS green code while the Minnhouse was originally built in Minneapolis, MN, it is expected to perform better in Seattle. Therefore, in a need to carry out a relevant comparison, both houses should be analyzed under Minneaoplis' climate.

Minneapolis is classified as Dfa in the Koppen classification. This corresponds to a warm or humid continental climate which is usually portrayed by significant annual variation in temperature caused by the lack of significant bodies of water close by. This climate is representative of the Upper Midwest in the way its winters are cold and dry while its summers are warm sometimes even hot and humid'. The average annual temperature of 45.4 °F (7 °C) gives the Minneapolis–St. Paul metropolitan area the coldest annual mean temperature.

### III.7.3 Denver, CO & Atlanta, GA

In order to get a broader array of climates pertinent to our analysis, two additional cities were considered: Denver and Atlanta.

Denver is classified as Bsk in the Koppen classification. This corresponds to a cold semi-arid climate. Denver's winters are cold and dry while its summers are very hot and also dry. The average temperature in Denver is 50.0 °F (10.0 °C) and the average high temperature in Denver throughout the whole year is 64.0 °F (17.8 °C). During winter, the normal high is 45°F (7.2 °C) and the average low is 17 °F (-8.3°C). During summer, the average high is 88 °F (31.1 °C) and the average low is 59 °F (15 °C).

Atlanta is classified as Cfa in the Koppen classification. This corresponds to a humid subtropical climate. This type of climate is generally characterized by hot, humid summers and cool winters. Winter averages 42.7 °F (5.9 °C) while summer high temperatures (in July) average 89 °F (31.7 °C).

# III.8 SIMULATION RESULTS

## III.8.1 Site weather data

| Months of the year | SEATTLE | | | | MINNEAPOLIS | | | | DENVER | | | | ATLANTA | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DBT (°C) | Wind Speed (m/s) | Sol. Rad. (kW/m$^2$) | RH (%) | DBT (°C) | Wind Speed (m/s) | Sol. Rad. (kW/m$^2$) | RH (%) | DBT (°C) | Wind Speed (m/s) | Sol. Rad. (kW/m$^2$) | RH (%) | DBT (°C) | Wind Speed (m/s) | Sol. Rad. (kW/m$^2$) | RH (%) |
| January | 5.43 | 2.41 | 21.03 | 81.04 | -11.39 | 4.58 | 94.31 | 64.27 | 0.79 | 3.80 | 149.63 | 46.65 | 3.97 | 4.56 | 113.40 | 69.71 |
| February | 6.57 | 2.54 | 91.37 | 73.56 | -4.84 | 4.70 | 102.60 | 63.18 | -0.05 | 3.47 | 128.77 | 54.35 | 7.94 | 5.19 | 114.65 | 61.70 |
| March | 9.18 | 2.90 | 69.47 | 74.76 | 2.04 | 5.14 | 130.65 | 63.26 | 6.13 | 4.36 | 183.37 | 40.52 | 13.76 | 4.89 | 144.89 | 60.43 |
| April | 11.03 | 2.69 | 103.32 | 71.92 | 7.54 | 4.99 | 142.38 | 64.48 | 5.83 | 5.31 | 133.76 | 61.51 | 17.22 | 3.95 | 153.55 | 65.55 |
| May | 13.33 | 3.03 | 115.89 | 70.71 | 16.51 | 4.78 | 168.14 | 59.62 | 15.49 | 3.80 | 179.91 | 52.55 | 20.84 | 3.50 | 149.11 | 71.44 |
| June | 15.76 | 2.48 | 105.64 | 68.78 | 20.36 | 4.18 | 170.78 | 59.67 | 23.10 | 3.45 | 219.87 | 42.27 | 24.80 | 3.85 | 153.76 | 70.66 |
| July | 19.02 | 2.39 | 204.06 | 62.80 | 23.78 | 4.45 | 167.24 | 66.36 | 22.27 | 2.99 | 203.05 | 50.34 | 26.06 | 3.24 | 144.91 | 80.25 |
| August | 18.79 | 2.76 | 169.31 | 68.83 | 20.63 | 3.99 | 144.57 | 71.38 | 22.61 | 4.52 | 189.51 | 44.96 | 26.55 | 3.39 | 133.70 | 79.39 |
| September | 15.98 | 2.17 | 180.39 | 67.50 | 15.83 | 4.45 | 127.31 | 69.21 | 19.16 | 4.10 | 184.73 | 40.81 | 22.52 | 3.06 | 113.44 | 73.84 |
| October | 11.73 | 2.06 | 65.30 | 82.76 | 8.20 | 4.44 | 109.55 | 71.82 | 10.04 | 3.80 | 160.63 | 61.02 | 16.02 | 4.05 | 142.46 | 75.62 |
| November | 8.79 | 2.40 | 23.82 | 83.96 | 0.30 | 4.60 | 74.31 | 69.09 | 2.90 | 4.20 | 118.30 | 52.13 | 11.94 | 4.16 | 109.50 | 65.50 |
| December | 6.18 | 3.12 | 27.81 | 85.23 | -6.97 | 4.79 | 70.68 | 65.99 | 1.43 | 3.19 | 126.04 | 48.82 | 7.70 | 4.69 | 107.01 | 67.50 |
| **Average for Current weather** | **11.82** | **2.58** | **98.12** | **74.32** | **7.67** | **4.59** | **125.21** | **65.69** | **10.81** | **3.92** | **164.80** | **49.66** | **16.61** | **4.04** | **131.70** | **70.13** |

