Towards a Proposed Framework for Analyzing Sustainable Renovation Building Envelope Assemblies

by

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presented to Ryerson University

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requirements for the degree of

Masters of Building Science

in the Program of

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ABSTRACT

This study proposes a framework for analyzing sustainable building envelope retrofits for residential homes. The research focuses on two existing residential wall assemblies types with a total of assembly options. Each assembly is simulated in a variety of software to determine their energy and moisture performance, as well as their environmental impact in eight categories. A summary of the information is organized into a two page review for each assembly. Analysis of the retrofit options was conducted through four categories: thermal performance, moisture performance, constructability, and overall environmental impact. It is clear from the research that truly sustainable retrofits must take into consideration each of these categories and that even high thermally performing retrofits cannot be labelled sustainable if they utilize high impact materials such as spray foam. Along with future parallel studies, this research will help home owners, designers and builders to evaluate the applicability of sustainable renovation techniques for their buildings.

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1 Introduction

The existing residential building sector represents a significant environmental burden and is responsible for 16% of the energy consumption in Canada[1] and 15% of its green house gas emissions[2]; 57 % of the energy use is consumed for space heating[3]. Over the past five years there have been approximately one million new housing starts across Canada, but there has been a significant lack of attention to implementing sustainable building designs, and thus the environmental impacts of the residential building sector have been overlooked[4]. In the upcoming years, a large majority of Canadian homes will need significant renovations and upgrades, and thus there is a need to develop renovation techniques that can convert existing energy and environmentally inefficient homes into more sustainable ones. The proposed research aims to contribute to the development of the Sustainable Renovation Index research program currently under study in the Sustainable Buildings Group at Ryerson University (www.ryerson.ca/richman/research). The research focuses on analyzing typical (industry standard), energy reducing and sustainable envelope assemblies across the Greater Toronto Area (GTA), which represents a significant percentage of the existing Canadian housing stock.

The research potentially influences the design and construction of both existing and new homes across Canada. It can be used to help develop a new section within provincial Building Codes that directly regulates renovation of existing structures using the sustainable strategies researched. The research completed here, along with the development of the Sustainable Renovation Index, will help home owners, designers and builders to evaluate the applicability of sustainable renovation techniques for their buildings. It will help respond to the public's desire for usable information on sustainable renovations, as well as providing a true evaluation of sustainable design, going beyond energy efficiency alone.

1.1 Objectives

The overall goal of the research is to provide a framework to analyze existing and proposed construction assemblies in order to develop a database of sustainable renovation techniques for retrofitting existing buildings.

The research questions that arise from this are:

1. What type of envelope assemblies and retrofits should be included in the study?

- What envelope assemblies represent the GTA housing stock?
- What envelope assemblies have the lowest thermal performance?
- What envelope assemblies are easiest to retrofit?
- What are common retrofits which target energy efficiency?
- What are retrofits which target energy efficiency as well as overall environmental impacts?

2. What material properties and environmental impact indicators should be reviewed?

- Which properties/ indicators impact the environment/ IAQ the most?

3. How will the assemblies be tested for thermal and hygrothermal performance?

- What simulation tools should be used?
- How will thermal bridging inherent in most assemblies be taken into account?
- Which parts of the assemblies are most susceptible to moisture problems?

4. How will the final overall performance of the assemblies be analyzed?

- How will environmental/ health impacts be weighed against energy efficiency and durability performance?

It is important to note that this research serves solely to develop a framework for sustainable renovations and, therefore, by no means will all the research questions be answered or answered in their entirety.

As such, the objectives are:

1. Developing a list of existing and proposed retrofit assemblies which will act as a model for the types of assemblies to be included in such a database.
2. Providing a review of the material properties and environmental impact indicators that should be researched for each assembly to give adequate data on the environmental effect of retrofit options.
3. Proposing a system for simulating the thermal and hygrothermal properties of retrofits using computer software in order to assess a retrofit's thermal resistance and moisture performance.
4. Analyzing the retrofit options to develop generalizations about thermal and moisture performance, constructability, and environmental performance, as well as drawing conclusions on the overall performance of the retrofits through contrast with one another.

Once a list of existing and proposed assemblies is produced, a collection of data on the commonly used and proposed energy efficient and sustainable building envelope assemblies is needed. On a material level, this data includes information on material properties such as chemical composition, long-term off-gassing characteristics, and the existence of known allergens. Other environmental impact indicators such as embodied energy, fossil fuel consumption, material resource use, global warming potential, acidification potential, human health respiratory effect potential, aquatic eutrophication potential, ozone depletion potential, and smog potential, will be reviewed.

When renovating an assembly it is also important to understand any changes to the moisture and thermal properties of the assembly. Increasing or moving the thermal plane could have positive or negative effects on the ability of an assembly to control moisture. Thermally, it is important that an effective U and RSI value is calculated so that different renovations can be compared for thermal performance. Therefore, on an assembly basis, hygrothermal characterization will be analyzed in addition to thermal resistance as it relates to a building's energy intensity.

2 Literature Pertinent to Sustainable Renovations

The focus in Canada on sustainable, low impact residential homes has been almost entirely on new construction. Retrofitting/renovating existing homes with current techniques and approaches in an attempt to achieve similar performance attributes as new construction is seen as more costly. It is also much more challenging using current practices to renovate an existing home into a low-impact one in a sustainable manner. For this reason, the development of cost effective sustainable renovation strategies is imperative to dealing with the inefficient existing housing stock, without letting the invested embodied energy and materials embedded within our existing homes go to waste.

Although a review of literature from the Institute for Research in Construction at the National Research Council of Canada (IRC at NRC)[5] and the Canadian Mortgage and Housing Corporation (CMHC)[6] shows concentration on new sustainable construction, there are reports which address renovating existing homes. These texts however usually only focus on improving energy efficiency and rarely take into account environmental, social, economic, and health aspects that are involved with renovating an existing home. The Eco-energy program developed by the NRC published a report titled "*Keeping the Heat In*"[7]which serves as a guide to retrofitting residential homes. The report includes information on materials, air leakage, insulation etc. With respect to exterior walls, many retrofit strategies are addressed. When insulating from the interior, both solid brick and wood frame construction may be evaluated in relatively the same way. Insulated walls may be built over the existing walls, but the old wall must not have a vapour retarder. If the existing interior finish is to be removed, cross strapping may be added so that additional insulation may be installed. For exterior retrofits, the report recommends either rigid insulation if siding is to be replaced, or an exterior truss system to provide a cavity for insulation. The downfall of the report is that it primarily focus' on assemblies with exterior siding, while those with brick veneer are not addressed, and solid brick construction is addressed minimally. Information about recommended insulation levels is also not provided, as well as any environmental or health impacts of the retrofits.

A publication by the CMHC examines achieving net zero energy in an existing home, called the Now House, but the research does not take into account some of the environmental and health outcomes that may arise from such renovations. The main exterior wall retrofit strategy called for the removal of the exterior siding, and the addition of an offset truss system, which was filled with 133mm (5.25 inches) of spray applied polyurethane insulation, adding RSI 5.45 (R31) to the insulation value of the wall. The report quoted, “the project showed how Canada’s existing building stock could be renewed while achieving significant energy reductions. Rejuvenating an old building can, in many instances, conserve natural resources and avoid the significant embodied energy costs associated with a new building”[8]. Such a statement illustrates a lack of acknowledgment of the environmental implications that some retrofits strategies may produce. Although any retrofit avoids the significant embodied energy costs of new construction, the embodied energy and environmental impacts of polyurethane foam, for example, are significant.

The CMHC also provides home owner information reports on strategies to renovate different types of existing homes for energy efficiency, such as pre WWII homes, post 60’s two storey homes, split-level homes, and so on [6]; these reports provide a basis for information on current renovation techniques and strategies. The information provided is relatively limited when pertaining to exterior wall improvements. For those homes with exterior siding, the CMHC recommends insulating the cavity behind the sheathing, if not already insulated, as well as adding a layer of exterior rigid insulation and house wrap. It is unusual that these reports do not directly address retrofitting solid brick walls, which make up a large portion of the Canadian housing stock.

Related to these reports, a much more detailed review is provided in a thesis dissertation by Blaszak [9] , which examined how the environmental effects arising from the existing building stock in Toronto might be used to help inform and rank retrofit options for single-family homes in an environmentally comprehensive manner. Four archetype homes were developed to represent Toronto's existing housing stock, but unlike the CMHC studies, this study investigated and ranked retrofit options on the basis of net environmental effect. Although energy performance was an influential factor in ranking retrofit options, under certain conditions the embodied effects determine the ranking of a retrofit. The study provides a much needed step forward to developing a true evaluation of sustainable renovations by looking beyond energy performance alone.

Apart from Canadian sources, the Building Science Corporation (BSC) serves as a database for a variety of articles, reports, manuals and insights from leading building scientists[10]. One document type called "Enclosures that Work"[11], provides information related to wall assemblies which are said to "work" in cold climate regions. A variety of articles also provide case studies of residential retrofits, where BSC was a part of the project team[12]. Many of these retrofits were a part of the National Grid Deep Energy Retrofit program. National Grid, an international electricity and gas provider, have a program which provides financial incentives to customers in Rhode Island and Massachusetts to complete a Deep Energy retrofit[13]. The program targets whole house retrofits from insulation to high efficiency HVAC systems. Most of the case studies provided by BSC involve uninsulated wood framed homes with exterior siding. With regards to exterior walls, most of the retrofits add blown cellulose into the wall cavity, if not already insulated, and then add a significant amount of exterior rigid insulation, usually around four inches; the insulation is either XPS or foil-faced polyisocyanurate. Although cellulose is used for the retrofit, it is a fairly small contribution to the overall R value of the wall. Like spray foam, XPS and polyisocyanurate have significant environmental impacts, which are not addressed by any of the case studies.

A report written by Dr. John Straube, accessed from the Building Science Digest portion of the website, reviews "*Interior Insulation Retrofits of Load-Bearing Masonry Walls in Cold Climates*"[14]. The report focuses on the moisture performance of retrofits, which directly relates to part of the research that will be carried on in this MRP. The findings indicate that any retrofit to load bearing masonry must take into account many types of moisture loads which include wetting from driving rain, vapour diffusion, air leakage etc. As for vapour control, optimal levels required can be easily calculated for specific building exposures and climates using dynamic one-dimensional hygrothermal analysis methods, such as Wufi. The report identifies the use of semi-permeable foam insulation on the back of the existing masonry as the most common successful strategy for interior insulation retrofits. The use of air and vapour permeable batt or semi rigid insulation is not recommended, as it is seen as risky due to the serious potential of moisture issues [14].

As with the publications and reports from the IRC and CMHC, there is a lack of consideration to other aspects (environmental, health, etc) involved with residential renovations, and a general focus on energy efficiency and occasionally on moisture performance.

Internationally, sustainable retrofits have been researched, and several sources exist. One of the more stringent sustainable building standards is Passive Haus. Apart from new construction, Passive Haus designers and builders also use the principles of the standard to retrofit existing homes. While it is possible to achieve the new build Passiv Haus Standard in the retrofit of an existing building and be fully certified as an approved Passiv Haus, it is often difficult to achieve without undertaking major works which involve greater costs[15]. For this reason, Passive Haus has developed the EnerPHit Standard as a good practice refurbishment guide for Passiv Haus renovations. Specific heat demand requirements are increased to 25 kWh/m^2 per year, instead of 15 kWh/m^2, and an infiltration rate of 1 ACH is required, instead of 0.6 ACH[16]. The EnerPHit criteria guide provides minimum insulation U value levels for below grade walls, exterior walls and roof assemblies. For exterior wall assemblies the guide requires an RSI 6.66 on the exterior and an RSI 3.33 on the interior, for a total RSI 10 (R57) for the wall assembly. It is evident within the guide that reduction in energy demand and increases in energy efficiency is one of the driving forces of this "sustainable" renovation standard. Once again, as with many other retrofit strategies, any environmental effects involved with achieving the standard are not required to be measured, nor are they mentioned.

Although the EnerPHit guide does not require calculations of the environmental impacts of assembly materials, recommendations about materials and their environmental impacts are addressed in "*Details for Passive Houses*", a booked developed by the Austrian Institute for Healthy and Ecological Building[17]. The book does not directly address Passive Haus retrofits, but does review a plethora of building assembly designs and materials, while also addressing ecological impact categories. Three impact categories are examined: green house gas potential, acidification potential, and non-renewable resource primary energy content. The book provides a model of how to organize and illustrate the environmental impacts of each assembly. For each assembly, a bar graph compares the impact category of each material for two wall assemblies; a common construction, and an alternative construction. An example of this is illustrated in Figure 1.

