<u>**Ecological Energy Efficient First Home**</u>

Marie-Josée Banville (260534535)
Alexandra Charlton (260481687)
Jessica Miville (260587378)
Charles Urtnowski-Morin (260535783)

McGill University
BREE 495: Design 3
Winter Semester 2016
Dr. Clark

Table of Contents

Executive Summary

This report presents the design of an affordable, ecological first home with a strong emphasis on energy efficiency, as requested by the client. The design makes use of combination of systems found in earth sheltered homes, passive solar homes as well as solar panels. The Revit analysis of the heat transfer through walls and energy consumption determined that it was possible to adhere to our implemented design elements as well as the criteria outlined by the client, though going slightly over budget (by 4.5%) for a total of $208,738. This ensures sufficient lighting in all rooms, 100% of the energy offset by the solar panels (1100 kWh per month), in-floor heating and earth covered walls. The COMSOL results showed that there is a 46% saving in energy using an earth-sheltered Passive house wall compared to a Canadian standard wall. Overall, the design project was deemed a success.

1. Introduction

The original clients behind this design process are Alexandre Banville and Sophie Lacourse who are both of an environmentally friendly mindset and are interested in buying an energy efficient first home together. However, many of the environmentally friendly and energy efficient homes on the market are quite expensive and are therefore beyond their means or are simply too small to meet their needs. As such, a design for an environmentally friendly home with an emphasis on energy efficiency, as well as fulfilling their other criteria was requested. As energy is inexpensive in Quebec and is mainly produced by hydroelectricity, a renewable resource, few homeowners are concerned for the energy efficiency of their homes. However, this may soon change, with the rise in cost of electricity. As such, this design could be an attractive housing option for many who wish to save on their electric bill and would like a small-scale home. Therefore, the goal of this project is to produce a design plan for a home which minimizes the house's electricity use for lighting, heating and appliances.

The goal is to be achieved by calculating the amount of energy released by walls and the roof, and the overall amount of energy needed to power the house, and provide solutions on how to increase insulation during the colder months, while keeping the house cool and ventilated during the summer. Of course there were several criteria raised by the client for this endeavor such as cost, space, location and environmental concern. As our clients have just graduated from university, money is limited and therefore the overall cost of the house must be less than

$200,000, the typical cost for a first home nowadays. The couple is planning on beginning and raising a family in that house therefore there must be enough space for two adults and an infant. This meaning that there must be at least two bedrooms and a big enough living room and dining area. Our clients already own a piece of land that is in the Montreal suburbs of St-Lazare. As such, the house must designed to withstand the Montreal climate and be built for their terrain. All of these criteria must respect the overall goal of making this house energy efficient.

This report is the continuation of the BREE 490: Design 2 course where we looked into already existing energy efficient housing options such as Leadership in Energy and Environmental Design (LEED), passive house, earth sheltered and earth-bermed, as well as ecocapsule homes. Through the evaluation of our client's criteria and heat transfer calculations, it was determined that an earth-bermed house incorporated with passive solar elements for insulation and windows, was the optimal design solution. An earth sheltered home was thought to be too costly for the insulation benefits it provided, especially since the roof could be used for generating energy using solar panels. The ecocapsule design was abandoned as it was thought be too small for our client's family to occupy.

Due to the additional insulation requirements set by the passive house standard, our team considered a geothermal heat pump in order to heat the house, and a wastewater heat recovery system in order to recover otherwise lost heat. It was calculated that approximately 13 500 kWh would be needed for heating and electrical functions of the house per year. With such little energy requirements, it was thought that solar panels could be a long-term economical solution. This report further analyzes the energy consumption using Revit for more precise heat transfer calculations, the economic feasibility of installing solar panels and the overall cost of the design. Several other design considerations are discussed such as proper lighting in all rooms, the materials used for insulation and the basic skeleton structure of the house.

2. Analysis and Specifications

2.1 General Design

The final design seen in Figure 1 very much resembles the design proposed last semester. The bedrooms are situated in the back of the house in order to maximize the amount of sunlight coming into the rooms that are most used, namely the kitchen and the living room. The bathroom is between both the master bedroom (shown as “Bedroom” in Figure 1) and the baby room and centered in the middle of the house. This allows all occupants to have easy access to the bathroom. In order to minimize the amount of noise heard from the office, it was decided that the office should be furthest away from the kitchen. This way the resident working will be able to concentrate on the work at hand even during noisy meal times. The office is also located next to the baby room which allow parents working to hear and easily check up on the child. The baby room is designed to be large enough for child’s room or even a teenager’s room when the baby grows up. A wall between the kitchen and the living room is depicted as this would be the wall supporting the kitchen appliances, such as the stove, stove fan and fridge. Not depicted in Figure 1 are the solar panels on the roof, with the roof at an angle of 45° to maximize solar irradiation which will generate more energy. The plumbing under the floors is not shown either, however it was decided that the house should have in-floor heating, generated by the heat pump that will heat water and distribute it through the floors to heat the entire house.

The home was designed to have as much storage space as can fit in a smaller house. This is shown by the closet by the entrance to the house, the pantry in the corner of the kitchen and the walk-in closet in the bedroom. The walk-in closet, though not a criteria for the design is often sought after by couples when buying a house. As such, it was seen as a design component that the future homeowners would enjoy and it also increases retail value, as 60% of buyers said that they would pay more should a house include a walk-in closet (Weigley, 2013).

As can be seen from the insulation drawn in on the sides and back of the house, the residence is covered in earth, which will increase the amount of heat retained. The front of the house is not covered and has large windows in order to allow the sunlight to light and warm the house. The windows in the living room also double as doors to the patio. This allows the owners to have two entrances to their house and the ability to have fresh air enter the house when it is warm in the summer. The patio design was implemented as Revit did not allow for the addition of larger than normal windows.