**Table III.8.1.1 - Current weather data for different locations**

| Months of the year | SEATTLE | | | | MINNEAPOLIS | | | | DENVER | | | | ATLANTA | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DBT (°C) | Wind Speed (m/s) | Sol. Rad. (kW/m$^2$) | RH (%) | DBT (°C) | Wind Speed (m/s) | Sol. Rad. (kW/m$^2$) | RH (%) | DBT (°C) | Wind Speed (m/s) | Sol. Rad. (kW/m$^2$) | RH (%) | DBT (°C) | Wind Speed (m/s) | Sol. Rad. (kW/m$^2$) | RH (%) |
| January | 6.35 | 2.32 | 21.68 | 79.61 | -9.14 | 4.66 | 91.34 | 63.75 | 3.32 | 3.72 | 146.97 | 44.28 | 5.97 | 4.56 | 114.94 | 64.68 |
| February | 7.40 | 2.48 | 96.09 | 71.85 | -3.15 | 4.85 | 103.61 | 62.39 | 2.22 | 3.55 | 122.80 | 50.05 | 9.67 | 5.33 | 116.92 | 57.48 |
| March | 10.32 | 2.95 | 70.61 | 72.27 | 4.34 | 5.26 | 122.52 | 60.59 | 8.34 | 4.45 | 181.23 | 36.71 | 16.15 | 4.94 | 151.13 | 55.47 |
| April | 13.30 | 2.69 | 104.14 | 68.40 | 9.88 | 5.07 | 142.06 | 60.61 | 8.35 | 5.40 | 137.50 | 56.72 | 19.58 | 3.95 | 158.24 | 61.94 |
| May | 15.23 | 3.03 | 121.14 | 67.34 | 19.15 | 4.83 | 178.56 | 55.19 | 18.31 | 4.01 | 187.05 | 46.17 | 23.73 | 3.53 | 155.56 | 67.23 |
| June | 18.35 | 2.46 | 116.83 | 64.36 | 23.53 | 4.27 | 181.14 | 54.37 | 27.24 | 3.68 | 226.53 | 33.05 | 27.88 | 3.99 | 163.80 | 63.18 |
| July | 23.35 | 2.57 | 232.65 | 51.73 | 27.24 | 4.28 | 180.07 | 60.01 | 26.16 | 2.98 | 209.77 | 42.53 | 29.77 | 3.57 | 151.54 | 71.46 |
| August | 22.98 | 3.06 | 184.33 | 59.26 | 24.75 | 3.92 | 161.11 | 62.97 | 26.90 | 4.41 | 198.25 | 36.44 | 30.12 | 3.49 | 139.42 | 72.80 |
| September | 19.48 | 2.22 | 193.52 | 59.03 | 19.67 | 4.34 | 135.64 | 64.22 | 22.92 | 3.94 | 183.49 | 39.45 | 25.83 | 2.87 | 113.54 | 72.17 |
| October | 14.20 | 2.06 | 63.23 | 80.70 | 11.53 | 4.62 | 116.02 | 67.79 | 13.47 | 3.81 | 159.73 | 57.62 | 18.83 | 4.13 | 143.77 | 74.32 |
| November | 10.54 | 2.33 | 24.01 | 82.62 | 3.11 | 4.69 | 71.69 | 66.60 | 5.39 | 4.23 | 114.46 | 48.54 | 14.66 | 4.06 | 122.39 | 63.19 |
| December | 8.30 | 3.12 | 25.63 | 84.51 | -4.05 | 4.88 | 65.91 | 65.28 | 4.16 | 3.19 | 130.94 | 45.19 | 10.05 | 4.64 | 110.60 | 64.03 |
| **Average for 2050** | **14.15** | **2.61** | **104.49** | **70.14** | **10.57** | **4.64** | **129.14** | **61.98** | **13.90** | **3.95** | **166.56** | **44.73** | **19.35** | **4.09** | **136.82** | **65.66** |

**Table III.8.1.2 - Future weather data for different locations**

| Months of the year | SEATTLE | | | | MINNEAPOLIS | | | | DENVER | | | | ATLANTA | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Δ DBT (°C) | Δ Wind Speed (m/s) | Δ Sol. Rad. (kW/m$^2$) | RH (%) | Δ DBT (°C) | Δ Wind Speed (m/s) | Δ Sol. Rad. (kW/m$^2$) | RH (%) | Δ DBT (°C) | Δ Wind Speed (m/s) | Δ Sol. Rad. (kW/m$^2$) | RH (%) | Δ DBT (°C) | Δ Wind Speed (m/s) | Δ Sol. Rad. (kW/m$^2$) | RH (%) |
| January | 0.92 | -0.09 | 0.65 | -1.43 | 2.25 | 0.08 | -2.97 | -0.52 | 2.53 | -0.08 | -2.66 | -2.37 | 2.00 | 0.00 | 1.54 | -5.03 |
| February | 0.83 | -0.06 | 4.72 | -1.71 | 1.69 | 0.15 | 1.01 | -0.79 | 2.27 | 0.08 | -5.97 | -4.30 | 1.73 | 0.14 | 2.27 | -4.22 |
| March | 1.14 | 0.05 | 1.14 | -2.49 | 2.30 | 0.12 | -8.13 | -2.67 | 2.21 | 0.09 | -2.14 | -3.81 | 2.39 | 0.05 | 6.24 | -4.96 |
| April | 2.27 | 0.00 | 0.82 | -3.52 | 2.34 | 0.08 | -0.32 | -3.87 | 2.52 | 0.09 | 3.74 | -4.79 | 2.36 | 0.00 | 4.69 | -3.61 |
| May | 1.90 | 0.00 | 5.25 | -3.37 | 2.64 | 0.05 | 10.42 | -4.43 | 2.82 | 0.21 | 7.14 | -6.38 | 2.89 | 0.03 | 6.45 | -4.21 |
| June | 2.59 | -0.02 | 11.19 | -4.42 | 3.17 | 0.09 | 10.36 | -5.30 | 4.14 | 0.23 | 6.66 | -9.22 | 3.08 | 0.14 | 10.04 | -7.48 |
| July | 4.33 | 0.18 | 28.59 | -11.07 | 3.46 | -0.17 | 12.83 | -6.35 | 3.89 | -0.01 | 6.72 | -7.81 | 3.71 | 0.33 | 6.63 | -8.79 |
| August | 4.19 | 0.30 | 15.02 | -9.57 | 4.12 | -0.07 | 16.54 | -8.41 | 4.29 | -0.11 | 8.74 | -8.52 | 3.57 | 0.10 | 5.72 | -6.59 |
| September | 3.50 | 0.05 | 13.13 | -8.47 | 3.84 | -0.11 | 8.33 | -4.99 | 3.76 | -0.16 | -1.24 | -1.36 | 3.31 | -0.19 | 0.10 | -1.67 |
| October | 2.47 | 0.00 | -2.07 | -2.06 | 3.33 | 0.18 | 6.47 | -4.03 | 3.43 | 0.01 | -0.90 | -3.40 | 2.81 | 0.08 | 1.31 | -1.30 |
| November | 1.75 | -0.07 | 0.19 | -1.34 | 2.81 | 0.09 | -2.62 | -2.49 | 2.49 | 0.03 | -3.84 | -3.59 | 2.72 | -0.10 | 12.89 | -2.31 |
| December | 2.12 | 0.00 | -2.18 | -0.72 | 2.92 | 0.09 | -4.77 | -0.71 | 2.73 | 0.00 | 4.90 | -3.63 | 2.35 | -0.05 | 3.59 | -3.47 |
| **Average increase** | **2.33** | **0.03** | **6.37** | **-4.18** | **2.91** | **0.05** | **3.93** | **-3.71** | **3.09** | **0.03** | **1.76** | **-4.93** | **2.74** | **0.04** | **5.12** | **-4.47** |
| **Variation of weather parameters from present to future (%)** | **19.75** | **1.10** | **6.49** | **-5.63** | **37.91** | **1.05** | **3.14** | **-5.65** | **28.59** | **0.81** | **1.07** | **-9.93** | **16.52** | **1.09** | **3.89** | **-6.37** |

**Table III.8.1.3 - Weather data trends for each location**

## III.8.2 Influence of Design

This simulation compares the energy consumed by the Seahouse and by the Minnhouse during present weather in order to define the influence of the passive solar design on the energy consumption.

