FINAL GREEN BUILDING DESIGN PROJECT REPORT

FOR ENVE 4105 – GREEN BUILDING DESIGN [PROFESSOR O'BRIEN]

l to btm	# of panels w to btm	Area l to btm	Area w to btm	best	total KWH striking panels	KWI
9	6	44.001036	39.112032	44.001036	65811.31175	
9	6	44.001036	39.112032	44.001036	65811.31175	
8	5	39.112032	32.59336	39.112032	58498.94378	
8	5	39.112032	32.59336	39.112032	58498.94378	
7	5	34.223028	32.59336	34.223028	51186.5758	
7	4	34.223028	26.074688	34.223028	51186.5758	
6	4	29.334024	26.074688	29.334024	43874.20783	

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TABLE OF CONTENTS

DISTRIBUTION OF WORK

PROJECT COMPONENT	LEAD TEAM MEMBER	SUPPORT TEAM MEMBER
FINAL REPORT		
1 - Introduction	Julia Dalphy	Arlin Otto
2 – Problem Definition	Julia Dalphy	Arlin Otto
3 – Sketch Design	Julia Dalphy	Max St-Jacques
4 – Detailed Design		
Design Strategies & Integrated Design	Max St-Jacques	All
Building Envelope	Julia Dalphy & Arlin Otto	Isabelle Kosteniuk
HVAC	Isabelle Kosteniuk	Julia Dalphy & Arlin Otto
Daylighting & Lighting Systems	Yazan Zafar	Arlin Otto
Solar Energy System	Simon Buckley	Max St-Jacques
Additional Considerations		
Indoor Environment Quality (Thermal & Acoustic Comfort)	Isabelle Kosteniuk	Yazan Zafar
Indoor Environment Quality (Visual Comfort)	Yazan Zafar	Isabelle Kosteniuk
Interior Design	Max St-Jacques	Yazan Zafar
Material Selection for Low Enviro Impact	Arlin Otto	Julia Dalphy
Occupant Behavior & Engagement	Simon Buckley	Max St-Jacques
5 - Conclusion	Julia Dalphy	Arlin Otto
Final Compilation & Formatting	Julia Dalphy	Arlin Otto
Final Review & Editing	Arlin Otto	All
FINAL PRESENTATION		
Slide Content	All	
PPT Compilation & Formatting	Julia Dalphy	Arlin Otto
PPT Review & Editing	Arlin Otto	All
Presentation to Class	All	

1.0 INTRODUCTION

Through an integrated, iterative, and prescriptive approach, it was possible to design a net-positive three-storey townhouse-style building in Ottawa—in just one short semester. This report serves to explain how.

Guided by key constraints and a clear objective, the team was first able to first review the relevant ASHRAE standards to get an idea of minimum code compliance requirements. Then, Climate Consultant software helped kick-start the project and guided massing and passive design decision. Daylighting & lighting systems and the solar energy system were then balanced, to optimize roof space and shading with natural lighting and solar gains, when needed. An iterative process was taken with the building envelope and HVAC system to strike the right balance of wall thickness and thermal performance. Finally, the system could be modelled to determine the amount of energy needed on an annual basis, versus the amount produced. Other considerations such as indoor environment quality, interior design, material selection for environmental impact, and occupant behavior were also considered.

With additionally tweaking and careful changes, the project successfully resulted in a net-positive result, while fitting all the constraints and hitting the objective.

2.0 PROBLEM DEFINITION

The project requires the design of a three-storey (plus basement), 150 m^2 net-zero energy townhouse for the Ottawa climate to minimize environmental impact (life-cycle energy and GHG emissions), maximize resilience to power failure and climate change, while being practical and comfortable. The building alone should produce enough renewable energy on-site to offset all of its energy needs on an annual basis.

CONSTRAINTS

- Three-story + basement
- Maximum 150 m^2
- 5m maximum South-facing width
- East & West walls shared with occupants of adjacent townhouse
- Must use active solar energy system (PV, solar thermal, or a hybrid)
- Exploit passive solar techniques
- Roof design cannot shade neighbor's such that they could not too be net-zero
- Only building-mounted or integrated renewable energy systems permitted
- There's an East-West roof peak that is 8 meters directly South of the front face of the building

OBJECTIVES

- Produce enough renewable energy on-site to offset all of its energy needs on an annual basis

PERFORMANCE METRICS

- Annual energy consumption vs. production (and net difference) [MWh]
- Energy intensity [kWh/person]
- Iridescence [kWh/m^2]

3.0 SKETCH DESIGN

The final building design consists of a three-story apartment building. The first, second, and third floors are one-bedroom apartments featuring a South-facing open-concept kitchen and living room. The basement is a general, unfinished space that houses the mechanical systems.

Rough SketchUp architectural drawings can be seen below (in Figures 1 to 3), to give a better visual idea of the structure's massing and apartment layouts.

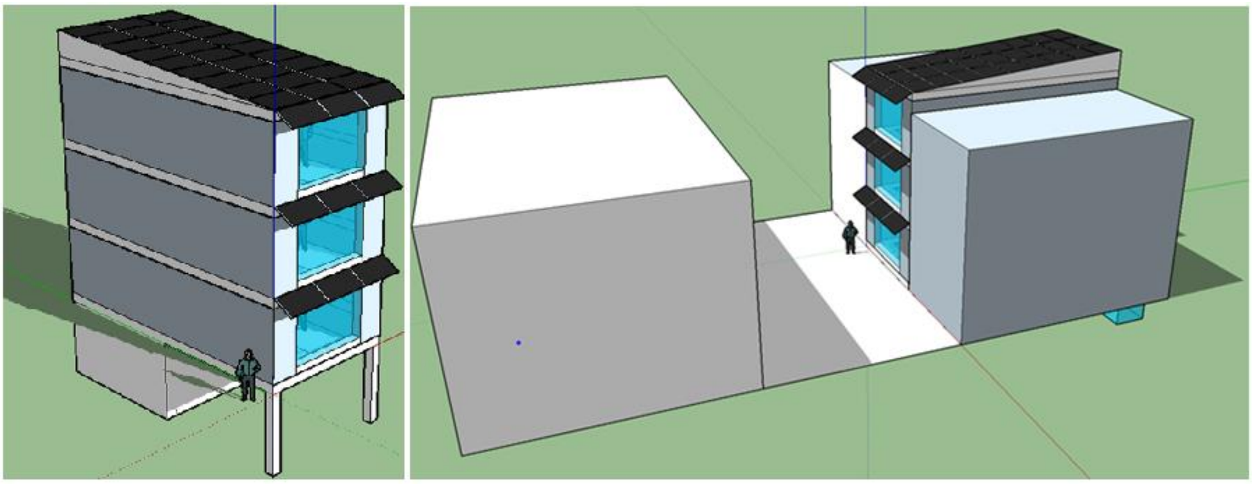


Figure 1: *Isometric view of building (left, adjacent buildings removed) & Perspective view, with surroundings (right)*

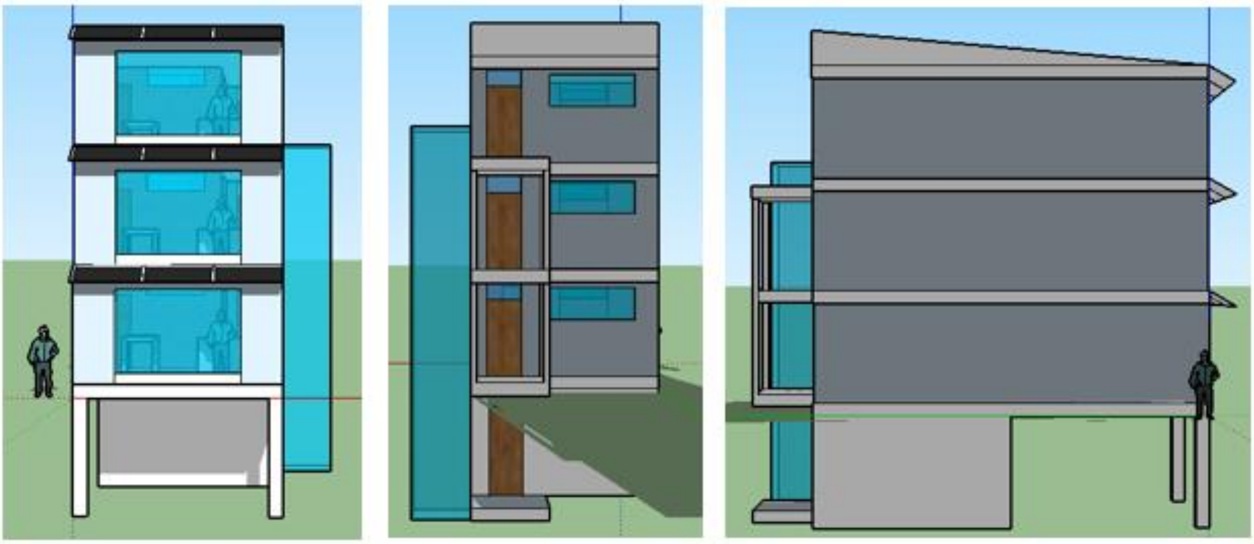


Figure 2: *Elevations of North (left), South (middle), and West (right, ignoring the other building it's attached too)*

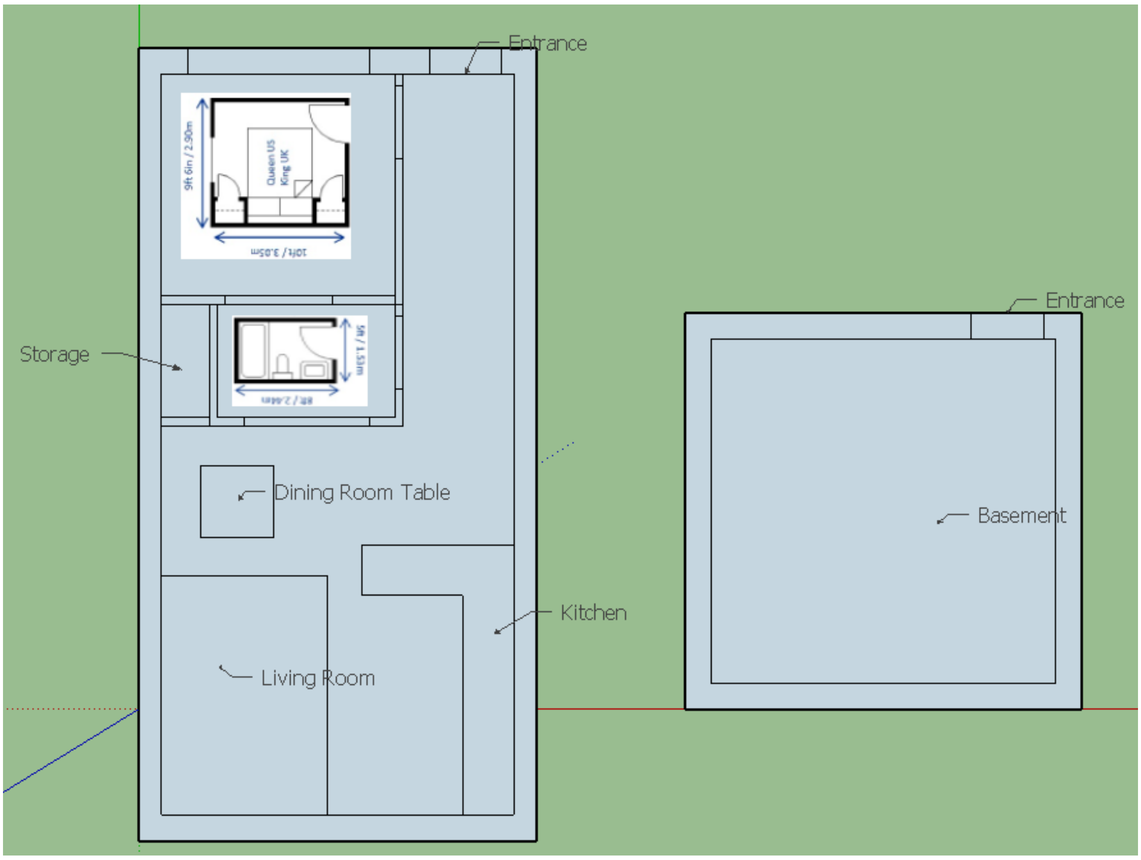


***Figure 3:** Apartment plan typical for floors 1, 2, and 3 (left) & basement plan*

Design choices were carefully thought out, and will be explained in further detail throughout the remainder of this report.

4.1.1.1 Net-Zero Energy Achievement

At the end of the project and integration, the building did indeed come out to be net-zero. The Energy Summary Table, below, shows the breakdown of values proving this.

Table 1: Energy Summary Table

COMPONENT	ENERGY (MWh)
Roof Solar Panels	+13
2nd and 3rd Floor Overhangs Solar Panels	+2.35
1st Floor Overhang Solar Panels	+1.12
Total Produced	+17.19
Total Required	15.5
Difference	**+1.69**

The subsequent detailed design sections of this report highlight how this came to be, and what design choices were made to get there.

4.0 DETAILED DESIGN

4.1 DESIGN STRATEGIES & INTEGRATED DESIGN [Max St-Jacques]

4.1.1 Design Concepts

For the project, we used a prescriptive approach as it is easier to apply and appropriate for this scope of a multi-family structure. The prescriptive approach is considered a bottom-up approach using detailed building specification. It should be noted that Ottawa falls under ASHRAE Climate Zone 6. The standards that will be used are outlined Table 2:

Table 2: Applicable ASHRAE Standards to Outline Minimum Code Compliances

ASHRAE 90.2	minimum insulations levels, glazing areas, window performance, and lighting
ASHRAE 62.2	minimum ventilation rates
ASHRAE 55	minimum thermal comfort levels

The integrated building design process used the knowledge of the whole design team to optimize building design for yearly annual energy use and gains. The team met frequently to share ideas and results. The team sought mutualistic opportunities while also openly criticizing each other work.

Climate Consultant 6.0, alongside *ASHRAE 55*, will be utilized to develop suitable passive strategies for the Ottawa based building. Working with the Daylighting & Lighting and Solar Energy team members, an optimization was created allowing for overhangs to be installed on higher floors. This strategy allowed optimal natural light to enter the room while producing solar gains only when needed in the winter (this basic concept is demonstrated in Figure 4, below, which shows the lower winter sun being able to penetrate the window). Furthermore, the overhangs were made large enough to install solar panels for further energy gains. It was also decided to use the rooftop for PV system, and to use no skylights.

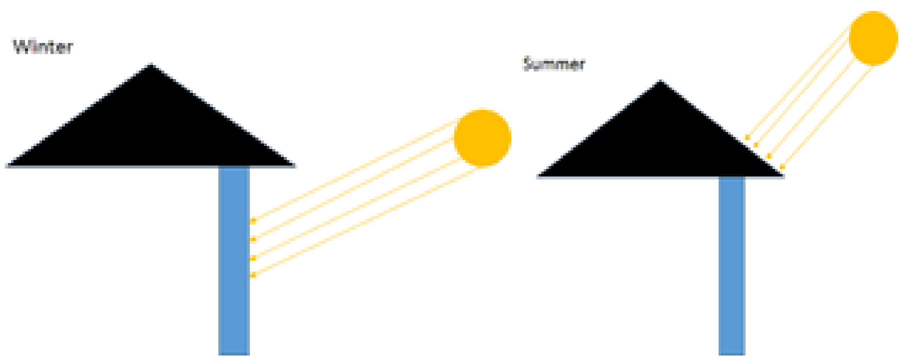


***Figure 4:** Demonstrating optimal seasonal fixed shading*

Working with the Building Envelope and HVAC team members, an iterative process was taken to maximize the wall systems R-value while minimizing its thickness. It was decided to make an initial decision on the wall system to then size the HVAC system using a radiant flooring system. The HVAC system could start to be sized using average energy of ~27 MWh/year (see Appendix A.1 for calculations).

4.1.2 Analysis Methodology

Using *Climate Consultant 6.0* with *ASHRAE Standard 55*, and the *Current Handbook of Fundamentals Model*, we aimed to receive 99% comfort using the following technology categories and given guidelines (see Appendix A.2 for the psychometric chart):

- Comfort (677 hrs)
  - Keep the building small
- Sun Shading of Windows (269 hrs)
  - Design overhangs to shade during summer
- Natural Ventilation Cooling (47 hrs)
  - Steep pitched roof with a vented attic
- Internal Heat Gain (1848 hrs)
  - High level of insulations
  - Insulate Basement
  - Insulating Blinds
- Passive Solar Direct Gain – Low Mass (950 hrs)
  - Glass area to the south to maximize winter sun exposure
  - Clear windows on south side and high performance for north side
  - Thermal mass to store winter daytime solar gains
  - Organize floorplan for winter sun to penetrate into daytime use spaces
- Dehumidification Only (401 hrs)
- Heating (5324 hrs)
  - High efficiency furnace

4.1.2.1 Building Form (Iterative Design)

A building design which keeps corners and joints to a minimum reduces the possibility of creating thermal bridges through which heat can dissipate to the outside of a building [1]. With this in mind, the home is oriented due South to maximize sunlight and solar gains with a simple box shape. Following known constraints, the home will consist of three stories and an unfinished basement for a total living floor space of 150 m^2. The building form also had a secondary objective to have thermal mass to allow the sun to be absorbed in the floor to keep the room temperature comfortable to then have the heat can be released at a cooler time. The team went through multiple iterations and hand sketches during meetings with some samples seen in Appendix A.3**.** *SketchUp 2015* was used to model the Ottawa building in 3D.

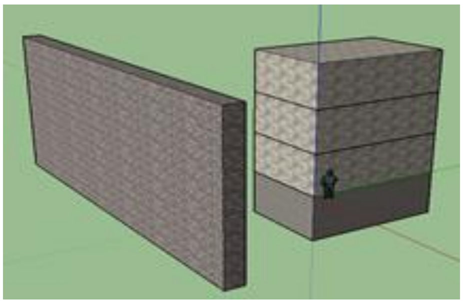


Figure 5: *First Iteration 3D Model [Single-family home]*

The initial model consisted of a one family home having a large, open-concept first floor for living space and double storey height ceilings cutting down on the second floor. The southern windows were large with overhangs to shade them during summer and small northern windows. The solar arrays were to be installed on an added built on the roof to shade the rooftop patio while also providing optimal angle for photovoltaics.

However, the model was quickly changed to a two apartment model where the two first floors would be a single apartment and the third floor being a bachelor apartment.

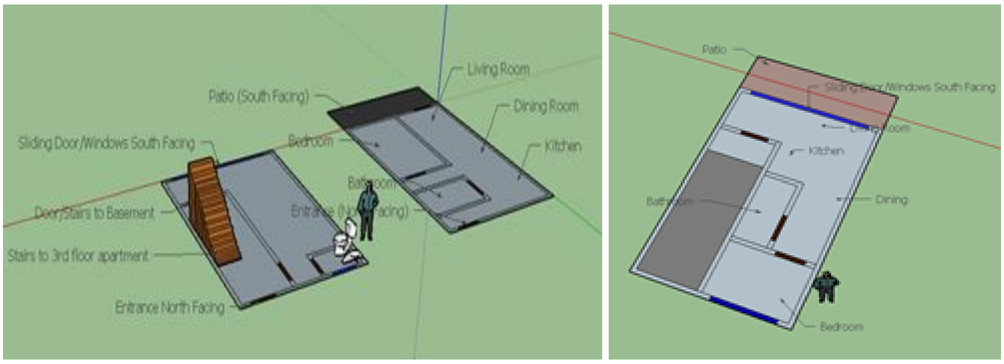


Figure 6: *Second Iteration 3D Model [2-storey apartment + 1-storey apartment]*

The second building form was dropped due to lack of realistic living space with natural daylights.

The team then opted for each floor to be a bachelor apartment to allow more of an open concept, to simplify the model, and to lower the buildings energy intensity (kWh/person).