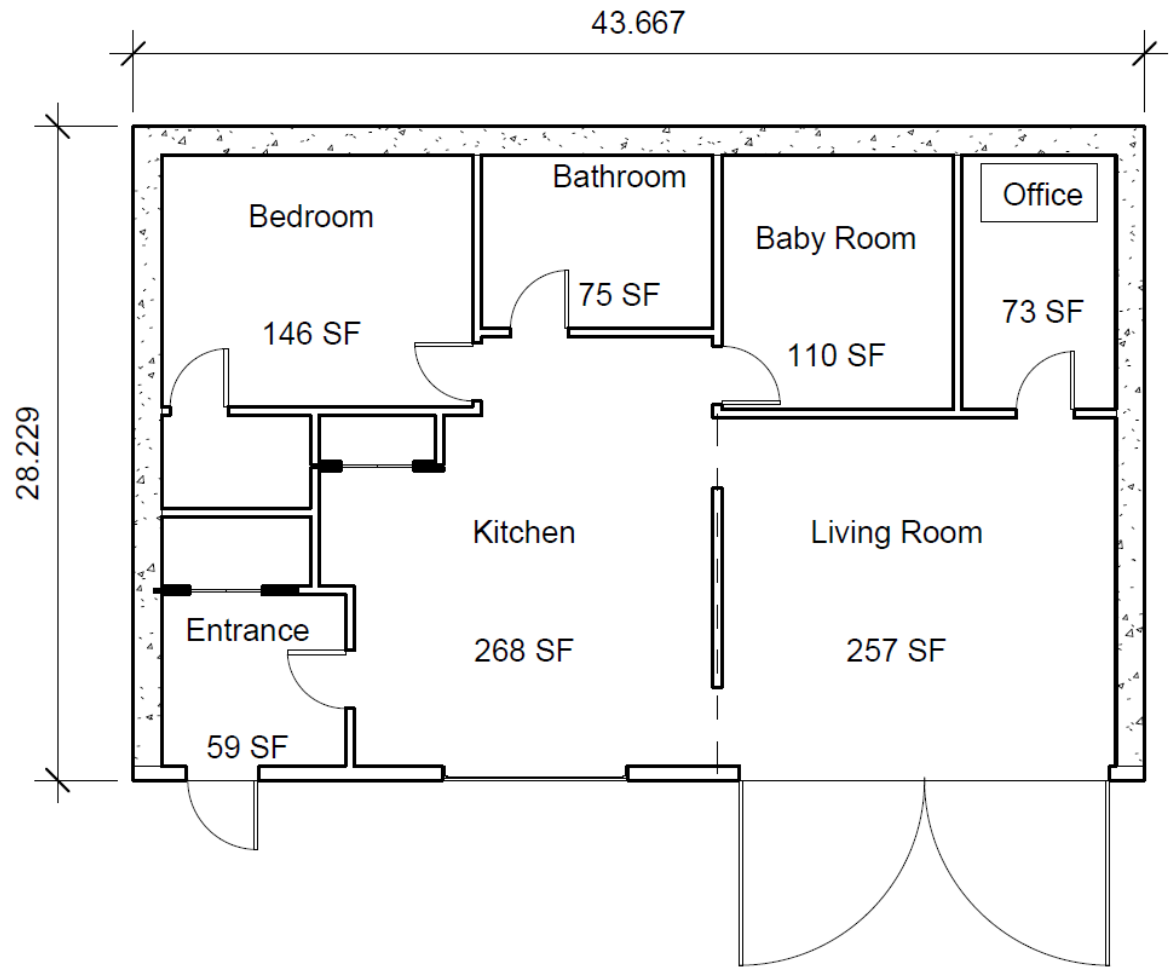


Figure 1: Floor Plan

2.2 Design of Subunits

2.2.1 Solar Panels

In order to get a more precise estimate regarding power generation and cost of solar panels, we contacted Quebec Solar Solutions, a solar panel company established in Montreal. They gave us an estimate cost of $26,000, which includes the cost of materials, installation, and connection to the grid by a master electrician, Hydro Quebec's approval and a structural engineer's approval. With this system is it estimated that 100% of the energy consumption (estimated at 1100 kWh per month) could be offset by the solar panels with a system size of 10.2 KW (39 panels) occupying an area of 64 m^2. It was evaluated that the accumulated electricity bill for the next 15 years would total $28,052 (based on a 5% annual electricity price increase), and as such the solar panels could be paid off in 15 years, 10 years before the manufacturer's warranty expiration at 25 years. It was suggested that a grid-tied system would be better than having a battery stored the energy, as it would be much less expensive and less wasteful since the government of Quebec offers the net metering program. This program allows the input of energy during the day while the sun is out, and the ability to retrieve this energy whenever necessary, such as in the evening. Should more energy be produced than consumed in a given month, a credit is given which can be used to lower the cost of future energy bills, over a period of 24 months. No remuneration will accorded for producing more energy than the household consumes (Bart Wlodarczak, Quebec Solar Solutions, personal communication, March 2016).

As this is will be the homebuyers' first home, the couple may be interested in selling the house in the future. As such, resale value can be an important factor to consider. Research conducted by the Department of Energy in the United States found that buyers are willing to pay more (by about $15,000 for the average 3.6 kW system) for a house with solar panels (Prevost, 2016). Of course these findings are for American households who have higher energy cost and derive most of their energy from non-renewable sources. However we like to believe that the same green mindset applies to those living Quebec towards solar panels. Considering all of these factors, we believe that the implementation of the solar panels would be ideal for power generation due to the savings, the semi-independency of the system and the increase in retail value and salability.

2.2.2 Insulation

The insulation we chose was based on the R value we can obtain with a reasonable thickness, recommendation from the contractor according to standards and experience, and cost. The ceiling of our home is insulated with cellulose that is 14 inch, 3 inches more than the norm in order to achieve the passive solar standard (Banville et al., 2015). As for the exterior walls, we used polyurethane as it is used in basements of high end constructions and offered flexibility to obtain the desired R-value. Since it is sprayed we can easily double the amount applied to the walls (7 inches instead of the usual 3.5 inches applied by Habitation Harmony) and it will fill in cracks and corners to better insulate the home. When it came to insulating the floor, limitations arose due to our decision to include heated floors. We opted for a product from Isolofoam called IsoRad. This is an expanded polystyrene product which is safe to use with hydronic floor heating and has the grooves necessary to maximize insulation once the pipes are installed (Groupe

Isolofoam, 2006). Once again we are doubling the insulation to obtain our R-values obtained in our BREE 490: Design 2 report.

2.3 Cost

Due to the type of project we are undertaking, cost is an extremely important consideration. As stated in the BREE 490: Design 2 report, our goal was to maintain the cost of our project below $200,000. This did not include the lot as our client had already purchased it. The reason for this value was to be able to compete with other options our client might be considering as they purchase their first home.

According to a study conducted by the Bank of Montreal, the average amount spent by home buyers on their first purchase is around $240,000 (BMO Financial Group, 2014). This value included buyers who opted for apartments, condominiums, town houses or houses. We believe that by offering a standalone home that has energy efficient features for a similar price we can satisfy our customer's needs and remain competitive.

In order to assess the costs associated with our design, we relied on a process used by Construction Harmonie in quoting jobs and making a budget for new constructions. To have the most accurate price, we broke down the project into sections. The exact breakdown and relevant information are included in Appendix 1. The first two sections are costs that are deemed as standard for a dwelling of our caliber regardless of energy efficiency. The first includes all the costs entailed before construction actually begins such as the costs for the plans, surveyor, permits, insurance, warranties, and container rentals. This totaled $9,160. Anybody trying to build a house of similar size in a similar are would need to pay this amount to begin their construction (Sylvie Rozon, Habitations Harmonie, vocal communication, January to March 2016). The second was in regard to everything inside the home that has not been modified by our design. These costs would have been equivalent even if our client had opted for a condominium or apartment of equal quality. This included all the standard plumbing and electrical work including fixtures and accessories. In addition we added the cabinetry, flooring and all inside wall components (gypsum and plastering, finishing and painting. This second category totaled $34,100 windows, and lowered cost of labor (Sylvie Rozon, Habitations Harmonie, vocal communication, January to March 2016).

However, the expenses caused by the design decision to make our home earth-bermed were slightly more elevated than usual. The design requires a 28x44x7 cubic feet excavation which alone costs $10,000. Furthermore, we require extra labor, material and pumps for the concrete to build the foundation, footings and slab which add up to $26,725 (Sylvie Rozon, Habitations Harmonie, vocal communication, January to March 2016). Typically, a home with this kind of foundation would have a 3,456 square feet living area spread out on three stories if it were built with a basement and two stories above it. Therefore our decision to surround our design with earth represents a much higher percentage of our total cost. Luckily this decision also allowed for a design with only one face of the house being an exterior wall which requires siding. The cost for the wall covering is $1,800, which is one third of what it would have been had we opted for the standard four-walled home (Sylvie Rozon, Habitations Harmonie, vocal communication, January to March 2016).

Since we wanted to obtain the insulation values of a passive house, we needed to increase our costs. As discussed above, the roof insulation was 1.5 times the cost of that in a normal home and the polyurethane was double the cost. This added $4,000 to our materials and $500 to the roof insulation. Labor is also affected. We will spend a total of $40,814 on all carpentry materials, insulation, roofing materials and all the labor involved in putting the structure of the house together (Sylvie Rozon, Habitations Harmonie, vocal communication, January to March 2016).

The last items to include in our budget are specific to our design. In this category we include the heated floors which cost $8 per square feet, the triple paned windows, the heat pump and the ventilation system. This resulted in an additional $45,356.

The final total cost for our design is $208,738 and this includes a 10% profit in addition to all taxes. This is slightly higher than our initial budget by about 4.5%. However, this budget includes the solar panels, which alleviate cost from future hydroelectricity bills since the solar panels can 100% of the energy requirements.

2.4 Prototyping, Testing, Optimization

In order to visualize and to validate our design, a proper 3-dimensional model of the house was required, along with an energy simulation. Due to its widespread use in architecture and building engineering, we decided to use Autodesk Revit software (2016). COMSOL Multiphysics (2015) and AutoCAD (2016) were also considered, but the limited design that would be possible in COMSOL due to processing capacity limitations and the absence of energy simulator in AutoCAD pushed us towards Revit. Its features include site selection, weather, topography, building materials and systems (HVAC, plumbing, electricity, and appliances) and a detailed energy simulation (solar irradiation, wind, heating and cooling loads, electricity costs, photovoltaic potential). However, to obtain a precise comparison of energy flux between our wall design and a Canadian standard wall, we used COMSOL as well.

2.4.1 Revit drawings and analysis

The first step in Revit prototyping was to draw our revised floor plan, which was designed last term by Banville et al. (2015). The greatest advantage of the Revit software was that it allowed to build the three-dimensional walls directly while drawing the floor plan. This eliminated the need to extrude a two-dimensional shape as would be necessary in AutoCAD. We could add at this stage our windows and doors on the exposed wall as designed last semester (Banville et al., 2015). The height from floor surface to ceiling is 8 feet.

The next step was to draw the roof. In order to meet the optimal angle of 45°, we had initially planned for a cathedral roof design that would please our client, with skylights in the earth-covered rooms. The roof summit would need to be at three-quarters along the length of our side walls, facing south. However, we knew a flat roof would give us a better insulative value, as the surface area would be smaller, at a lower cost. Moreover, The National Building Code of Canada requires every room to have an accessible window with an area of at least 3.8 ft^2 with no dimension less than 15 inches in case of a fire emergency (Seacliff Inspections, 2016). Skylights were thus not allowed. Therefore, we designed a flat ceiling which would be our insulated layer, while the outside roof was strictly structural. We added four windows (one per room) each 1.5 feet high by 3 feet wide. We wanted to keep them small to minimize heat loss on the north side while allowing some light to please the client and to keep our design regulatory. At this stage, our three-dimensional model was complete (see Figure 2).