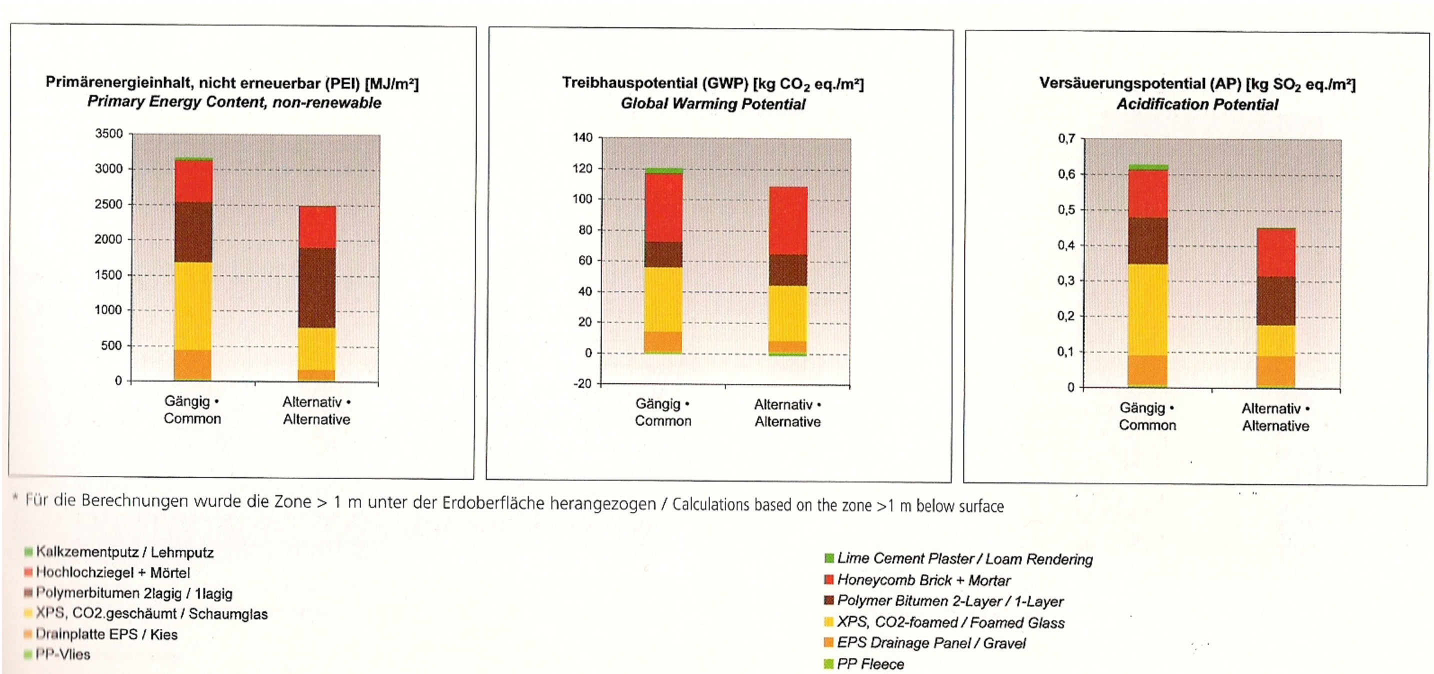


Figure 1- Example of Passive Haus ecological profile graph

The text also provides information on environmental and health aspects of many common and green building materials. Overall, the text provides an example of a sustainable design framework; although the text addresses new construction, the framework can easily be modified to sustainable renovation assemblies.

A less technical review of sustainable renovations is addressed in a research paper developed by the Department of Architecture at Cambridge University, and the Research Institute for Housing in the Netherlands. The paper presents an overview of the characteristics of the residential stock, current renovation activities and incentives in the Netherlands, Germany, Finland, Sweden, the U.K., France, Switzerland, and Austria. The paper mostly covers policy towards renovations, rather than their specific construction details [18]. It provides an overview of the challenges of renovating some of the older building stock due to aesthetic and historical concerns, as well as other barriers. Although the paper reviews existing policies and incentives to reduce energy use and CO_2 emissions for their impacts on the existing building stock, once again the environmental impacts of such renovations and policies are not addressed.

In Ireland, a sustainable retrofit programme called Greenprint was developed along with the Institute of International and European Affairs[19]. The programme was developed to address the inefficient existing housing stock, and to create jobs in the building industry. Like the previous paper reviewed, Greenprint also goes over policies and challenges in implementing sustainable renovations. The programme calls for 1.2 million existing homes to be upgraded to a Building Energy Rating (BER) of C1, which has an energy demand of 150kWh/m^2/yr. This rating system consists of 15 levels, from A1 (most efficient) to G. Improvements range from insulating walls and attics, to installing more efficient boilers and lighting. The guide does not specify exact insulation levels but acts more as a case and overview for the implementation of a National Energy Efficiency Retrofit Programme in Ireland, and presents initial thoughts on how such a programme might be financed. After a review of the document, it is evident that focus of the renovations is solely on energy efficiency alone.

There are two texts that come out of the United Kingdom which address sustainable retrofits. The first, "*The ZEDBook*"[20], mainly addresses new zero energy development, but does contain a section regarding retrofitting existing homes. The text quickly overviews internal and external insulation options with a preference to external insulation because it maintains the internal thermal mass of the brick in solid brick construction and keeps the structure warm and dry. Specifics on R values or material selection are very minimal. The second text, "*Sustainable Home Refurbishment*"[21], was developed by Earthscan, a world leading publisher on climate change, sustainable development and environmental technology. The text provides a whole building overview of sustainable renovations from air tightness to efficient HVAC systems. On an assembly basis, the text provides several recommendations for internal and external retrofits along with recommend target RSI values. For exterior walls, the text recommends RSI 3.33 (R19) for solid brick walls, and RSI 2.1 (R12) for uninsulated wood frame walls. The RSI values may seem low but may be adequate for the U.K. climate. Apart from these recommendations the text also addresses how Passive Haus standards may be achieved in retrofit scenarios. Although energy efficiency is the driving theme of the text, it also provides a short summary of many common insulation materials as well as more sustainable options. A brief summary of insulation properties, environmental aspects and embodied energy data is provided. Although not fully developed, the Earthscan text has taken a step to providing a truer sustainable outlook on retrofits, over the typical status-quo of energy efficiency.

Dr. Danny Harvey has published several reports, publications, and books which will act as a source on retrofits for reducing energy[22]. Harvey provides exterior wall retrofit options as well as many case studies regarding energy reduction retrofits[23][24]. Unlike other literature, Harvey usually examines the environmental effects of retrofit strategies or materials. In one such report, Harvey examines the net climate impact of spray foam insulations, one of the most common materials used to “sustainably” retrofit a home. The report investigates three factors: “the greenhouse gas emissions associated with the energy used to make the insulation; the climatic impact of leakage of the halocarbon blowing agent from the insulation during its manufacture, use, and at the time of disposal; and the reduction in heating and/or cooling energy use and associated greenhouse gas emissions”[25]. Harvey concludes that whenever possibly cellulose or other natural insulation should be used when trying to achieve significantly high levels of insulation value (RSI 10/ R57). Marginal payback times of foam insulation at these levels range from 25 years to 200 years. It is relatively clear that true sustainable retrofit options cannot opt for foam insulation products with non-air based insulants.

This literature review has mentioned some of the key texts and studies relevant to the project at hand, and is by no means an exhaustive review. With this said it is evident, through the literature so far, that there is a lack of published sources concerning renovating high impact residential homes into low impact dwellings in a **sustainable** manner. “A key factor in the deficiency of research on sustainable renovation is the lack of a clear framework for defining, quantifying and evaluating outcomes of its application”[4]. Research is limited and usually focuses on a singular aspect such as energy efficiency; sustainable renovations should encompass a multitude of different aspects such as environmental, social, economic, and health ones. The need for a comprehensive framework for sustainable renovation applicable to Canadian homes is evident.

A significant observation noticed within the literature is that the phrase ‘sustainable renovation’ is rarely, if ever used; instead ‘energy efficient renovation’ is the phrase usually associated with renovating existing homes. The concept of energy efficiency and sustainability are often interchanged. If the proposed research is to analyze sustainable renovation techniques and strategies, then there is a need for a clear definition of sustainability as it pertains to existing residential buildings. The research defines sustainability using the following fundamental criteria:

- Energy performance (reduction of consumption over efficiency)

- Occupant health and comfort (thermal, environmental sensitivity)
- Hygrothermal performance (durability and moisture management)
- Indoor air quality (air changes per hour, off-gassing, contaminant existence)
- Material choice (embodied energy, chemical composition, sourcing and shipping)

3 Methodology

The proposed framework will establish a direction on the research that is needed to develop a sustainable renovations database and how this research can be conducted using certain tools. The proposed framework/ research will be carried out in the following phases: 1) assembly identification, 2) material data collection, 3) thermal/ hygrothermal computer software simulation, and 4) analysis and discussion.

The research first defines a list of typical existing envelope assemblies in the GTA which serves as the basis for the research. Along with existing assemblies, a list of potential retrofit strategies was gathered through literature and also through contact with professionals involved in the field. Data collection on building materials was gathered through review of manufacturer's literature and product specification in addition to data published by the Athena Institute. Work with willing manufacturer's to provide additional information on assembly materials was essential. With the time frame involved with the following research, unfortunately only data published by the Athena Institute is examined.

The analysis of the heat transfer and hygrothermal characteristics, of the existing construction styles and proposed solutions, took place using various simulation software such as: Therm 5.2 (i.e. heat transfer characterization), WUFI 4 Pro (i.e. hygrothermal characterization).

Three-dimensional analysis may be required in later stages as the preliminary research suggests. Once phases one through three were completed, analysis of the gathered information was required. Each assembly and proposed retrofit was analyzed through a combination of 4 categories: thermal control, durability as it pertains to moisture, constructability, and overall environmental impact.

3.1 Phase 1: Assembly Identification

There are a variety of different building assemblies across the GTA. According to the CMHC, the construction of the existing GTA residential building stock can generically be separated into two main constructions types: load bearing brick masonry construction, and wood frame construction.

'Appendix A' contains a list of the preliminary wall and roof assemblies that were developed for the research. It first outlines some of the common existing residential assemblies. Once the base assemblies were identified, retrofit options were examined. These retrofit options were categorized into two divisions: 1) energy efficient retrofits, and 2) environmental energy efficient retrofits. The reason for the division was that a majority of common energy efficient retrofits practices today do not take into account the health and environmental effects of the materials used. For example, the materials for such retrofits may not be environmentally responsible, i.e spray foam insulation.

Once this preliminary research of existing and retrofitted wall assemblies was produced, it was realized that for the time frame of the research, the list of assemblies had to be reduced, organized and broken down into a clearer framework. As well, the following research only focuses on a limited pallet of existing and retrofitted exterior wall assemblies in order to set up an organized framework for analyzing assemblies. The following flow diagram illustrates the existing and retrofitted wall assemblies to be examined. As with the preliminary list developed earlier, the assemblies are broken down into 3 categories: Existing, Energy Efficient Upgrades, and Environmental Energy Efficient Upgrades.

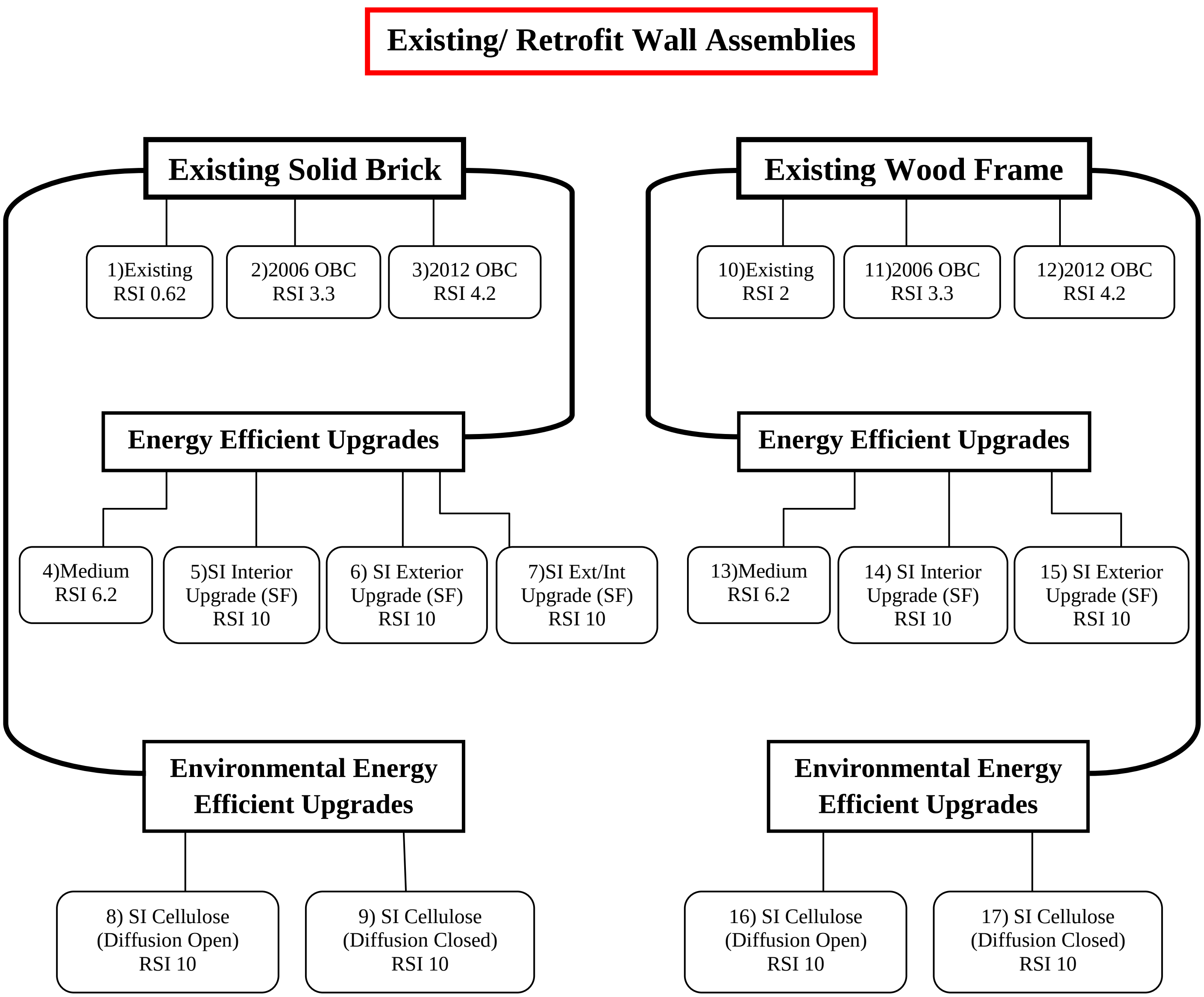


Figure 2- Flow Diagram of Assemblies

Flow Diagram Abbreviation Reference

Existing- Existing Baseline assembly

2006 OBC- Retrofit to minimum RSI value of 2006 Ontario Building Code.

2012 OBC- Retrofit to minimum RSI value of 2012 Ontario Building Code

Medium- Adapted from a high R value foundation wall assembly design used in the construction industry

SI Interior Upgrade (SF)- Super insulated retrofit to Passive Haus EnePHit Guide RSI 10 using spray applied polyurethane foam on the interior.

SI Exterior Upgrade (SF)- Super insulated retrofit to Passive Haus EnePHit Guide RSI 10 using Extruded Polystyrene insulation on the exterior.