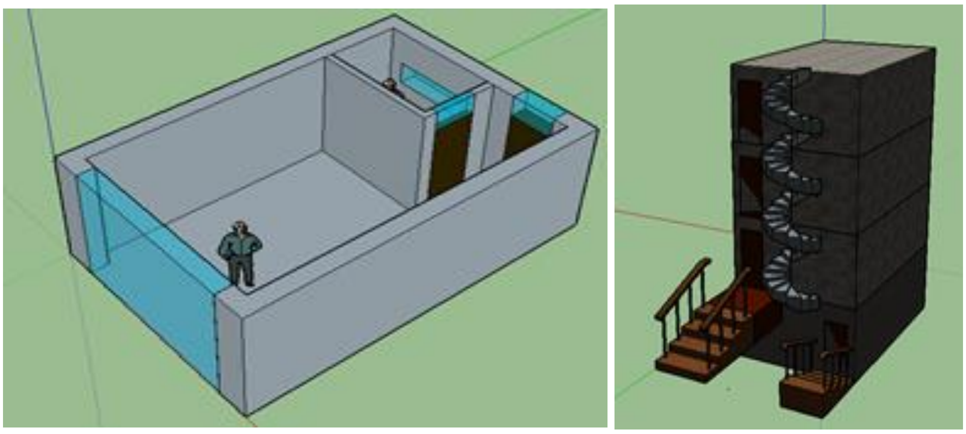


Figure 7: *Third Iteration 3D Model [3 bachelor apartments]*

After reviewing the third version, the team made the decision to move forward with the apartment idea.

However, the team felt privacy to be an important and to add a bedroom able to hold a queen size bed. Additionally, upgrading from bachelors to one-bedrooms could increase the amount of people per unit—decreasing the energy intensity metric. To try this idea out, an online tool (see Appendix A.4) was used to verify the minimum working size for bedrooms, bathrooms, living rooms, etc. Furthermore, each floor was enlarged from 5m x 7.5m to 5m x 10m; with the 5mx5m basement for the mechanical system, storage, and shared washer & dryer.

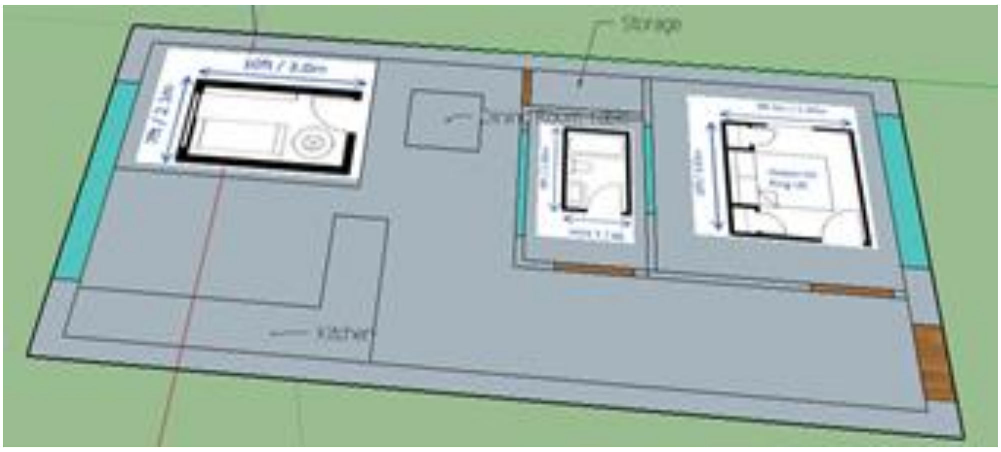


Figure 8: *Fourth Iteration Floor Plan [3 one-bedroom apartments +shared basement]*

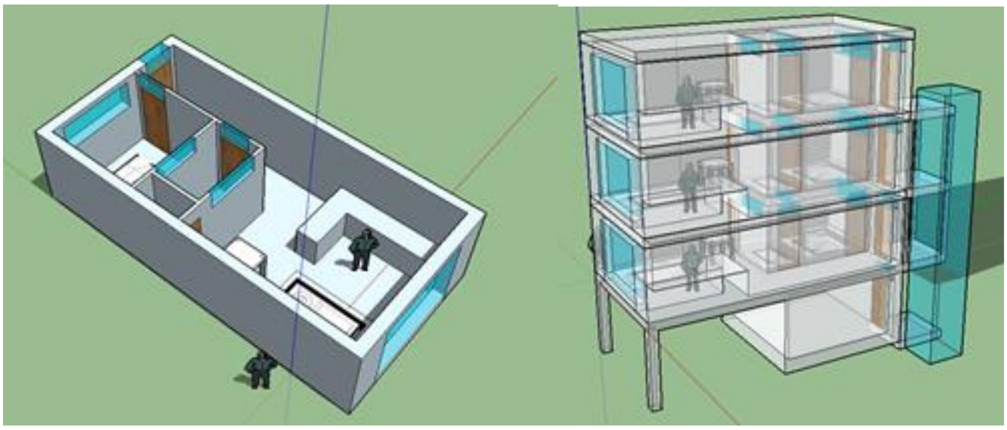


Figure 9: *Fourth Iteration 3D Model [3 one-bedroom apartments +shared basement]*

4.1.2.2 Shading

Using general rule of thumbs as a starting point, windows should not exceed 2/3 of the envelope and fixed overhands should be designed to have a depth of roughly 50% of the height from the glass to the tip of the overhang [1]. The tools used for the shading design and analysis are *SketchUp 2015*, *Climate Consultant 6.0* and *Susdesign.com*.

Our building has the potential to be shaded by a neighboring 8-meter-tall peak 8 meters across the road. Initially using *Climate Consultant 6.0*, the table from Appendix A.5 was filled out to view the buildings shading effects over a year. We can see that the bottom of the first-floor window is shaded 18% of sunshine hours from the neighbour across the street. Furthermore, the bottom of the second-floor window is shaded 14% of sunshine hours as its top is shaded 0%. These data points were further confirmed by taking snapshots of the *SketchUp* model around solar noon for each season (see Appendix A.6). Furthermore, shading from overhangs will also be calculated to maximize solar gains in the winter and minimize them in the summer. Using *Susdesign.com*, an initial overhangs model with 0 pitch was designed using June 21st to be fully covered and December 21st to be fully uncovered.

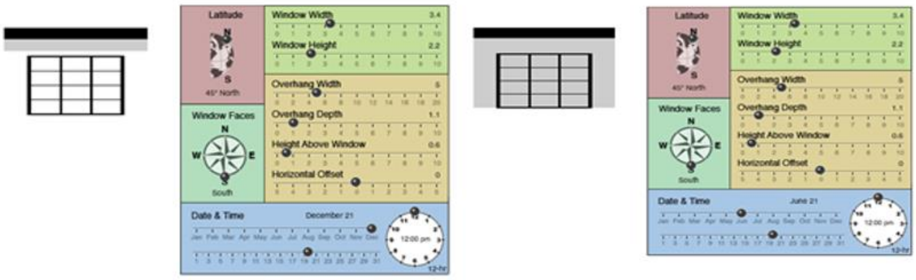


Figure 10: Susdesign.com Tool for Overhang Design [2]

Using this initial model and knowing that the overhang must be designed to hold photovoltaic panels. The panels were set to be at a pitch of 30 degrees, and be at least 0.8 m in length. Using a trial and error method, the following overhang was designed to have May - July mostly shaded and Nov - Jan unshaded as seen on the shading map in Appendix A.7.

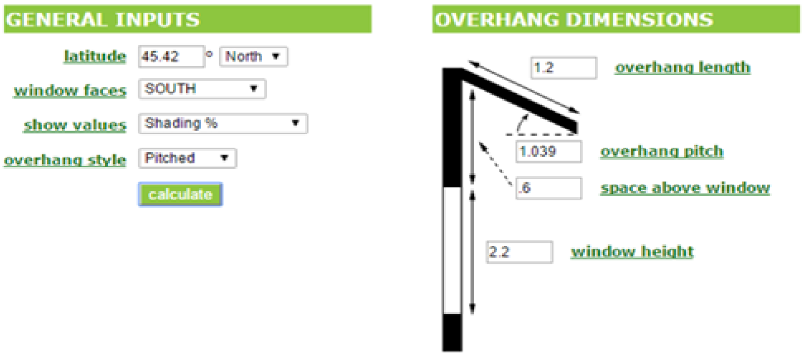


Figure 11: Susdesign.com Tool for Overhang Design with Pitch [2]

One of the optimization we looked at closely, was the balance between having the roof PV at the correct angle while also minimizing the amount of shading to our northern neighbour. We assumed a situation where 8m tall neighbours are on either side of us and the northern neighbour being 8m north from our household. Using a trial and error method with *Climate Consultant 6.0*, we determined the maximum height for us to reach should be 10 m height. Our final model has a height of 9.71 m with *Climate Consultant* gave us the following shading data at floor level for our northern neighbour. See Appendix A.8 for the sun shading chart.

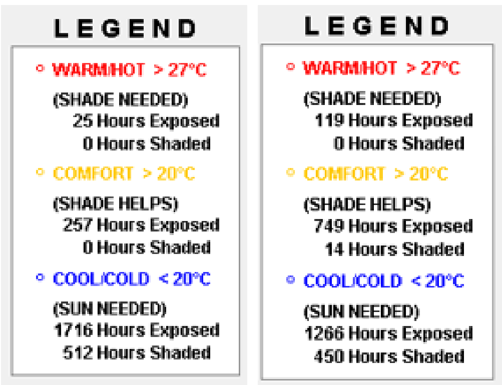


Figure 12: Shading guide values by Climate Consultant
December 21 to June 21 (left) June 21 to December 21(right)

4.1.2.3 Natural Ventilation

When there is a difference between outdoor and indoor temperature, ventilation can be accomplished by natural means. Strategically placed windows make use of prevailing winds to allow ventilation, bringing in fresh air while removing warm or stale air. Ventilation also has an impact on heating and cooling [1]. Using *Climate Consultant* as a reference, natural ventilation could be used in an Ottawa home to offset cooling minimally. Generally speaking, the *Climate Consultant* model simulated that 47 hours of additional comfort could be achieved via Natural Ventilation. However, we shouldn't orient the building to maximize natural ventilation but rather to maximize heat gains from the sun by orientating the house due South. Natural ventilation can also be created from this internal heat gain by creating a gradient of air temperature within any room to be taken advantage of. An example of this is to have an air inlet at a lower level and an air outlet at a higher level causing the colder air to be circulated and the hotter air to be exhausted (sketch in Appendix A-9).

From *Climate Consultant*, it is possible to see that historically in Ottawa, the climate goes above comfort level during the months of June, July, and August. These are the months that need to be looked at when speaking of passive cooling strategies. Following *ASHRAE 55*, air speeds appropriate for indoors do not exceed 0.2 m/s and maximum allowable elevated airspeed of 1.5 m/s for air speeds that will increase acceptable temperature. Looking at the wind rose for those months dictates that:

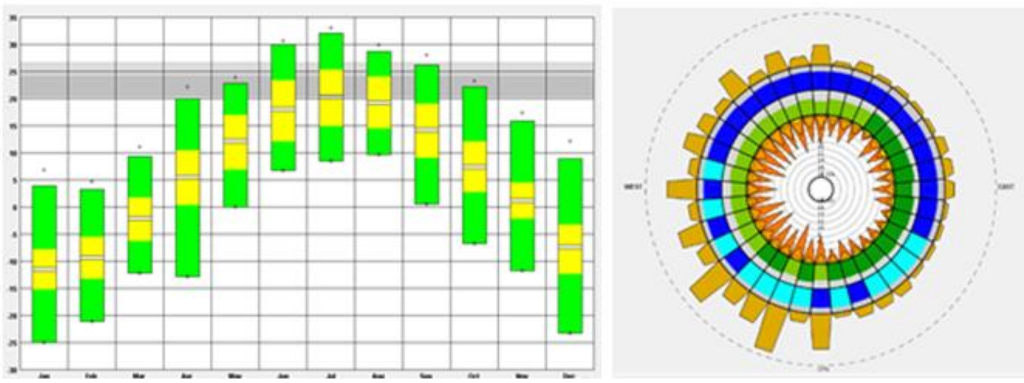


Figure 13: *Ottawa summer months wind rose*

Wind coming from South → Cross Ventilation South to North
Wind coming from West → Need to steer the wind to head South to North

As the building is sandwiched between neighbours, we will rely on cross ventilation from southern and northern facing windows. Cross ventilation occurs between windows on different exterior wall elevations [1]. The open concept of the interior will allow for better air circulation and mixing. The open windows will be staggered compared to their opposite walls. Moreover, the entry point for this cross wind will be low on the South side and a high exit on the North side. The reason for this to allow for more wind movement while moving colder air indoors and pushing hotter air outdoors. For any closed rooms (i.e. bathrooms and bedrooms), awning windows will be installed over the door to allow better air circulation with closed doors. A vented attic is also installed to shed from rain and snow while also helping prevent ice dams. The ventilation also helps the cooling of solar panels during the summer time. See a common detail, from *Climate Consultant*, in Figure 14 below. See Appendix A.9 for a hand sketch of Natural Ventilation strategies.

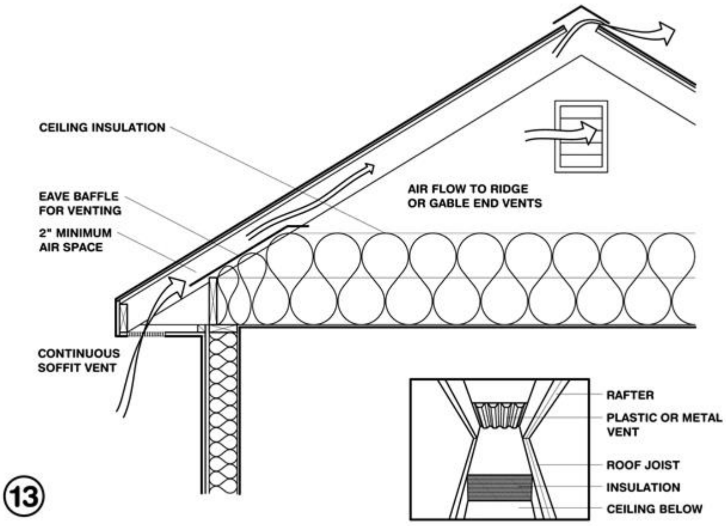


***Figure 14**: Vented Attic Sketch*

4.2 BUILDING ENVELOPE [Julia Dalphy & Arlin Otto]

4.2.1 Design Concepts

4.2.1.1 Walls

The final wall design chosen for this project was a modified insulated concrete form (ICF) wall. The west, east and south walls are 150 mm ICF blocks (ICF blocks are referenced by their interior concrete thickness) that are comprised of two 63.5 mm layers of EPS board and a 150 mm poured concrete core. Based on requirements from project components, the north wall was insulated with an extra layer of 63.5 mm EPS insulation on the exterior face. In ICF construction, gypsum wallboard can be mounted directly on the interior wall; therefore no interior "stud-style" framing is needed. The final wall thickness is 291 mm (excluding the cement impregnated siding), which can vary and adds relatively little to the thermal performance of the wall system. The final walls sections are as follows:

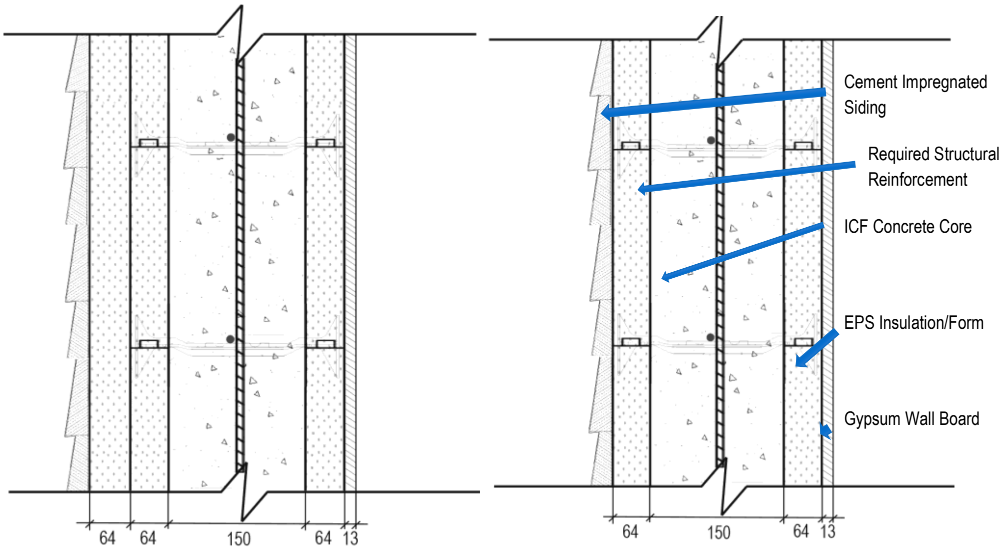


***Figure 15**: North-facing & South-facing wall sections*

4.2.1.2 Windows

The final window design selected for this project was a triple paned window system with argon gas fill. The exterior panes of glass have are double-glazed and have double low-e coatings on clear glass to allow full visibility while incorporating the low-e coatings. The glass used was specified from China Southern Glass (CSG) from the *LBNL Window 7.4* (v.7.4.8) database. The center pane of glass was a 14 Mil clear glass by Saint-Gobain as it did not require any more coating to meet the established benchmark from other team members.

All the windows for the building utilized the same material however they varied in size, refer to more details in the Analysis Methodology section (and to see the final specifications of them).

4.2.1.3 Roof

Due to the requirements of the integrated design with the slope of the roof, a warm roof detail was used, as was outlined in Figure 14, earlier in the report. The roof will be made of standard wood trusses at 600 mm on center with 1m of mineral fiber batt insulation to obtain this required RSI-value. The requirements from the team meetings made this the only suitable option for insulating the roof structure, as can be seen in Figure 14, earlier in the report. The insulation and roof envelope structure was also governed by ventilation requirements established by other members.

4.2.1.4 Foundation

The foundations for this project were also constructed out of ICF, identical to the wall construction. This was a priority as it gave the same thermal performance as the wall sections, eliminating the potential for any thermal sinks in the system. From a constructability point of view, it is more realistic to specify an entire ICF wall assembly rather than a partial assembly.

A summary of all final component performance values can be seen in Table 3, below:

Table 3: Summary of Building Envelope Performance Values

	Min. RSI Required by *ASHRAE 90.2* (for climate zone 6)	RSI [units]	U [units]	A [m2]	UA [units]	Infiltration Rate [ach]
Roof	8.6	10	0.1	1	0.1	*N/A*
Foundation	2.6	5.5	0.2			*N/A*
East & West Walls	2.6	3.8	0.3	25	6.5	*N/A*
Window Over Door	2.0	0.3	3.2	0.4	1.3	*N/A*
Window in Bedroom	2.0	0.5	2.0	2.5	4.9	*N/A*
North ICF Wall	2.6	5.5	0.2	8.8	1.6	*N/A*
North Wall Total				12.5	2.3	*N/A*
Door [with integrated window]	2.2	0.4	2.5	0.8	2.1	*N/A*
Window	2.0	0.6	1.6	7.5	11.6	*N/A*
South ICF Wall	2.6	3.8	0.3	5.0	1.3	*N/A*
South Wall Total				12.5	7.5	*N/A*
Total		*N/A*	*N/A*	*N/A*	*N/A*	0.75/h

4.2.2 Analysis Methodology

4.2.2.1 Walls

To determine the most appropriate building envelope components, we chose two high-performing alternatives and evaluated them on a benefit and cost-basis. Additionally, we also performed the same analysis on a conventionally "average" steel-stud framed wall, for due diligence and comparison's sake. Other key considerations included referencing *ASHRAE's 90.2* minimum RSI-values & U-values.