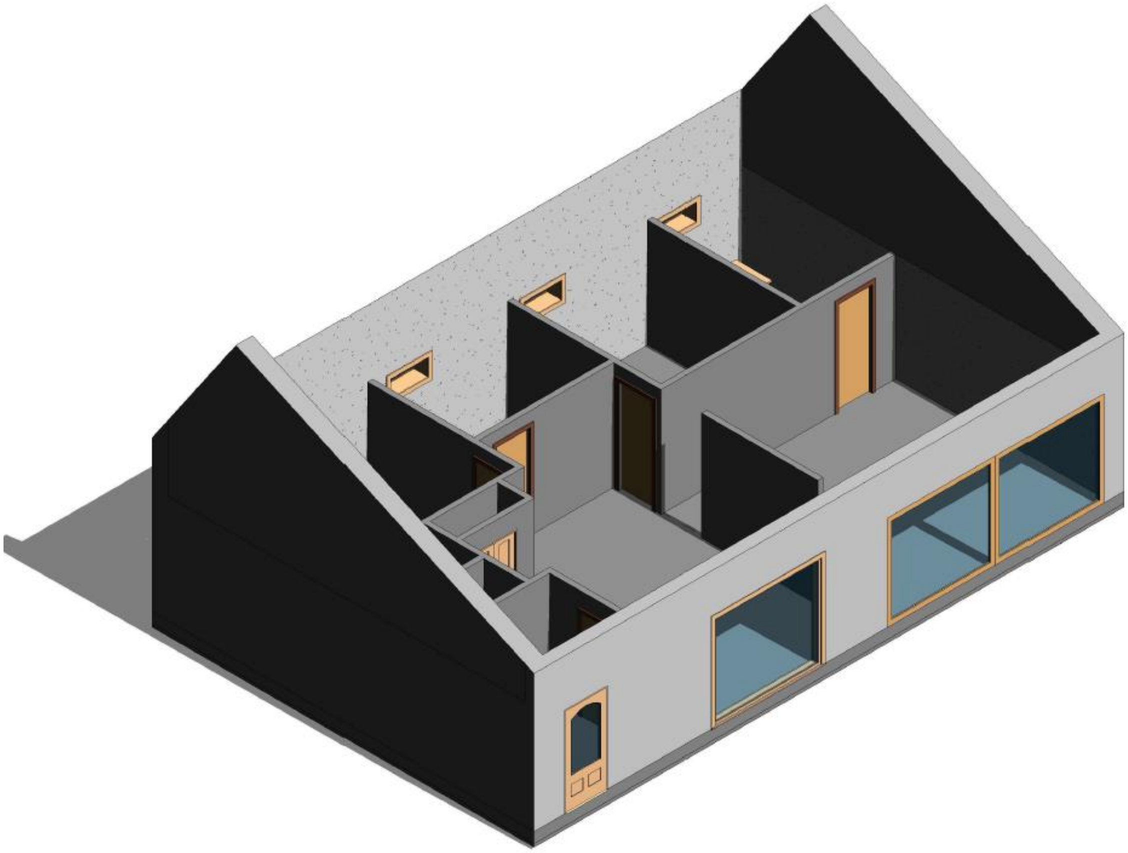


Figure 2: Inside of the House

The next step was then to add our components and layers of insulation, according to Appendix 3. Revit calculates the R-value based on the thermal properties of each layer of material entered. The final R-values are shown in Table 1.

Table 1: Final R-values

Component	R-Value (BTU/(h•°F•ft^2))
Exposed wall	62.5
Earth-covered walls	51.5
Ceiling	69.1
Floor slab	55.0

The following step was to replicate the topography of the purchased lot at the best our knowledge. A constant slope of around 10% is currently what is observed, but the building surrounding will of course be excavated to fit our design of an earth-sheltered house. This allowed us to embed our house into the slope. The earth-covered walls are 6 feet underground, leaving 2 feet exposed for windows and roof overhangs. We were able to add the site location for weather data and sun path for solar irradiation. The latter is particularly important for the solar gain from the windows and solar panels. The whole property is shown in Figure 3.

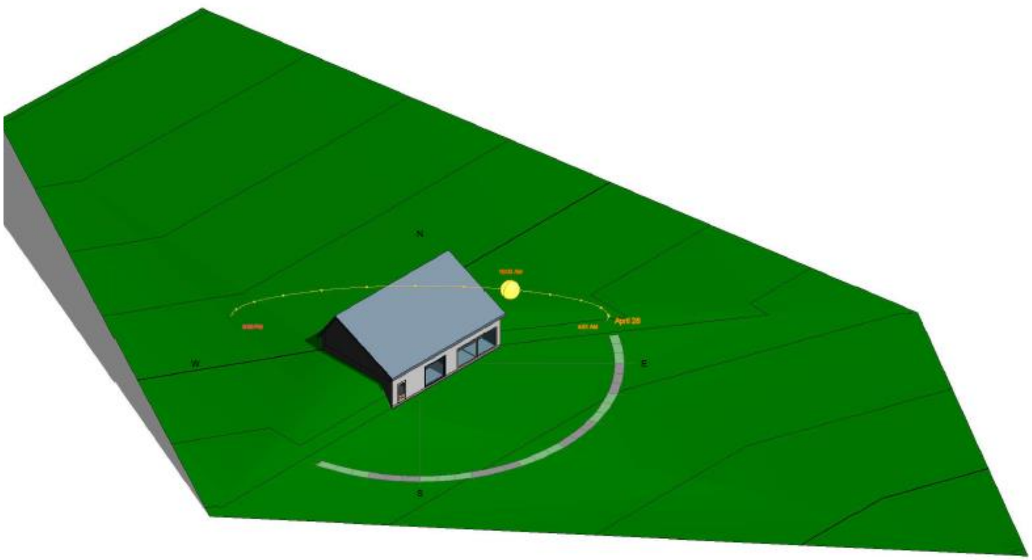


Figure 3: Topography of the Terrain

The final step in the Revit modelling process was the energy simulation. To do so, we had to specify the heating system, the number of people and their occupancy schedules. The other parameters were automatically generated by Revit. A Residential 17 SEER/9.6 HSPF Split HP <5.5 ton heat pump with in-slab heating was chosen, as it was the most efficient and resembled standard geothermal heat pumps' performance (HSPF). The simulation was ran and the results presented in Figures 4, 5, 6. The whole analysis is presented in Appendix 2.

Figure 4 shows the monthly heating load of our design, highlighting the sources of heat losses and gains. We can see that the biggest source of heat loss is the underground surrounding, which was expected since our house is underground. Only a small amount of heat is lost from the walls, roof and windows. However, we expected a greater heat gain from the windows.