SI Ext/Int Upgrade (SF)- Super insulated retrofit to Passive Haus EnePHit Guide RSI 10 using Extruded Polystyrene insulation on the exterior and spray applied polyurethane foam on the interior.

SI Cellulose (Diffusion Open)- Super insulated retrofit to Passive Haus EnePHit Guide RSI 10 using blown in cellulose insulation without 6 mil polyethylene sheeting.

SI Cellulose (Diffusion Open)- Super insulated retrofit to Passive Haus EnePHit Guide RSI 10 using blown in cellulose insulation with 6 mil polyethylene sheeting.

A detailed breakdown of each assembly composition is located in ‘Appendix B’. A description of each retrofit, along with a review of the environmental, thermal and moisture performance characteristics will be examined in phase 4.

Assumptions

- For solid brick wall assemblies, unless noted, interior plaster, lathe and furring to be removed.
- For wood frame wall assemblies, unless noted, interior gypsum board, 6mil polyethylene and fibreglass batt insulation to be removed.

3.2 Phase 2: Assembly Environmental Impact Data Collection

Developing a framework for true sustainable retrofits involves a gathering and understanding of the environmental impacts of such retrofits. Although a database of sustainable renovation techniques will require data collection on building materials gathered through review of manufacturer's literature, product specification and data published by the Athena institute, the following framework only reviews data published by the Athena Institute. Data was collected using a software program developed by the Athena Institute called the *Athena Impact Estimator*. The program was designed to evaluate whole buildings and assemblies based on internationally recognized life cycle assessment (LCA) methodology[26]. The Estimator takes into account the environmental impacts of:

- Material manufacturing, including resource extraction and recycled content
- Related transportation
- On-site construction
- Regional variation in energy use, transportation and other factors
- Building type and assumed lifespan
- Maintenance and replacement effects
- Demolition and disposal

The program allows the user to build a wall, and other building assemblies, and specify each material within the assembly and its thickness. The *Impact Estimator* outputs data into 8 environmental impact categories [26]:

- **Fossil fuel use-** the estimated amount of fossil feul energy used in the extraction, processing, construction, transportation, and disposal o each material. Measured in Mega joules.
- **Material resource use-** estimated raw materials required for extraction, processing, construction, transportation, and disposal of each material. Measured in mass units.
- **Global warming potential-** green house gas emissions measured in CO_2 equivalent
- **Acidification potential-** amount of acid forming chemicals, measured in moles of hydrogen equivalents.
- **Respiratory effect potential-** estimated airborne particles that lead to asthma, bronchitis, acute pulmonary disease etc. Measured in mass unit of 2.5 micron particulate matter.
- **Aquatic eutrophication potential-** estimated amount of water nitrifying substances that can lead to the proliferation of photosynthetic aquatic species. Measured in mass units of nitrogen equivalents.
- **Ozone depletion potential-** estimated amount of ozone depleting substances (CFC's, HFCs, and halons). Measured in mass units of CFC-11 equivalents.
- **Smog potential-** the estimated amount of chemicals that would produce photochemical smog and ground-level ozone when exposed to sunlight. Measured in mass units of ethylene equivalents.

With respect to the environmental impact indicators, the research does not weigh one impact more so than another. For the time being each impact was reviewed as equal to the others. Determining whether certain impacts should have more significance than others is a field of research onto itself and thus will not be addressed at the time in this particular framework.

Assumptions

- The proposed retrofit wall assemblies were all nominalised to a $1m^2$ wall section and any original assembly components were not factored into the environmental impact of the retrofit.
- Spray applied polyurethane foam is not available in the Athena database, therefore the closest substitute was polyisocyanurate foam, which was the only foam product available in the program but shares similar properties with polyurethane foam. According to the report by Harvey[22], both polyisocyanurate foam and polyurethane spray foam share similar blowing agents (HCFC-141b, GWP-713, Pentane, etc), as well as are made with similar materials (polyol and methylene diphenyl diisocyanate).
- The Roxul rigid drainage board was substituted with mineral wool insulation.

3.3 Phase 3: Thermal/ Hygrothermal Computer Software Simulation

3.3.1 Thermal Simulation

Thermal analysis of each existing assembly and retrofit was carried out using the computer software program Therm 5.2. Therm can model two-dimensional heat-transfer effects in building components such as windows, walls, foundations, roofs, and doors; appliances and other products where thermal bridges are of concern. Models of each wall assembly were constructed in Therm to determine both the “assembly thermal resistance” and the “effective assembly thermal resistance”. The “assembly thermal resistance” was modelled without stud partitions while the “effective assembly thermal resistance” takes into account the thermal bridging of the studs. Both these values are given in the breakdown of each assembly, along with the “insulation values” which gives the thermal resistance of solely the thermal insulation.

Assumptions

- For the "effective assembly thermal resistance" calculations, the length of the interior U factor tag corresponds with the on-centre spacing of the studs and the stud is placed within the centre of the model. Thus an assembly with a stud spacing of 610mm will have a U factor tag of 610mm, and so forth.
- With respect to those wood frame retrofits which include studs at both 610mm and 406mm o/c, two models were tested to determine the thermal resistance of two different section sizes. Figure 3 and Figure 4 show these two different models using assembly #14 as an example. The difference in the calculated thermal resistance of each model is minute. The 1210mm interior U factor tag has a RSI 10.01 while the 508mm has a RSI 10.1. For the purpose of time restrictions and model simplicity, the 508mm model is used throughout the double stud conditions.

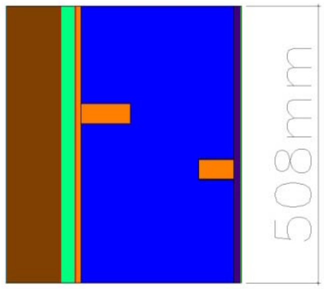


Figure 3- 406mm & 610mm Studs- 1210mm U Factor tag

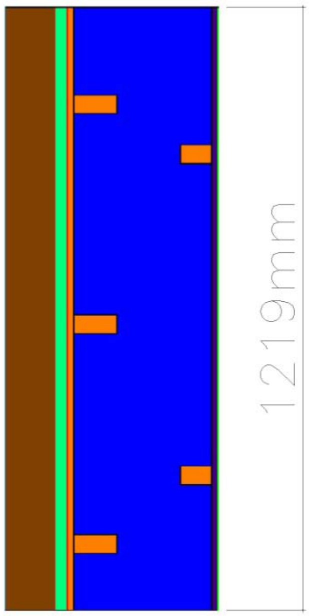


Figure 4-406mm & 610mm Studs- 508mm U Factor tag

- All thermal conductivities used in the model for insulation materials were taken from the average values listed in the Passive Haus PHPP software:
  - Mineral Batt RSI 0.59/ inch (R 3.33)
  - Fiber Batt Insulation RSI 0.59/ inch (R 3.33)
  - Spray applied closed cell polyurethane foam RSI 0.94/ inch (R5.36)
  - XPS insulation RSI 1.01/inch (R 5.72)
  - Blown in cellulose RSI 0.62/ inch (R 3.5)

Table 1 shows the R value per inch given by ASHRAE and also one or two manufacturer's values.

Table 1- Insulation Material R Value per inch

Insulation Material	Used	ASHRAE [27]	Manufacturer's
Mineral Batt	3.3	3.4-4	4 [28]
Fiberglass Batt	3.3	2.9 – 3.4	3.7 [29]
Spray Foam Closed Cell	5.36	5 - 6.8	6 [30]
XPS	5.72	4.7 – 6.5	5 [31][32]
Cellulose	3.5	3.2 - 3.6	3.8 [33]; 3.6 [34]

- Thermal conductivities of all other material were gathered from [35].
- Thermal conductivity for the Roxul rigid drainage board was acquired from the manufactures website as RSI 0.7 per inch or R 4 per inch [36].
- The vented air cavities of the brick veneer and wood siding retrofit were modelled under Therm material "Frame Cavity Slightly Ventilated NFRC". The "Frame Cavity NFRC" was not employed because its conductivity value does not take into account ventilation.

Its value corresponds to the *Building Science for a Cold Climate* value of a 25mm plane airspace of 0.11 W/(m×K). The "Frame Cavity Slightly Ventilated NFRC" has a conductivity of 0.21 W/(m×K) and will be used in the simulations and should more accurately simulate a vented cavity. The effect on the overall assembly RSI value is minimal, decreasing the overall RSI by only 0.1 m^2 ×K/W.

3.3.2 Hygrothermal Simulation

Understanding how an assembly deals with moisture is one of the most important issues within the construction industry, especially in cold climates. Excess moisture can cause negative respiratory effects (i.e. mould), durability issues (i.e. rot), and aesthetic problems (i.e. water staining). Hygrothermal analysis of the assemblies was carried out in Wufi 4.2 which models 1 dimensional moisture flow and can account for the two-dimensional effects of ventilation within wall assemblies.

Assumptions

- Each assembly was simulated under the Toronto cold year climate file provided in Wufi. A climate analysis can be observed in Figure 5.
- Each assembly was simulated under two different orientations, north and south-east. The north exposure, with no direct sunlight and the lowest sun radiation, allowed the analysis to take into account an accurate effect of indoor to outdoor vapour drive in the winter, and outdoor to indoor vapour drive in the summer, without the effect of sun driven moisture and high amounts of driving rain. The south-east exposure allowed the analysis to take into account both high levels of sun radiation and driving rain, which will provide a scenario of high exterior to interior vapour drive.

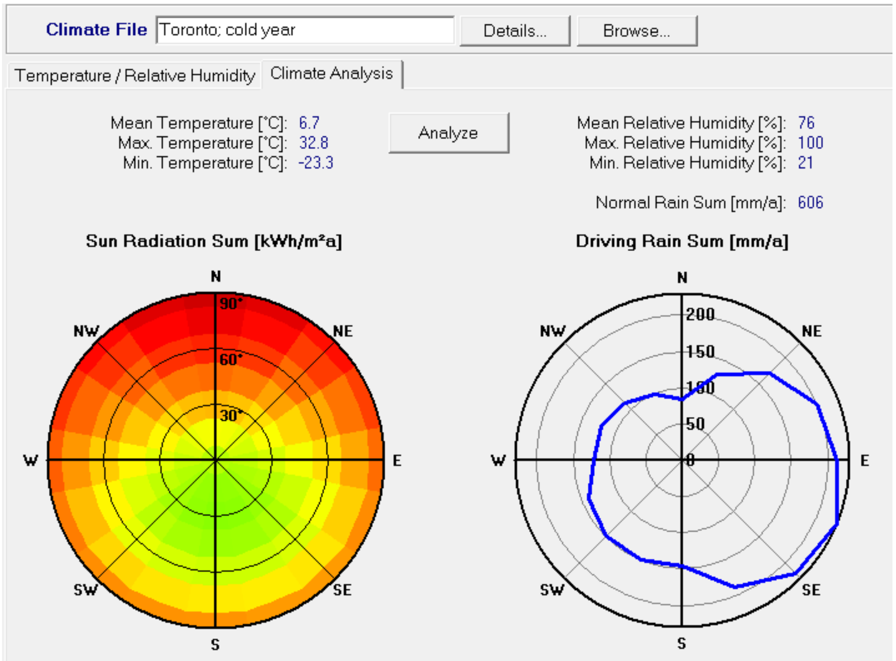


Figure 5- Wufi Toronto Climate Analysis

- Yearly Interior temperatures were set at a mean value of 22°C with an amplitude of 2°C. Interior RH values are set at a mean value of 35% with an amplitude of 5%.
- Each assembly was modelled with an initial 80% RH in each material, and modelled for a time span of 3 years.
- For both the solid brick and wood frame construction, exterior short wave absorptivity and emissivity was selected as “brick, red” and a rain water absorbtion factor “according to inclination and construction type”.
- Table 2 illustrates which materials in the Wufi database were selected for each material in the assemblies. As many properties as possible, of the materials selected in the Wufi database, were examined to ensure that they were similar to the properties of the actual materials (i.e density, conductivity, permeance, porosity, specific heat capacity). The house wrap defined in the assembly is spun bonded polyethylene which is known as

Tyvek. Another name for spun bonded polyethylene is spun bonded polyolefin and is available in the Wufi material database.

Table 2- Wufi Materials Used

Material	Source	Name of Wufi Material
Brick	Generic North American Database	Brick (old)
25mm Air space	Generic Materials	Air Layer 25mm
OSB	Generic North American Database	Oriented Strand Board
Spun Bonded Polyethylene	Generic North American Database	Spun Bonded Polyolefine
Closed Cell Spray Applied Polyurethane Foam	Generic North American Database	Sprayed Polyurethane Foam; closed cell
Fibreglass Batt Insulation	Generic North American Database	Fibreglass
Mineral Batt Insulation	Fraunhofer-IBP-Germany	Mineral Wool
XPS Insulation	Generic North American Database	Extruded Polystyrene Insulation
Composite Wood Siding	Generic North American Database	Composite Wood Siding
Roxul Rigid Drainage Board	Fraunhofer-IBP-Germany	Mineral Insulation Board
Cellulose Insulation	Generic North American Database	Cellulose Fibre Insulation
6 mil polyethylene	Generic North American Database	Vapour retarder (0.1 perm)
Gypsum Wall Board	Generic North American Database	Gypsum Board (USA)
Interior Plaster Finish	Fraunhofer-IBP-Germany	Cement Plaster

- With regards to the 25mm air spaces in some of the assemblies, a Wufi air change source was added. Values for air changes per hour (ACH) were adopted from a research report obtained from the building science corporation on ventilated wall claddings [37].
- For brick veneer air spaces an ACH of 20 was simulated, while for the wood siding air spaces an ACH of 200. These are average values given by the report.
- In cases where a batt insulation is utilized in a retrofit, a mineral batt is selected over fibreglass batt. The main reason for the substitution is the superior moisture performance of mineral batt insulation over fibreglass. Unlike fibreglass batt which acts as a sponge when in contact with water, mineral batt insulation does not absorb water or hold

moisture and thus will not sag nor lose RSI value as fibreglass insulation would. Along with superior moisture performance, mineral wool is also fire repellent.