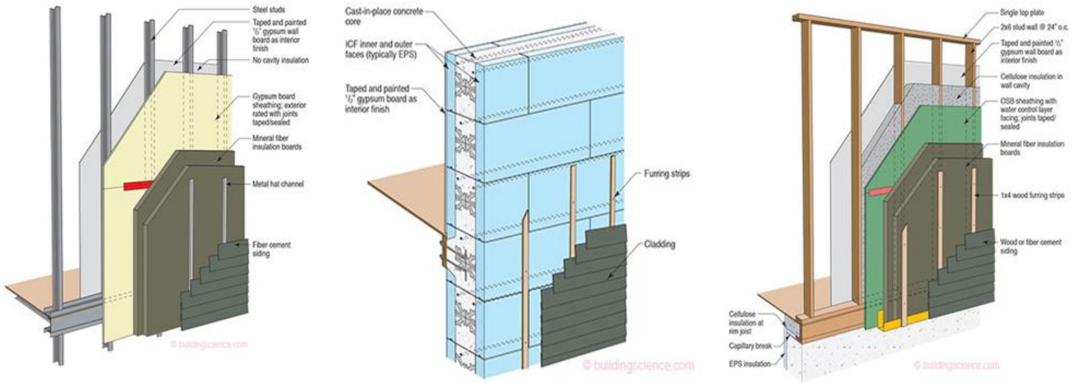


***Figure 16**: 3 Alternative Wall Systems, in order of lowest to highest determined RSI-value*
(Left): Traditional steel stud wall, with mineral fibre insulation
(Middle): ICF assembly, with no added insulation
(Right): High-performing sprayed-in wood-framed, with mineral fiber insulation board

With the help of parallel plane method diagrams, *Microsoft Excel* was then used to calculate the estimated RSI-values of each assembly, based on each component's thickness ('width') and thermal conductivity (k). As well, their price per m^2 was also estimated. Then, heat loss was calculated for each, as well as heating costs and Net Present Value. All *Excel* sheets and parallel plane sketches can be seen in Appendix B.1.

Then, the three alternative were compared and contrasted to come up with the best fit for our building, as was outlined in Section 4.2.1.1, above.

4.2.2.2 Windows

Windows were selected based on performance needs of the space, as well as reasonable cost. A starting point for appropriate assemblies was researching similarly scoped high-performing buildings, in particular from the CHMC Equilibrium project. These houses seemed the most relevant as they had similar design objects, smaller floor plans and the use of upcoming technology. In some of these projects, such as the *Green Dream Home, Abondance le Soleil* and *Riverdale Net Zero Project* provided starting points for design iterations among the team.

Another aspect that was considered where the minimum *ASHRAE* standards for U- and R-values *ASHRAE's 90.2* standard. Meeting this value was not an issue as the researched systems all surpassed the minimum values.

Several single or double paned windows were modelled in *LBNL Window 7.4* (v7.4.8) however it appeared that the desired U-value could not be achieved. For this reason, and from the background research, triple paned windows were considered.
The window frames were quite important as they can often act as thermal weak points or sinks in an assembly. For this reason, as the performance of the windows was key to not overloading requirements from other systems, vinyl or aluminum frames with thermal breaks were considered [3] [4] [5].

Low-e coatings were investigated and it was deemed reasonable as they reduce long way radiation [6].

Triple-paned windows, with either double or triple glazing incorporated a high efficiency and reasonable U value with a realistic system for a high efficiency building. In some case studies the windows were different on all sides on the house [5]. Through a design charrette this was deemed unrealistic due to the unfavourable nature of having constructability compromised. After settling on triple paned windows, glass types were researched and day lighting was prioritized leading to the choice of clear glass in the window design.

The final part of the window design, once the triple paned and low-e coatings were established, was the fill. It was suggested that non-air gas fill should be used to reduce convective loops between panes additionally it was recommended that space between panes be 12.7 mm as this is the optimum value [7].

LBNL Window 7.4 (v7.4.8) was used to model the windows for the envelope. Key results from this analysis can be seen in the summary Figures 17-20, below.

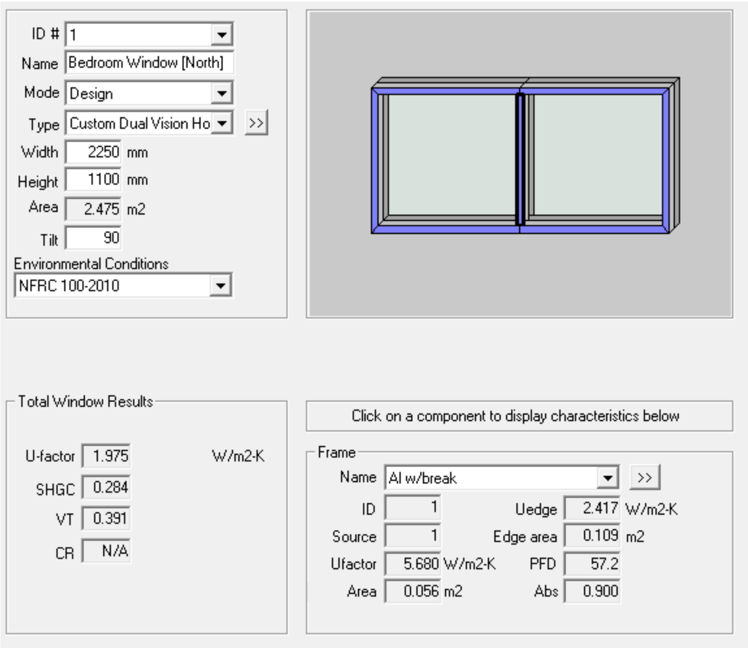


Figure 17: *Key modelling information from LBNL Window analysis (bedroom window)*

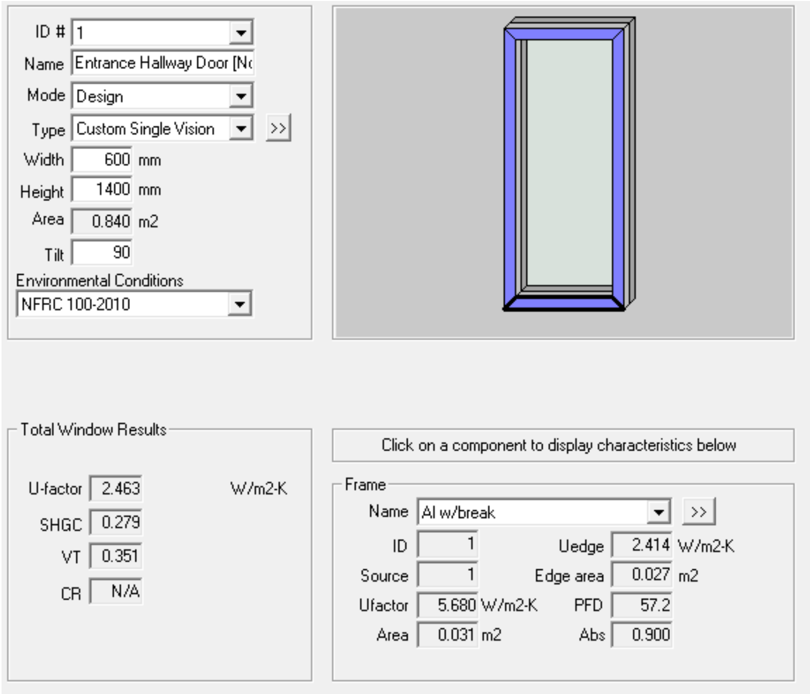


Figure 18: *Key modelling information from LBNL Window analysis (entrance hall door window)*

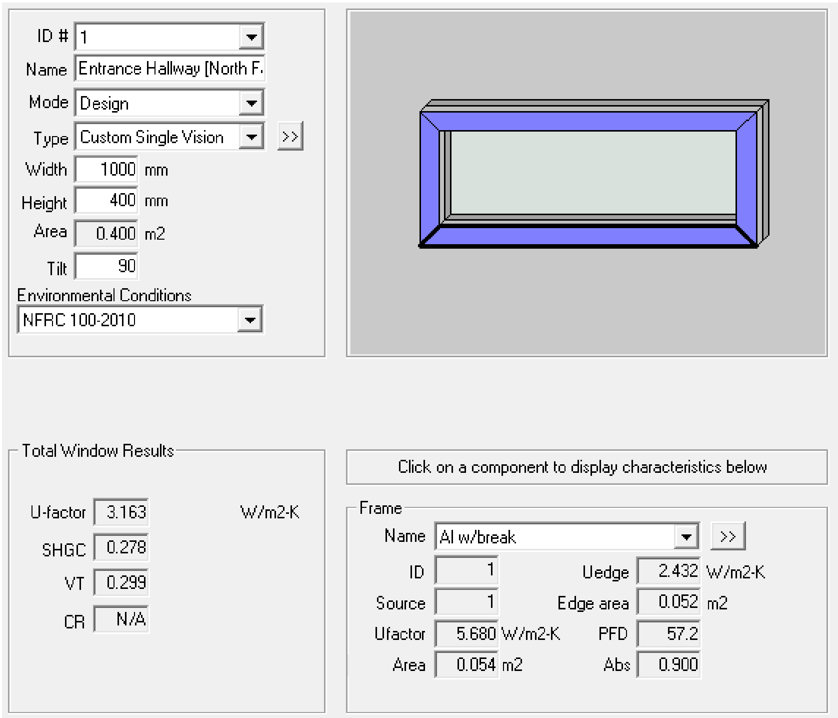


Figure 19: *Key modelling information from LBNL Window analysis (entrance hall top window)*

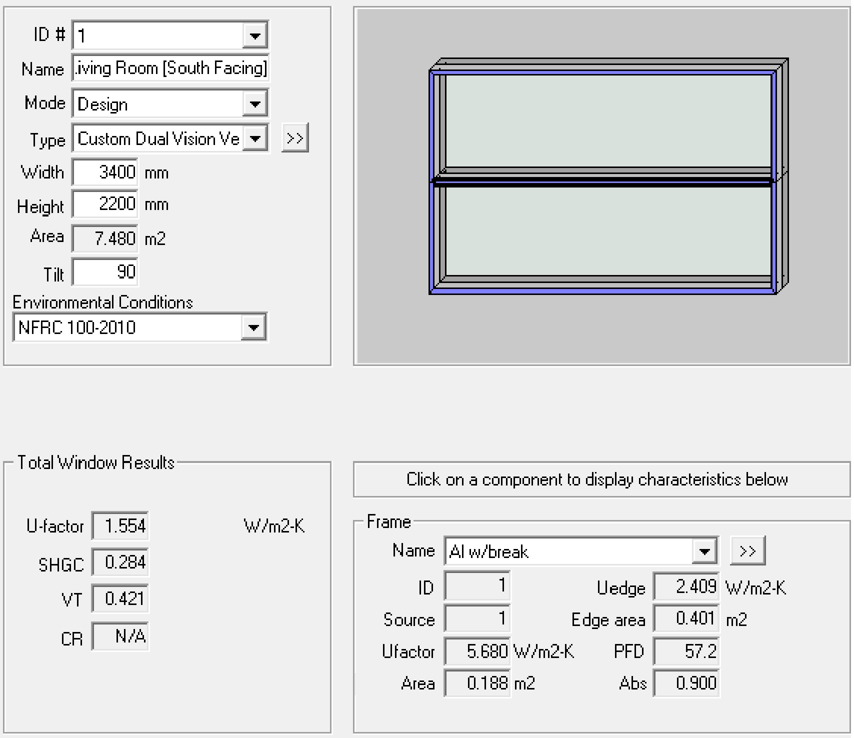


Figure 20: *Key modelling information from LBNL Window analysis (living room window)*

Window design relied heavily on collaboration with the Daylighting & Lighting Systems and HVAC team members. Details on the dimensions needed, glazing desires, and performance values dictated the specification of the windows. For details on the determination of these factors, please see the Daylighting & Lighting Systems and HVAC sections, below.

Some limitations were encountered in the *LBNL Window Software*, for example the exact geometry of the window was not possible. In this case, the closest option was models and this was deemed and acceptable level of error for the data taken from the software for the other components in the design.

4.2.2.3 Roof

Roof design was based on the minimum *ASHRAE* values acceptable. Beyond this, the thought process was to follow the restrictions of the Integrated Design team member, who intended the use of a certain warm roof detail. The HVAC team member was content with the value this yielded, and so we did not need to iterate further to improve it.

4.2.2.4 Foundation

Foundation design was based on the minimum *ASHRAE* values acceptable. The foundation design did not require much interdisciplinary design collaboration because after choosing the wall type, the feasible foundation type was ICF due to constructability. The 150 mm ICF system easily surpassed the required R-value and design airtightness value [5].

4.3 HEATING, VENTILATION, & AIR CONDITIONING (HVAC) [Isabelle Kosteniuk]

4.3.1 Design Concepts

The HVAC system for this house was integrated into passive design elements such as envelope and daylighting in order to provide necessary heating and cooling to the space. There was considerable focus placed on reducing the mechanical load of the dwelling when designing the interior space, glazing, and envelope. Including operable transom windows allows for natural cross-ventilation and light penetration, decreasing the fan power and electric lighting demand. Having a combination of occupant-operated and automatic controls also increases comfort levels while reducing energy use. Designing a tight envelope lowered heat losses due to mechanical ventilation, and insulating the north wall more heavily reduced transmission losses. In the cooling season, fixed overhangs and a low SHGC on south facing windows prevent overheating. The HVAC system was designed iteratively with other elements of the house, improving metrics while maintaining occupant appeal.

The mechanical loads of the house are still substantial, and the renewable energy system was designed to offset annual energy consumption.

The HVAC system is composed of a combination ground source heat pump, capable of supplying radiant in-floor heating, forced air heating/cooling, and domestic hot water heating. To reduce energy use, a drain heat recovery unit and HRV are used. Table 5, at the end of this section, summarizes all components. The sub-sequent sections, directly below, will explain the design decisions and equipment specifications.

4.3.1.1 Ground Source Heat Pump (GSFP)

A ground source heat pump was selected due to its versatility and high efficiency in cold climates. The *Geocomfort CT036* is a combination GSHP, capable of supplying radiant heat, forced air heat, and hot water [8]. Its features include a programmable thermostat, hydronic air handler, and an internal auxiliary electric heater, which allows for a more conservatively sized heat pump. A vertical ground loop allows for the heat pump to be installed in a residence with a small footprint.

4.3.1.2 HRV & Drain Heat Recovery Unit

The HRV reduces heat losses due to ventilation significantly. In initial drafts of the house, losses due to ventilation were as high as 50%. By sourcing an efficient, HVI certified HRV, this figure was reduced to 35%. The drain heat recovery unit reduces the amount of energy required to heat domestic hot water draws. Domestic hot water accounts for 43% of energy use.

4.3.1.3 Radiant In-Floor Heating

Radiant floor panels were chosen as the primary heating distribution system due to their high efficiency and comfort. Distributing heat using in-floor panels heats the space evenly, even with floor coverings such as carpets. In-floor panels are also able to space heat at a lower operation temperature than perimeter radiators, decreasing their energy use. Using a water-water heating system prevents a feeling of ‘draftiness’ often caused by convective heat transfer in water-air systems. As well, a radiant system decreases the amount of fan power required in the house, and carries significantly more heat per kg/s of flow.

4.3.1.4 Forced-Air Heating/Cooling

A heat pump capable of supplying both water-water and water-air was selected in order to supply the most comfortable heat and coolness to the space. At this point in time, the performance of radiant cooling is not well documented, and thus a forced air system is used to provide effective cooling and dehumidification during the warmer months.

4.3.1.5 Controls

The HVAC control system includes both mechanical and manual components. Operable exterior and transom windows allow occupants an immediate increase in ventilation. The Geocomfort CT036 can be automated to reduce heat/coolness supply during low-demand periods such as overnight and during the work day. Zoned heating and cooling also improves the performance of the system, as occupants can modify their own thermal environment.

In summary, Tables 4 & 5 list the energy expectations and specifications for the HVAC system:

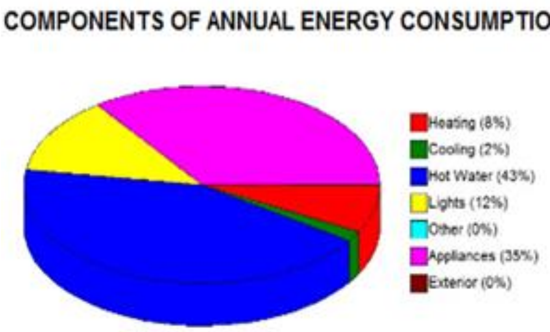
Table 4: Comparison of GSHP vs. Baseboard System

Model	Energy Use [kWh per year]	Heating [MJ]	Cooling [kWh]
GSHP + HRV + Drain Heat Recovery	15 573	4183	230
Baseboards + Central AC	25 999	8728	648

Table 5: Summary of HVAC Equipment Specifications

Equipment Type	Make/Model	Description
GSHP	*Geocomfort CT036*	COPc = 21.5, COPh = 3.9, 8.76 kW part load heating capacity
HRV	*vanEE 1001 HRV*	HVI certified, 75% efficiency
Drain Heat Recovery Unit	*Power pipe R4-120*	73% efficiency

Additionally, the pie charts in Figures 21 below demonstrate the annual energy consumption breakdown, as well as the components of annual heat loss.



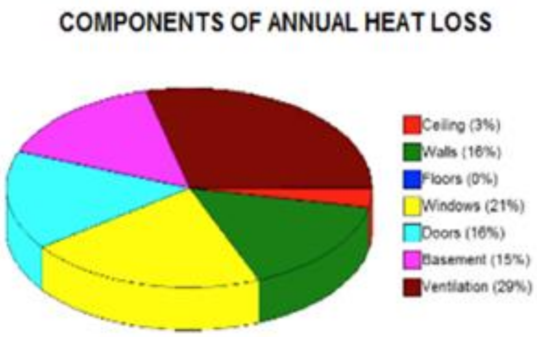


Figure 21 :
(left): Components of Annual Energy Consumption
Note: 'other' and 'exterior' energy usage is bundled with 'appliances'
(right): Components of Annual Heat Loss

Overall, by designing an HVAC system that is closely linked to building envelope and building design, annual energy use was decreased by 40% as compared to a similar building without integrated HVAC. The total annual energy use is about half that of an average Canadian home [9]. As well, the heating and cooling load was reduced to 10% of total annual energy use. This value can be considered reasonable, as it falls in the same range as a high efficiency GSHP according to Natural Resources Canada's Heating Energy Cost Comparison [10].

4.3.2 Analysis Methodology

4.4.2.1 Tools & Legitimacy

The main tools used to design and analyze the HVAC system of the house were *HOT2000*, *Energy Plus* weather data, *ASHRAE* design condition charts, and several governmental resources for estimating loads. Equipment was selected from Home Ventilation Institute and Energy Star databases.

Each tool has its own set of limitations and advantages. *HOT2000* was the most extensively used resource, so its legitimacy is discussed here in detail:

Much of the analysis *HOT2000* performs is carried out within a black box, and as such it is difficult to estimate a margin of error on the final figures. Only components with well-documented performance are available as variables in *HOT2000*, making it challenging to include novel systems. Also, *HOT2000* is not configurable for many parameters of HVAC systems, particularly ground source heat pumps. For example, ground loop parameters and COP curves affect the heat pump's performance, but are not variables in *HOT2000*. Natural ventilation is also difficult to model with *HOT2000*, as is occupant behavior and control settings. The heat pump's programmable thermostat improved the space heating and cooling load of the house, but this is not reflected in the model.

The *ASHRAE* temperature design condition chart and *Standard 62.2* table used to calculate peak loads and required ventilation rates are based on generalized data and as such introduce errors. The same is true for the *Energy Plus* weather data and the *CanmetENERGY* study, both used to estimate base loads.

4.4.2.2 Peak Load Calculation

Design conditions based on *ASHRAE* Design conditions for Ottawa International Airport [11]. Indoor conditions comply with *ASHRAE 55*. See Appendix C-3 & C-4 for summaries of these.

Table 6: Design Conditions

	Heating (indoor)	Cooling (indoor)	Heating (outdoor)	Cooling (outdoor)
Air	21	25	-24.5	30.3
Ground	-	-	-10	10

The infiltration rate was estimated through comparison to similarly enveloped high performance buildings, such as the Green Dream Home from the Equilibrium housing project. However, in accordance with the minimum ACH value allowable in *HOT2000*, an infiltration rate of 1.5 ACH/hour at 50 Pa (common for tightly-enveloped houses) was used in calculations.