| Months of the year | SEAHOUSE (SH) in : | | | | | | | | MINNHOUSE (MH) in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) |
| January | 2.50 | 0.00 | 6.53 | 0.02 | 2.21 | 0.19 | 2.06 | 0.10 | 35.00 | 0.00 | 79.02 | 0.00 | 39.22 | 0.02 | 33.97 | 0.01 |
| February | 1.35 | 0.11 | 3.91 | 0.05 | 2.21 | 0.10 | 1.24 | 0.12 | 25.31 | 0.01 | 52.76 | 0.00 | 36.81 | 0.01 | 22.51 | 0.05 |
| March | 1.09 | 0.06 | 2.58 | 0.04 | 1.20 | 0.06 | 0.33 | 0.21 | 21.71 | 0.03 | 38.23 | 0.01 | 24.73 | 0.09 | 10.43 | 0.17 |
| April | 0.55 | 0.05 | 1.49 | 0.20 | 1.47 | 0.02 | 0.13 | 0.40 | 14.44 | 0.09 | 23.53 | 0.18 | 24.67 | 0.10 | 5.05 | 0.40 |
| May | 0.26 | 0.10 | 0.18 | 0.54 | 0.24 | 0.32 | 0.01 | 1.25 | 9.27 | 0.13 | 6.34 | 0.53 | 7.12 | 0.35 | 1.76 | 0.99 |
| June | 0.09 | 0.18 | 0.03 | 1.20 | 0.00 | 1.61 | 0.00 | 3.00 | 5.25 | 0.21 | 2.07 | 0.98 | 1.20 | 1.52 | 0.71 | 3.08 |
| July | 0.02 | 0.85 | 0.00 | 2.67 | 0.00 | 1.59 | 0.00 | 3.97 | 2.18 | 0.75 | 0.77 | 2.65 | 1.40 | 1.50 | 0.43 | 4.46 |
| August | 0.02 | 0.76 | 0.02 | 1.43 | 0.00 | 1.48 | 0.00 | 4.21 | 2.36 | 0.56 | 1.82 | 1.13 | 1.27 | 1.39 | 0.33 | 4.64 |
| September | 0.09 | 0.56 | 0.40 | 0.68 | 0.06 | 0.88 | 0.00 | 1.84 | 5.90 | 0.35 | 8.80 | 0.40 | 3.80 | 0.71 | 1.25 | 1.45 |
| October | 0.66 | 0.10 | 1.16 | 0.12 | 0.72 | 0.39 | 0.22 | 0.59 | 16.53 | 0.04 | 23.42 | 0.05 | 17.37 | 0.17 | 7.56 | 0.28 |
| November | 1.57 | 0.02 | 3.25 | 0.06 | 1.92 | 0.18 | 0.51 | 0.27 | 25.55 | 0.00 | 45.16 | 0.00 | 33.82 | 0.01 | 14.72 | 0.05 |
| December | 2.37 | 0.01 | 5.66 | 0.02 | 2.31 | 0.19 | 1.24 | 0.19 | 33.74 | 0.00 | 68.86 | 0.00 | 39.11 | 0.02 | 25.14 | 0.02 |
| **Total 2010 (kWh/m2)** | **10.56** | **2.82** | **25.18** | **7.03** | **12.35** | **7.04** | **5.76** | **16.16** | **197.23** | **2.18** | **350.76** | **5.93** | **230.51** | **5.89** | **123.85** | **15.61** |
| **Total Heat. + Cool.** | **13.38** | | **32.21** | | **19.39** | | **21.92** | | **199.40** | | **356.69** | | **236.40** | | **139.46** | |
| **Energy saved by choosing the SH over the MH(%)** | **93.29** | | **90.97** | | **91.80** | | **84.28** | | | | | | | | | |

**Table III.8.2 – Influence of Design on energy consumption**

### III.8.2.1 Influence of Shape

In this simulation, all characteristics of the Seahouse but its shape were changed to the MH (such as HVAC system, R-values, construction materials, etc.). The resulting design was called SH1 for Seahouse modified n°1. The simulation was run for present weather.

| Months of the year | Modified SEAHOUSE (SH1) in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) |
| January | 16.01 | 0.00 | 42.27 | 0.04 | 14.49 | 0.38 | 13.34 | 0.21 |
| February | 8.86 | 0.21 | 25.14 | 0.10 | 14.39 | 0.21 | 8.15 | 0.23 |
| March | 7.18 | 0.14 | 16.47 | 0.08 | 7.98 | 0.14 | 2.50 | 0.41 |
| April | 3.82 | 0.13 | 9.62 | 0.38 | 9.61 | 0.06 | 1.07 | 0.78 |
| May | 1.84 | 0.19 | 1.34 | 0.99 | 1.71 | 0.63 | 0.12 | 2.26 |
| June | 0.68 | 0.37 | 0.26 | 2.10 | 0.03 | 2.80 | 0.01 | 5.03 |
| July | 0.16 | 1.51 | 0.00 | 4.50 | 0.05 | 2.75 | 0.00 | 6.59 |
| August | 0.17 | 1.38 | 0.16 | 2.47 | 0.03 | 2.55 | 0.00 | 6.94 |
| September | 0.88 | 1.02 | 2.72 | 1.21 | 0.55 | 1.58 | 0.06 | 3.11 |
| October | 4.51 | 0.20 | 7.77 | 0.24 | 5.17 | 0.75 | 1.73 | 1.10 |
| November | 10.11 | 0.04 | 20.96 | 0.12 | 12.56 | 0.36 | 3.70 | 0.51 |
| December | 15.26 | 0.03 | 36.63 | 0.03 | 15.12 | 0.38 | 8.27 | 0.36 |
| **Total (kWh/m2)** | **69.48** | **5.22** | **163.34** | **12.27** | **81.70** | **12.58** | **38.95** | **27.53** |
| **Total Heat. + Cool.** | **74.70** | | **175.61** | | **94.28** | | **66.47** | |
| **Energy saved by choosing the SH1 over the MH (%)** | **62.54** | | **50.77** | | **60.12** | | **52.34** | |

**Table III.8.2.1– Influence of shape on energy consumption**

### III.8.2.2 Influence of Insulation

In this simulation, the R-values of the Seahouse were replaced in the Minnhouse design. The resulting design was called SH3 for Seahouse modified n°3. The simulation was run for present weather.

| Months of the year | Modified SEAHOUSE (SH2) in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) |
| January | 32.58 | 0.00 | 72.87 | 0.00 | 35.51 | 0.02 | 31.39 | 0.00 |
| February | 23.32 | 0.01 | 48.81 | 0.00 | 33.60 | 0.01 | 20.69 | 0.03 |
| March | 20.16 | 0.02 | 35.57 | 0.01 | 22.38 | 0.05 | 9.32 | 0.10 |
| April | 13.26 | 0.05 | 21.89 | 0.13 | 22.65 | 0.05 | 4.25 | 0.22 |
| May | 8.59 | 0.06 | 5.59 | 0.36 | 6.22 | 0.17 | 1.39 | 0.68 |
| June | 4.82 | 0.10 | 1.73 | 0.74 | 0.85 | 1.13 | 0.54 | 2.66 |
| July | 1.79 | 0.54 | 0.61 | 2.34 | 1.03 | 1.14 | 0.37 | 4.01 |
| August | 1.96 | 0.40 | 1.50 | 0.94 | 0.95 | 1.09 | 0.30 | 4.22 |
| September | 4.87 | 0.26 | 7.83 | 0.31 | 3.00 | 0.53 | 0.98 | 1.23 |
| October | 15.18 | 0.03 | 21.38 | 0.04 | 15.37 | 0.12 | 6.59 | 0.21 |
| November | 23.71 | 0.00 | 41.62 | 0.00 | 30.68 | 0.01 | 13.14 | 0.03 |
| December | 31.26 | 0.00 | 63.45 | 0.00 | 35.33 | 0.02 | 23.03 | 0.01 |
| **Total (kWh/m2)** | **181.50** | **1.46** | **322.84** | **4.85** | **207.59** | **4.32** | **111.97** | **13.40** |
| **Total Heat. + Cool.** | **182.96** | | **327.69** | | **211.91** | | **125.37** | |
| **Energy saved by choosing the SH2 over the MH (%)** | **8.24** | | **8.13** | | **10.36** | | **10.10** | |