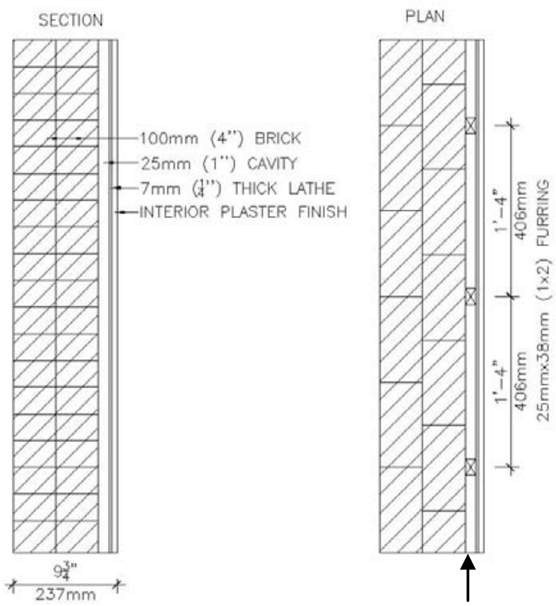
4 Results and Discussion

The final phase of the research analyzes and discusses each assembly individually, as well as compared to one another. A part of developing a proposed framework to analyze existing and proposed construction assemblies is the need to organize the gathered data in a concise and informative manner in order for the information to be easily accessible and comparable. The first portion of this phase provides a two page breakdown of each assembly, while the second portion compares the assembly options with one another.

4.1 Two Page Assembly Breakdown

The two page break down of each assembly will include a section and plan drawing of the assembly, a general note, and information gathered from section 3.2 and 3.3 of the research. Information includes the value of insulation thermal resistance in the assembly, the total assembly thermal resistance, and the effective assembly thermal resistance. The document will discuss the moisture performance of the assembly and highlight any areas of concern while providing temperature and RH graphs of these areas. Problem areas within the graphs are boxed in and the arrows (↑) in the "PLAN" drawings represent where in the wall the RH graphs are taken. Some assemblies will contain a subsection which will discuss any previous iterations of the assembly and their implications.

1. Existing Brick



Insulation Thermal Resistance

0

Assembly Thermal Resistance

RSI 0.62 m²·K/W (R 3.5 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 0.62 m²·K/W (R3.5 ft²·°F·h/Btu)

General Note

This assembly will act as the control for the existing solid double wythe brick masonry wall to be retrofitted which represents a large portion of the Toronto building stock. The existing assembly does not have any insulation and relies solely on the mass of the brick and adjacent air films for thermal performance, making it a poor thermally performing wall. As well as performing poorly thermally, this wall assembly can have very poor air tightness.

Environmental Impact

Since this assembly acts as a baseline for the retrofit options, it does not include data on the environmental impact of the assembly because it contains only existing materials. All retrofit assemblies will have a table listing data for the eight environmental impact indicators. A comparative review between each assembly is developed in section 4.2.4 which provides a better understanding of the comparative magnitude of this data.

Moisture Performance

All materials within the assembly are vapour permeable, thus moisture may be able to dry inwards or outwards. In north facing exposure simulations, no moisture issues are present and RH values do not exceed 82%. South-east exposure simulations show high RH values in the interior side of the brick as high as 97% from approx October to February (Figure 6). The high absorbtivity of the brick, sun driven moisture, as well as increased driving rain seem to contribute to such issues. Condensation problems may also occur if interior humidity levels are kept too high.

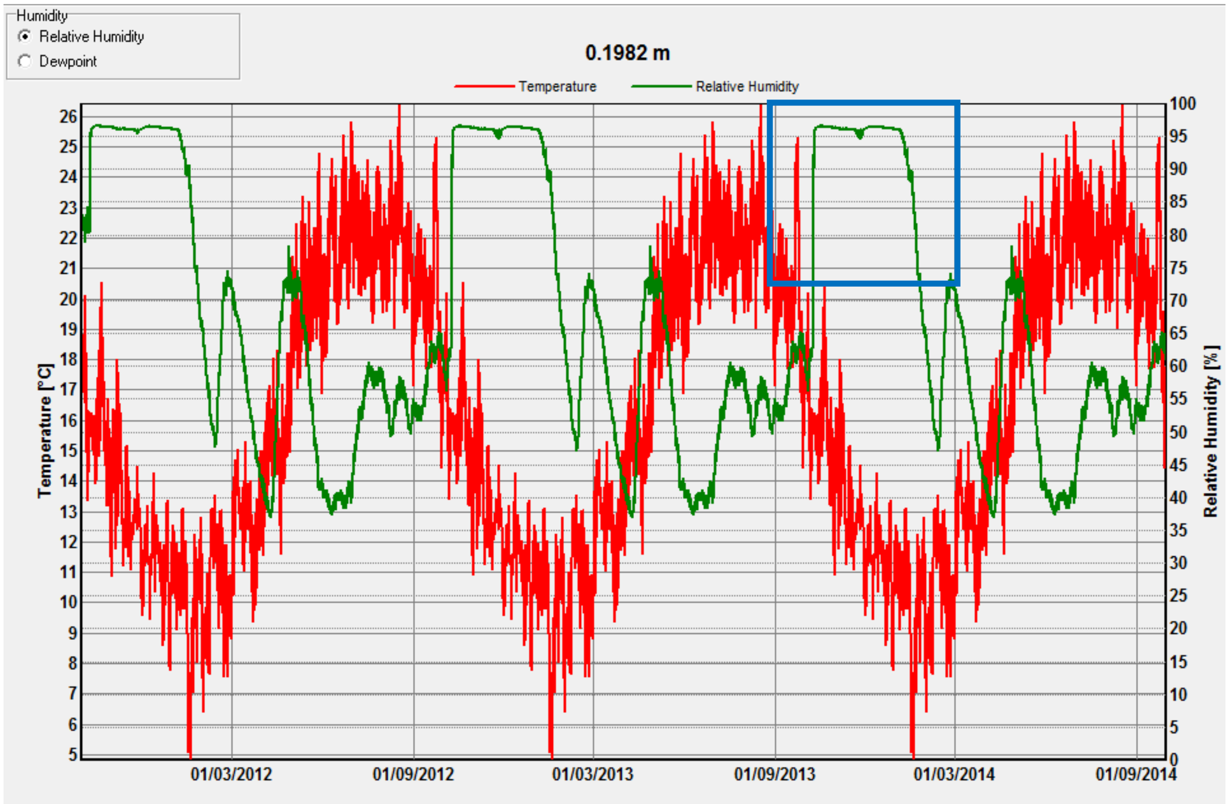
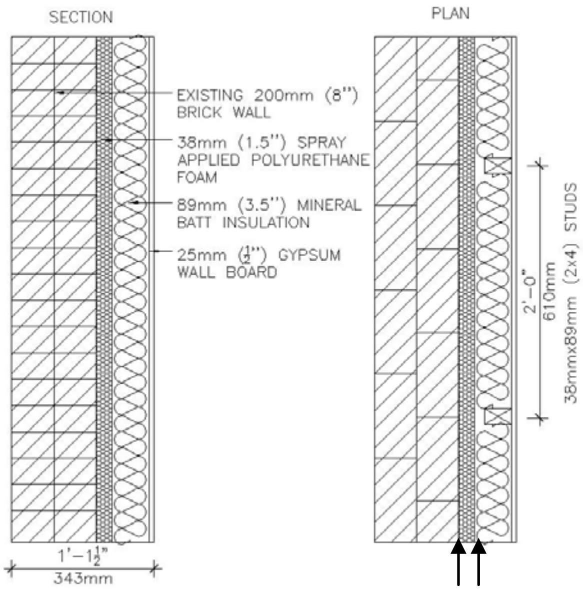


Figure 6- Existing Brick- Interior Brick Interface (SE)

2. Brick 2006 OBC



Insulation Thermal Resistance

RSI 3.45 m²·K/W (R 19.6 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 3.99 m²·K/W (R 22.7 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 3.86 m²·K/W (R 21.9 ft²·°F·h/Btu)

General Note

This retrofit aims to achieve the minimum thermal resistance required for the 2006 Ontario Building Code (RSI 3.35) and marks a significant improvement thermally over the existing assembly, as well as providing a much more airtight wall. Thermal bridging of the studs is reduced by the spray foam and offsetting of the studs away from the brick wall. The spray foam acts as an excellent air barrier by providing an airtight assembly through the sealing of any cracks or air passages throughout the wall. Long term airtightness can be achieved since spray foam does not crack and is permanently bound to the wall.

Environmental Impact

Both the spray foam and mineral batt contribute to the environmental impact of the retrofit, yet compared to other options using similar materials, overall impact is lower than other retrofits due to lower insulation levels.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
268.59	25.34	48.32	16.42	0.2	0.01	0.07	0.2

Moisture Performance

The use of spray foam acts as a moisture retarder, and any small amount of rain penetration through the brick masonry wall that might occur will be localized, controlled and water will not be able to collect and run down and collect at floor penetration. Rain water absorbed into the masonry can diffuse to the outside or diffuse to the inside through the interior finish. The hygrothermal simulations for both elevation exposures show the only area in which high RH levels (93%) are reached are between the brick and the spray foam during winter months (Figure 7). These levels are not of concern because of the previously mentioned statement, and that there is no potential for mould growth on either of the materials assuming inorganic substances are present.

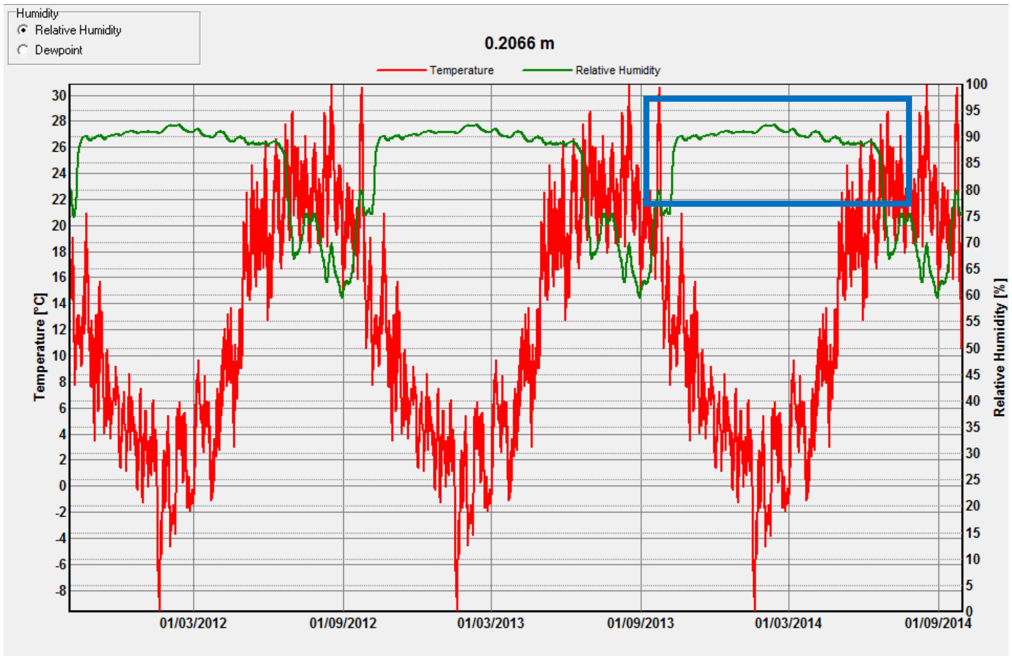


Figure 7- Brick 2006 OBC- Brick/ Spray Foam Interface (SE)

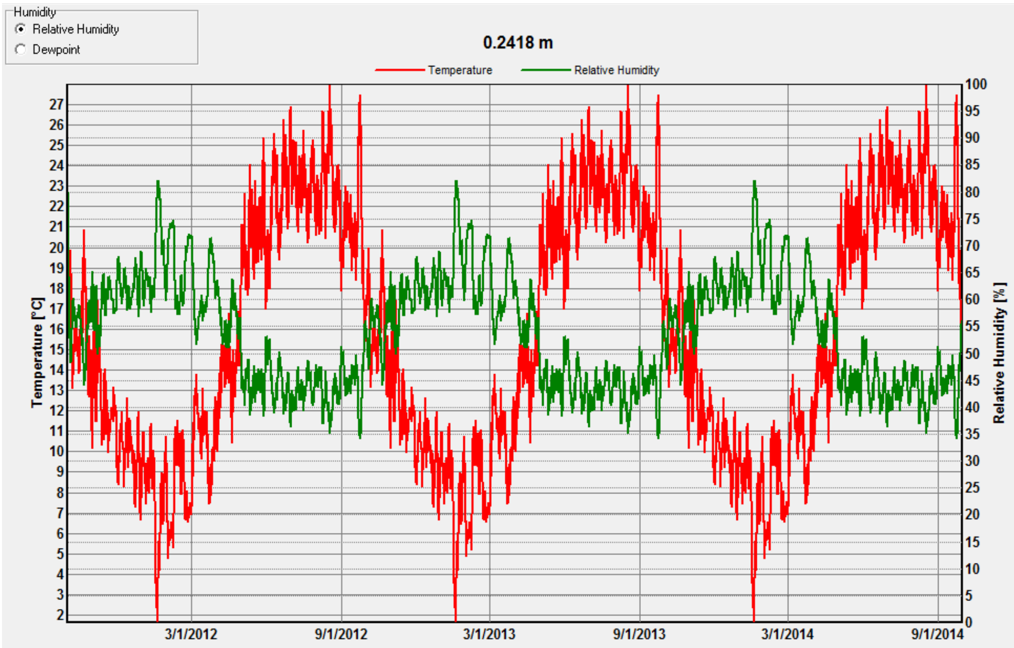


Figure 8- Brick 2006 OBC without Poly- Spray Foam/ Batt Interface (SE)

Iterations

As a result of previous simulations, 6 mil polyethylene sheeting was decided not to be incorporated into this retrofit strategy since the results indicate trapped moisture within the wall not allowing diffusion of moisture inward, and increasing the RH especially in summer months. RH levels are much higher in the Brick as well as in the exterior side of the mineral batt. Figure 8 and Figure 9 illustrate the difference between the assembly with and without poly. Unlike the retrofit without the poly, the total moisture content of the assembly increases from 0.75 kg/m^2 to 1.06 kg/m^2. Because of the high absorbtivity of the brick and the solid construction, which limits diffusion outward at times, diffusion inward is necessary as it is impeded by the presence of the 6 mil polyethylene sheeting.