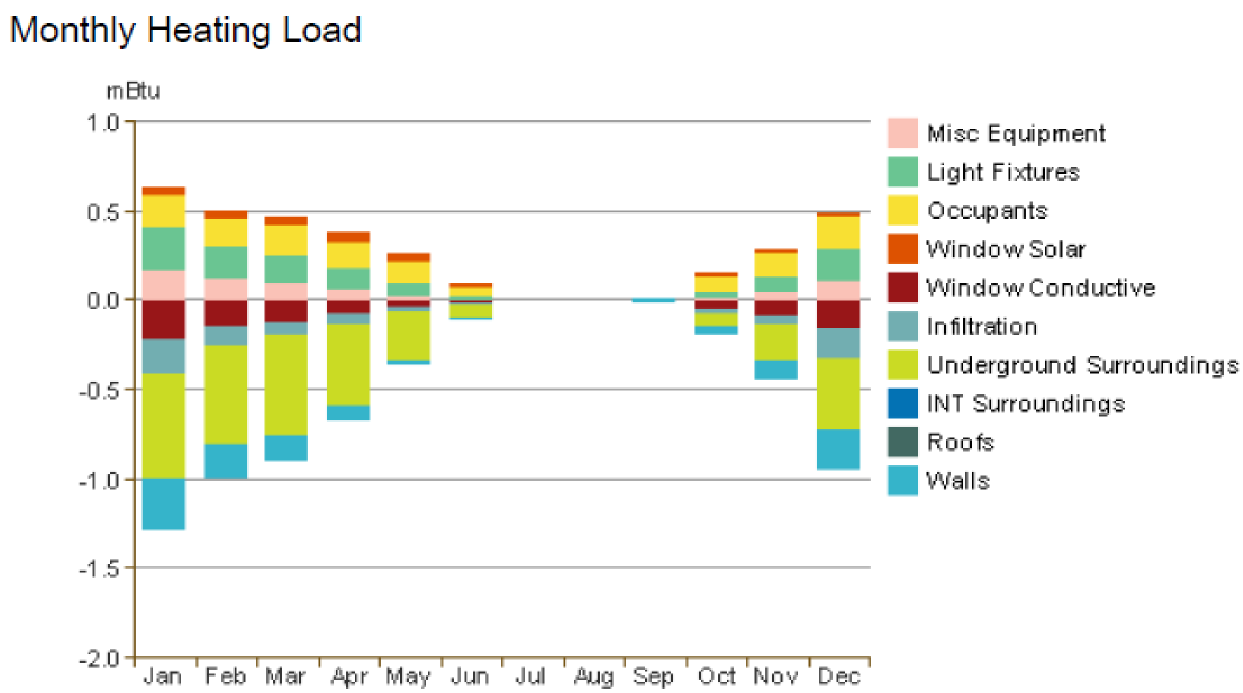
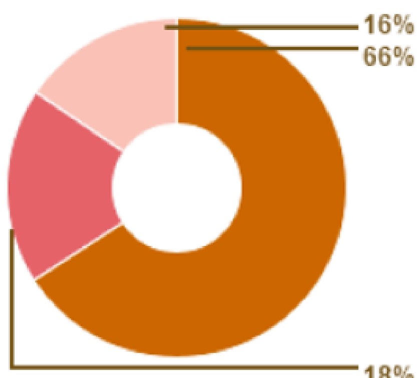


Figure 4: Monthly Heating Load

Figure 5 shows the energy requirements for the HVAC, lighting and miscellaneous equipment. It totaled to 10,306 kWh, with 6,786 kWh for HVAC. According to Revit, at a 6 cents/kWh price, the heating, ventilation and air conditioning costs are $433 per year.



			(kWh)
HVAC	66%	$433	6,786
Lighting	18%	$122	1,920
Misc Equipment	16%	$102	1,600
		$657	10,306

Figure 5: Energy Requirements of the House (Earth-Bermed)

Revit uses solar irradiation data for the selected site in order to calculate the renewable energy potential. A medium efficiency roof-mounted photovoltaic system would be sufficient to meet all of our electricity demands, as shown in Table 2.

Table 2: Renewable Energy Potential

Renewable Energy Potential

Roof Mounted PV System (Low efficiency):	6,261 kWh / yr
Roof Mounted PV System (Medium efficiency):	12,522 kWh / yr
Roof Mounted PV System (High efficiency):	18,783 kWh / yr
Single 15' Wind Turbine Potential:	1,329 kWh / yr
*PV efficiencies are assumed to be 5%, 10% and 15% for low, medium and high efficiency systems	

In order to validate the calculations performed last semester by Banville et al (2015) regarding the advantage of having earth covered walls with regard to lower heat loss, we performed an energy simulation on our model not earth covered. In fact, we simply lowered the topography to the level of the floor slab, exposing all the walls to the outside air. The annual energy requirement is 12 260 kWh (see Figure 6), thus 19% more than for our final design. Although this is a smaller percentage than we previously calculated, it still shows that our design is the most energy efficient.

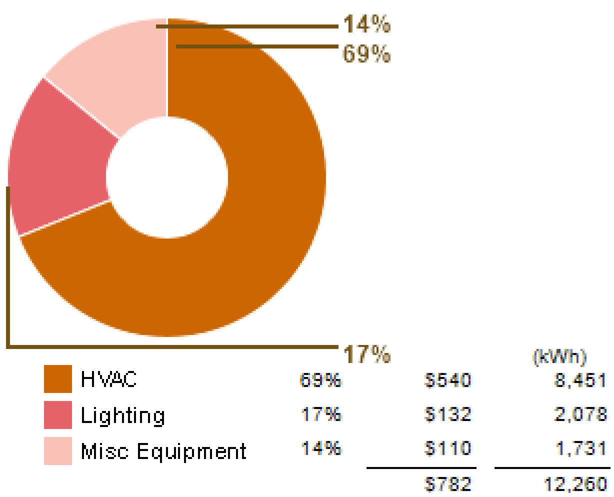


Figure 6: Energy Requirements of the House (Above Ground)

2.4.2 Limitations

Despite our best intentions, there were many features of our design that could not be implemented in Revit exactly as we had designed. Firstly, the heat recovery system we had planned last term could not be added in our model. It was supposed to reduce hot water requirements by 40 to 60% (Banville et al., 2015). In addition, there were no parameters to change the water heating system in Revit, and a system using fuel was automatically used by Revit. No information was available on the efficiency of this system, so no comparison could be made. In fact, our geothermal heat pump will supply the hot water for our house.

Secondly, we had designed for a geothermal heat pump with a COP of 4. On the other hand, Revit did not offer this option. We thus chose a heat pump that had the closest performance factor (HSPF) to at least get similar results for energy consumption.

Thirdly, our student version of Revit did not allow us to add solar panels to our roof. However, we did obtain results for a roof-mounted photovoltaic system, although the occupied area was not given.

Fourthly, we were not able to add larger than normal windows in Revit. As such, the window in the living room became a patio door, allowing access to the outdoors. The windows were necessary in order to adhere to the passive solar window criteria in order to have proper lighting and heating from the sun. As such, the Revit value for heat retention in the house is slightly lower than what it should be since additional heat is lost from the cracks in the patio door that a window would not have.

Lastly, and most importantly, it is unknown to us how Revit performs the energy simulation. In fact, we don’t know how the software accounts for the ground surrounding our walls. For example, Revit calculated that the non-earth-sheltered house required 158 kWh extra for lighting and 131 kWh for miscellaneous equipment, which to us doesn't make much sense. In addition, we do not know if Revit accounts for the temperature distribution in the ground and which temperature it uses. Our calculations had given us a bigger difference between the covered and non-covered walls. Moreover, we had calculated a yearly consumption of 9434 kWh, as compared to 3520 kWh, of electricity for lighting and miscellaneous equipment (Banville et al., 2015). We don't know what is included in these equipment in Revit. We also don't know how it calculated the efficiency of the in-slab heating. Therefore, all these features would require improvements using a more advanced version of Revit.

2.4.3 COMSOL Wall

In order to further assess the efficacy of our design with regards to heat transfer through our walls and to validate our calculations from last term (Banville et al., 2015), we made a computational model using COMSOL Multiphysics (2015) of our exterior wall design versus a standard house exterior wall.

Two different systems are compared in 2 dimensions as transverse sections of the walls. The Canadian standard exterior wall assembly comprises of a standard North American brick siding (194 × 92 × 57 mm) (Wikipedia, 2016), 19 mm air gap, 30 mm polystyrene, 406 mm spaced c.c. 2x6 (38 mm x 140 mm) framing with fiberglass insulation, 19 mm air gap, followed by a 13 mm gypsum board. The second system comprises of earth (300 mm thick earth for the purpose of the model), 203 mm thick concrete, 406 mm spaced c.c. 2x6 (38 mm x 140 mm) framing with polyurethane insulation, 19 mm air gap, followed by a 13 mm gypsum board. The earth-sheltered passive house wall has a greater insulation value and a smaller temperature difference across the wall. The extent to which this translates to heat savings is to be determined.

In this simulation, we first tested the temperature distributions across the various wall components of an earth-sheltered passive house wall and a standard Canadian wall to see the effect of the difference in insulation and outside temperature. In addition, we tested for the temperature distributions in the x-axis (along the length of the wall), and we wanted to see how the 2x6 studs in the wall serve as thermal bridges. The temperature distribution in a Canadian standard wall is shown in Figure 7. We can see that the fiberglass batts show the greatest temperature distribution, around 15°C, meaning it offers the greatest insulative value. This was expected. In addition, the air gap shows a temperature variation of 5°C in only ¾ inch (19 mm) thick, adding a great insulative value to the design. However, the 2x6 studs showed only slightly warmer temperatures along the y-axis (across the wall) and thus act only as a slight thermal bridge. This is due to the lower than expected thermal conductivity of spruce wood. On the other hand, the majority of the temperature differences in the passive house design occur in the polyurethane insulation layer, as shown in Figure 8.

Note: The exact properties of the materials used are described in Appendix 3 in that specific order.