The ventilation rate was calculated using *ASHRAE 62.2* for a 120 m^2 dwelling [13].

Table 7: Ventilation Rates

Infiltration Rate [ach]	Ventilation Rate [L/s]
1.5 *(@ 50 Pa)*	60

Using UA values calculated in the building envelope section, the following peak loads were calculated (See Appendix C-1 for the calculation sheet used.):

Table 8: Peak Loads

Heating [kW]	Cooling [kW]
8.14	6.93

4.4.2.3 Base Load Calculation (Appliances, Lighting, and Hot Water)

A 2012 study conducted by CanmetENERGY was used to calculate the base electrical load of the house [14]. This value includes lighting as well as major and minor appliances. The study was based off of an average Canadian single family home with 3 occupants, with a base load of 19kWh/day. For a 25% increase in number of occupants using entirely energy efficient appliances and lighting (assuming an energy savings of 25%), this value remains unchanged. A lighting load of 5 kWh per day was calculated in the daylighting section of this report, resulting in an appliance load of 14 kWh per day. An average of 250 liters per person per day of hot water usage is reported by Environment and Climate Change Canada [15]. Low flow appliances such as toilets, showerheads, and washing machines can reduce water usage by around 40%, thus resulting in 150 liters at 55 degrees Celsius per person per day [16].

Table 9: Base Loads and DHW

Appliances [kWh/day]	Lighting [kWh/day]	Domestic Hot Water [L/day]
14	5	150

See Appendix C-2 for the calculation sheet used.

4.4 DAYLIGHTING & LIGHTING [Yazan Zafar]

4.4.1 Design Concepts

4.4.1.1 Fenestration

This portion of the project looks at the types and sizes of windows, while taking into account the daylight penetration during various times of the year. This is complimented with the evaluation of technologies that include shading, light fixtures and light distribution mechanism. The same fenestration plan is used across the apartments of all three floor levels.

Living Room Window (South-Facing)

As these are the only windows on the south side of the apartment building, the windows account for 60% of the total surface area, suggested as the maximum WWR by Building Science Corporation [17]. This was chosen by performing illuminance iterations for windows ranging from 40%, 50% and 60% using the *DiaLUX* software. The size of this window is modeled considering the illumination of the living room. Optimum lighting zone is 1.5 to 2.5 times the height of the window [18]. Based on this, the following calculations are made to determine the windows dimensions:

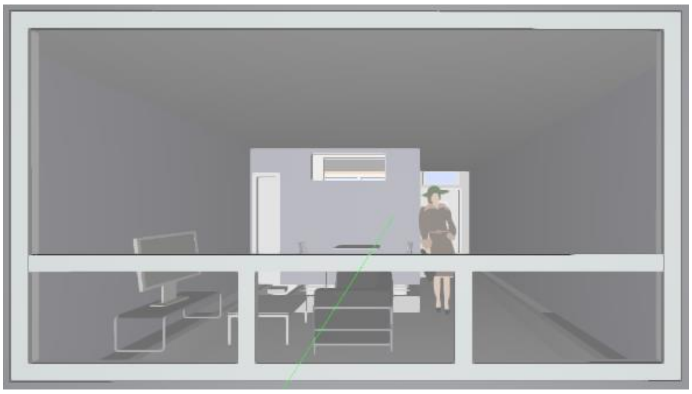
Depth of living room = 5.5 m

Therefore, height of window for sufficient illumination = (5.5 m) / (2.5 m)
= 2.2 m

Window Area requirement for 60% coverage = (total wall area) x (0.6)
= (2.5m x 5m) x (0.6)
= (2.5m x 5m) x (0.6)

Therefore, window width = (7.5 m^2) / (2.2m)
= 3.4 m

Determining the type of windows required heavy integration with the HVAC and envelope members of the team. The HVAC member is concerned with the operation for cross ventilation, whereas the envelope team required all dimension and framing characteristics. The following type of window is used:



Window Dimensions:
2.2m x 3.4m

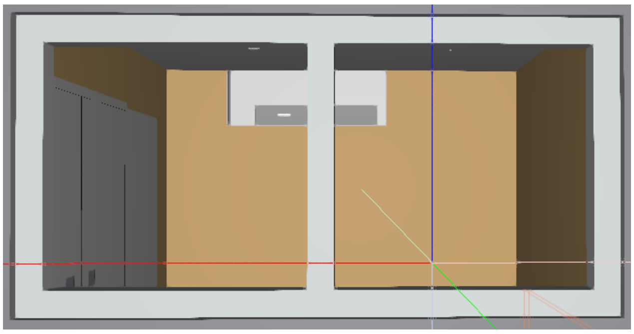
Transom Height: 0.7m

Figure 22: *Living Room Window Plan (from SketchUp model)*

It was decided that the amount of window framing was to be minimized, as this is how 10% of heat is lost in a typical house [19]. Since operable portions are required for HVAC needs, the window is partitioned with a transom and two mullions.

Bedroom Window (North-Facing)

The window to wall ratio of the north side for the design was determined to be 27%, the optimum for high performance buildings as determined by Joseph Lstiburek [20]. The area of the bedroom window has to be considered by taking into account the size of the other windows on the north side of the building. The height for the window was determined considering the room depth, an identical calculation to the south facing, giving a height of 1.1 meters. For occupant comfort purposes, it was decided that the width of the bedroom window would be larger than usual to allow for more illumination, based on the iterations similar to those done for the living room. The following dimensions and window type was used for the bedroom window:



Bedroom Window Dimensions:
1.1m x 2.5m

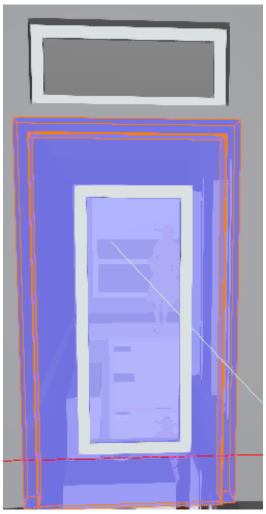
Figure 23: *Bedroom Window Plan (from SketchUp model)*

Working alongside the Building Envelope members, it was determined that the type of window would be a single mullion window. This would allow the window to be operable and well insulated. The placement of the window would be as high as possible, to reduce the amount of glare—this positions the window 1.2 meters from the floor.

Entrance Hallway Windows (North-Facing)

Two windows are to be installed on the North side to illuminate the entrance hallway. In order to sufficiently illuminate the hallway, the height of windows was calculated by dividing the hallway depth by 2.5. This value was found to be 1.8 meters and was distributed between 2 windows. Working with the team member assigned to Design Strategies, the following designs have been developed:

The purpose of the top window is to provide light, and operate in tandem with the South-facing window for cross ventilation, as requested by the HVAC team member. In order to maximize ventilation, the window is placed as high up as possible, while the window on the south side is placed lower to the ground. This promotes the convective flow through the apartment [21]. This will be a standard window with high transmission frosted glass, fitted with an automated opener.



Top Window Dimensions:
0.4m x 1m

Bottom Window Dimensions:
(integrated into door)

Figure 24: *Entrance Hallway Window Plan (from SketchUp model)*

The bottom window is fixed in the door, features frosted glass (for privacy), and is not operable. Collectively, both these windows should provide sufficient illumination for the hallway.

Bathroom

The bathroom is placed in the center of the building and will have small windows along the top of its North and South walls to allow daylight illumination to protrude from the larger apartment space. These will be large enough to pass light, and still provide privacy by being placed high-up.

4.4.1.2 Daylighting

The home will utilize a passive solar system in order to illuminate the apartments. This portion of the project focuses on daylighting in the apartment, including shading and light distribution mechanisms.

Shading

To block the summer sun, overhangs are installed for the south-facing windows. This affects the amount of daylight penetration in the building. Iterations are made to calculate the illuminance in the rooms; these results are considered for the daylight animation in *DiaLUX* that are done for the window size calculation in *Section 4.1.2.2*).

During winter, the sun path chart shows that the south-facing window on the ground floor will be completely shaded. Enough diffused light will enter the building however, and since daylight sensors are installed in the light fixtures for the living room, the illuminance will be matched for optimum levels.

'Smart' Filter

This section specifically addresses the south-facing windows of the apartment building. The sun is directly penetrating through the windows during the winter months, causing significant amounts of glare. To combat this, the windows will be fitted with a smart filter that can be changed from clear to translucent utilizing a current, constructed by *Smart Tint*. Translucent filter diffuses light, completely eradicating the glare. The difference can be observed in Figure 25 below. For the portion of the window under the transom, separate controls will be used to tackle the issue of glare when the occupant is in the work plane.

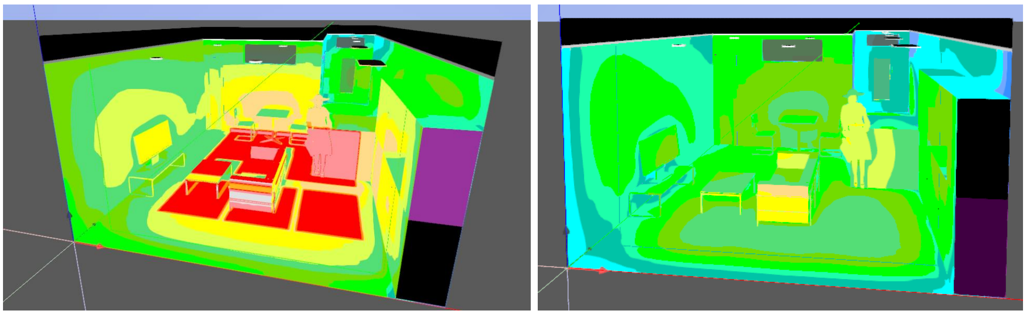


Figure 25: *Glare severity comparison (from DiaLUX model), for standard (left) vs. Smart-Tinted (right) South windows*
Note: a full-size version of this image can be seen in Appendix D-1

The cost of this material was quoted at approximately $400 for this specific window. Alternatives that were considered are light diffusing blinds that cost $80 [22]. These would function from the ceiling down however, not allowing to be used for the independent pieces of glass. Flexibility of glare reduction justifies the installation of the more expensive choice.

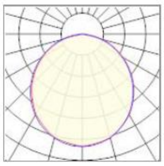
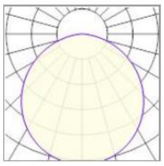
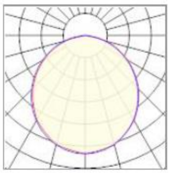
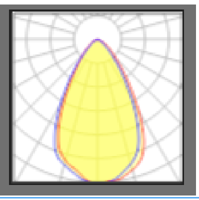
4.2.3 Interior Lighting

Light Selection and Placement

Even with a heavy emphasis on smart passive daylighting design, there is still some need for installed interior lighting systems.

Specific fixture types were selected based on recommended values and needs; for example, the Illuminating Engineering Society recommends a value of 200 lux in the living room and bedroom [23]. The following table displays detailed information about the lights that are used for the building, per apartment:

Table 10: Interior Lighting Selections

Placement	Image & Distribution Pattern		Recommended	Characteristics
Living Room + Entrance Hallway			2200 K – 3000 K 1500 – 3000 lm	3000 K 1300 lm/fixture 7 fixtures
Kitchen			2700 K – 5000 K 4000 – 8000 lm	3000 K 1600 lm/fixture 2 fixtures
Bathroom			3000 K – 5000K 4000 – 8000 lm	4000 K 4000 lm/fixture 1 fixture
Bedroom			2700 K – 3000 K 1500 – 4000 lm	2500 K 800 lm/fixture 4 fixtures

The *DiaLUX* model was rendered for nighttime, which yielded an average of 198 lux in the living room and entrance hallway. A value of 214 lux was determined for the bedroom. The bathroom and kitchen have a suggested value of 250-400 lux [23], which is why different fixtures will be used in the space. From the models generated, it is possible to see that the illumination of these areas is at 200 lux in the brightest areas. The lighting fixtures to be installed in the apartment are to be located in the optimal position for even light distribution, as modelled in the below thermal light maps and light displays for each room in the apartment (Figures 26-29) rendered from *DiaLUX*.

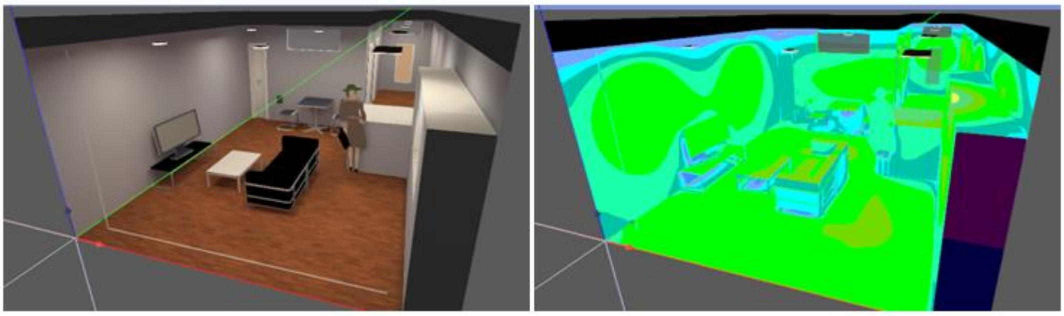


Figure 26: *Living Room Light Display (left) & Thermal Light Map (right)*

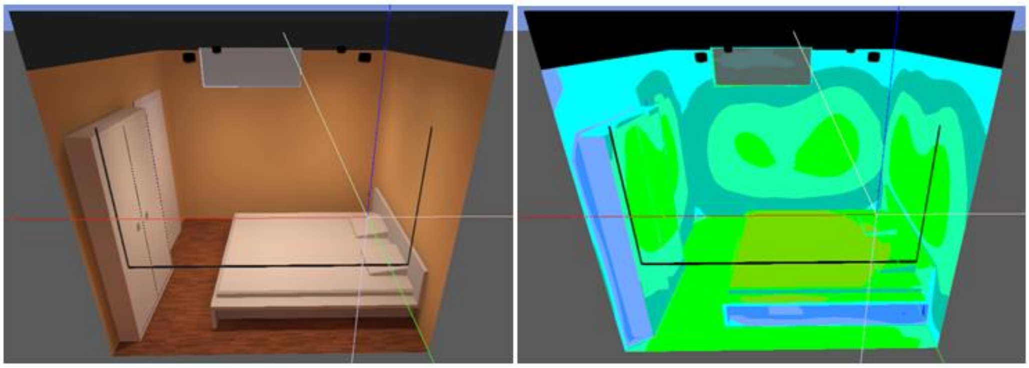


Figure 27: *Bedroom Light Display (left) & Thermal Light Map (right)*

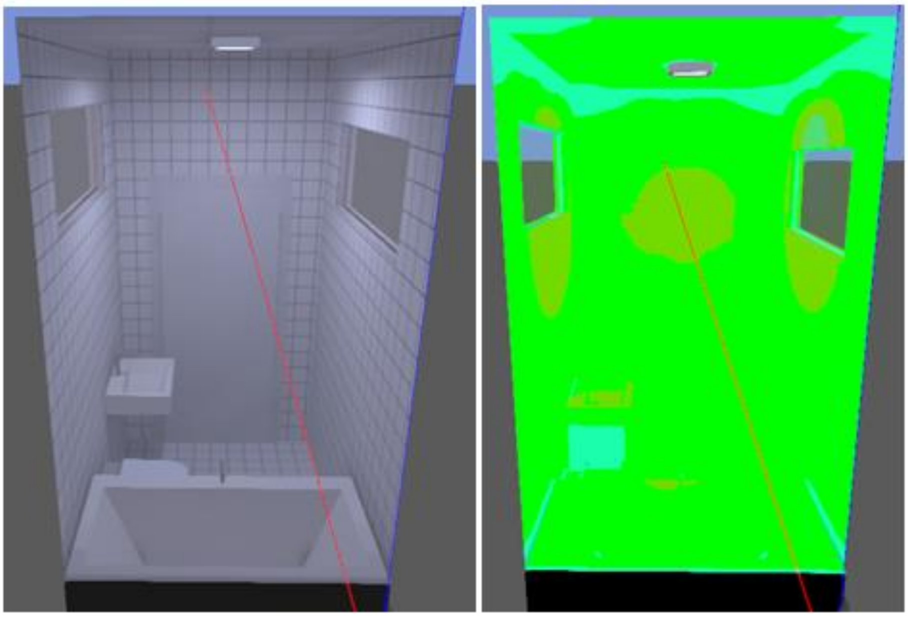


Figure 28: *Bathroom Light Display (left) & Thermal Light Map (right)*

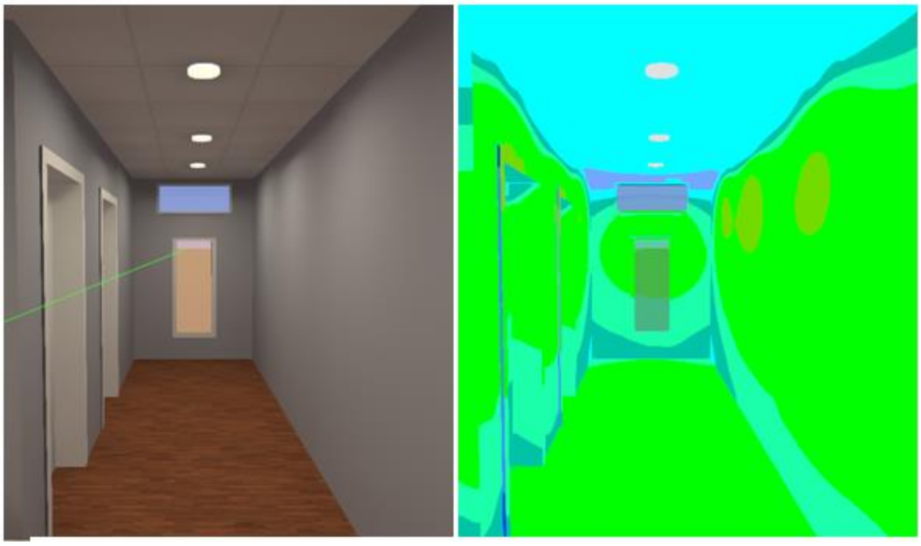


***Figure 29**: Entrance Hallway Light Display (left) & Thermal Light Map (right)*

Control Systems

Smart lighting systems make a significant difference to overall energy usage. Daylight and motion sensors were used throughout the apartment when modeled in *DiaLUX.* The energy usage was for each apartment was 1167 kWh/year normally, but only 892 kWh/year with sensors. The sensors will be used in all apartments, placed 2/3 the depth of the room from the window, as suggested by Lutron [24].

4.4.2 Analysis Methodology

Daylighting & Lighting Systems was analyzed through an iterative process that included both hand calculations and digital modelling.

4.4.2.1 Fenestration

Multiple iterations of window layouts were made using the *DiaLUX* software in order to choose a window size that would sufficiently illuminate each room, according to its use. Hand calculations were done to optimize initial designs, and then were verified.

Using the data from the daylighting spreadsheet produced in Assignment 2 of the course, the days that had the most daylight penetration were used to render the simulation in *DiaLUX*, and were then evaluated for illumination performance. As the visual transmittance of the windows (calculated in the Building Envelope section) is low, the windows are generally large. However, each type of window has special considerations, and is evaluated differently, as was outlined in the Fenestration section above (4.3.2.1).

4.4.2.2 Daylighting

The components that affected daylighting were programmed into the *DiaLUX* model. The software rendered results by utilizing this, and an evaluation on the spreadsheet used for the Fenestration (*Section 4.2.1*) iterations determined that amount of daylighting present at various times of the year.

It was observed that during all times the sun was up, there was sufficient illumination in the house. This was calculated using *DiaLUX* for overcast days, for various times in the year. During the times when the sun had set and lights were needed to maintain a certain level of illumination, the light fixtures would come on and make up for the deficient light. This is described in more detail in the next section.