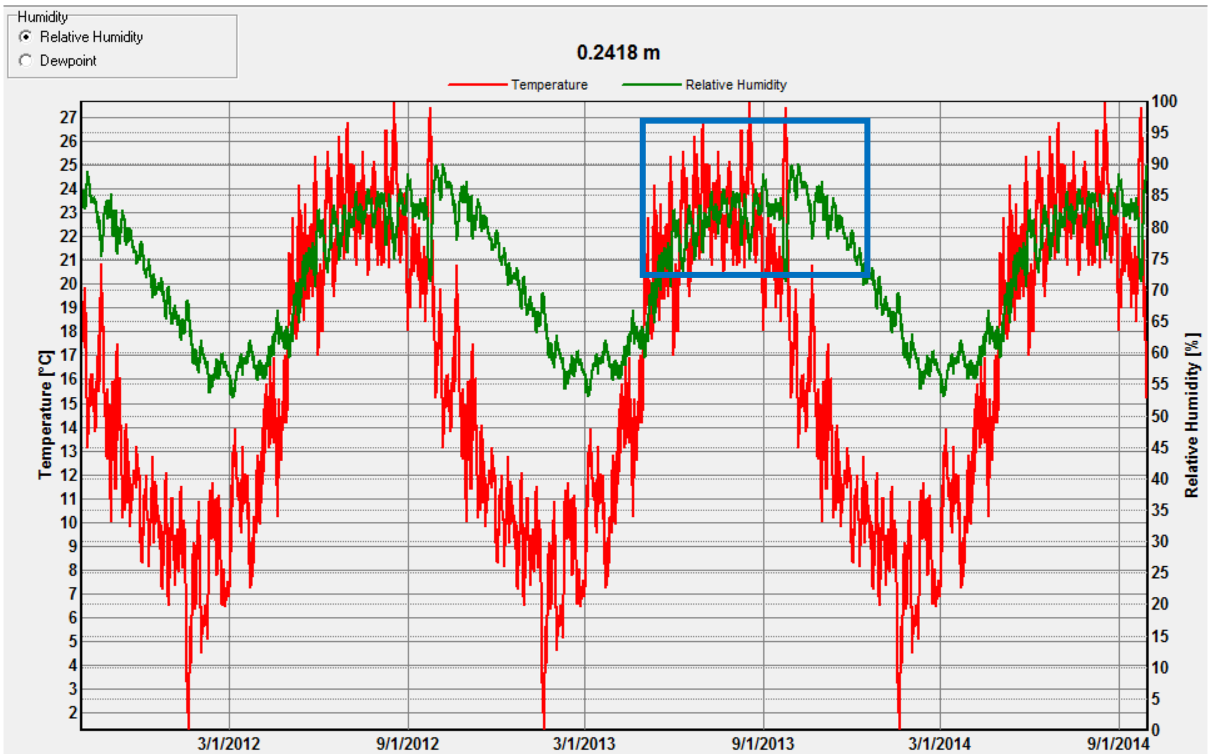
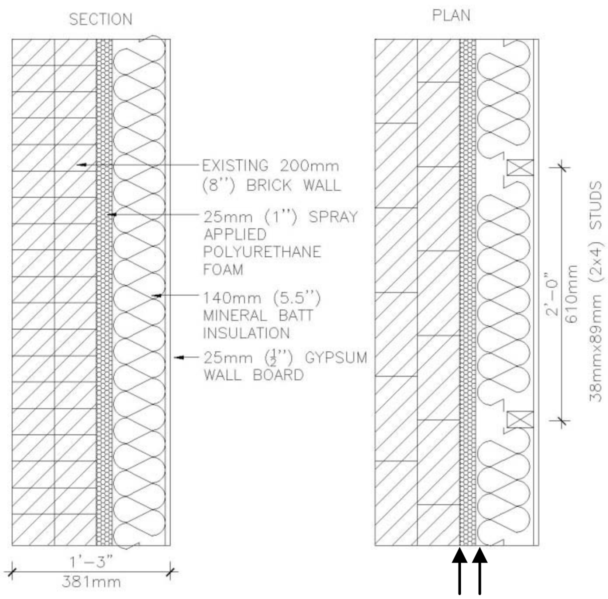


Figure 9- Brick 2006 OBC w/ Poly- Spray Foam/ Batt Interface (SE)

3. Brick 2012 OBC



Insulation Thermal Resistance

RSI 4.17 m²·K/W (R 23.7 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 4.69 m²·K/W (R 26.6 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 4.56 m²·K/W (R 25.9 ft²·°F·h/Btu)

General Note

This retrofit aims to achieve the medium range thermal resistance required for the 2012 Ontario Building Code (RSI 4.23) and provides an added thermal improvement over the 2006 OBC retrofit, while still providing an airtight wall. Thermal bridging of the studs is reduced by the spray foam and the offsetting of the studs away from the brick. The spray foam acts as an excellent air barrier by providing an airtight assembly through the sealing of any cracks or air passages throughout the wall. Long term airtightness can be achieved since spray foam does not crack and is permanently bound to the wall.

Environmental Impact

The added insulation value of this retrofit results in slightly higher impacts in each category over the 2006 OBC retrofit. Both mineral batt and spray foam are high impact materials and thus this option is categorized only as an energy efficient upgrade.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
322.26	31.72	59.03	23.28	0.3	0.02	0.1	0.3

Moisture Performance

The use of spray foam acts as a moisture retarder, and any small amount of rain penetration through the brick masonry wall that might occur will be localized, controlled and water will not be able to collect and run down and collect at floor penetration. Rain water absorbed into the masonry can diffuse to the outside or disuse to the inside through the interior finish. Within the hygrothermal simulations for both elevation exposures, the only area in which high RH levels (93%) are reached are between the brick and the spray foam during winter months (Figure 10). These levels are not of concern because of the previously mentioned statement and that there is no potential for mould growth on either of the materials assuming inorganic substances are present as it is impeded by the presence of the 6 mil polyethylene sheeting.

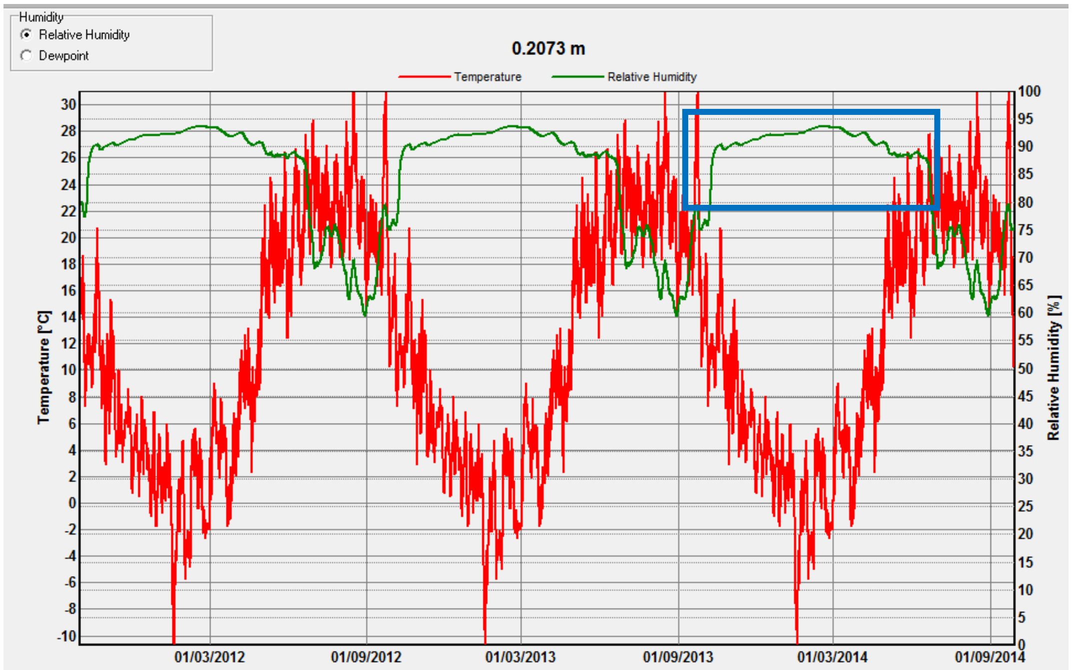


Figure 10- Brick 2012 OBC- Brick/ Spray Foam Interface (SE)

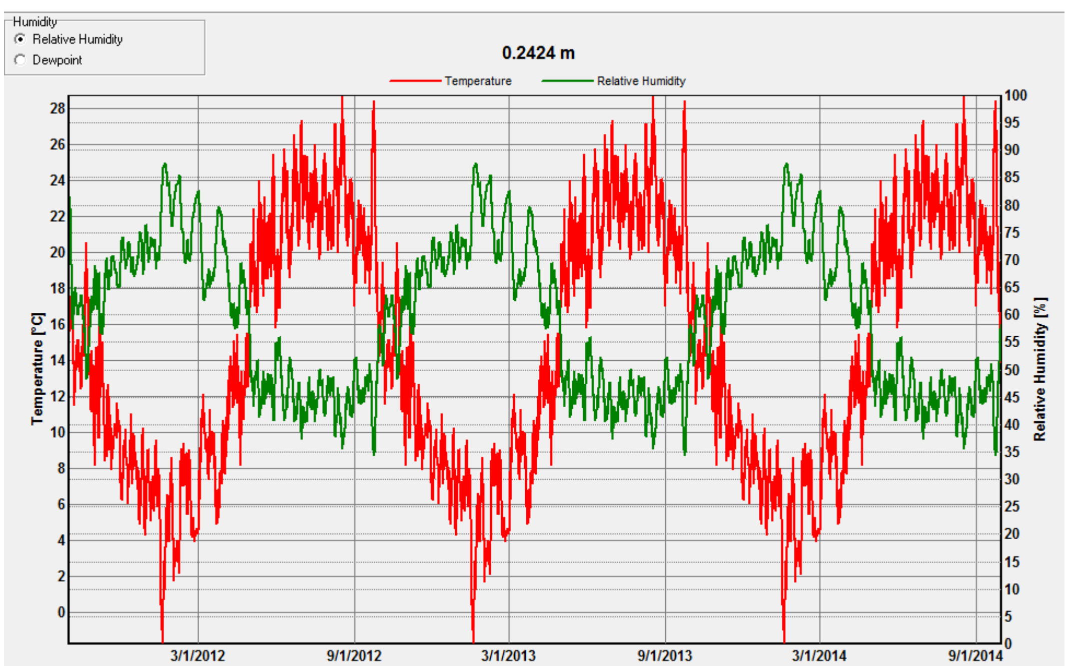


Figure 11- Brick 2012 OBC- Spray Foam/ Batt Interface (SE)

Iterations

As a result of previous simulations, a 6mil poly vapour retarded was decided not to be incorporated into this retrofit strategy because it seems to trap moisture within the wall not allowing diffusion of moisture inward, and increasing the RH especially in summer months. RH levels are much higher in the brick as well as in the exterior side of the mineral batt. Figure 11 and Figure 12 show the difference in RH at the spray foam/ batt interface with and without the poly. Unlike the retrofit without the poly, the total moisture content of the assembly increases from 0.84 kg/m^2 to 1.17 kg/m^2. Because of the high absorbtivity of the brick and the solid construction, which limits diffusion outward at times, diffusion inward is necessary as it is impeded by the presence of the 6 mil polyethylene sheeting.

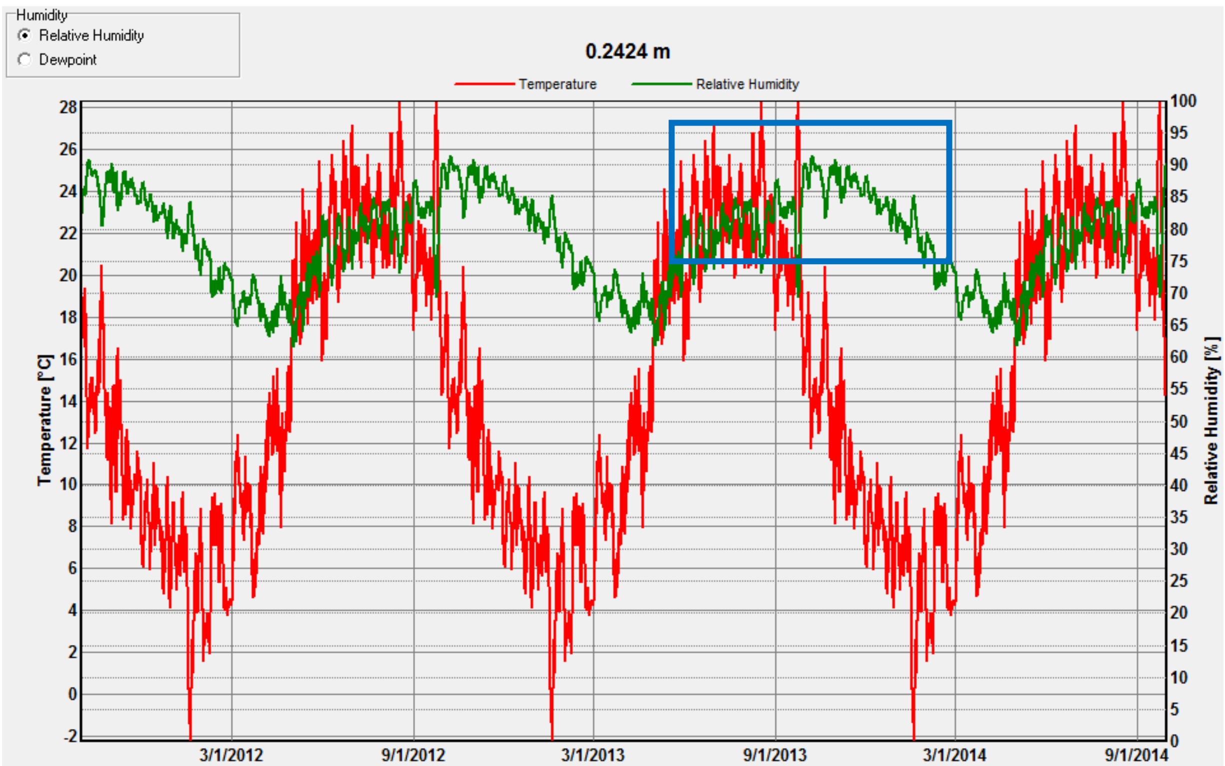
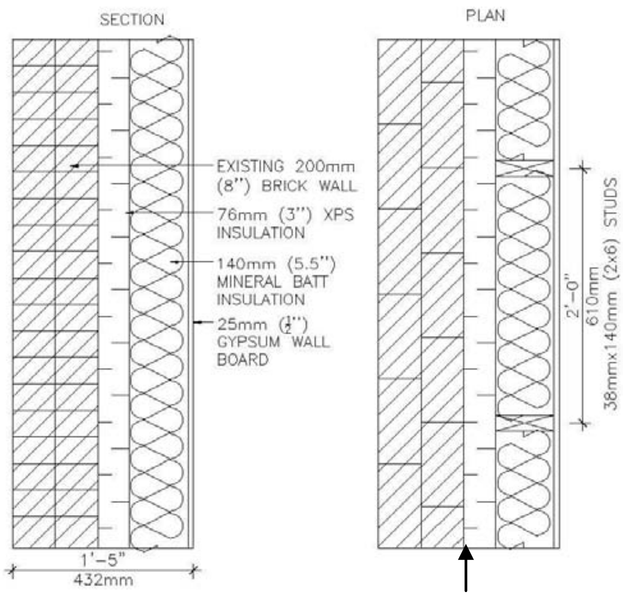