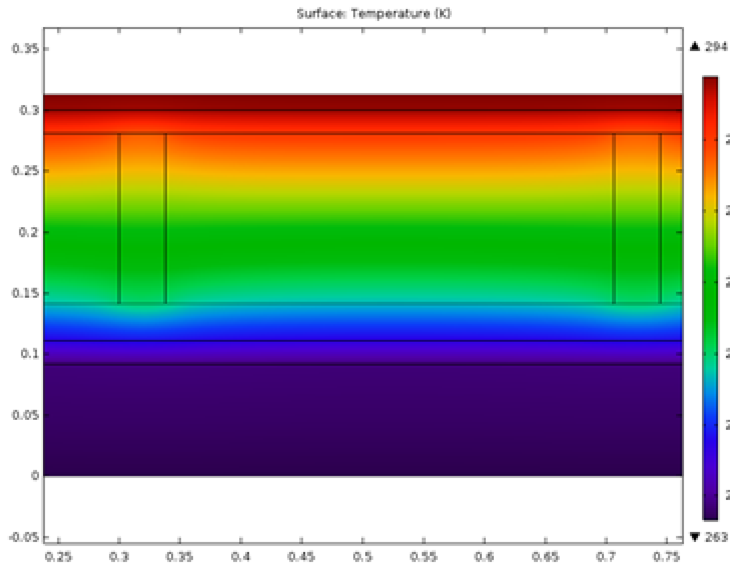


Figure 7: Temperature Distribution through a Canadian Standard Exterior Wall Assembly

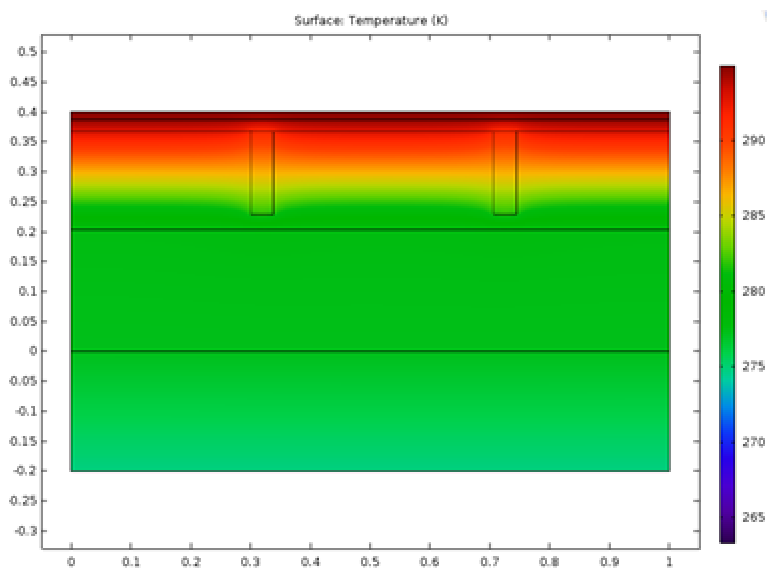


Figure 8: Temperature Distribution through an Earth-Sheltered Passive Wall Assembly

We were also able to obtain the heat flux through the walls as shown in Table 3 below:

Table 3: Heat Flux Results

Model	Heat flux along y-axis (W/m^2)
Passive earth-sheltered wall	-2.5064
Canadian standard wall	-5.4333

This represents a 46% saving in energy using an earth-sheltered Passive house wall compared to a Canadian standard wall. However, calculations from last term had estimated a 75% reduction in heat flux (Banville et al., 2015). These observations serve to, at least in part, validate our model.

2.5 Risk Assessment

As with every design, there are risks involved, and in order to mitigate these risks to ensure safety for the future inhabitants and protect ourselves from a lawsuit, a risk assessment was conducted. The following is a Failure Modes and Effect Analysis (FMEA), followed by a Fault Tree Analysis (FTA). Since our design is large and will be built to follow the Quebec Building Code, the risk assessment below only includes components that would not be seen in a typical household such as solar panels, earth-bermed walls and passive solar windows and insulation.

FMEA

The FMEA is an analysis of what faulty equipment could eventually cause should they break or malfunction. In the case of our house, as it is a big system, many things have the possibility of failing. For example, the walls may collapse inward due to the force of the earth acting upon them, which can utterly destroy the foundations, the house, the belongings of those in the house and injure or cause loss of life. The walls may also crack and allow moisture to enter, which can lead to rotting and cause the same issues as previously listed, as well as cause illness due to the mold. Cracks in walls can also allow vermin to infest the household, which can cause disease, destruction of property and power outages should the electrical wiring be affected all of which is costly to the homeowner. Similarly, should moisture attain the insulation, this can commence rotting and should there be an infestation, could be eaten away. The insulation can also fail to provide proper insulation, which would drive up the cost of the hydroelectricity bill. The solar panels can also cause issues should they fail to produce electricity. This would increase the cost of the hydroelectricity bill, defeating the purpose of installing the solar panels in the first place. They could also potentially be a fire hazard due to electrical wiring failures or debris in the hot sun catching fire due to the heat produced by the panels and setting the rest of the house on fire. A geothermal heat pump was installed in the household in order to heat the house. As this is not a usual occurrence, one must be aware that it could explode if it is overheated or a defective unit; stop functioning altogether, leaving the house unheated, which could cause the pipes the freeze and burst causing serious damage. The passive solar windows need to be properly sealed in order to keep the heat from escaping, especially during the winter, otherwise this will increase the hydroelectricity bill the homeowners will have to pay. Finally, the in-slab heating could potentially leak, which would be expensive to renovate or not function, which would pose a serious threat to the homeowners' safety should this happen during the winter.

FTA

The FTA is an analysis of possible catastrophes that can occur and what events can lead up to these disasters. Foundation wall collapse can arise due to the formation of cracks or rot in the walls or uneven weight distribution, such as the earth pushing against the walls creating an uneven load distribution. Water infiltration can also occur due to cracks in the wall, as well as improper drainage or irrigation or pipes suddenly bursting. Moisture retention on the other hand can be caused by improper material choice and failure of the ventilation system. Cracked windows can happen due to manufacture defects, improper installation and insulation or an extreme event, such as an extreme hail storm. A cold home could be due to improper calculations on our part as to how much insulation is appropriate. Freezing pipes, heat pump and solar panel failure can be caused by power outages (the sun as a source of power for the solar panels) or manufacturer's defect.

2.6 Results and Conclusions

The analysis from Revit demonstrate that for $208,738 (4.5% over budget) it is possible to include our chosen design elements and meet the criteria and constraints outlined by the client. The result is a unique energy efficient home characterized by its earth covered walls, large passive solar windows, solar panels to generate energy and in-floor heating. There is sufficient lighting in all rooms and electricity supplied by the solar panels to meet all of the energy requirements of 1100 kWh per month. The COMSOL results showed that there is a 46% saving in energy using an earth-sheltered Passive house wall compared to a Canadian standard wall, which means that though an earth sheltered house is expensive upfront, it saves on cost in the long run. The solar panels also represent an upfront cost that makes it less expensive for the owners in the long run with a payback period on the solar panels of 15 years and a manufacturer warranty of 10 years, potentially meaning 10 years of “free” energy. Of course there are limitations to what we have found using Revit. We were unable to add the heat recovery system we had decided upon last semester and were unable to determine how Revit calculated its energy simulation calculations for both the heat transfer through the walls and the energy consumed by household appliances. Therefore for future considerations regarding this design several models could be used to simulate what the others are lacking or an actual full-size prototype of our design on which we could do further tests.

There are possibly several risks outlined by our design but following the building code and having our design revised by a contractor ensures that our design mitigated as many of these risks as possible. As such, it can be said that our design was a success despite slightly going over budget. Of course, one of the reasons we went over budget was for the profit margin that we would be making as engineers providing this service. Adding the profit margin to the upfront costs of the solar panels, additional costs of insulation for the passive solar aspect and the earth-sheltered walls, the slight increase in price is a reasonable and a lucrative investment.

Acknowledgements

Acknowledgements to our mentor Sylvie Rozon, a contractor at Habitations Harmonie for aiding us with our project.

References

ASHRAE. 2013. Heat, air, and moisture control in building assemblies - Material properties. *ASHRAE handbook of fundamentals.*

AutoCAD. 2016. *Autodesk AutoCAD 2016.* San Rafael, CA: Autodesk Inc.

Bank of Montreal Financial Group. 2014. BMO Home Buying Report: First-Time Buyers' Budgets Increase to $316,100 While Rising Prices Cause Delays. Available at: https://newsroom.bmo.com/press-releases/bmo-home-buying-report-first-time-buyers-budgets-tsx-bmo-201403180933880001. Accessed April 14 2016.

Banville, M. J., A. Charlton, J. Miville, C. Urtnowski-Morin. 2016. Your Energy Efficient First Home. Ste Anne-de-Bellevue, Quebec.: McGill University, Department of Bioresouce Engineering.