4.4.2.3 Interior Lighting Systems

To determine sufficient illuminance for each room, multiple iterations using trial and error were made. This was done by observing the thermal maps rendered by *DiaLUX,* which showed whether sufficient lighting was present in the rooms. Multiple versions of the model can be seen in Figures 30-32, below.

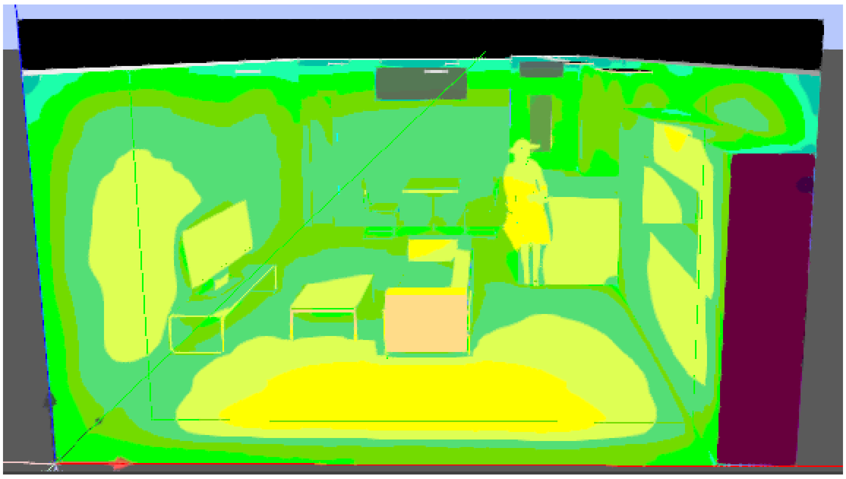


***Figure 30**: Daylight Penetration w/ 60% WWR*

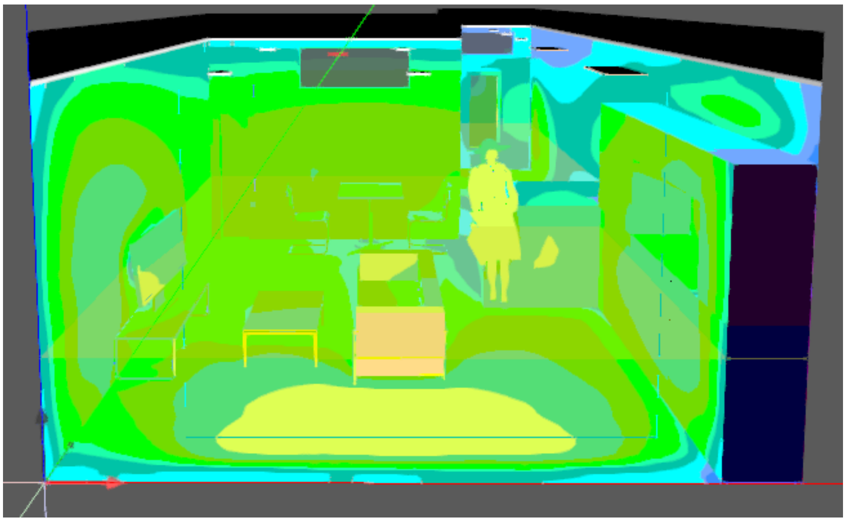


***Figure 31:** Daylight Penetration w/ 50% WWR*

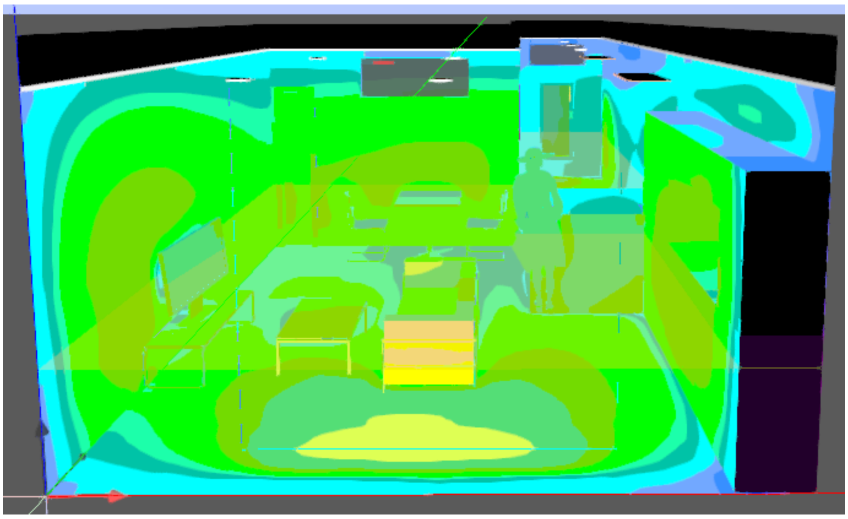


Figure 32: Daylight Penetration w/ 40% WWR

4.5 SOLAR ENERGY SYSTEM [Simon Buckley]

4.5.1 Design Concepts

We defined a net zero home as a residence that, over the course of the year, will produce more power than it uses. This means that the home could at times be drawing more energy from the grid than it is producing, so long as over the course of one year it has a positive or neutral energy yield to the electrical grid. There are very few practical technologies available at the moment for residential power generation. The two main technologies are solar photovoltaic, and solar heat collectors. Solar heat collectors work in tandem with the HVAC system to reduce the heating load. While this was originally part of our plan, it was ultimately decided not to include them. This meant that the household energy production would primarily be driven by solar panels.

The first step in evaluating the amount of solar energy available to us was to model the energy per square foot of roof space. A weather model was constructed using Climate Consultant. Climate consultant can reference past weather data for a specific geographical location and model the effects of shading from nearby obstructions. The weather data then gets exported to Microsoft Excel where we can apply principles taught in this class to calculate the yearly energy striking a specific surface. In our case we want to know the solar energy per square meter of roof space. By multiplying this number first by the area of the roof and then by the efficiency of the solar panels and inverter we can estimate the total energy produced by the house. To maximize solar gains we also attached solar panels to the overhangs above the southern windows. The dimensions of the overhangs did not allow us to use the same panels as the roof so new panels had to be sourced. The lowest overhang also required a unique model as it is affected by shading from the building across the street. The total household energy yield was found as the sum of the 4 surfaces using three models. One for the roof, one for the first overhang, and one for the second and third overhang.

The roof design which would maximize energy production would be a flat wedge shaped roof with the lowest edge pointing towards the south at a slope of 30 degrees. There are two main problem with this design. This make the northern edge of the roof over 5.77 meters higher than the southern edge. The worry is that this will contribute to shading neighbors living to the north of us and hinder their own PV generation. The second problem is that a steep wedge shaped roof is not an attractive design. A traditional pitched roof with a peak in the center of the house is much more visually appealing. The problem becomes that if we reduce the height of the roof we reduce the area on which we can capture sunlight as well as increase the angle of incidence which the light strikes the panel. Several roof models were then calculated with variable roof pitch positions and incident angles. The purpose of creating multiple models was so that once the net power consumption of the house is calculated, we could pick the model that satisfied the net zero requirement and had the lowest roof height.

The solar panels were sourced by sorting through products by efficiency of energy conversion. We selected the sun power *SPR-X21-345* as it had a very high efficiency (21.5%) and was available on the commercial market [25]. The solar panels mounted on the window overhangs are the *Panasonic VBHN240SJ25*. They had a narrower frame which fit the required dimensions and had an efficiency of 19.5% [26]. The inverter was chosen once again with efficiency as the primary concern. We decided on the *SMA 6000-TL-US* as it had a maximum efficiency of 98.5% with a working efficiency of around 97% [27].

4.5.2 Analysis Methodology

The first step in analyzing the potential solar energy is to input local climate data into climate consultant program. This is done by downloading the *EPW* file for Ottawa from energyplus.net. The file can be exported to an excel file and then the data can be manipulated to find out how much solar energy our panels can collect at any given hour of the year. This is too many calculations to do by hand so all calculation were done by Microsoft Excel. It is important to know that the weather data will provide values for direct and diffuse energy per square meter but this is not what actually that strikes a panel. The angle which sunlight will strike the panel is dictated by the geometry of the earth, its tilt, and the movement of the earth around the sun. To calculate the solar incidence angle first you must calculate the apparent solar time. The apparent solar time tells us the true hour of the day based on the sun rather than the standardized time which we commonly use.

$$AST = LST + ET + 4(LSM - LON)$$

Where LST is the local standard time (hrs), ET is the equation of time (hrs), LSM is the local standard meridian (Deg) and LON is the local longitude. The Equation of Time is a value in hours that reflect the change in the sun's position relative to the time of year

$$ET = 9.87 sin(4\pi(n - 81) \div 364) - 7.53 cos(2\pi(n - 81) \div 364) - 1.5 sin(2\pi(n - 81) \div 364)$$

Where n is the nth day of the year. With the equation of time and the apparent solar time, calculated we can calculate the hour angle which is the angle of the sun relative to solar noon.

$$h = (AST - 12) * 15 deg/h$$

We next need the solar declination which is the angle of the sun relative to the equator.

$$\delta = 23.45 sin(360 * (284 + n)/365$$

With the solar declination we can now calculate the solar altitude, which is the angle between the sun's rays and the horizon.

$$\alpha = sin^{-1}(cos(L) * cos(\delta) * cos(h) + sin(L) * sin(\delta))$$

Where L is the latitude of the location. We can also calculate the solar azimuth angle which is the angle between the horizontal projection of the sun's rays and due south.

$$\varphi = cos^{-1}((sin(\alpha) * sin(L) - sin(\delta))/(cos(\alpha) * cos(L)))$$

The surface solar azimuth is the angle between the surface azimuth and the solar azimuth. In the case of the panels on the house, they are all facing south, the surface azimuth is 90 and the surface solar azimuth becomes:

$$\gamma = \varphi - 90$$

Now we finally have all the tools calculate the solar incidence angle.

$$\theta = cos^{-1}(cos(\alpha) * cos|\varphi| * sin(\beta) + sin(\alpha) * cos(\beta)$$

Where Beta is the angle of the solar panel relative to the ground. With all of these values we can calculate the direct energy captured as well as the, diffuse energy, and the energy reflected from the ground onto the solar panel.

$$Idirect = Idirect(env) * cos(\theta)$$

$$Idiffuse = Idifuse(env) * (1 + cos(\beta))/2$$

$$Iground = (Idirect(env) * sin(\alpha)+Idifuse(env)) * GReflect * (1 - cos(\beta))/2$$

Where $GReflect$ is the ground reflectance, The sum of these three values will yield the hourly energy striking the solar panel per meter squared.

By implementing these formulas in *Excel* and applying those to the weather data can calculate yearly solar energy per square meter of roof space. The next step was create a model which produced enough power to achieve our needs while having the smallest roof pitch possible to prevent shading any potential neighbors to the south. We decided on a single flat pitched roof as it had the best performance in energy production vs. height. We also had the added benefit of three extra collection surfaces on the overhangs above the south facing windows where we could attach solar panels. The energy consumption models gave a nominal yearly energy consumption of 15.5 MWh of energy per year. After producing several iterations we found that we could achieve this with a 5 degree slope. Our house was 5 meters wide by 10 meters long. At 5 degrees of pitch we had a total roof area of 50.19 m^2. The roof only adds 0.87 meters to the height of the roof. Our rooftop solar panels were most efficiently placed with their longest side facing south in a 3X9 grid covering 44m^2. By multiplying the solar incidence irradiance calculated for a 5 degree slope by 44m ^2 we can calculate the yearly KWh of energy striking the panels to be around 65.8 MWh. By further multiplying this results by the panel and inverter efficiencies we can achieve a net energy input to the system of 13.7 MWh. Using climate consultant we modeled the potential shading from the obstruction across the street.

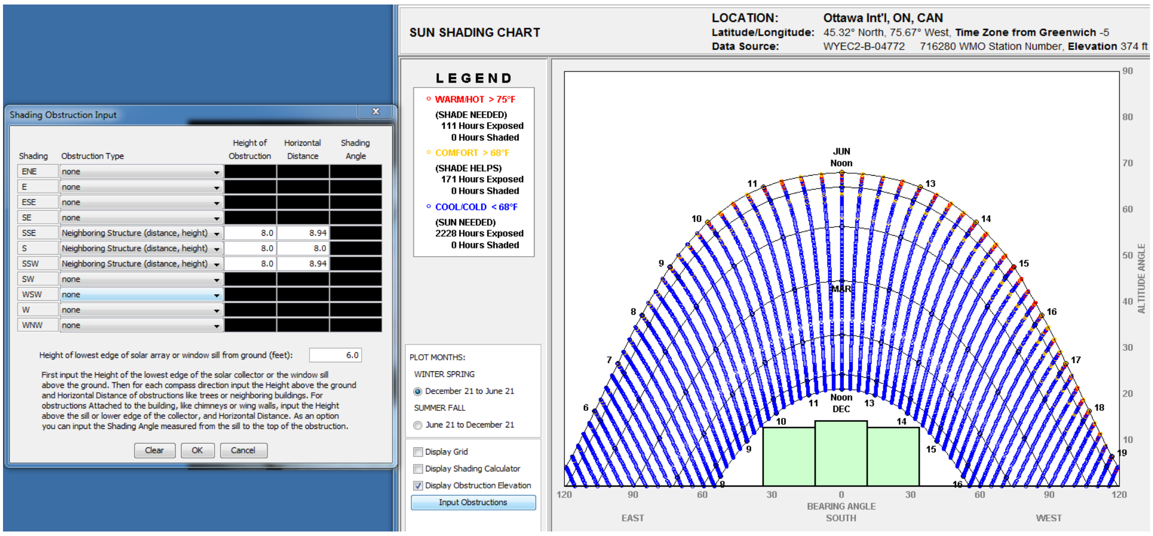


Figure 33: Shading on the South face, at 6 meters

Figure 33 shows that any object above 6m will not be affected by shading so our result can be accepted. *Excel* calculations can be found in the Appendix E-1.

To place solar panels on our overhangs, we needed to construct two new models. The first model was for the first overhang and was subject to shading from the building to the south.

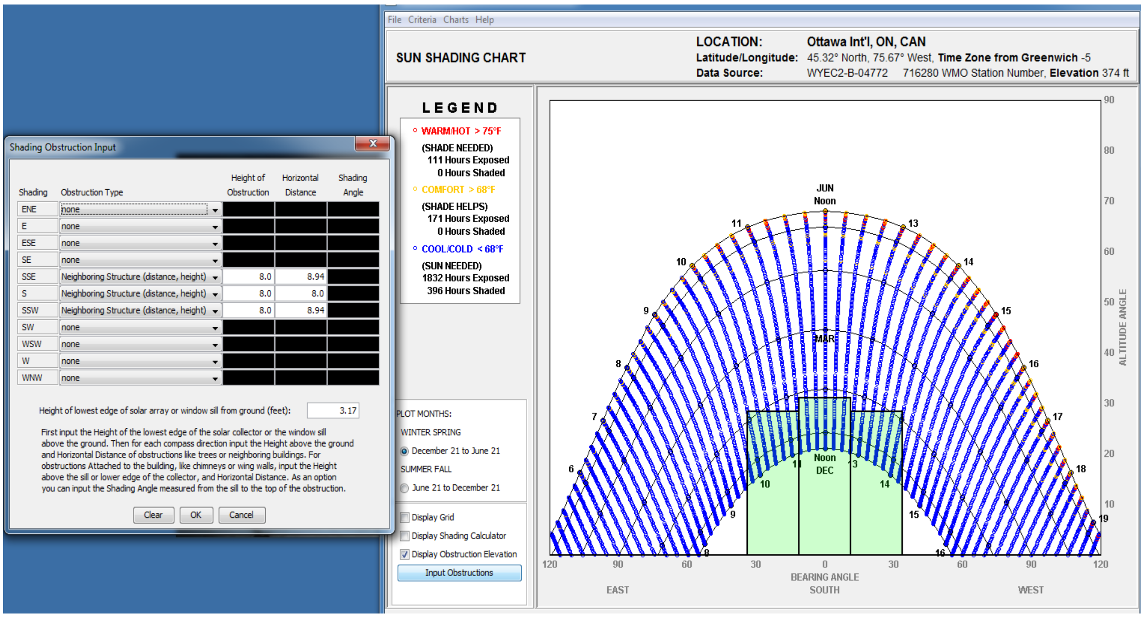


Figure 34: Shading on the South face at 3.17 meters.

Figure 34 shows that the panels will be shaded for 396 hours of the year. By removing these hours from the energy data we were able to get an estimation of the true amount energy striking the panels per year. As stated earlier, we used Panasonic panels for dimensional reasons. Our overhang supported a 1x3 grid at a 30 degree angle. The first floor overhang produced 1.12 MWh per year. The second and third floor overhangs were both above 6 meters so they were not affected by shading and their calculations could be done together. Their power production was 2.35 MWh combined. The sum of our power sources is, therefore, 17.2 MWh.

Our goal was to create a house that was net-neutral. The house consumes 15.5MWh of power each year and the combination of our power sources was 17.2MWh. This means our house has a net surplus of 1.7 MWhs of power per year. Overall, we were successful in designing a net neutral home, and the neighbors will not be upset at the height of our roof!

4.6 ADDITIONAL CONSIDERATIONS

4.6.1 Indoor Environment & Air Quality (IEQ)

4.6.1.1 Thermal Comfort

This townhouse was designed to achieve a high level of thermal comfort. Each unit in the building has a dedicated programmable thermostat in order to allow individual occupants to control their thermal environment. Operable windows, both exterior and transom, increase occupant comfort by allowing users to modify temperatures and ventilation rates. The radiant in-floor heating panels provide even heating throughout the space and avoid a feeling of draftiness often caused by forced-air heating. The building's glazing was designed to prevent overheating during summer months, while allowing winter sun to enter the apartments. The design conditions fall within the *ASHRAE 55*, as shown in Figures 35 and 36. The high percentage of glazing, particularly on the southern walls, could be a source of discomfort when exterior temperatures are extreme.

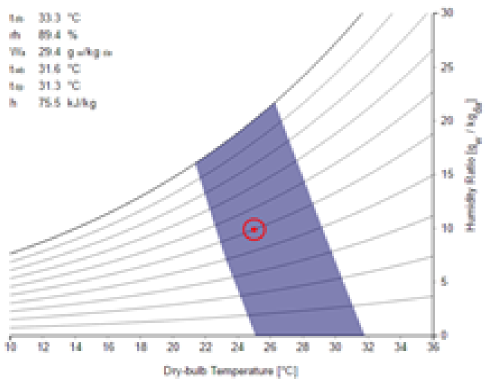


Figure 35 *- Summer Design Conditions*
Summer design: 25 C, 50% RH, 0.5 clo.

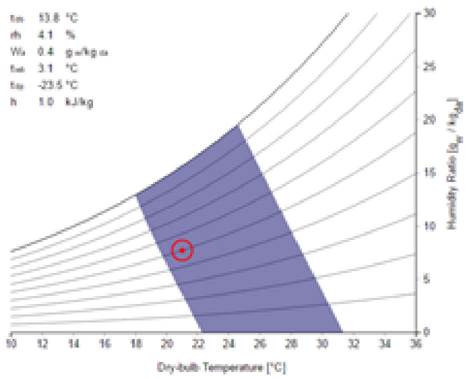


Figure 36 *- Winter Design Condition*
Winter design: 21 C, 50% RH, 1.0 clo

4.6.1.2 Acoustic Comfort

The HVAC system was designed to cause minimal noise contamination in the apartment, as all large equipment is located in the basement utility room. As well, the radiant in-floor heating panels are exceptionally quiet, as they don't require blower fans to operate. The efficiency of the panels is not decreased by floor coverings, so carpet can be laid in the apartment to muffle excess noise reflection. The ceilings are a reasonable height, preventing echoes. Sound can travel through the operable transom windows, but otherwise will propagate through each unit much like a conventional single story Ottawa apartment. Possible sources of discomfort include noise through shared eastern and western walls, as well as exterior noise. The ducting hatch could also allow sound to travel between units, which would be undesirable for privacy reasons.