**Table III.8.2.2 – Influence of insulation on energy consumption**

### III.8.2.3 Influence of HVAC system

In this simulation, the whole HVAC system of the Minnhouse was replaced with the HVAC system of the Seahouse in the intent to assess the influence of the energy-efficient

HVAC system on annual energy consumption. The resulting design was called SH2 for Seahouse modified n°2. The simulation was run for present weather.

| Months of the year | Modified SEAHOUSE (SH3) in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) |
| January | 5.32 | 0.00 | 12.00 | 0.00 | 5.95 | 0.02 | 5.16 | 0.01 |
| February | 3.84 | 0.01 | 8.02 | 0.00 | 5.59 | 0.01 | 3.41 | 0.03 |
| March | 3.29 | 0.02 | 5.81 | 0.01 | 3.75 | 0.06 | 1.56 | 0.11 |
| April | 2.18 | 0.06 | 3.57 | 0.10 | 3.73 | 0.07 | 0.74 | 0.27 |
| May | 1.39 | 0.08 | 0.94 | 0.33 | 1.06 | 0.23 | 0.25 | 0.61 |
| June | 0.78 | 0.14 | 0.30 | 0.59 | 0.18 | 0.95 | 0.10 | 1.58 |
| July | 0.31 | 0.47 | 0.11 | 1.37 | 0.21 | 0.95 | 0.06 | 2.13 |
| August | 0.34 | 0.37 | 0.26 | 0.65 | 0.19 | 0.88 | 0.05 | 2.23 |
| September | 0.86 | 0.24 | 1.31 | 0.25 | 0.55 | 0.49 | 0.18 | 0.83 |
| October | 2.50 | 0.03 | 3.55 | 0.03 | 2.61 | 0.12 | 1.12 | 0.19 |
| November | 3.88 | 0.00 | 6.86 | 0.00 | 5.14 | 0.01 | 2.22 | 0.03 |
| December | 5.13 | 0.00 | 10.46 | 0.00 | 5.94 | 0.02 | 3.81 | 0.01 |
| **Total (kWh/m2)** | **29.82** | **1.42** | **53.20** | **3.34** | **34.90** | **3.79** | **18.66** | **8.04** |
| **Total Heat. + Cool.** | **31.24** | | **56.54** | | **38.68** | | **26.70** | |
| **Energy saved by choosing the SH3 over the MH (%)** | **84.33** | | **84.15** | | **83.64** | | **80.85** | |

**Table III.8.2.3 – Influence of HVAC system on energy consumption**

### III.8.2.4 Influence of Coefficient of Performance (CoP)

For this simulation, the values of the MH HVAC system were replaced by the ones of the SH HVAC system. Therefore, the central gas furnace now had a CoP of 4.3 instead of 0.65 and the electric AC had a CoP of 4.3 instead of 2.5. When these systems could not in theory obtain such values for their CoPs, this simulation was run to understand the influence of the CoP on the energy consumption within DesignBuilder.

| Months of the year | Modified SEAHOUSE ($SH_{COP}$) in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) |
| January | 5.29 | 0.00 | 11.94 | 0.00 | 5.92 | 0.01 | 5.13 | 0.00 |
| February | 3.78 | 0.00 | 7.98 | 0.00 | 5.56 | 0.01 | 3.40 | 0.03 |
| March | 3.28 | 0.02 | 5.78 | 0.01 | 3.74 | 0.05 | 1.58 | 0.10 |
| April | 2.18 | 0.05 | 3.56 | 0.11 | 3.73 | 0.06 | 0.76 | 0.24 |
| May | 1.40 | 0.07 | 0.96 | 0.31 | 1.08 | 0.20 | 0.27 | 0.57 |
| June | 0.79 | 0.12 | 0.31 | 0.57 | 0.18 | 0.89 | 0.11 | 1.79 |
| July | 0.33 | 0.44 | 0.12 | 1.54 | 0.21 | 0.87 | 0.07 | 2.60 |
| August | 0.36 | 0.36 | 0.28 | 0.66 | 0.19 | 0.81 | 0.05 | 2.70 |
| September | 0.91 | 0.24 | 1.33 | 0.23 | 0.57 | 0.41 | 0.19 | 0.84 |
| October | 2.50 | 0.02 | 3.54 | 0.03 | 2.63 | 0.10 | 1.14 | 0.17 |
| November | 3.86 | 0.00 | 6.83 | 0.00 | 5.11 | 0.00 | 2.22 | 0.03 |
| December | 5.10 | 0.00 | 10.41 | 0.00 | 5.91 | 0.01 | 3.80 | 0.01 |
| **Total (kWh/m2)** | **29.79** | **1.33** | **53.02** | **3.45** | **34.84** | **3.43** | **18.72** | **9.07** |
| **Total Heat. + Cool.** | **31.12** | | **56.47** | | **38.27** | | **27.79** | |
| **Energy saved by choosing the $SH_{COP}$ over the Minnhouse (%)** | **84.39** | | **84.17** | | **83.81** | | **80.07** | |