COMSOL. 2015. *COMSOL Multiphysics version 5.2*. Burlington, MA: COMSOL Inc.

Engineering Toolbox. 2016. Thermal Conductivity of Materials and Gases. Available at http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html. Accessed on 14 April 2016.

Groupe Isolofoam. 2016. Isorad: Isolation Pour Plancher Radiant Hydronique. Available at http://www.isolofoam.com/francais/isorad. Accessed 14 April 2016.

Prevost, L. 2015. Appraising Solar Energy's Value. New York City, New York.: New York Times. Available at: http://www.nytimes.com/2015/02/22/realestate/solar-panels-and-home-values.html?_r=1. Accessed 14 April 2016.

Revit. 2016. *Autodesk Revit 2016*. San Rafael, CA: Autodesk Inc.

Seacliff Inspections. 2016. Emergency Egress Window Requirements for Bedrooms. Available at: http://www.seacliffhomeinspections.com/egress.php. Accessed 14 April 2016.

Weigley, S. 2013. 11 Features Buyers Will Pay Extra For. USA Today. Available at: http://www.usatoday.com/story/money/personalfinance/2013/04/28/24-7-home-features/2106203/. Accessed 14 April 2016.

Wikipedia. 2016. Brick. Available at: https://en.wikipedia.org/wiki/Brick. Accessed 1 April 2016.

Appendices

Appendix 1: Detailed Budget

Budgetary costing for construction of Eco house

All costs were estimated in collaboration with Habitations Harmonie inc. using previous quotes and estimates by comparing budgets for previous similar constructions.

Plans	**$ 2,000**
Surveyor	**$ 1,250**
Plot plan, piqueting lot, certificate of location	
Permits	**$ 750**
Tree cutting, septic system, construction	
Insurance	**$ 775**
Construction site insurance for theft, vandalism, civil responsibility	
« New Home » Warranty	**$ 2,385**
Costs to register the building with the GCR and inspection costs for 1 year	
Wood Cutting	**$ 800**
Excavation	**$10, 000**
Digging and back fill of foundation and slab 44x28x7 c.f	
Connection to city water and rain water city pipes,	
3 bedroom standard septic system	
Installation of french drain	
10 loads of sand to be removed ($1,150)	
Copper Coil & SDR	**$ 500**
Foundation	**$ 4,000**
30''x10' footing (4 sides)	
9'0'' x 8''walls on 3 sides	

2 x ½''metal rods in footing and 5 in walls

Cement for foundation and footings **$ 3,750**

20mpa +25 MPa with air

2 Pumps (for the foundation) **$ 1,000**

Stone slinging **$ 1,300**

Tarring **$ 1,000**

Container (40yd) (2) **$ 1500**

Roof Trusses **$ 3,000**

Based on trusses 10.5' high and 28' long with ¼- ¾ dimensions

Materials (loose) **$23 064**

Estimated in comparison with 5 other jobs of small houses.

For Interior walls, 1 exterior wall (not pre-fab), all vapour barriers, gypsum, plywood, all wood materials, loose insulation, steel rods for foundation, polystyrene insulation, 2x6s, polyurethane at 3.50$ per square feet for 3.5 inches thickness.

Rough carpentry **$ 7,000**

Building front wall, inside walls, installing trusses and plywood, framing, shower and tub, window/door/skylight installation, insulation of foundation walls from top to the footing with isofoil (add 1000).

Cimentier pouring and levelling of the slab (labour) **$1,500**

Cement (for slab) **$ 1,875**

25 MPa as per construction code

Pump (for slab) **$ 800**

Roofer **$6,450**

Labour and material (Asphalt shingle lifetime warranty, Ice water shield on complete surface, 1 large Maximum, 1 plumbing vent)

Roof cellulose insulation **$ 1478.40**

Door and windows **$5,500**

Front metal insulated door, one 8x7 double patio door, one quadruple patio door, all triple paned.

3 (2x3) skylights

Plumbing **$ 5,600**

Pex & ABS. water and drain pipes

60 gallon electrical water heater ($800 installer)

Submersible sump pump and pit

1 exterior water outlets.

Installation of the following fixtures;

Plumbing accessories **$ 1,500**

Main bathroom

1 sinks

1 faucets.

1 toilet

1 bath (alcove)

Bath/Shower faucet on adjustable rail

Kitchen

One double stainless above counter

Pull out faucet stock

Electricity **$5,000**

200 amps entry wired as per code for plugs and switches

LED Pot lighting (10)

Ventilation **$2,000**

High end air exchanger and heat recovery system

Bathroom fans, kitchen fan and dryer duct

Exterior finishing	**$ 1,800**
Back wall (44 l.ft x 9 high) double 5 Genteck vinyl	
Cabinetry	**$ 8,000**
Kitchen	
Bathroom vanity	
Gypsum and plastering	**$ 3,600**
Ceramics and vinyl flooring (materials & labour)	**$ 6,400**
Bathroom ceramics $8/sq ft	
Vynil flooring everywhere else $5/sq.ft	
Finition /Boiseries mat & labour	**$ 4,000**
Interior doors (9), baseboards, frames, quarter rounds, closet shelves	
Painting	**$ 3,400**
1 primer + 2 coats of Sico Expert paint on main floor	
Eavesthroughs	**$ 800**
Solar Pannels	**$ 26 000**
Heated Floors	**$ 9856**
Heat pump	**$ 4000**
Parging	**$ 700**
Total House	**$164 333.40**
Profit and Admin. 10%	**16 433.34**
TPS	**$9038.34**
TVQ	**$18 933.06**
Total	**$208 738.10**

Appendix 2: Energy Analysis from Revit

Energy Analysis Report

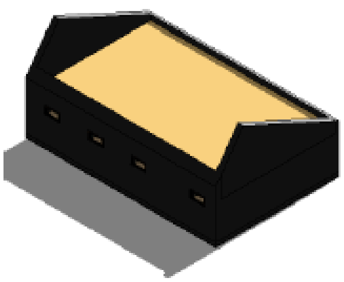
AUTODESK.

Mure avec extra insulation

Mur avec extra insulation

Analyzed at 4/11/2016 11:28:17 AM

Energy Analysis Result



Building Performance Factors

Location:	Rue du Salerne, St-Lazare, QC J7T, Canada
Weather Station:	49670
Outdoor Temperature:	Max: 90°F/Min: -26°F
Floor Area:	1,005 sf
Exterior Wall Area:	1,243 sf
Average Lighting Power:	0.80 W / ft²
People:	2 people
Exterior Window Ratio:	0.06
Electrical Cost:	$0.06 / kWh
Fuel Cost:	$0.69 / Therm

Energy Use Intensity

Electricity EUI:	12 kWh / sf / yr
Fuel EUI:	21 kBtu / sf / yr
Total EUI:	61 kBtu / sf / yr

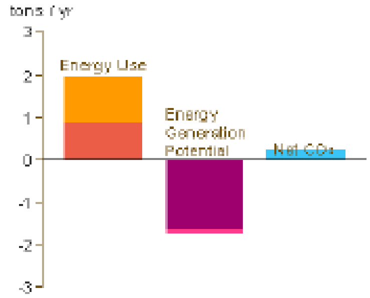
Life Cycle Energy Use/Cost

Life Cycle Electricity Use:	309,217 kWh
Life Cycle Fuel Use:	5,600 Therms
Life Cycle Energy Cost:	$10,714
*30-year life and 6.1% discount rate for costs	

Renewable Energy Potential

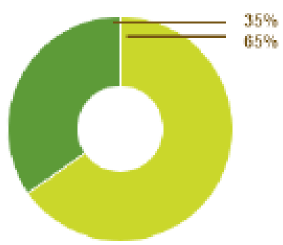
Roof Mounted PV System (Low efficiency):	6,261 kWh / yr
Roof Mounted PV System (Medium efficiency):	12,522 kWh / yr
Roof Mounted PV System (High efficiency):	18,783 kWh / yr
Single 15' Wind Turbine Potential:	1,329 kWh / yr
*PV efficiencies are assumed to be 5%, 10% and 15% for low, medium and high efficiency systems	

Annual Carbon Emissions



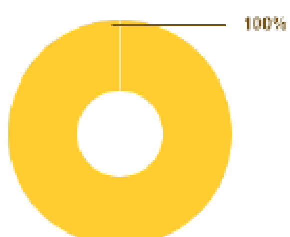
	(tons / yr)
Electricity Consumption	0
Fuel Consumption	1
Roof PV Potential (High Efficiency)	-1
Single 15' Wind Turbine Potential	0
Net CO_2	0