4.6.1.3 Visual Comfort

Staying within the recommended room surface reflection reduces the need for the occupant's eyes to adapt to over bright or dark surfaces. This plays a significant part in the visual comfort, as it directly reflects in the brightness of the room. During hours of darkness, the colour temperature of the lights affects the mood and visual clarity of the occupant. For further details about light colour temperature and surface reflectivity, see Tables 10 and 11.

4.6.2 Interior Design

Bedrooms generally require less heat and light, so being placed on the North side of the layout was fitting. On the other hand, frequently used rooms (such as a home office, or the living or dining rooms of a residential building), should be located on the southern side where they can be warmed by sunlight throughout the day [1]. So, this was implemented. Also, thermal mass shelves allow heat energy to be stored heat energy and then released gradually, contributing to consistently comfortable interior temperature [1].

Light-coloured paints can make spaces look and feel brighter with their "reflectance", while also mitigating the heat island effect through reduced heat absorption [1]. A study that took place about the reflectance of areas inside a house by the US Department of Energy mentions approximate guidelines for homeowners. This indicated that the reflectance of the ceiling should be 80%, walls to be 30%-50% and floors to be 10%-20%. The following table shows what will be used for the construction of the apartments.

Table 11: Interior Material Selections, Based on Reflection Values

Interior Space	Recommended Value	Material & Reflectance
Living & Kitchen Ceiling	80%	Ceiling Tiles (80%)
Living & Kitchen Walls	30% - 50%	Signal Gray (37.2%)
Living & Kitchen Floor	10% - 20%	Makassar (16%)
Bedroom Ceiling	80%	Ceiling Tiles (80%)
Bedroom Walls	30% - 50%	Pastel Yellow (45%)
Bedroom Floor	10% - 20%	Makassar (16%)
Bathroom Ceiling	80%	Ceiling Tiles (80%)
Bathroom Walls	30% - 50%	White Tiles (64%)
Bathroom Floor	10% - 20%	Black & White Tiles (34%)

The discrepancies seen with the bathroom are primarily because this is an area of the house that should have high illuminance. The amount of daylight that is penetrating the bathroom is quite small, hence reflective tiles are used to amplify this.

Renders of the interior design and layout can be seen in the renders, below (Figure 37).

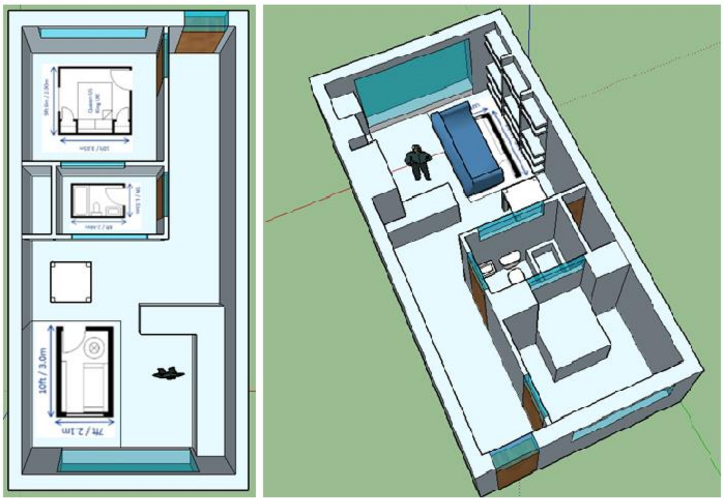


Figure 37: 3D rendering of one of the apartment units' thoughtful interior design and massing

4.6.3 Material Selection for Low Environmental Impact

Material choices have an impact in the overall performance of a building, particularly from an environmental impact. A high efficiency building should also incorporate sustainable and reasonable material choices. As environmental impact is often difficult to quantify, life cycle assessment analysis can be used to justify the used of ICF forms in this building. Although ICF forms have a high initial environmental impact, they have a longer lifespan making them essentially "pay back" on this impact. Another key point is that a lot of the environmental impact comes from the daily routines of a building rather than the construction cost. This means that if these maintenance, heating and cooling requirements can be reduced the building will have an overall lessened impact. ICF provides a solution to this idea [28].

4.6.4 Occupant Behavior & Engagement

Major sources of energy waste can be avoided by modifying our behavior to be more energy efficient. As discussed in the comfort section, we can save energy by dressing with the season. In the winter dressing warmer and setting the thermostat no higher than 21 degrees can reduce heating bills. In the winter, heating can account for up to 30% of one's utility bill [29]. In the summer by wearing lighter clothes, the temperature can be set as high as 25 degrees and still maintain optimal ASHRAE conditions.

Appliances are a large portion of the household load, however using them in a more efficient manner can reduce their impact. Using cold water to wash your clothes is a good example of this. Appliances will leak current while not in use. By unplugging them when they are idle, power can be saved. Instead of thawing food in the microwave, putting the food in the fridge the morning before as an energy saving alternative.

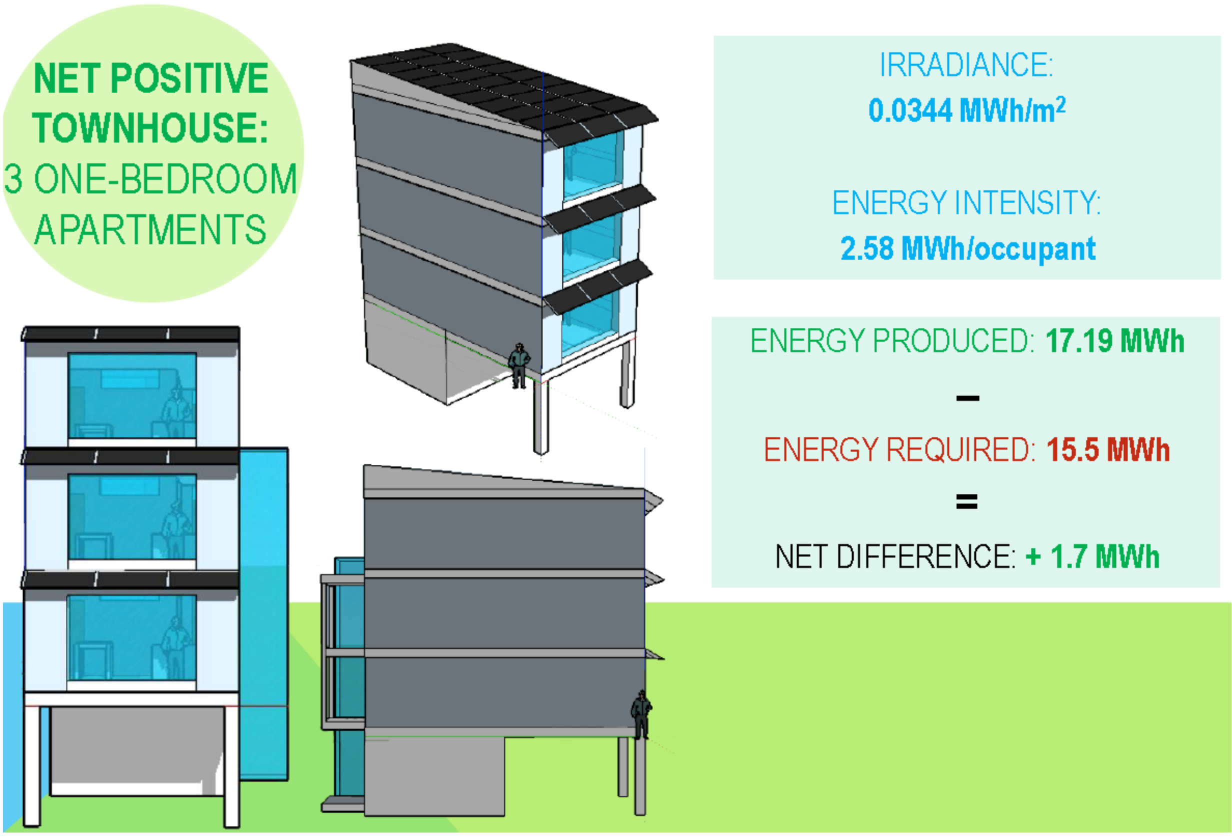
It is important to inspect ones property. Do a walk around of the building to check for damages in the insulation or cracks in the windows or doors. Any crack or gap means that the buildings envelope is compromised and the building will be underperforming. Performing maintenance on such issues is important. One such task is changing the filter in your furnace. By following the filter replacement schedule outlined in the manufacturer's documentation for the furnace electricity bills will be reduced.

The house has lots of windows. During the day, keep the blinds open and use the sun's energy to light up the room. Energy can further be reduced if the occupant take short showers and don't leave the water on while shaving or brushing their teeth. These routines may seem silly but they will save the occupants plenty of energy.

5.0 CONCLUSION

Once set with a goal, constraints, and guidelines, the team was able to start the design of a three-storey townhouse apartment. Smart massing and passive design decisions were made to set the stage for the rest of the design elements. Daylighting & lighting systems and the solar energy system balanced roof space and shading with natural lighting and solar gains. Building envelope and HVAC systems were balanced optimize wall thickness and thermal performance. Finally, determining the amount of energy needed on an annual basis, versus the amount produced, was done in an over-arching *HOT 2000* model. The additional consideration of indoor environment quality, interior design, material selection for environmental impact, and occupant behavior further strengthened the design.

The final performance metrics were calculated, and are summarized in the infographic below. Looking at it in an annual scale, the building is performing 40% better than the aggregate average for Canada, which we took common baseline values for Canada as 17.83 MWh/m^2 (irradiance) and 0.17 MWh/apt (energy intensity).



Designing the schematics of a net-positive building in just one fall semester was quite the undertaking, and a great learning experience. Working together with a team, all members leading different components, emphasized the importance of communication, coordination, and integration for a successful project.

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APPENDICES

APPENDIX A: DESIGN STRATEGIES & INTERGRATED DESIGN

APPENDIX A.1: HOUSEHOLD ENERGY USE HAND CALCULATIONS

Secondary Energy Use

Data from Excel Sheets from: open.canada.ca

Energy Use Data Handbook Tables (Canada) – Residential Sector

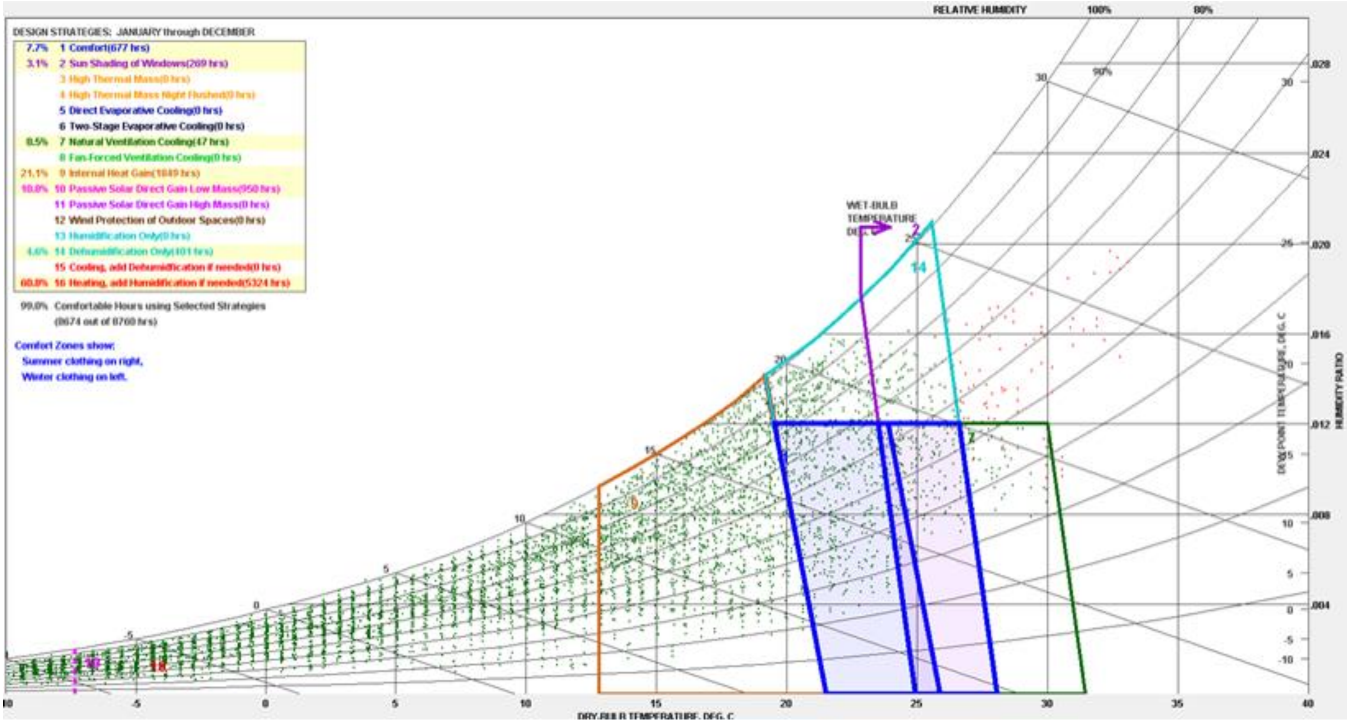
Using 2013 Data $\quad 1\ GJ = 277.\dot{7}\ kWh$

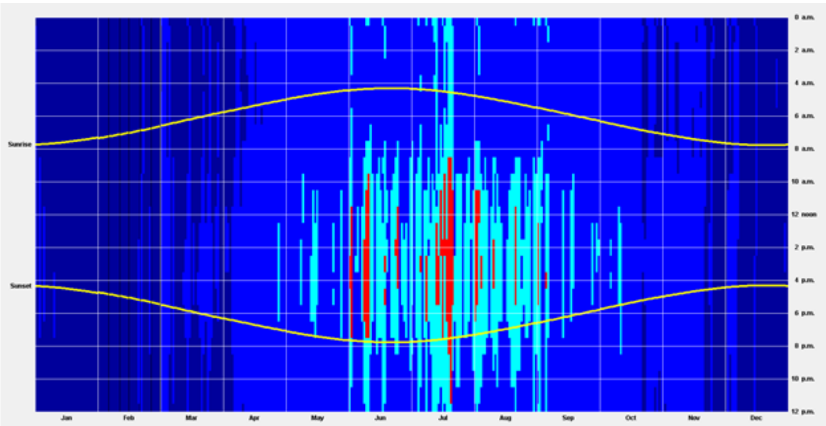
	Residential Single Attached	Residential Apartments
Energy Intensity GJ/m^2	$0{,}67\ GJ/m^2 \times 150\ m^2$ $\therefore 100{,}5\ GJ$ $\sim 27\ 916{,}\dot{6}\ kWh$	$0{,}64\ GJ/m^2 \times 150\ m^2$ $\therefore 96\ GJ$ $\sim 26\ 666{,}\dot{6}\ kWh$
Energy Intensity GJ/household	$96{,}7\ GJ/household$ $\therefore 96{,}7\ GJ$ $\sim 26\ 861{,}\dot{1}\ kWh$	$64{,}2\ GJ/household \times 3$ $\therefore 192{,}6\ GJ$ $\sim 53\ 500\ kWh$

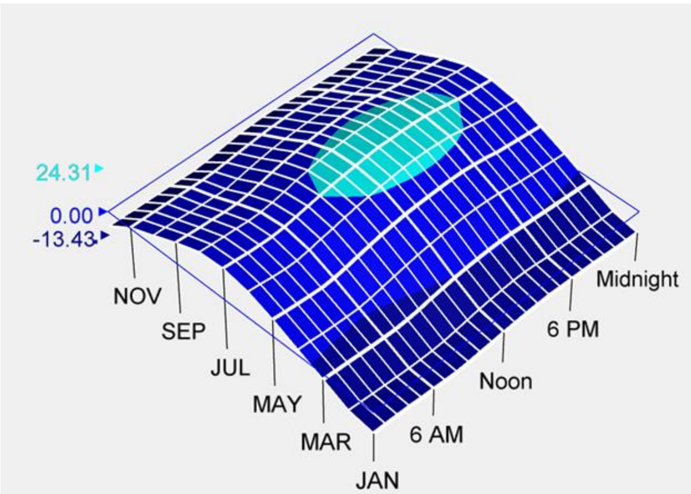
$\therefore$ Annual Secondary Energy Use of building this size would be ~27 MWh/year

Sources: Statistics Canada, Report on Energy Supply & Demand in Canada, 1990-2013, Ott, 2015
Natural Resources Canada, Residential End-Use Model, Ottawa, 2015

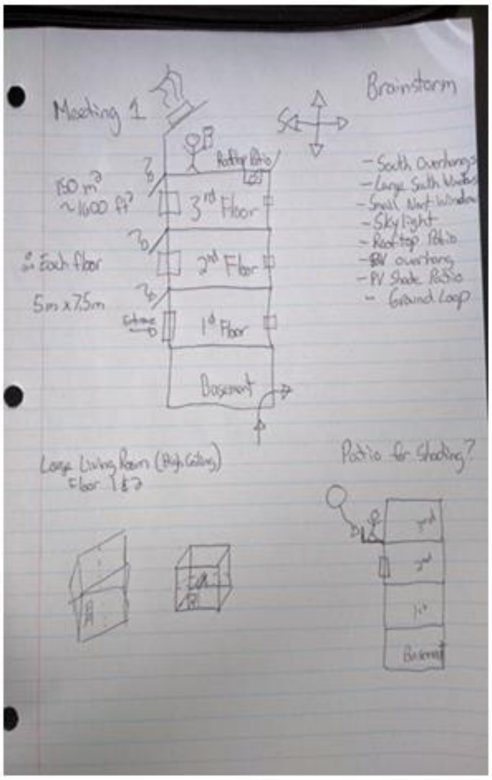
APPENDIX A.2: PSYCHROMETRIC CHART, DRY BULB TEMPURATURE

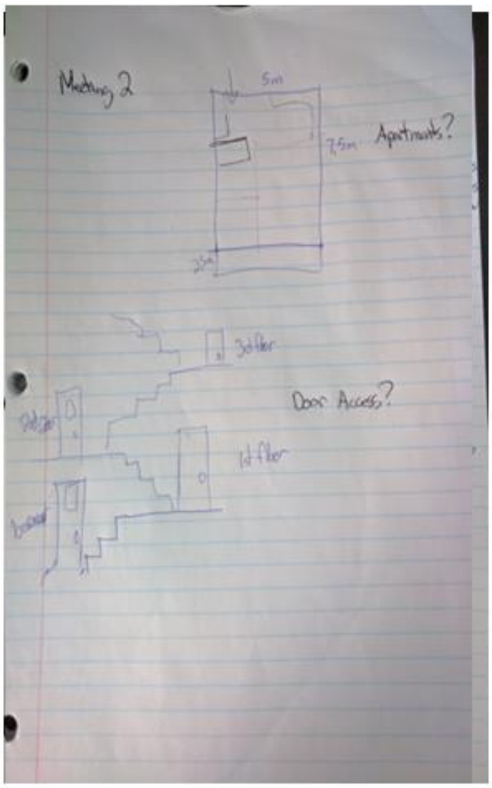






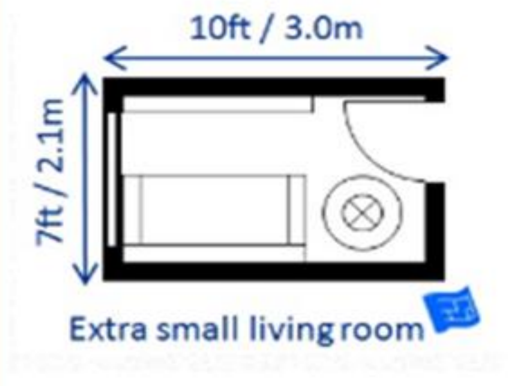
APPENDIX A.3: BUILDING FORM SKETCHES





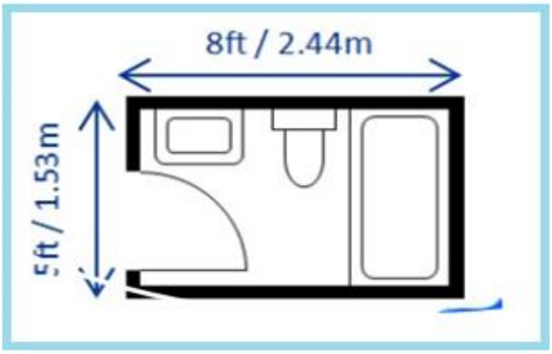
APPENDIX A.4: HOUSE PLANS HELPER SITE [30]