**Table III.8.2.4 – Influence of CoPs on energy consumption**

## III.8.3 Influence of Climate change

### III.8.3.1 Heating and cooling energy consumption during 2050

| Months of the year | SEAHOUSE (SH) in : | | | | | | | | MINNHOUSE (MH) in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) |
| January | 2.12 | 0.01 | 5.85 | 0.02 | 1.71 | 0.19 | 1.61 | 0.13 | 30.94 | 0.00 | 72.10 | 0.00 | 33.34 | 0.02 | 28.77 | 0.02 |
| February | 1.11 | 0.12 | 3.50 | 0.05 | 1.81 | 0.10 | 0.99 | 0.18 | 22.50 | 0.01 | 48.14 | 0.00 | 32.04 | 0.02 | 18.92 | 0.08 |
| March | 0.84 | 0.09 | 2.04 | 0.03 | 0.84 | 0.08 | 0.16 | 0.42 | 17.94 | 0.04 | 32.16 | 0.01 | 20.09 | 0.10 | 6.62 | 0.29 |
| April | 0.27 | 0.11 | 1.11 | 0.38 | 1.09 | 0.06 | 0.06 | 0.85 | 9.56 | 0.13 | 18.46 | 0.39 | 19.24 | 0.13 | 3.09 | 0.76 |
| May | 0.11 | 0.21 | 0.08 | 1.07 | 0.13 | 0.73 | 0.00 | 2.52 | 5.46 | 0.24 | 3.73 | 0.97 | 4.48 | 0.69 | 0.84 | 2.41 |
| June | 0.02 | 0.58 | 0.01 | 2.44 | 0.00 | 2.71 | 0.00 | 4.57 | 2.19 | 0.49 | 0.98 | 2.56 | 0.52 | 2.94 | 0.40 | 5.68 |
| July | 0.00 | 2.35 | 0.00 | 4.70 | 0.00 | 2.83 | 0.00 | 6.09 | 0.78 | 2.59 | 0.32 | 5.93 | 0.52 | 3.13 | 0.17 | 8.14 |
| August | 0.00 | 2.14 | 0.00 | 3.40 | 0.00 | 2.82 | 0.00 | 6.48 | 0.78 | 1.90 | 0.72 | 3.81 | 0.45 | 3.18 | 0.13 | 8.77 |
| September | 0.02 | 1.31 | 0.17 | 1.74 | 0.01 | 1.73 | 0.00 | 3.56 | 2.66 | 0.78 | 4.76 | 1.51 | 1.66 | 1.65 | 0.51 | 3.69 |
| October | 0.29 | 0.16 | 0.59 | 0.24 | 0.38 | 0.61 | 0.07 | 1.15 | 10.40 | 0.06 | 15.47 | 0.08 | 11.11 | 0.29 | 3.84 | 0.67 |
| November | 1.09 | 0.02 | 2.50 | 0.05 | 1.49 | 0.19 | 0.22 | 0.43 | 20.00 | 0.00 | 37.30 | 0.01 | 28.15 | 0.01 | 9.26 | 0.17 |
| December | 1.78 | 0.02 | 4.81 | 0.03 | 1.76 | 0.21 | 0.83 | 0.23 | 27.06 | 0.00 | 60.00 | 0.00 | 32.92 | 0.01 | 19.59 | 0.03 |
| **Total 2050 (kWh/m2)** | **7.64** | **7.12** | **20.66** | **14.17** | **9.21** | **12.25** | **3.94** | **26.60** | **150.27** | **6.23** | **294.13** | **15.27** | **184.51** | **12.17** | **92.15** | **30.71** |
| **Total Heat. + Cool.** | **14.76** | | **34.83** | | **21.46** | | **30.54** | | **156.50** | | **309.40** | | **196.68** | | **122.86** | |
| **Energy saved by choosing the SH over the MH(%)** | **90.57** | | **88.74** | | **89.09** | | **75.14** | | | | | | | | | |
| **Variation of energy consumption from 2010 to 2050(%)** | **10.36** | | **8.14** | | **10.67** | | **39.34** | | | | | | | | | |

**Table III.8.3.1 - Heating and cooling energy consumption during 2050**

## III.8.3.2 Influence of temperature

| Months of the year | SEAHOUSE (SH) in : | | | | | | | | MINNHOUSE (MH) in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) |
| January | 2.26 | 0.00 | 5.87 | 0.03 | 1.72 | 0.22 | 1.66 | 0.13 | 32.97 | 0.00 | 72.96 | 0.00 | 33.73 | 0.03 | 29.65 | 0.02 |
| February | 1.19 | 0.11 | 3.51 | 0.06 | 1.79 | 0.12 | 1.01 | 0.18 | 23.67 | 0.01 | 48.76 | 0.00 | 32.32 | 0.02 | 19.42 | 0.08 |
| March | 0.90 | 0.09 | 2.01 | 0.04 | 0.85 | 0.10 | 0.17 | 0.41 | 19.35 | 0.04 | 32.64 | 0.02 | 20.52 | 0.11 | 7.14 | 0.27 |
| April | 0.31 | 0.11 | 1.14 | 0.40 | 1.16 | 0.05 | 0.06 | 0.85 | 10.62 | 0.12 | 19.34 | 0.40 | 20.62 | 0.11 | 3.28 | 0.73 |
| May | 0.13 | 0.19 | 0.09 | 1.03 | 0.14 | 0.74 | 0.00 | 2.48 | 6.44 | 0.20 | 4.17 | 0.86 | 4.98 | 0.64 | 1.00 | 2.24 |
| June | 0.03 | 0.49 | 0.01 | 2.43 | 0.00 | 3.17 | 0.00 | 4.80 | 2.89 | 0.37 | 1.16 | 2.41 | 0.61 | 3.51 | 0.44 | 5.85 |
| July | 0.00 | 2.46 | 0.00 | 4.77 | 0.00 | 3.13 | 0.00 | 6.57 | 0.97 | 2.60 | 0.41 | 5.84 | 0.68 | 3.44 | 0.21 | 8.68 |
| August | 0.00 | 2.21 | 0.00 | 3.45 | 0.00 | 3.16 | 0.00 | 6.79 | 0.99 | 1.85 | 0.90 | 3.69 | 0.56 | 3.51 | 0.17 | 9.00 |
| September | 0.02 | 1.30 | 0.20 | 1.69 | 0.01 | 1.70 | 0.00 | 3.52 | 3.10 | 0.72 | 5.47 | 1.39 | 1.93 | 1.57 | 0.64 | 3.51 |
| October | 0.34 | 0.17 | 0.65 | 0.22 | 0.41 | 0.62 | 0.08 | 1.11 | 11.75 | 0.06 | 16.70 | 0.06 | 12.01 | 0.29 | 4.41 | 0.62 |
| November | 1.19 | 0.02 | 2.54 | 0.06 | 1.50 | 0.21 | 0.26 | 0.39 | 21.78 | 0.00 | 38.35 | 0.01 | 28.74 | 0.02 | 10.17 | 0.14 |
| December | 1.86 | 0.02 | 4.83 | 0.04 | 1.78 | 0.23 | 0.88 | 0.23 | 28.84 | 0.00 | 61.16 | 0.00 | 33.28 | 0.01 | 20.39 | 0.03 |
| **Total (kWh/m2)** | **8.24** | **7.16** | **20.84** | **14.23** | **9.36** | **13.45** | **4.11** | **27.46** | **163.37** | **5.97** | **302.02** | **14.68** | **189.98** | **13.26** | **96.93** | **31.16** |
| **Total Heat. + Cool.** | **15.40** | | **35.07** | | **22.80** | | **31.57** | | **169.35** | | **316.71** | | **203.24** | | **128.09** | |
| **Energy saved by choosing the SH over the MH(%)** | **90.91** | | **88.93** | | **88.78** | | **75.35** | | | | | | | | | |
| **Variation of energy consumption from 2010 to 2050(%)** | **15.15** | | **8.88** | | **17.60** | | **44.04** | | | | | | | | | |