Annual Energy Use/Cost



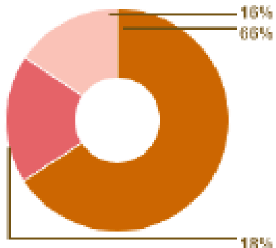
Electricity	65%	$659	10,307	kWh
Fuel	35%	$128	186	Therms
		$787		

Energy Use: Fuel



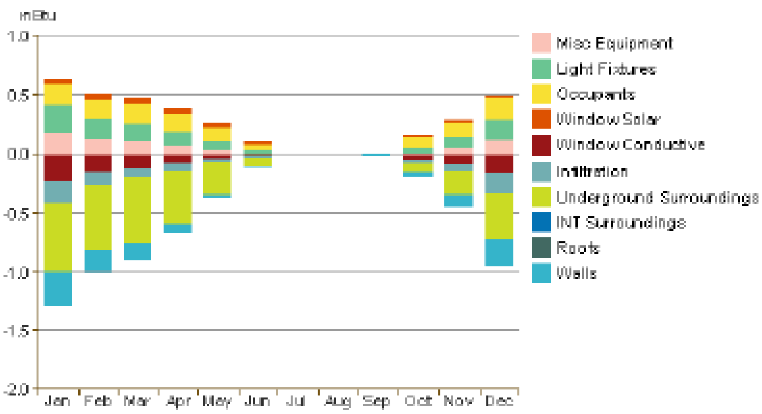
			(Therms)
HVAC	0%	$0	0
Domestic Hot Water	100%	$127	186
		$127	186

Energy Use: Electricity

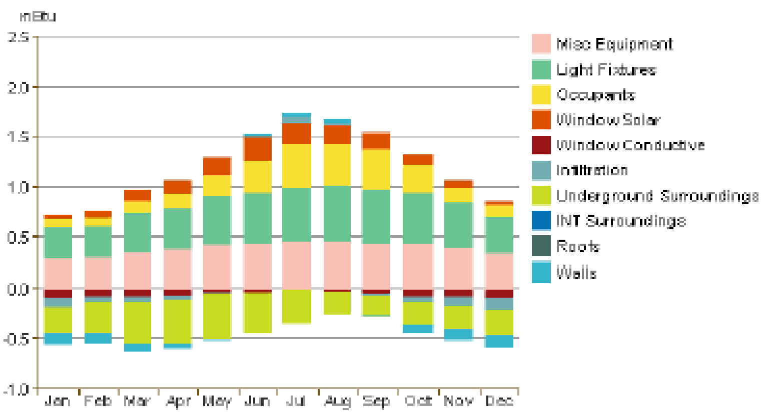


			(kWh)
HVAC	66%	$433	6,780
Lighting	18%	$122	1,920
Misc Equipment	16%	$102	1,600
		$657	10,300