EXTRA SMALL LIVING ROOM & TV VIEWING DISTANCE CHART

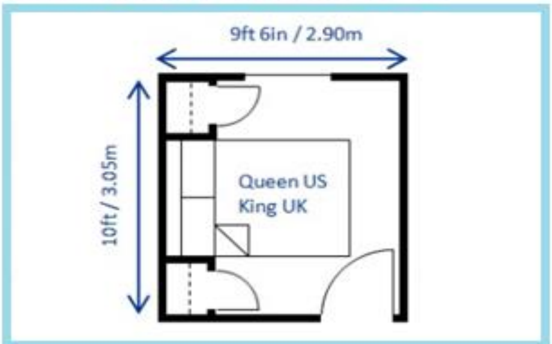


Diagonal screen size	TV viewing distance range in feet (m)
26"	3'3" - 6'6" (1.0 m – 2.0 m)
32"	3'8" - 7'6" (1.1m - 2.3m)
37"	4'3" - 8'5" (1.3m - 2.6m)
43"	5'3" - 10'5" (1.6m - 3.2m)
47"	5'9" - 11'8" (1.8m - 3.6m)
51"	6'3" - 12'5" (1.9m - 3.8m)
55"	6'9" - 12'8" (2.1m - 3.9m)
60"	7'5" - 15' (2.3m - 4.6m)
65"+	8'1" - 16'2" (2.5m - 4.9m)

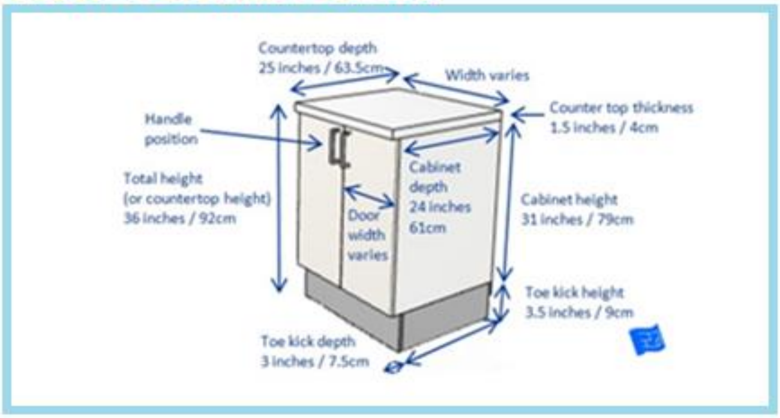
MINIMUM BATHROOM SIZE



MINIMUM BEDROOM SIZE

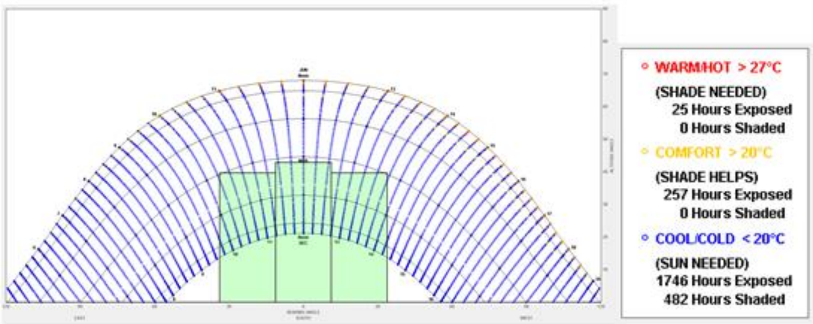


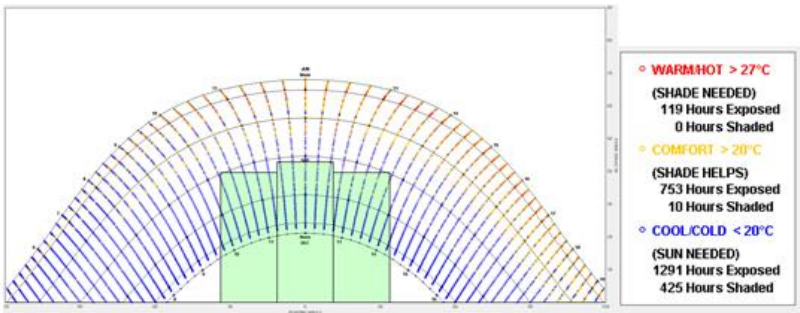
KITCHEN CABINET SIZING



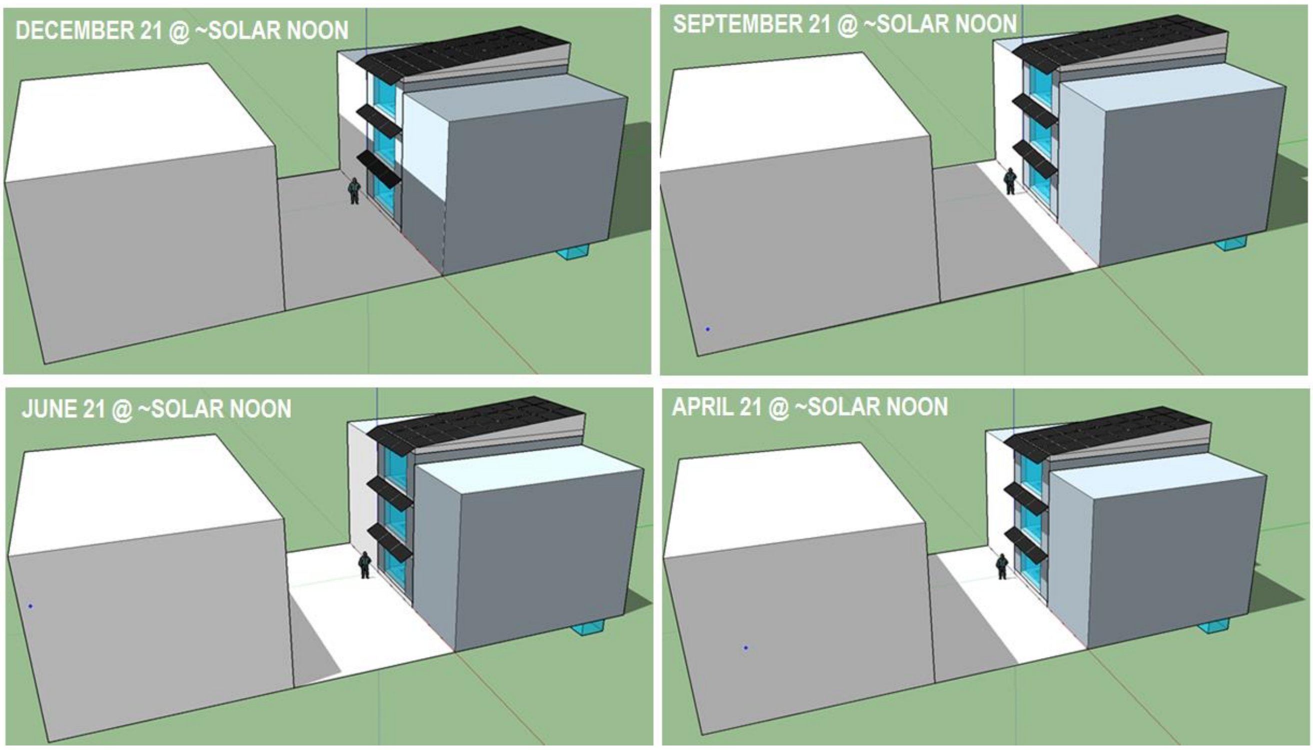
APPENDIX A.5: SHADING FROM ACROSS THE STREET NEIGHBOR

			Shades Needed			Shades Help			Sun Needed			Overall		
What Height?	Height (m)	Season	Exposed (hr)	Shaded (hr)	Percentage	Exposed (hr)	Shaded (hr)	Percentage	Exposed (hr)	Shaded (hr)	Percentage	Exposed (hr)	Shaded (hr)	Percentage
1st Floor Window Bottom	0.58	Winter/Spring	25	0	0.00%	257	0	0.00%	1746	482	21.63%	2028	482	19%
		Summer/Fall	119	0	0.00%	753	10	1.31%	1291	425	24.77%	2163	435	17%
		Year	**144**	**0**	**0.00%**	**1010**	**10**	**0.98%**	**3037**	**907**	**23.00%**	**4191**	**917**	**18%**
1st Floor Overhang	2.77	Winter/Spring				257	0	0.00%	1815	413	18.54%	2097	413	16%
		Summer/Fall				763	0	0.00%	1358	358	20.86%	2240	358	14%
		Year				**1020**	**0**	**0.00%**	**3173**	**771**	**19.55%**	**4337**	**771**	**15%**
2nd Floor Window Bottom	3.42	Winter/Spring							1848	380	17.06%	2130	380	15%
		Summer/Fall							1396	320	18.65%	2278	320	12%
		Year							**3244**	**700**	**17.75%**	**4408**	**700**	**14%**
2nd Floor Overhang	5.6	Winter/Spring							2228	0	0.00%	2510	0	0%
		Summer/Fall							1716	0	0.00%	2598	0	0%
		Year							**3944**	**0**	**0.00%**	**5108**	**0**	**0%**
3rd Floor Window Bottom	6.25	Winter/Spring												
		Summer/Fall												
		Year												
3rd Floor Overhang	8.45	Winter/Spring												
		Summer/Fall												
		Year												





APPENDIX A.6: SKETCHUP SHADING FROM NEIGHBOR



APPENDIX A.7: WINDOW HEAT GAIN & SHADING FROM DESIGNED [30]

GROUND

surface: default or unknown surface

ground reflectance: 0.2 (0.0 to 1.0)

WINDOW

window: triple-glazed low-E superwindow 0.08x2 (insul. vinyl)

SHGC: 0.37 (0.0 to 1.0)

orientation: SOUTH

OUTPUT FORMAT

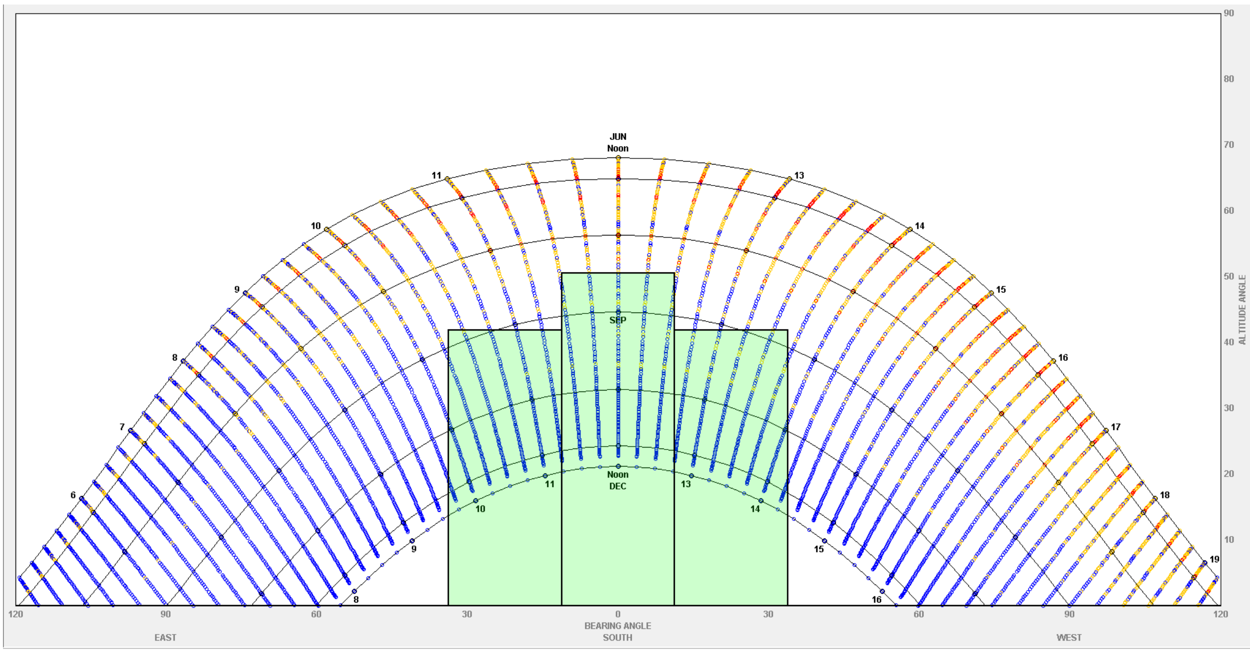
units: kilowatt-hours / m2

calculate

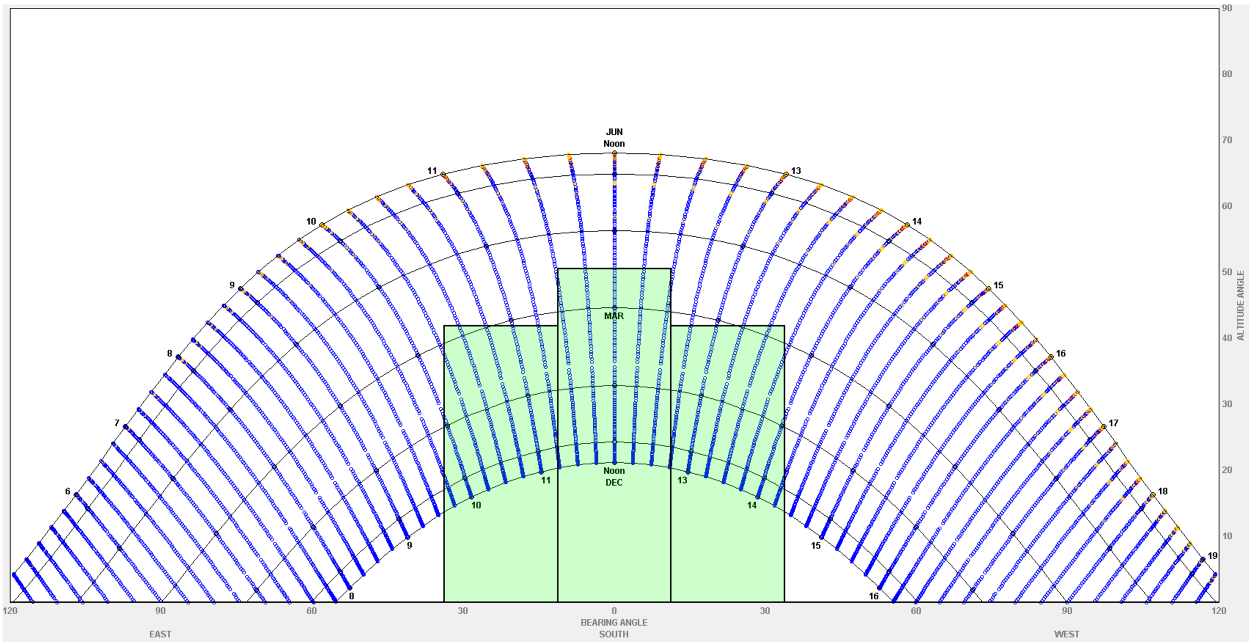
	MORNING									AFTERNOON									
	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	MONTHLY	
Jan					1.5	5.5	8.2	9.8	10.2	9.8	8.2	5.5	1.5					Jan	60
Feb				0.3	2.9	5.7	7.7	8.9	9.3	8.9	7.7	5.7	2.9	0.3				Feb	61
Mar				0.9	3.4	5.9	7.8	9	9.4	9	7.8	5.9	3.4	0.9				Mar	64
Apr			0.2	0.8	2.3	4.3	6	7	7.4	7	6	4.3	2.3	0.8	0.2			Apr	49
May		0.1	0.4	0.8	1.6	3.1	4.6	5.7	6	5.7	4.6	3.1	1.6	0.8	0.4	0.1		May	39
Jun		0.2	0.5	0.9	1.3	2.4	3.7	4.6	4.9	4.6	3.7	2.4	1.3	0.9	0.5	0.2		Jun	32
Jul		0.1	0.5	0.9	1.5	2.7	4.1	5.1	5.4	5.1	4.1	2.7	1.5	0.9	0.5	0.1		Jul	35
Aug			0.3	0.8	2	3.7	5.4	6.4	6.8	6.4	5.4	3.7	2	0.8	0.3			Aug	44
Sep			0.1	0.9	2.9	5.1	6.8	7.9	8.3	7.9	6.8	5.1	2.9	0.9	0.1			Sep	56
Oct				0.6	3.3	6.1	8.2	9.4	9.9	9.4	8.2	6.1	3.3	0.6				Oct	65
Nov					1.9	5.6	8	9.4	9.9	9.4	8	5.6	1.9					Nov	60
Dec					1	5.1	8	9.6	10.1	9.6	8	5.1	1					Dec	57
	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	ANNUAL	
	MORNING									AFTERNOON								620	

	MORNING									AFTERNOON								
	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	
Jan					0%	0%	0%	0%	0%	0%	0%	0%	0%					Jan
Feb				0%	0%	1%	5%	7%	8%	7%	5%	1%	0%	0%				Feb
Mar				13%	20%	22%	23%	23%	24%	23%	23%	22%	20%	14%				Mar
Apr				100%	83%	62%	54%	51%	50%	51%	54%	62%	84%	100%				Apr
May					100%	100%	97%	86%	83%	86%	97%	100%	100%					May
Jun					100%	100%	100%	100%	100%	100%	100%	100%	100%					Jun
Jul					100%	100%	100%	100%	97%	100%	100%	100%	100%					Jul
Aug				100%	100%	86%	71%	65%	63%	65%	71%	86%	100%	100%				Aug
Sep				56%	41%	36%	35%	34%	34%	34%	34%	36%	40%	54%				Sep
Oct				0%	3%	9%	12%	13%	13%	13%	12%	9%	3%	0%				Oct
Nov					0%	0%	0%	0%	0%	0%	0%	0%	0%					Nov
Dec					0%	0%	0%	0%	0%	0%	0%	0%	0%					Dec
	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	
	MORNING									AFTERNOON								