**Table III.8.3.2 – Influence of climate-change temperature on energy consumption**

## III.8.3.3 Influence of solar radiation

| Months of the year | SEAHOUSE (SH) in : | | | | | | | | MINNHOUSE (MH) in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) | Heating (kWh/m$^2$) | Cooling (kWh/m$^2$) |
| January | 2.36 | 0.00 | 6.54 | 0.02 | 2.22 | 0.16 | 2.02 | 0.10 | 33.08 | 0.00 | 78.29 | 0.00 | 38.93 | 0.01 | 33.15 | 0.01 |
| February | 1.26 | 0.11 | 3.92 | 0.04 | 2.24 | 0.08 | 1.23 | 0.13 | 24.12 | 0.01 | 52.12 | 0.00 | 36.54 | 0.01 | 21.95 | 0.07 |
| March | 1.02 | 0.07 | 2.58 | 0.02 | 1.15 | 0.05 | 0.31 | 0.21 | 20.18 | 0.03 | 37.62 | 0.01 | 24.18 | 0.07 | 9.77 | 0.19 |
| April | 0.51 | 0.05 | 1.46 | 0.23 | 1.45 | 0.03 | 0.12 | 0.43 | 13.27 | 0.09 | 225.62 | 0.24 | 23.64 | 0.10 | 4.73 | 0.46 |
| May | 0.21 | 0.15 | 0.16 | 0.58 | 0.20 | 0.37 | 0.01 | 1.41 | 8.03 | 0.18 | 5.74 | 0.50 | 6.35 | 0.41 | 1.45 | 1.20 |
| June | 0.06 | 0.26 | 0.02 | 1.37 | 0.00 | 1.70 | 0.00 | 3.21 | 4.19 | 0.28 | 1.71 | 1.22 | 1.03 | 1.64 | 0.62 | 3.45 |
| July | 0.01 | 1.09 | 0.00 | 2.91 | 0.00 | 1.76 | 0.00 | 4.27 | 1.65 | 1.09 | 0.61 | 3.11 | 1.12 | 1.72 | 0.32 | 5.02 |
| August | 0.01 | 0.93 | 0.01 | 1.65 | 0.00 | 1.64 | 0.00 | 4.46 | 1.83 | 0.74 | 1.42 | 1.42 | 1.00 | 1.68 | 0.25 | 5.14 |
| September | 0.07 | 0.69 | 0.34 | 0.81 | 0.05 | 0.92 | 0.00 | 1.94 | 5.16 | 0.37 | 7.74 | 0.57 | 3.26 | 0.85 | 1.00 | 1.61 |
| October | 0.61 | 0.21 | 1.08 | 0.15 | 0.69 | 0.39 | 0.19 | 0.62 | 15.08 | 0.04 | 22.12 | 0.04 | 16.47 | 0.18 | 6.79 | 0.35 |
| November | 1.47 | 0.01 | 3.18 | 0.04 | 1.92 | 0.16 | 0.44 | 0.27 | 23.71 | 0.00 | 43.97 | 0.00 | 33.20 | 0.01 | 13.56 | 0.11 |
| December | 2.32 | 0.01 | 5.65 | 0.02 | 2.31 | 0.18 | 1.22 | 0.18 | 32.00 | 0.00 | 67.80 | 0.00 | 38.85 | 0.01 | 24.41 | 0.02 |
| **Total (kWh/m2)** | **9.91** | **3.59** | **24.95** | **7.84** | **12.25** | **7.45** | **5.55** | **17.23** | **182.31** | **2.83** | **544.75** | **7.11** | **224.57** | **6.71** | **118.01** | **17.63** |
| **Total Heat. + Cool.** | **13.51** | | **32.79** | | **19.70** | | **22.78** | | **185.14** | | **551.87** | | **231.27** | | **135.64** | |
| **Energy saved by choosing the SH over the MH(%)** | **92.70** | | **94.06** | | **91.48** | | **83.21** | | | | | | | | | |
| **Variation of energy consumption from 2010 to 2050(%)** | **0.98** | | **1.80** | | **1.59** | | **3.93** | | | | | | | | | |

**Table III.8.3.3 – Influence of climate-change solar radiation on energy consumption**

## III.8.3.4 Influence of relative humidity

| Months of the year | SEAHOUSE in : | | | | | | | | MINNHOUSE in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) |
| January | 2.50 | 0.00 | 6.56 | 0.02 | 2.22 | 0.19 | 2.07 | 0.10 | 35.09 | 0.00 | 79.13 | 0.00 | 38.93 | 0.01 | 33.15 | 0.01 |
| February | 1.35 | 0.10 | 3.93 | 0.05 | 2.22 | 0.10 | 1.26 | 0.12 | 25.30 | 0.01 | 52.74 | 0.00 | 36.54 | 0.01 | 21.95 | 0.07 |
| March | 1.10 | 0.07 | 2.55 | 0.03 | 1.16 | 0.06 | 0.33 | 0.18 | 21.65 | 0.03 | 38.08 | 0.01 | 24.18 | 0.07 | 9.77 | 0.19 |
| April | 0.55 | 0.05 | 1.51 | 0.21 | 1.54 | 0.02 | 0.12 | 0.37 | 14.43 | 0.08 | 23.49 | 0.21 | 23.64 | 0.10 | 4.73 | 0.46 |
| May | 0.25 | 0.09 | 0.18 | 0.48 | 0.23 | 0.27 | 0.01 | 1.18 | 9.21 | 0.14 | 6.36 | 0.39 | 6.35 | 0.41 | 1.45 | 1.20 |
| June | 0.09 | 0.16 | 0.03 | 1.11 | 0.00 | 1.28 | 0.00 | 2.68 | 5.25 | 0.19 | 2.03 | 0.91 | 1.03 | 1.64 | 0.62 | 3.45 |
| July | 0.02 | 0.71 | 0.00 | 2.45 | 0.01 | 1.37 | 0.00 | 3.54 | 2.14 | 0.68 | 0.77 | 2.43 | 1.12 | 1.72 | 0.32 | 5.02 |
| August | 0.01 | 0.65 | 0.01 | 1.28 | 0.00 | 1.22 | 0.00 | 3.83 | 2.35 | 0.49 | 1.82 | 0.99 | 1.00 | 1.68 | 0.25 | 5.14 |
| September | 0.09 | 0.53 | 0.38 | 0.66 | 0.05 | 0.86 | 0.00 | 1.80 | 5.95 | 0.27 | 8.71 | 0.43 | 3.26 | 0.85 | 1.00 | 1.61 |
| October | 0.68 | 0.11 | 1.16 | 0.13 | 0.74 | 0.37 | 0.22 | 0.58 | 16.49 | 0.04 | 23.50 | 0.03 | 16.47 | 0.18 | 6.79 | 0.35 |
| November | 1.58 | 0.01 | 3.21 | 0.05 | 1.93 | 0.17 | 0.49 | 0.24 | 25.49 | 0.00 | 45.02 | 0.01 | 33.20 | 0.01 | 13.56 | 0.11 |
| December | 2.40 | 0.02 | 5.67 | 0.03 | 2.32 | 0.20 | 1.28 | 0.17 | 33.78 | 0.00 | 68.97 | 0.00 | 38.85 | 0.01 | 24.41 | 0.02 |
| **Total (kWh/m2)** | **10.61** | **2.49** | **25.20** | **6.49** | **12.42** | **6.10** | **5.78** | **14.77** | **197.13** | **1.94** | **350.64** | **5.41** | **224.57** | **6.71** | **118.01** | **17.63** |
| **Total Heat. + Cool.** | **13.10** | | **31.69** | | **18.51** | | **20.55** | | **199.06** | | **356.05** | | **231.27** | | **135.64** | |
| **Energy saved by choosing the SH over the MH(%)** | **93.42** | | **91.10** | | **92.00** | | **84.85** | | | | | | | | | |
| **Variation of energy consumption from 2010 to 2050(%)** | **-2.08** | | **-1.64** | | **-4.74** | | **-6.67** | | | | | | | | | |