Figure 12- Brick 2012 OBC w/ Poly- Spray Foam/ Batt Interface (SE)

4. Brick Medium



Insulation Thermal Resistance

RSI 6.25 m²·K/W (R 35.8 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 6.79 m²·K/W (R 38.5 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 6.46 m²·K/W (R 36.7 ft²·°F·h/Btu)

General Note

This retrofit option was adapted from a high R value foundation wall assembly design used in the construction industry. The assembly provides a significant thermal resistance increase over building code standards. Thermal bridging of the studs is significantly reduced by the Extruded Polystyrene insulation (XPS) providing a continuous insulating layer between the suds and the masonry. For this retrofit it may be easier to implement the interior drywall as the air barrier instead of the XPS, since it would be difficult to seal transitions between the XPS floor/ceiling joists.

Environmental Impact

The use of XPS and mineral batt results in higher impacts in each category over the previous retrofits. Both mineral batt and XPS are high impact materials and using them together results in relatively high impact in each of the eight categories. Therefore this option is categorized only as an energy efficient upgrade.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
466.69	35.07	76.16	26.46	0.3	0.02	0.1	0.6

Moisture Performance

Hygrothermal analysis of the retrofit shows concern with the interface between the brick and the XPS during both exposures, but is more pronounced on the south-east elevation. RH levels steadily hover near 95% from November until June, thus there is potential for condensation to occur at the interface (Figure 13). The reduced inward diffusion added by the XPS, appears to contribute to the high moisture levels at the interface. This may result in moisture to collect between the interface and run down to the floor penetration. With knowledge of the increased condensation potential, foundation wall applications of this assembly typically allow drainage of condensate water at the brick/XPS plan to exit the assembly at the bottom (i.e. the footing) and into the free draining material typically found below basement slabs. It is not anticipated this drainage mechanism can be adequately designed in above-grade applications and caution must be taken when adopting this assembly as a retrofit option.

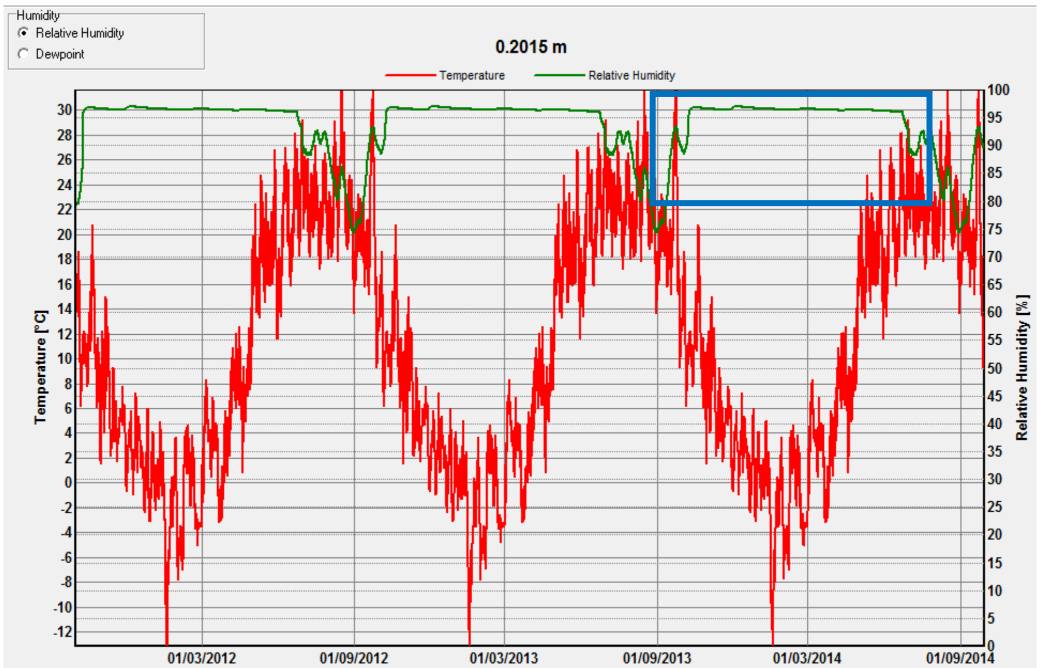
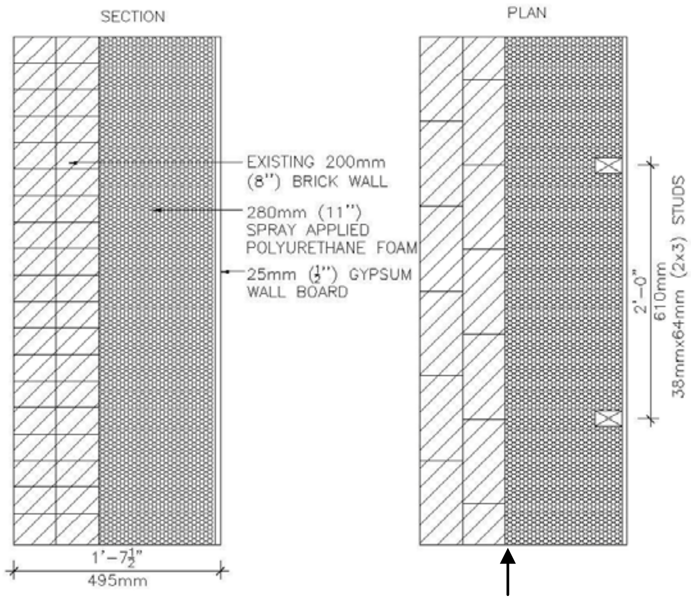


Figure 13- Brick Medium- Brick/XPS Interface (SE)

Iterations

As a result of high moisture levels between the brick and the XPS, as well as a review of pertinent literature, a second alternative to this retrofit was developed. In an attempt to minimize the potential for any moisture build up at this interface from collecting and running down the wall, it is recommended that a liquid applied, highly vapour permeable air and water barrier should be applied to the interior side of the brick to prevent any localized water penetrating and collecting on floor penetrations, while being vapour permeable enough to allow vapour to move in either direction [14].

5. Brick Super Insulated Interior Spray Foam



Insulation Thermal Resistance

RSI 10.37 m^2·K/W (R 58.9 ft^2·°F·h/Btu)

Assembly Thermal Resistance

RSI 10.94 m^2·K/W (R 62.1 ft^2·°F·h/Btu)

Effective Thermal Resistance

RSI 10.63 m^2·K/W (R 60.4 ft^2·°F·h/Btu)

General Note

This super insulated retrofit option employs a significant amount of spray foam to achieve Passive Haus EnerPHit guide required thermal resistance of RSI 10 and a virtually air tight wall assembly. The spray foam acts as the air barrier and fills any cracks or openings where air leakage may occur. Long term airtightness can be achieved because spray foam does not crack and is permanently bound to the wall. As a result of such high insulation value, there is a significant loss off floor area due to the increased wall thickness over other retrofit options.

Environmental Impact

Because of the reliance of such a large thickness of spray foam insulation, the environmental effects of this retrofit are significant and thus this is one of the highest impact retrofits in the research and can only be categorized as an energy efficient upgrade. The highest impacts occur in fossil fuel consumption, global warming, and acidification.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
693.19	72.59	42.93	16.66	0.07	0.005	0.01	0.1

Moisture Performance

The use of spray foam acts as a moisture retarder, and any small amount of rain penetration through the brick masonry wall that might occur will be localized, controlled and water will not be able to collect and run down onto the floor penetration. Rain water absorbed into the masonry will likely have to diffuse to the exterior, as 11 inches of closed cell spray foam will act as a significant vapour retarder. The hygrothermal simulations for both elevation exposures show the only area in which high RH levels (95%) are reached are between the brick and the spray foam (Figure 14). These levels are not of concern because of the previously mentioned statement, and that there is no potential for mould growth on either of the materials assuming inorganic substances are present.

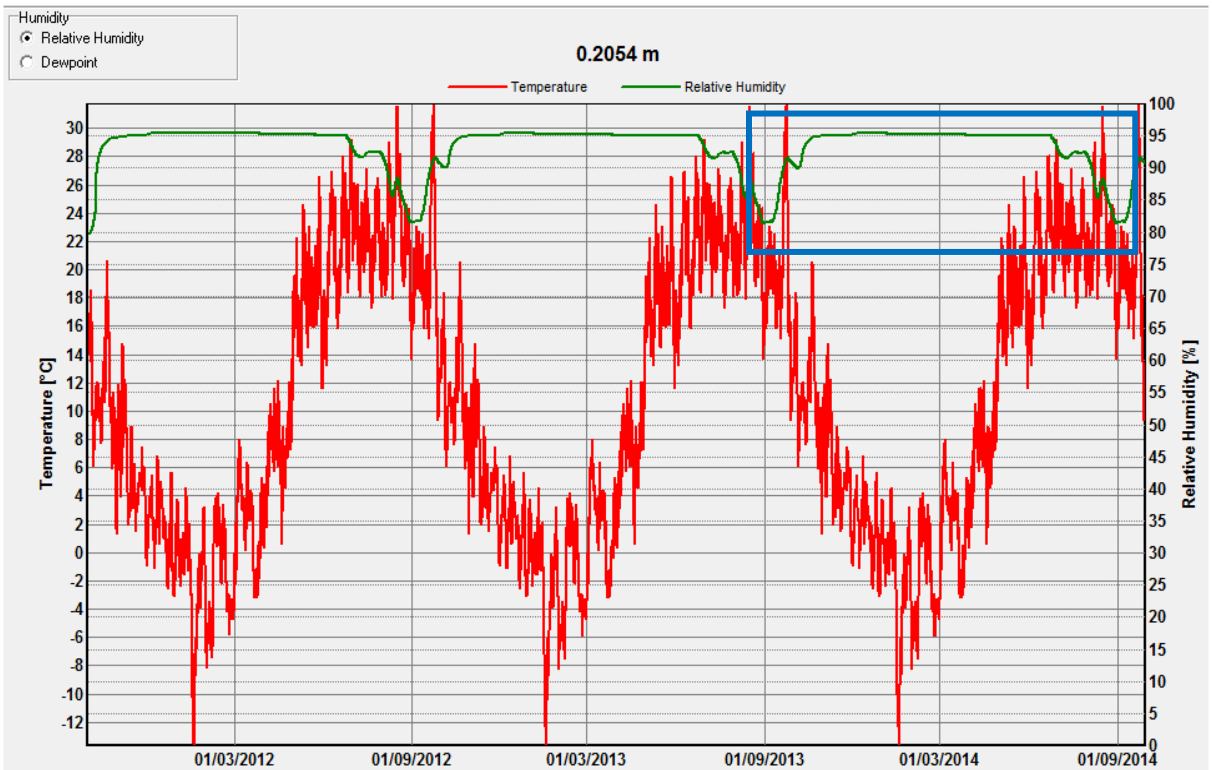
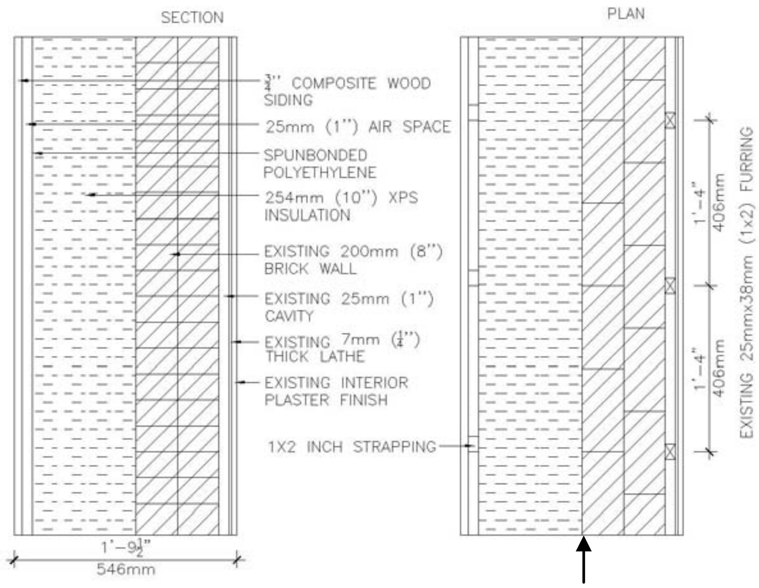


Figure 14- Brick SI Spray Foam- Brick/ Spray Foam Interface (SE)

6. Brick Super Insulated Exterior Insulation



<u>Insulation Thermal Resistance</u>

RSI 10.07 m²·K/W (R 57.2 ft²·°F·h/Btu)

<u>Assembly Thermal Resistance</u>

RSI 10.1 m²·K/W (R 57.3 ft²·°F·h/Btu)

<u>Effective Thermal Resistance</u>

RSI 10.1 m²·K/W (R 57.3 ft²·°F·h/Btu)

<u>General Note</u>

This super insulated retrofit option employs a significant amount of exterior XPS insulation to achieve Passive Haus EnerPHit guide required thermal resistance of RSI 10. This retrofit employs the XPS as the air barrier outboard of the structure. The durability of the air barrier is dependent on the longevity of the tape between the seams of the XPS or the proper installation of the house wrap. Exterior insulation keeps the brick structure warm and dry, and significantly reduces any thermal bridging. On the other hand, as a result the exterior of the brick will be covered up, which may not be preferred by the homeowner. Also, depending on neighbourhood, such a retrofit may not meet zoning specifications, and thus not be possible.