APPENDIX A.8: SUN PATH CHARTS

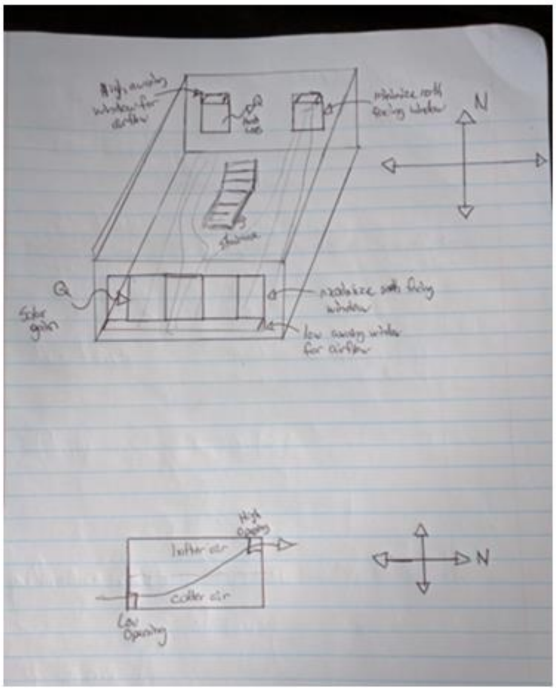


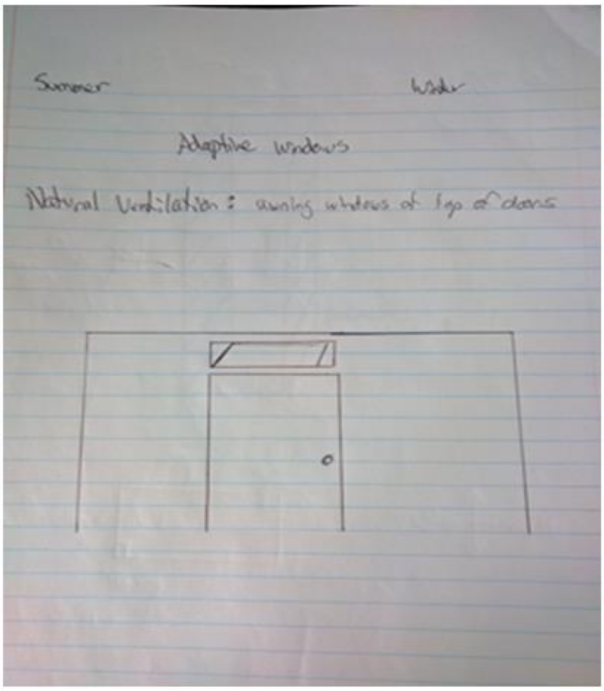
June 21 to Dec 21



Dec 21 to June 21

APPENDIX A.9: NATURAL VENTILATION SKETCHES

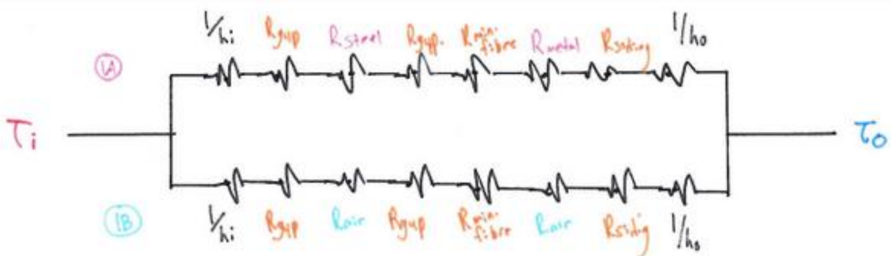




APPENDIX B: BUILDING ENVELOPE

APPENDIX B.1: BUILDING ENVELOPE ANALYSIS

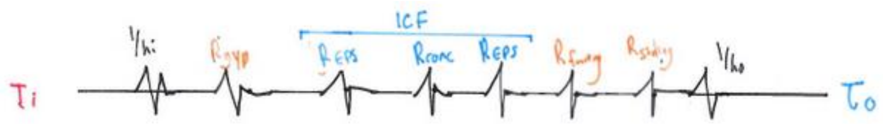
Wall Assembly #1: Non-Combustible Steel-Framed Wall Construction with Mineral Fiber Insulation



Components	Width [in]	Width [m]	Est. Cost ($/m^2)	k [W/m-k]	RSI-Value	Cost Source	k Source
Interior Air	-	-	-	-	0.20		
Interior Gypsum Wall Board	0.50	0.0127	$2.86	0.17	0.07	https://www.homedepot	http://www.engineeringt
Steel Studs	5.5	0.1397	$8.45	54	0.00	https://www.menards.c	ENVE 4105 slides
Air Gap [where: no Steel Stud]	5.5	0.1397		1	0.14		ENVE 4105 slides
Gypsum Board Sheating	0.625	0.015875	$5.68	0.17	0.09	https://www.homedepot	http://www.engineeringt
Mineral Fiber Insulation Boards	4	0.1016	$37.31	0.048	2.12	http://www.buyinsulatio	http://www.engineeringt
Metal Hat	0.375	0.009525	$3.53	54	0.00	http://www.rona.ca/en/	ENVE 4105 slides
Air Gap [where: no Metal Hat]	0.375	0.009525		1	0.01		ENVE 4105 slides
Fiber Cement Siding	0.31	0.0079375	$11.57	0.17	0.05	http://www.homedepot.	https://framecad.com/ge
Exterior Air	-	-	-	-	0.10		
TOTAL			**$69.39**		**2.76**		
1A: Section through metal studs					2.63		
1B: Section through air gaps					2.78		

Heat Loss [kWh/m^2]	(4500)*(1/RSI)*24/1000 **39.09695615**
Heating Cost ($/m^2)	heat loss * $0.1 **$3.91**
PV [$/m^2]	PV = A * [(1-(1+0.05)^-50)/(0.05)] PV = A * 18.26
Annuity:	$71.39
Capital:	$69.39
Total:	**$140.78**

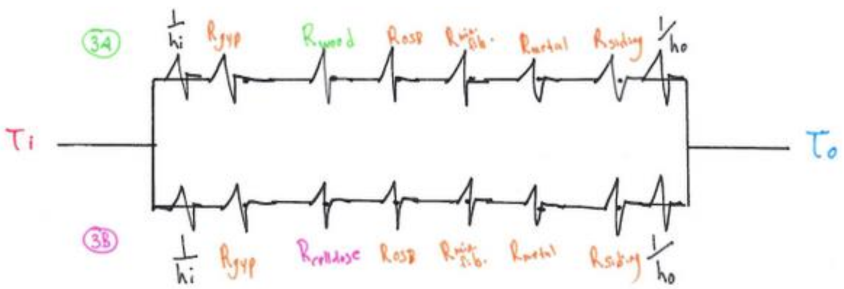
Wall Assembly #2: ICF Wall Blocks



Components	Width [in]	Width [m]	Est. Cost ($/m^2)	k [W/m-k]	RSI-Value	Cost Source	k Source
Interior Air	-	-	-	-	0.20		
Interior Gypsum Wall Board	0.50	0.0127	$2.86	0.17	0.07	https://www.homedepot	http://www.engineeringt
ICF - EPS Foam Board	2.5	0.0635		0.038	1.67		http://www.bcrmca.ca/
ICF - Concrete Core	6	0.1524	$40.90	2	0.08	https://www.homedepot	http://www.bcrmca.ca/
ICF - EPS Foam Board	2.5	0.0635		0.038	1.67		http://www.bcrmca.ca/
Furring strips	0.375	0.009525	$3.53	54	0.00	http://www.rona.ca/en/	http://www.engineeringt
Cladding [Assume Fiber Cement Siding]	0.3125	0.0079375	$11.57	0.17	0.05	http://www.homedepot.	https://framecad.com/ge
Exterior Air	-	-	-	-	0.10		
TOTAL			**$58.85**		**3.84**		

Heat Loss [kWh/m^2]	(4500)*(1/RSI)*24/1000
	28.12588838
Heating Cost ($/m^2)	heat loss * $0.1
	$2.81
PV [$/m^2]	PV = A * [(1-(1+0.05)^-50)/(0.05)]
	PV = A * 18.26
Annuity:	$51.36
Capital:	$58.85
Total:	**$110.21**

Wall Assembly #3: 2x6 Advanced Stud Frame Wall with Mineral Fiber Insulation Board



Components	Width [in]	Width [m]	Est. Cost ($/m^2)	k [W/m-k]	RSI-Value	Cost Source	k Source
Interior Air	-	-	-	-	0.20		
Interior Gypsum Wall Board	0.50	0.0127	$2.86	0.17	0.07	https://www.homedepot	http://www.engineeringt
Wood Studs	5.5	0.1397	$7.26	0.12	1.16	https://www.lowes.ca/c	ENVE 4106 Lecture No
Cellulose Insulation	5.5	0.1397	$8.13	0.04	3.49	http://www.rona.ca/en/	ENVE 4106 Lecture No
OSB Sheathing	0.25	0.00635	$3.01	0.12	0.05	http://www.homedepot.	ENVE 4106 Lecture No
Mineral Fiber Insulation Boards	4	0.1016	$37.31	0.048	2.12	http://www.buyinsulatio	http://www.engineeringt
Metal Hat/Air Gap	0.375	0.009525	$3.53	54	0.00	http://www.rona.ca/en/	http://www.engineeringt
Fiber Cement Siding	0.3125	0.0079375	$11.57	0.17	0.05	http://www.homedepot.	https://framecad.com/ge
Exterior Air	-	-	-	-	0.10		
TOTAL			$73.67		5.79		
3A: Section through wood stud					3.76		
3B: Section through cellulose insulation					6.08		

Heat Loss [kWh/m^2]	(4500)*(1/RSI)*24/1000
	18.64442879
Heating Cost ($/m^2)	heat loss * $0.1
	$1.86
PV [$/m^2]	PV = A * [(1-(1+0.05)^-50)/(0.05)]
	PV = A * 18.26
Annuity:	$34.04
Capital:	$73.67
Total:	**$107.71**

APPENDIX C: HVAC

APPENDIX C.1: PEAK HEATING / COOLING LOAD SPREADSHEET

transmission			section			design conditions (99.6%)			
area	u value	UA	north wall			indoor		outdoor	
6	1.4	8.4				heating	cooling	heating	cooling
1.2	3.2	3.84			air	22	25	-24.5	30.3
13.5	1.6	21.6			underground			-10	10
15	0.2	3							
22.5	1.4	31.5	south wall						
15	0.3	4.5							
40	0.1	4	roof						
105	0.2	21	bsmt/foundation						
infiltration ra	ACH @ normal pressure		air density (kg/m3)		mass flow rate (kg/s)				
1.5	0.075		1.225		0.01020833				
house volume (m^3)			cp (J/kg)						
400			1000						
ventilation target (L/s)									
60					0.0735				
HEATING				COOLING					
transmitted l	infiltration	ventilation		transmitted	infiltration	ventilation	other gains		
390.6	474.6875	3417.75		-44.52	-54.104167	-389.55	-1500	solar	
178.56				-20.352			-4500	appliance	
1004.4				-114.48			-400	occupant	
139.5				-15.9					
1464.75				-166.95					
209.25				-23.85					
186				-21.2					
672				315					
transmitted total				transmitted total					
4245.06				-92.252					
total heat loss				total heat gain					
8137.4975				-6935.9062					

APPENDIX C.2: BASE LOADS AND HOT WATER USAGE

base loads (kWh/day)				
average canadian house, 3 occupants				per occupant
19				6.33333333
average, 4 occupants		efficient appliances, 4 occupants		
25.3333333		19		
domestic hot water				
gpm				
avg	low flow	appliance	%	
4	1.6	toilet	0.4	
3	2	shower	0.66666667	
2.5	1.5	faucet	0.6	
43	27	washer	0.62790698	
average L/s usage in canada per person			with low flow	
250			145	

APPENDIX C.3: ASHRAE 62.2 VENTILATION RATE REQUIREMENTS

ASHRAE Standard 62.2 Table 4.1a Continuous Whole-Building Ventilation Rate in cfm					
Floor Area (sq ft)	Number of Bedrooms				
	0 - 1	2 - 3	4 - 5	6 - 7	> 7
< 1500	30	45	60	75	90
1501 - 3000	45	60	75	90	105
3001 - 4500	60	75	90	105	120

APPENDIX C.4: ASHRAE 62.2 DESIGN CONDITIONS FOR OTTAWA INTERNATIONAL AIRPORT

OTTAWA INT'L AIRPORT 716280 45.32N 75.67W 114 99.96 -5.00 NAE 7201

Annual Heating and Humidification Design Conditions

Coldest month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB	
			99.6%			99%			0.4%		1%			
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
2	3a	3b	4a	4b	4c	4d	4e	4f	5a	5b	5c	5d	6a	6b
1	-24.5	-21.8	-31.0	0.2	-23.5	-28.5	0.3	-21.4	12.4	-7.3	11.0	-8.1	3.5	290

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest month	Hottest month DB range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
7	8	9a	9b	9c	9d	9e	9f	10a	10b	10c	10d	10e	10f	11a	11b
7	10.1	30.3	21.4	28.7	20.5	27.0	19.5	22.9	28.2	21.8	26.4	20.8	25.3	4.3	220

APPENDIX D: DAYLIGHTING & LIGHTING SYSTEMS

APPENDIX D.1: LARGER MODEL RENDERS FOR SMART COATINGS

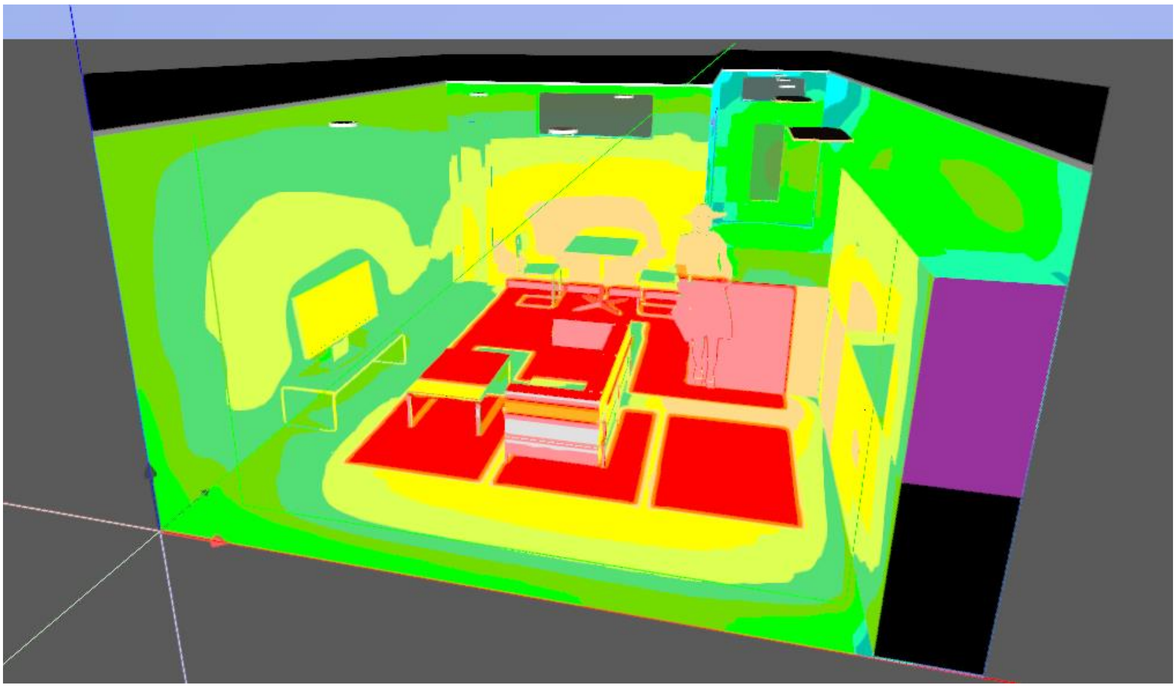


Figure 1: *Without Smart Tint*

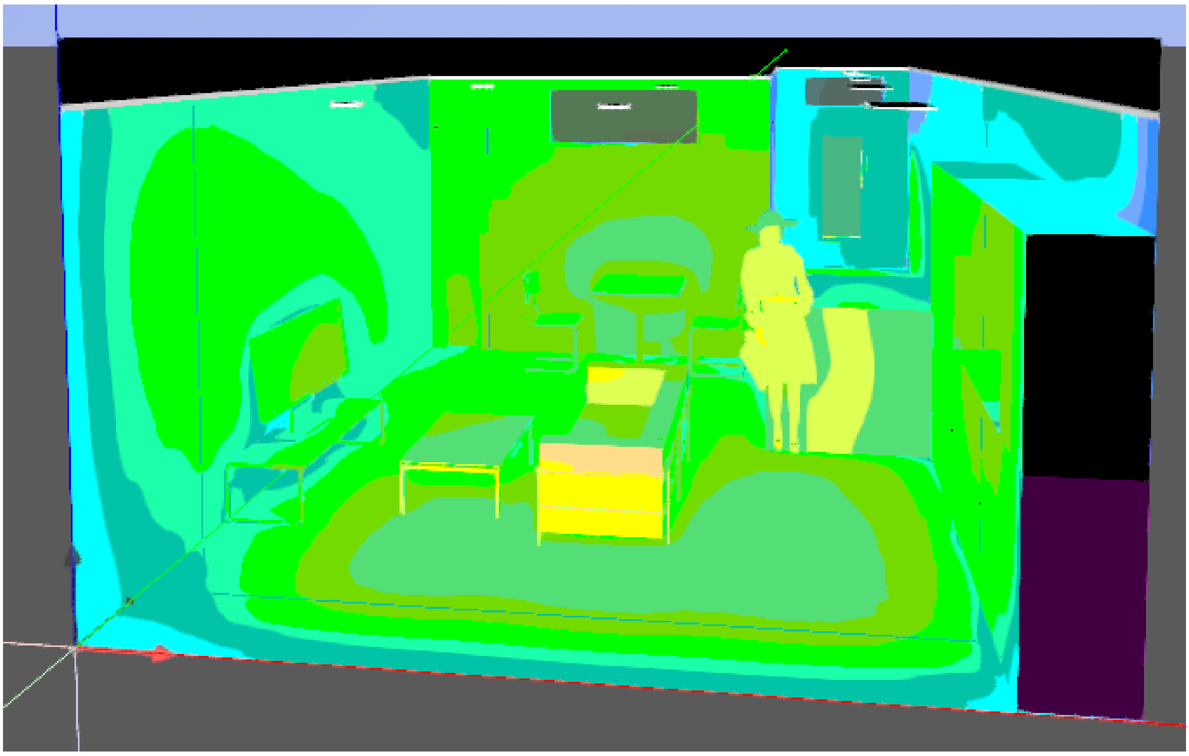


Figure 2: *With Smart Tint*

APPENDIX E: SOLAR ENERGY SYSTEM

APPENDIX E.1: BULK WORK & CALCULATIONS (EXCEL SHEETS)

Table E.1.1: Roof calculations (for purposes of evaluating the best roof design)

roof length(base)	roof width	angle	height	hyp	area
10	5	5	0.8748866353	10.03819838	50.19099188
9.5	5	5	0.8311423035	9.536288457	47.68144228
9	5	5	0.7873979717	9.034378538	45.17189269
8.5	5	5	0.74365364	8.532468619	42.6623431
8	5	5	0.6999093082	8.0305587	40.1527935
7.5	5	5	0.6561649764	7.528648782	37.64324391
7	5	5	0.6124206447	7.026738863	35.13369431

Table E.1.2: Roof top panel statistics and orientation options

Panel Efficiency	0.215	
Inverter Efficiency	0.97	
Panel length	1.558	
panel width	1.046	total length
Max stacked l to btm	3	4.674
Max stacked w to btm	4	4.184

Table E.1.3: Panel optimal orientation and power produced

# of panels l to btm	# of panels w to btm	Area l to btm	Area w to btm	best	total KWH striking panels	KWH from PV and inv
9	6	44.001036	39.112032	44.001036	65811.31175	13724.94907
9	6	44.001036	39.112032	44.001036	65811.31175	13724.94907
8	5	39.112032	32.59336	39.112032	58498.94378	12199.95472
8	5	39.112032	32.59336	39.112032	58498.94378	12199.95472
7	5	34.223028	32.59336	34.223028	51186.5758	10674.96038
7	4	34.223028	26.074688	34.223028	51186.5758	10674.96038
6	4	29.334024	26.074688	29.334024	43874.20783	9149.966043

Table E.1.4: Overhang panel statistics and orientation options

Panel Efficiency	0.194	
Inverter Efficiency	0.985	
Panel length	1.58	
panel width	0.798	total length
Max stacked l to btm	3	4.74
Max stacked w to btm	6	4.788

roof width	angle	height	hyp	area
5	30	0	1.02	5.1

Table E.1.5: Second and third overhang calculations

# of panels l to btm	# of panels w to btm	Area l to btm	Area w to btm	best	total KWH striking panels	KWH from PV and inv
1	0	3.78252	0	3.78252	6143.926185	1174.042855
						2 overhangs
						2348.085709

roof width	angle	height	hyp	area
5	30	0	1.02	5.1

Table E.1.6: First overhang calculations

# of panels l to btm	# of panels w to btm	Area l to btm	Area w to btm	best	total KWH striking panels	KWH from PV and inv
1	0	3.78252	0	3.78252	5866.187056	1120.969685

Table E.1.7: Final values calculated

2nd+3rd overhang	2348.09		
1st overhang	1120.97		
sum	3469.06		
Roof value	13724.94907		
sum all panels	17194.00907	Surplus	1694.009065