**Table III.8.3.4 – Influence of climate-change relative humidity on energy consumption**

## III.8.3.5 Influence of wind speed

| Months of the year | SEAHOUSE (SH) in : | | | | | | | | MINNHOUSE (MH) in : | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) | Heating ($kWh/m^2$) | Cooling ($kWh/m^2$) |
| January | 2.49 | 0.00 | 6.56 | 0.02 | 2.22 | 0.19 | 2.07 | 0.10 | 35.07 | 0.00 | 79.15 | 0.00 | 39.25 | 0.02 | 34.05 | 0.01 |
| February | 1.35 | 0.10 | 3.94 | 0.05 | 2.22 | 0.10 | 1.26 | 0.13 | 25.29 | 0.01 | 52.78 | 0.00 | 36.83 | 0.01 | 22.50 | 0.06 |
| March | 1.10 | 0.07 | 2.55 | 0.03 | 1.16 | 0.06 | 0.33 | 0.19 | 21.65 | 0.03 | 38.11 | 0.01 | 24.63 | 0.08 | 10.42 | 0.16 |
| April | 0.55 | 0.05 | 1.51 | 0.22 | 1.54 | 0.02 | 0.12 | 0.40 | 14.43 | 0.08 | 23.51 | 0.22 | 25.11 | 0.08 | 5.05 | 0.42 |
| May | 0.25 | 0.10 | 0.18 | 0.51 | 0.23 | 0.31 | 0.01 | 1.25 | 9.21 | 0.14 | 6.36 | 0.41 | 7.06 | 0.33 | 1.75 | 1.01 |
| June | 0.09 | 0.17 | 0.03 | 1.20 | 0.00 | 1.59 | 0.00 | 2.97 | 5.25 | 0.20 | 2.03 | 0.99 | 1.20 | 1.49 | 0.70 | 3.04 |
| July | 0.02 | 0.86 | 0.00 | 2.66 | 0.01 | 1.62 | 0.00 | 3.99 | 2.15 | 0.79 | 0.77 | 2.66 | 1.42 | 1.54 | 0.43 | 4.51 |
| August | 0.02 | 0.74 | 0.01 | 1.42 | 0.00 | 1.50 | 0.00 | 4.19 | 2.35 | 0.55 | 1.82 | 1.10 | 1.25 | 1.45 | 0.33 | 4.61 |
| September | 0.09 | 0.58 | 0.38 | 0.71 | 0.05 | 0.88 | 0.00 | 1.85 | 5.96 | 0.29 | 8.71 | 0.45 | 3.73 | 0.79 | 1.26 | 1.46 |
| October | 0.68 | 0.11 | 1.16 | 0.13 | 0.74 | 0.39 | 0.22 | 0.59 | 16.49 | 0.04 | 23.52 | 0.03 | 17.45 | 0.18 | 7.56 | 0.32 |
| November | 1.58 | 0.01 | 3.22 | 0.05 | 1.93 | 0.17 | 0.49 | 0.24 | 25.48 | 0.00 | 45.03 | 0.01 | 33.78 | 0.01 | 14.64 | 0.09 |
| December | 2.40 | 0.02 | 5.68 | 0.03 | 2.32 | 0.20 | 1.28 | 0.17 | 33.78 | 0.00 | 68.99 | 0.00 | 39.18 | 0.01 | 25.25 | 0.02 |
| **Total (kWh/m2)** | **10.61** | **2.81** | **25.22** | **7.04** | **12.42** | **7.03** | **5.78** | **16.07** | **197.11** | **2.13** | **350.78** | **5.88** | **230.88** | **5.99** | **123.94** | **15.69** |
| **Total Heat. + Cool.** | **13.42** | | **32.26** | | **19.45** | | **21.85** | | **199.25** | | **356.66** | | **236.87** | | **139.63** | |
| **Energy saved by choosing the SH over the MH(%)** | **93.26** | | **90.95** | | **91.79** | | **84.36** | | | | | | | | | |
| **Variation of energy consumption from 2010 to 2050(%)** | **0.34** | | **0.16** | | **0.32** | | **-0.34** | | | | | | | | | |

**Table III.8.3.5 – Influence of climate-change wind speed on energy consumption**

## III.8.4 $CO_2$ emissions of SH

### III.8.4.1 $CO_2$ emissions during 2010

| Months of the year | $CO_2$ emissions (kg $CO_2/m^2$) for: | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEAHOUSE in : (with Geothermal Heatpumps) | | | | | | | | MINNHOUSE in : (with Gas furnace + Electric AC) | | | | | | | |
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling |
| January | 0.41 | 0.00 | 4.61 | 0.01 | 1.99 | 0.17 | 1.25 | 0.06 | 12.95 | 0.00 | 29.24 | 0.00 | 14.51 | 0.02 | 12.57 | 0.00 |
| February | 0.22 | 0.02 | 2.76 | 0.03 | 1.99 | 0.09 | 0.75 | 0.07 | 9.36 | 0.00 | 19.52 | 0.00 | 13.62 | 0.01 | 8.33 | 0.03 |
| March | 0.18 | 0.01 | 1.82 | 0.03 | 1.08 | 0.05 | 0.20 | 0.13 | 8.03 | 0.01 | 14.15 | 0.01 | 9.15 | 0.08 | 3.86 | 0.10 |
| April | 0.09 | 0.01 | 1.05 | 0.14 | 1.32 | 0.02 | 0.08 | 0.24 | 5.34 | 0.01 | 8.70 | 0.13 | 9.13 | 0.09 | 1.87 | 0.25 |
| May | 0.04 | 0.02 | 0.13 | 0.38 | 0.22 | 0.29 | 0.01 | 0.76 | 3.43 | 0.02 | 2.34 | 0.37 | 2.63 | 0.32 | 0.65 | 0.60 |
| June | 0.01 | 0.03 | 0.02 | 0.85 | 0.00 | 1.45 | 0.00 | 1.82 | 1.94 | 0.03 | 0.76 | 0.69 | 0.44 | 1.37 | 0.26 | 1.87 |
| July | 0.00 | 0.14 | 0.00 | 1.88 | 0.00 | 1.44 | 0.00 | 2.41 | 0.80 | 0.12 | 0.28 | 1.87 | 0.52 | 1.35 | 0.16 | 2.71 |
| August | 0.00 | 0.12 | 0.01 | 1.01 | 0.00 | 1.33 | 0.00 | 2.56 | 0.87 | 0.09 | 0.67 | 0.80 | 0.47 | 1.25 | 0.12 | 2.82 |
| September | 0.02 | 0.09 | 0.28 | 0.48 | 0.05 | 0.79 | 0.00 | 1.12 | 2.18 | 0.06 | 3.25 | 0.28 | 1.40 | 0.64 | 0.46 | 0.88 |
| October | 0.11 | 0.02 | 0.82 | 0.08 | 0.65 | 0.35 | 0.14 | 0.36 | 6.12 | 0.01 | 8.66 | 0.03 | 6.43 | 0.15 | 2.80 | 0.17 |
| November | 0.26 | 0.00 | 2.29 | 0.04 | 1.73 | 0.17 | 0.31 | 0.16 | 9.45 | 0.00 | 16.71 | 0.00 | 12.51 | 0.01 | 5.45 | 0.03 |
| December | 0.39 | 0.00 | 3.99 | 0.01 | 2.08 | 0.17 | 0.76 | 0.11 | 12.48 | 0.00 | 25.48 | 0.00 | 14.47 | 0.02 | 9.30 | 0.01 |
| Total 2010 (kg $CO_2/m^2$) | 1.72 | 0.46 | 17.78 | 4.96 | 11.13 | 6.34 | 3.49 | 9.81 | 72.97 | 0.35 | 129.78 | 4.19 | 85.29 | 5.31 | 45.83 | 9.47 |
| Total Heat. + Cool. Emissions | 2.18 | | 22.74 | | 17.47 | | 13.30 | | 73.33 | | 133.97 | | 90.60 | | 55.30 | |
| Emissions saved by choosing SH over MH (%) | 97.03 | | 83.03 | | 80.72 | | 75.94 | | | | | | | | | |