<u>Environmental Impact</u>

As with the use of spray foam insulation, the significant use of XPS has a profound effect on the impact of this retrofit and therefore is categorized as an energy efficient upgrade only. XPS shows the highest impact in fossil fuel use, global warming, resource use and smog potential.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
911.49	47.43	104.4	20.65	0.09	0.01	0.002	0.8

Moisture Performance

By placing rigid insulation on the exterior of the brick, any moisture that is able to get behind the cladding will drain and be vented away. The spunbonded polyethylene on the exterior of the XPS helps to cover up any of the joints between the XPS sheets. If the joints are sealed and taped properly, the spunbonded polyethylene may not necessarily be required. RH values from the exterior of the brick to the interior never exceed 45% RH and follow the pattern of the indoor moisture levels (Figure 15).

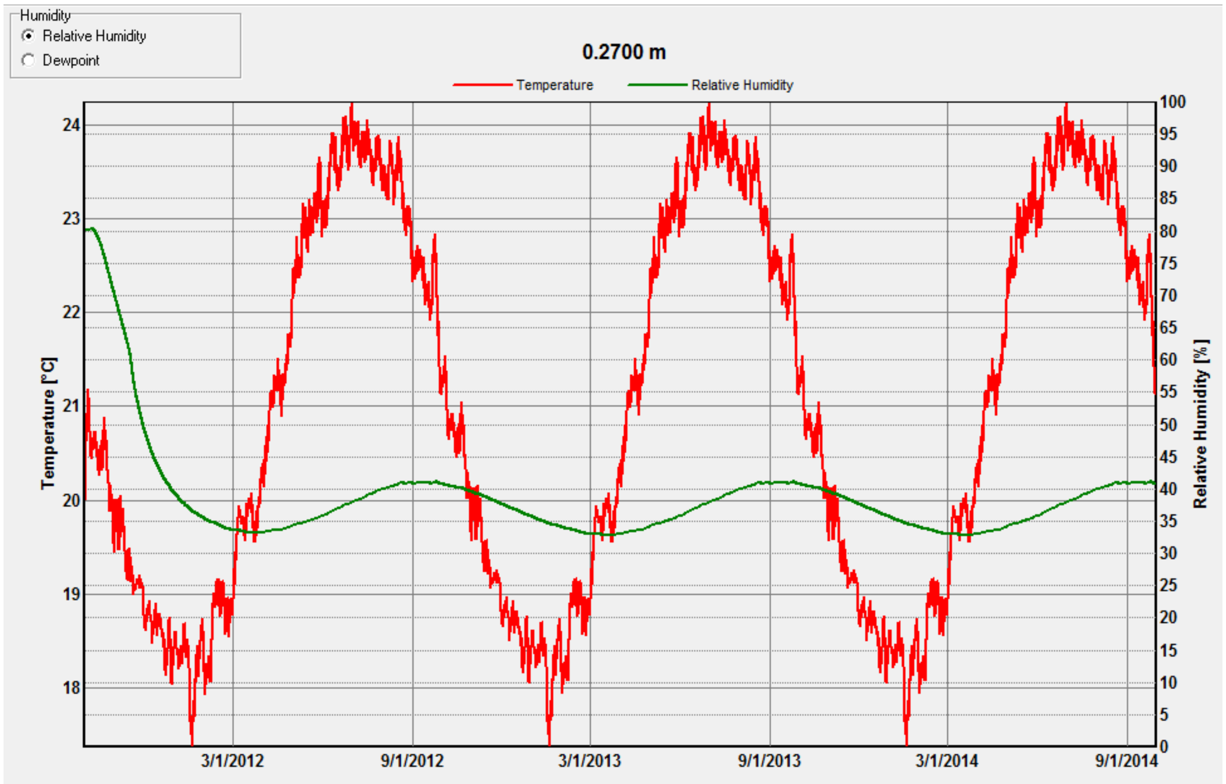


Figure 15- Brick SI Exterior- XPS/ Brick Interface (SE)

Iterations

One iteration which was simulated was the removal of the spunbonded polyethylene. Because Wufi is a one dimensional hygrothermal simulation tool, it cannot take into account joints in materials such as the XPS. The simulations shows no difference with or without the house wrap because XPS is water impermeable (Figure 16), thus it may only be necessary to tape up the joints in the XPS to make sure water is not able to run in behind it.

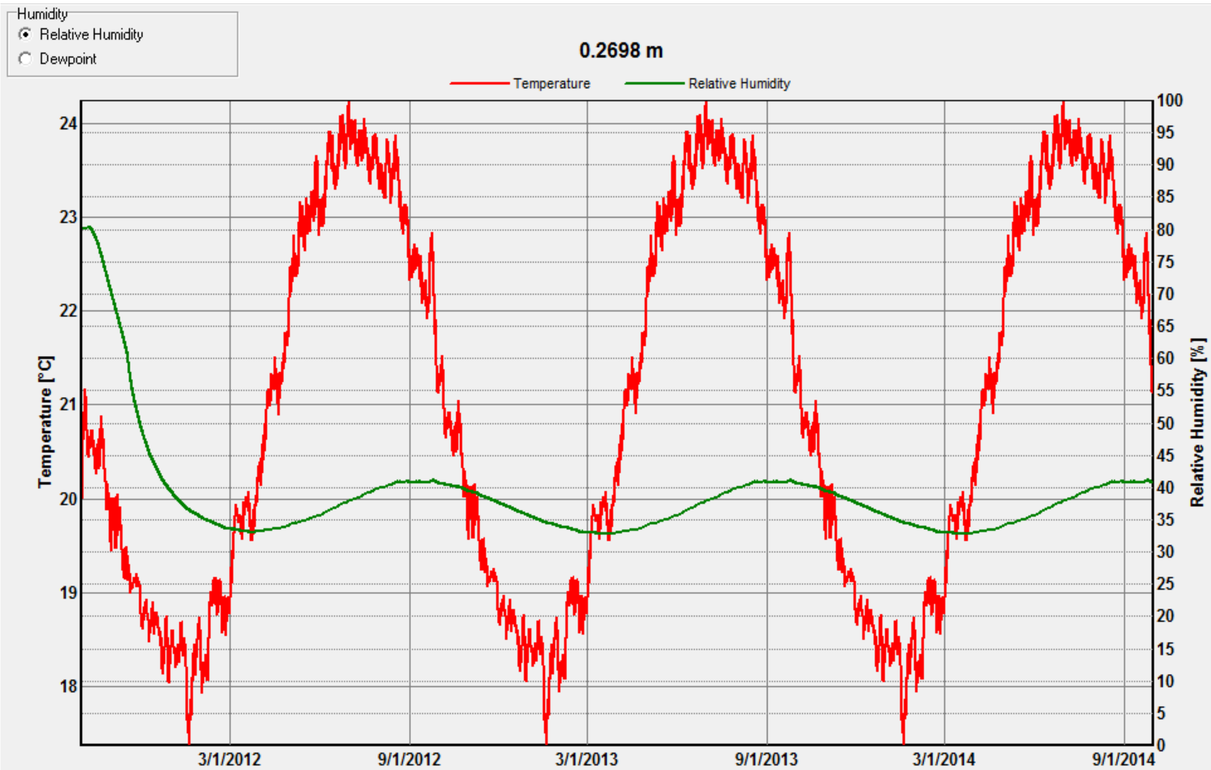
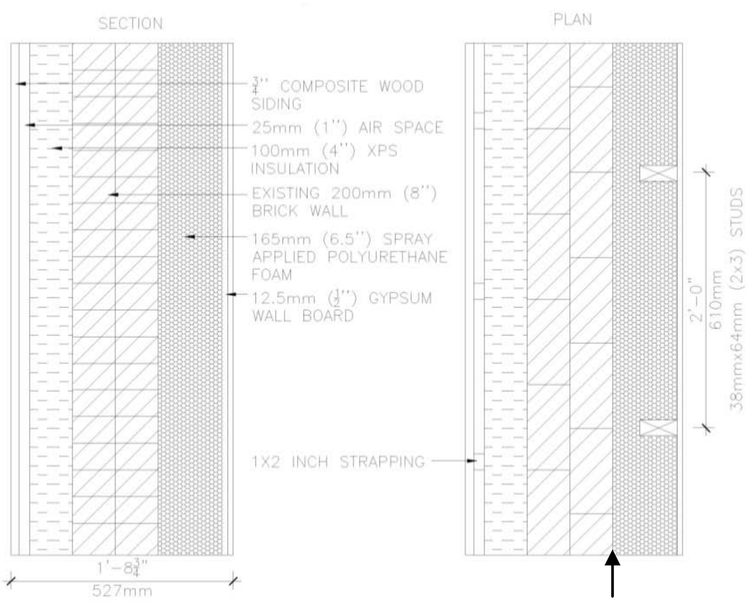


Figure 16- Brick SI Exterior no sunbonded polyethylene- XPS/ Brick Interface (SE)

7. Brick Super Insulated Interior/ Exterior Insulation



Insulation Thermal Resistance

RSI 10.17 m²·K/W (R 57.7 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 10.58 m²·K/W (R 60.1 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 10.26 m²·K/W (R 58.3 ft²·°F·h/Btu)

General Note

This super insulated retrofit option employs both interior and exterior insulation to achieve Passive Haus EnerPHit guide required thermal resistance of RSI 10. Naturally, this particular retrofit involves more work to implement. This option may be preferred if exterior and interior area are limited. The spray foam acts as the air barrier and fills any cracks or openings where air leakage may occur. Long term airtightness can be achieved because spray foam does not crack and is permanently bound to the wall.

Environmental Impact

As with the other assemblies which use only environmentally taxing materials (XPS and spray foam), the environmental effects of such a retrofit are significant and therefore the retrofit is only an energy efficient upgrade. The highest impact categories include fossil fuel use, global warming, resource use and acidification.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
791.77	60.89	103.18	18.32	0.09	0.008	0.008	0.4

Moisture Performance

By placing rigid insulation on the exterior of the brick, any moisture that is able to get behind the cladding will drain and be vented away. The XPS boards may be taped and sealed to stop any moisture getting behind the insulation. The spray foam adds the rest of the insulation value and provides an air tight enclosure, as well as acting as a vapour retarder from outward moisture diffusion. RH values in the brick level off to approx 50% and fluctuate very minimally (Figure 17). Overall the assembly performs very well hygrothermally.

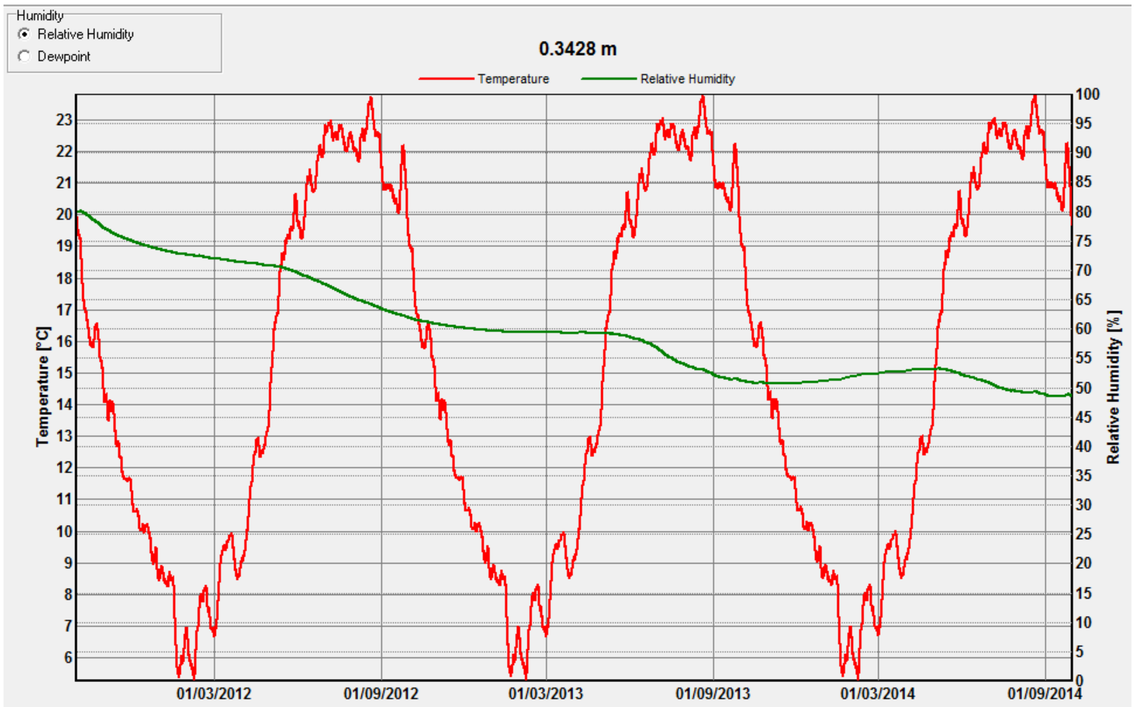
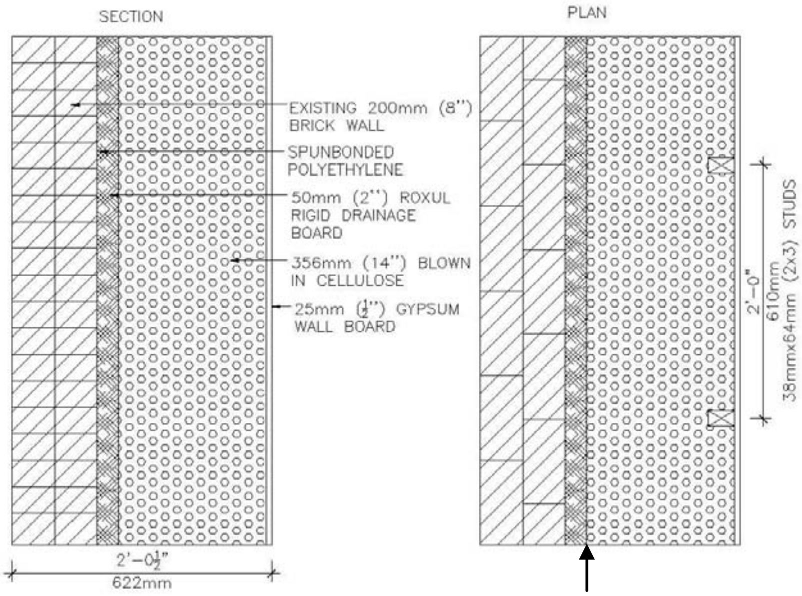