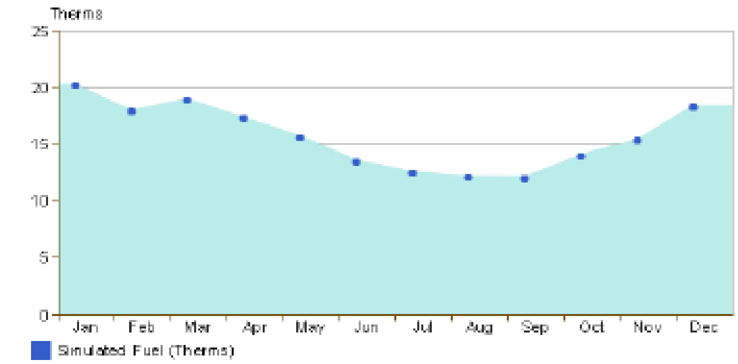
Monthly Heating Load



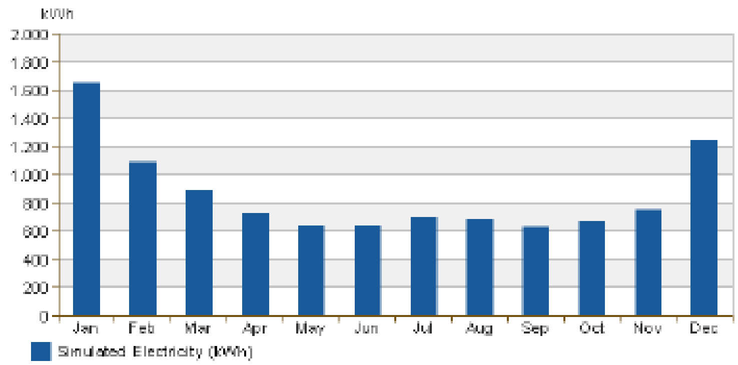
Monthly Cooling Load



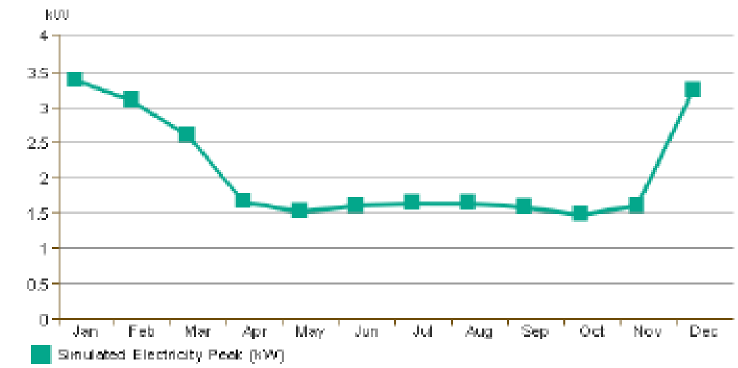
Monthly Fuel Consumption



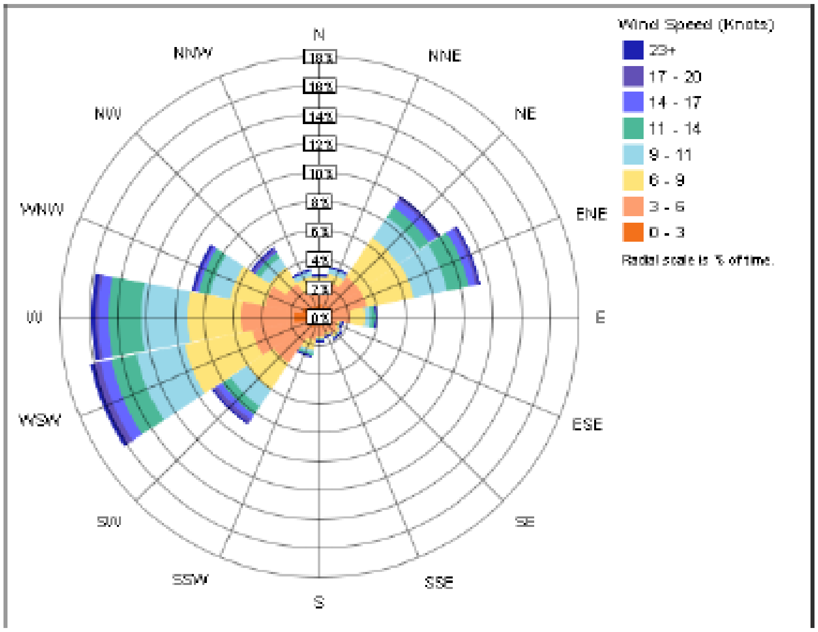
Monthly Electricity Consumption



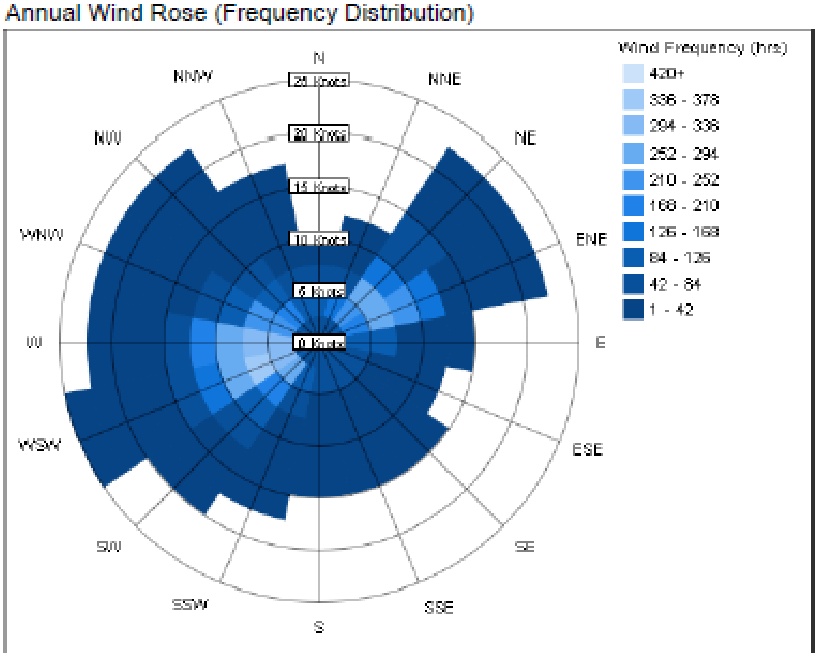
Monthly Peak Demand



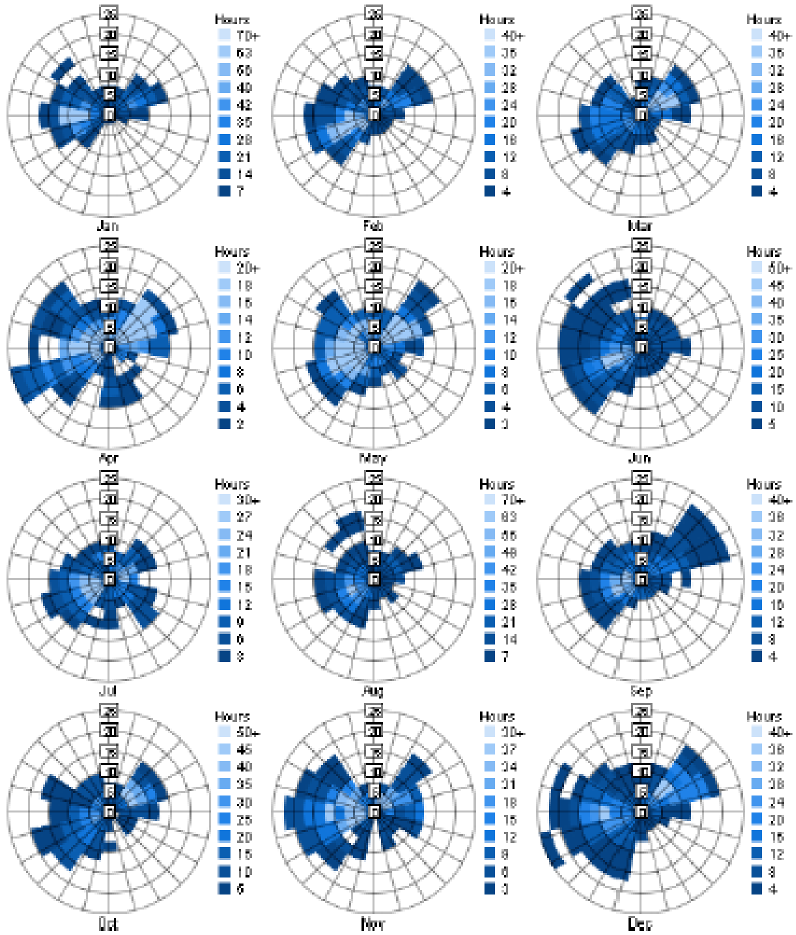
Annual Wind Rose (Speed Distribution)



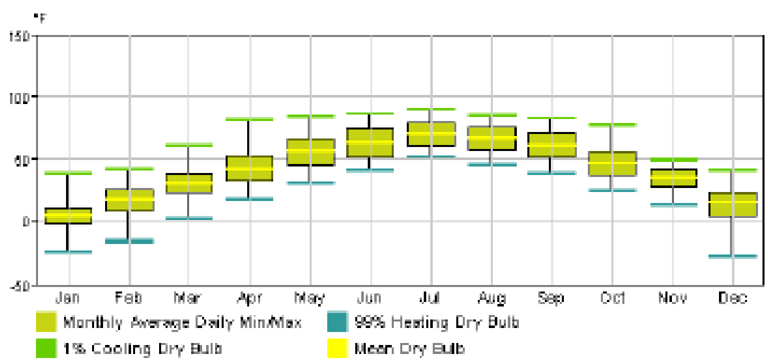
Annual Wind Rose (Frequency Distribution)



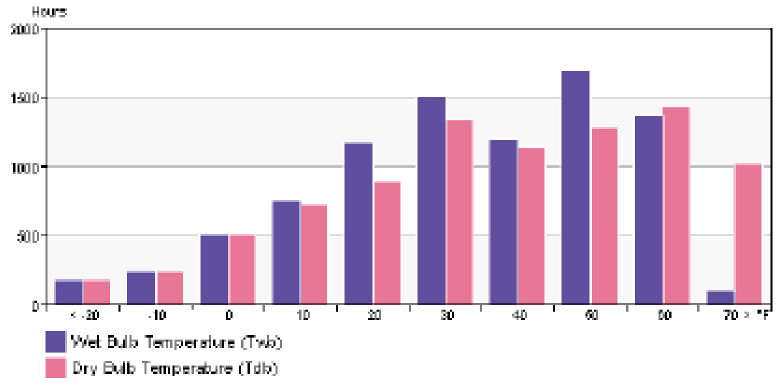
Monthly Wind Roses



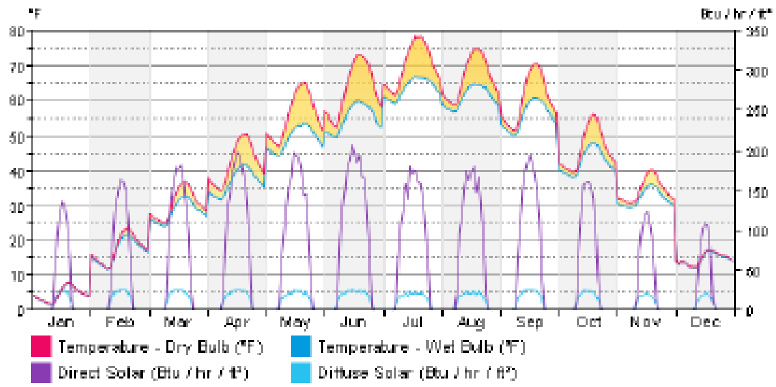
Monthly Design Data



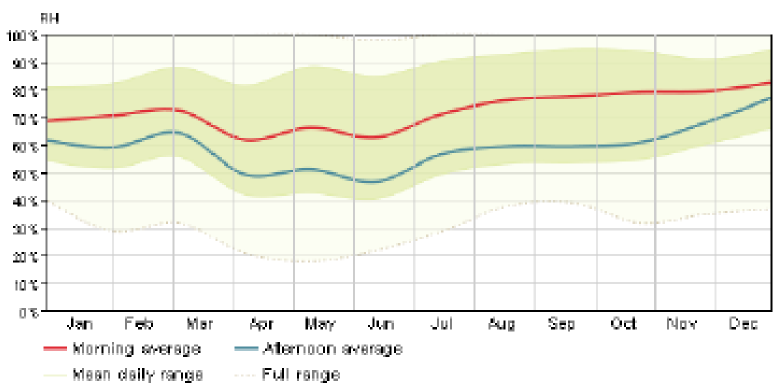
Annual Temperature Bins



Diurnal Weather Averages



Humidity



Energy Analysis Data

Appendix 3: Components in Wall Models

Table 4: Components of a standard exterior wall and the properties used in the COMSOL and Revit models.

Component	Height (m)	Width (m)	k (W/mK)	rho (kg/m³)	Cp (J/kgK)	Sources
1.Gypsum	0.0127	1	0.16	640	1.15	(ASHRAE 2013)
2. Air	0.0191	1	k(T[1/K])	(T[1/K])	C_p(T[1/K])	(COMSOL, 2015a)
3. 2x6 Wood	0.1397	0.0381	0.09	400	1.63	(ASHRAE 2013)
4. Fiberglass batts	0.1397	1	0.043	10	0.8	(ASHRAE 2013)
5. Polysterene	0.0302	1	0.034	29	1.5	(ASHRAE 2013)
6. Air	0.0191	1	k(T[1/K])	(T[1/K])	C_p(T[1/K])	(COMSOL, 2015a)
7. Brick	0.092	1	0.5	2000	900	(COMSOL, 2015a)

Table 5: Components of our passive earth-bermed wall design and their properties used in the COMSOL and Revit models.

Component	Height (m)	Width (m)	k (W/mK)	(kg/m³)	Cp (J/kgK)	Sources
1.Gypsum	0.0127	1	0.16	640	1.15	(ASHRAE 2013)
2. Air	0.0191	1	k(T[1/K])	(T[1/K])	C_p(T[1/K])	(COMSOL, 2015a)
3. 2x6 Wood	0.1397	0.0381	0.09	400	1.63	(ASHRAE 2013)
4. Urethane	0.1651	1	0.024	30	1.5	(ASHRAE 2013)
5. Concrete	0.2032	1	1.8	2300	880	(ASHRAE 2013)
6. Earth (sand)	0.2000	1	0.2	1300	1100	(Engineering Toolbox, 2016)