**Table III.8.4.1.1 - $CO_2$ emissions during 2010**

| Months of the year | $CO_2$ emissions (kg $CO_2/m^2$) for: | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SEAHOUSE in : (with Geothermal Heatpumps) | | | | | | | | MINNHOUSE in : (with Gas furnace + Electric AC) | | | | | | | |
| | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | | SEATTLE | | MINNEAPOLIS | | DENVER | | ATLANTA | |
| | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling | Heating | Cooling |
| January | 0.35 | 0.00 | 4.13 | 0.01 | 1.54 | 0.17 | 0.98 | 0.08 | 11.45 | 0.00 | 26.68 | 0.00 | 12.34 | 0.02 | 10.64 | 0.01 |
| February | 0.18 | 0.02 | 2.47 | 0.04 | 1.63 | 0.09 | 0.60 | 0.11 | 8.32 | 0.00 | 17.81 | 0.00 | 11.85 | 0.01 | 7.00 | 0.05 |
| March | 0.14 | 0.01 | 1.44 | 0.02 | 0.76 | 0.07 | 0.10 | 0.25 | 6.64 | 0.01 | 11.90 | 0.01 | 7.43 | 0.09 | 2.45 | 0.18 |
| April | 0.04 | 0.02 | 0.78 | 0.27 | 0.98 | 0.05 | 0.04 | 0.52 | 3.54 | 0.02 | 6.83 | 0.28 | 7.12 | 0.12 | 1.14 | 0.46 |
| May | 0.02 | 0.03 | 0.06 | 0.76 | 0.11 | 0.66 | 0.00 | 1.53 | 2.02 | 0.04 | 1.38 | 0.68 | 1.66 | 0.62 | 0.31 | 1.46 |
| June | 0.00 | 0.09 | 0.00 | 1.72 | 0.00 | 2.44 | 0.00 | 2.77 | 0.81 | 0.08 | 0.36 | 1.80 | 0.19 | 2.65 | 0.15 | 3.45 |
| July | 0.00 | 0.38 | 0.00 | 3.32 | 0.00 | 2.55 | 0.00 | 3.69 | 0.29 | 0.42 | 0.12 | 4.19 | 0.19 | 2.82 | 0.06 | 4.94 |
| August | 0.00 | 0.35 | 0.00 | 2.40 | 0.00 | 2.54 | 0.00 | 3.93 | 0.29 | 0.31 | 0.26 | 2.69 | 0.17 | 2.87 | 0.05 | 5.32 |
| September | 0.00 | 0.21 | 0.12 | 1.23 | 0.01 | 1.56 | 0.00 | 2.16 | 0.98 | 0.13 | 1.76 | 1.07 | 0.61 | 1.48 | 0.19 | 2.24 |
| October | 0.05 | 0.03 | 0.42 | 0.17 | 0.34 | 0.55 | 0.04 | 0.70 | 3.85 | 0.01 | 5.72 | 0.05 | 4.11 | 0.27 | 1.42 | 0.41 |
| November | 0.18 | 0.00 | 1.77 | 0.04 | 1.34 | 0.17 | 0.14 | 0.26 | 7.40 | 0.00 | 13.80 | 0.01 | 10.41 | 0.01 | 3.43 | 0.10 |
| December | 0.29 | 0.00 | 3.40 | 0.02 | 1.59 | 0.19 | 0.50 | 0.14 | 10.01 | 0.00 | 22.20 | 0.00 | 12.18 | 0.01 | 7.25 | 0.02 |
| Total 2010 (kg $CO_2/m^2$) | 1.25 | 1.16 | 14.59 | 10.00 | 8.29 | 11.04 | 2.39 | 16.15 | 55.60 | 1.02 | 108.83 | 10.78 | 68.27 | 10.96 | 34.09 | 18.64 |
| Total Heat. + Cool. Emissions | 2.41 | | 24.59 | | 19.33 | | 18.54 | | 56.62 | | 119.61 | | 79.23 | | 52.74 | |
| Emissions saved by choosing SH over MH (%) | 95.75 | | 79.44 | | 75.60 | | 64.85 | | | | | | | | | |
| Additional emissions when compared to 2010 | 10.36 | | 8.14 | | 10.67 | | 39.34 | | | | | | | | | |

**Table III.8.4.1.2 - $CO_2$ emissions during 2050**

### III.8.4.2 Variation of $CO_2$ emissions

This table corresponds to the variation or trend of $CO_2$ emissions between 2010 and 2050 for the SH design.

| Months of the year | $CO_2$ emissions (kg $CO_2/m^2$) for: | | | |
|---|---|---|---|---|
| | SEAHOUSE in : | | | |
| | SEATTLE | MINNEAPOLIS | DENVER | ATLANTA |
| | Total $CO_2$ emissions | Total $CO_2$ emissions | Total $CO_2$ emissions | Total $CO_2$ emissions |
| January | -0.06 | -0.47 | -0.45 | -0.26 |
| February | -0.04 | -0.28 | -0.37 | -0.12 |
| March | -0.04 | -0.39 | -0.31 | 0.02 |
| April | -0.04 | -0.15 | -0.31 | 0.23 |
| May | -0.01 | 0.31 | 0.26 | 0.76 |
| June | 0.05 | 0.86 | 0.98 | 0.95 |
| July | 0.24 | 1.44 | 1.11 | 1.29 |
| August | 0.22 | 1.38 | 1.21 | 1.38 |
| September | 0.11 | 0.59 | 0.72 | 1.04 |
| October | -0.05 | -0.32 | -0.11 | 0.24 |
| November | -0.08 | -0.53 | -0.39 | -0.07 |
| December | -0.10 | -0.59 | -0.47 | -0.23 |
| **Average variation of $CO_2$ emissions (kg $CO^2/m^2$)** | **0.23** | **1.85** | **1.86** | **5.23** |

**Table III.8.4.2 - Variation of $CO_2$ emissions for SH**