Figure 17- Brick SI Interior/ Exterior Insulation- Brick/ Spray Foam Interface (SE)

8. Brick Super Insulated Cellulose Diffusion Open



Insulation Thermal Resistance

RSI 10 m²·K/W (R 57 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 10.62 m²·K/W (R 60.3 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 10.48 m²·K/W (59.5 ft²·°F·h/Btu)

General Note

This super insulated retrofit option utilizes blown in cellulose as the major insulating value to achieve Passive Haus EnerPHit guide required thermal resistance of RSI 10. A house wrap and two inch layer of rigid Roxul insulation is used against the interior brick to help control excess moisture in the cellulose. Either the house wrap or interior drywall can act as the air barrier as long as each is properly detailed. Because the RSI value of cellulose is lower per unit of thickness than spray foam or XPS insulation, this retrofit option takes up more interior area than other retrofits.

Environmental Impact

The advantage of using a significant amount of cellulose is that the environmental effect of the assembly is usually significantly lower in each impact category. Elevated impacts in acidification and ozone depletion are a result of the mineral batt insulation. Since the average impact is significantly lower than all other brick retrofits and the major insulation value is provided by cellulose insulation, this retrofit is labelled as an environmental energy efficient upgrade.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
162.92	13.43	52.8	9.92	0.1	0.006	0.04	0.1

Moisture Performance

The major concern with this retrofit option is the moisture level of the cellulose insulation, especially near the exterior. Hygrothermal analysis during north and south-east exposure, show concerns of moisture issues in the exterior layer of the cellulose, but is more pronounced in south east exposure (Figure 18). ASHRAE 160P standard states RH values in mould sensitive materials should not exceed 80% above 5°C for more than 30 days. RH values in the cellulose exceed 80% for approx 90 days above 5°C, so there is a potential for mould growth to occur (Figure 19). These conditions only occur in the exterior inch to two inch of the cellulose layer. Further investigation is needed to determine if these high RH levels can be reduced in the cellulose and whether this retrofit is a viable option for solid brick masonry walls.

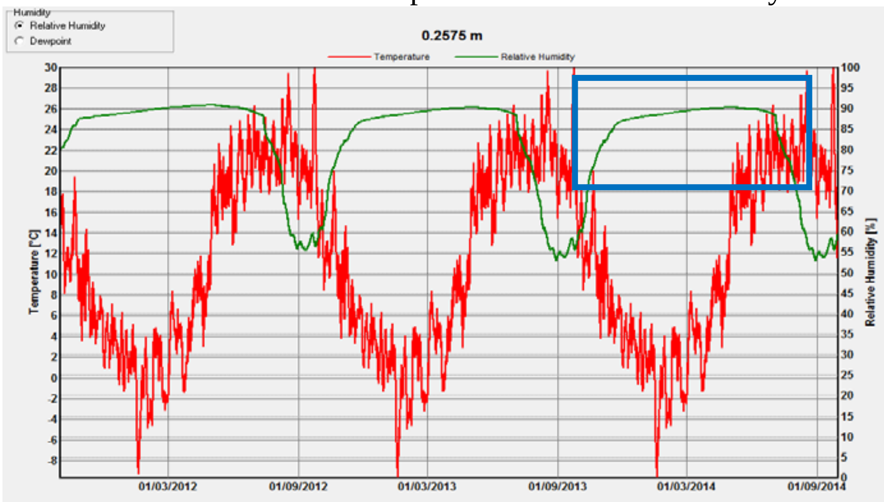


Figure 18- Brick SI Cellulose Open- Cellulose/Roxul Interface (SE)

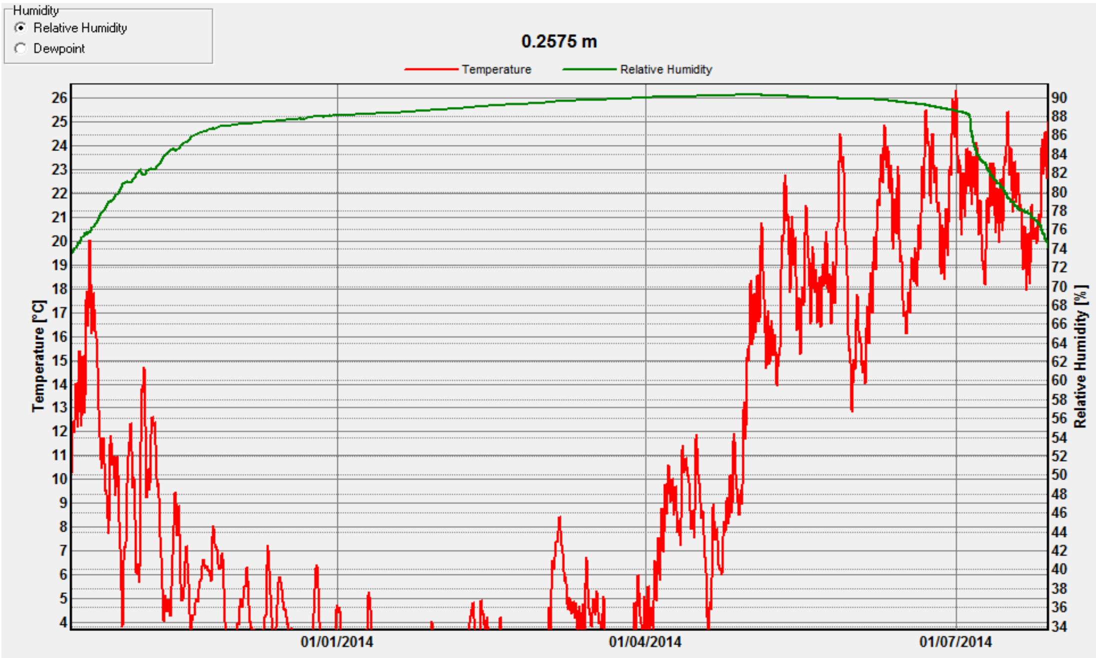


Figure 19- Brick SI Cellulose Open- Cellulose/ Roxul Interface (Detailed) (SE)

Iterations

The first option explored for this retrofit, only incorporated cellulose insulation without the spunbonded polyethylene or the Roxul rigid board. With the cellulose up against the brick, RH levels in the outer layer of the cellulose are above 88% throughout the year (Figure 20), and therefore it was decided that a material was needed to separate the cellulose from the brick. The next iteration applied the rigid board behind the cellulose which significantly reduced RH levels during winter months. Finally the spunbonded polyethylene was incorporated and reduced the RH a fraction lower.

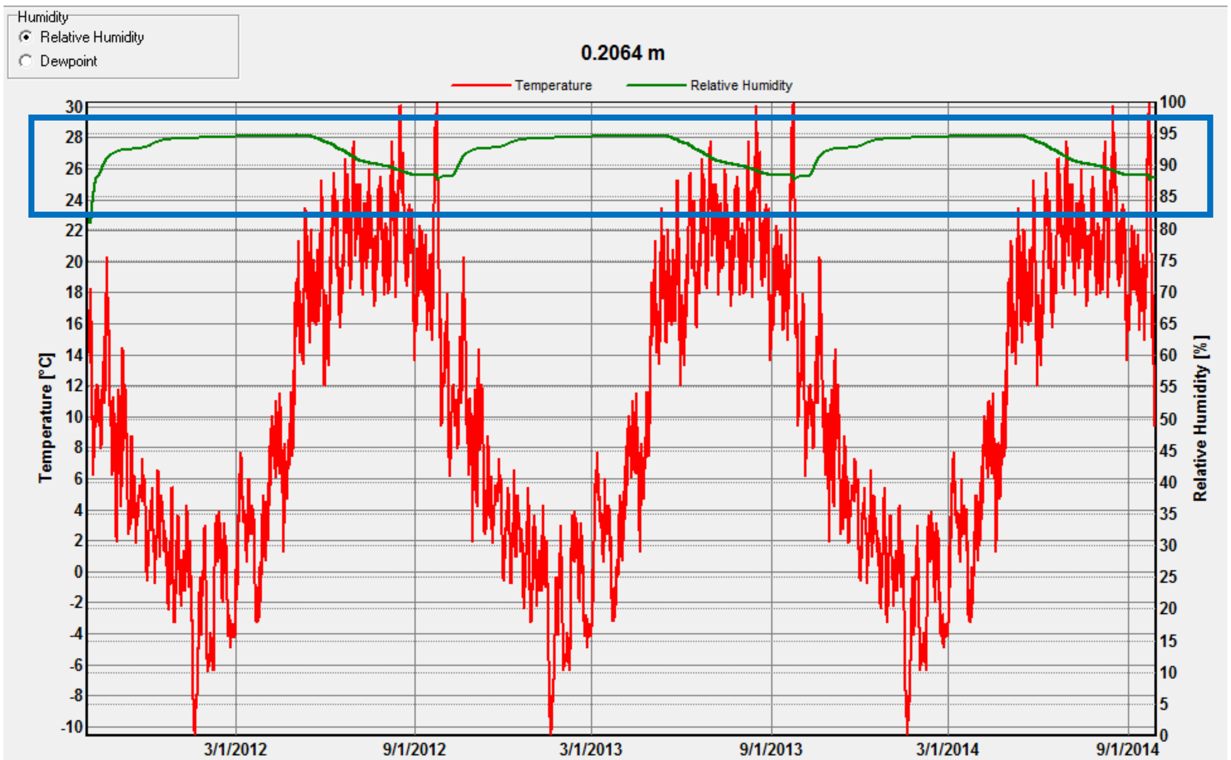
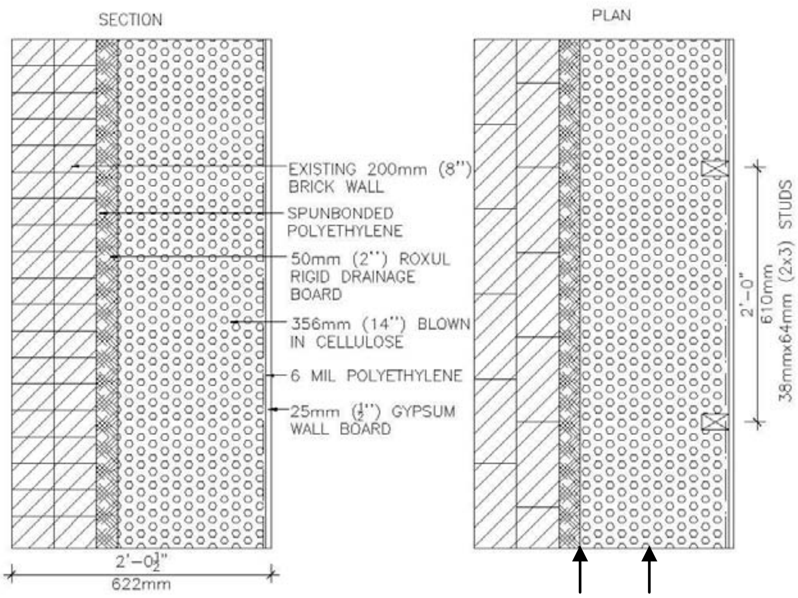


Figure 20- Brick SI Cellulose Open No Roxul/ House Wrap- Cellulose/Brick Interface (SE)

9. Brick Super Insulated Cellulose Diffusion Closed



Insulation Thermal Resistance

RSI 10 m²·K/W (R 57 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 10.62 m²·K/W (R 60.3 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 10.48 m²·K/W (59.5 ft²·°F·h/Btu)

General Note

This option is the same as retrofit #8 but has a 6 mil poly vapour retarder outboard of the drywall. The retrofit aims to determine whether a vapour retarder interior of the insulation will improve or worsen the moisture performance of the wall assembly.

Environmental Impact

As with assembly #8, the significant use of cellulose insulation creates the lowest impact in almost all categories and can be labelled as an environmental energy efficient upgrade.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
175.19	13.63	53.06	10.18	0.1	0.006	0.04	0.1

Moisture Performance

The addition of a vapour retarder inboard of the drywall creates serious moisture problems throught most of the assembly. The exterior of the cellulose is constantly above 90% throughout the year (Figure 21) and moisture content for the assembly has increased threefold. The middle section of the cellulose exceeds 80% RH from July to November (Figure 22). RH levels outboard of the poly spike to 88% RH and remain above 80% for approx 3 months from about July to October. Overall serious potential for mould growth is likely throughout the cellulose layer.

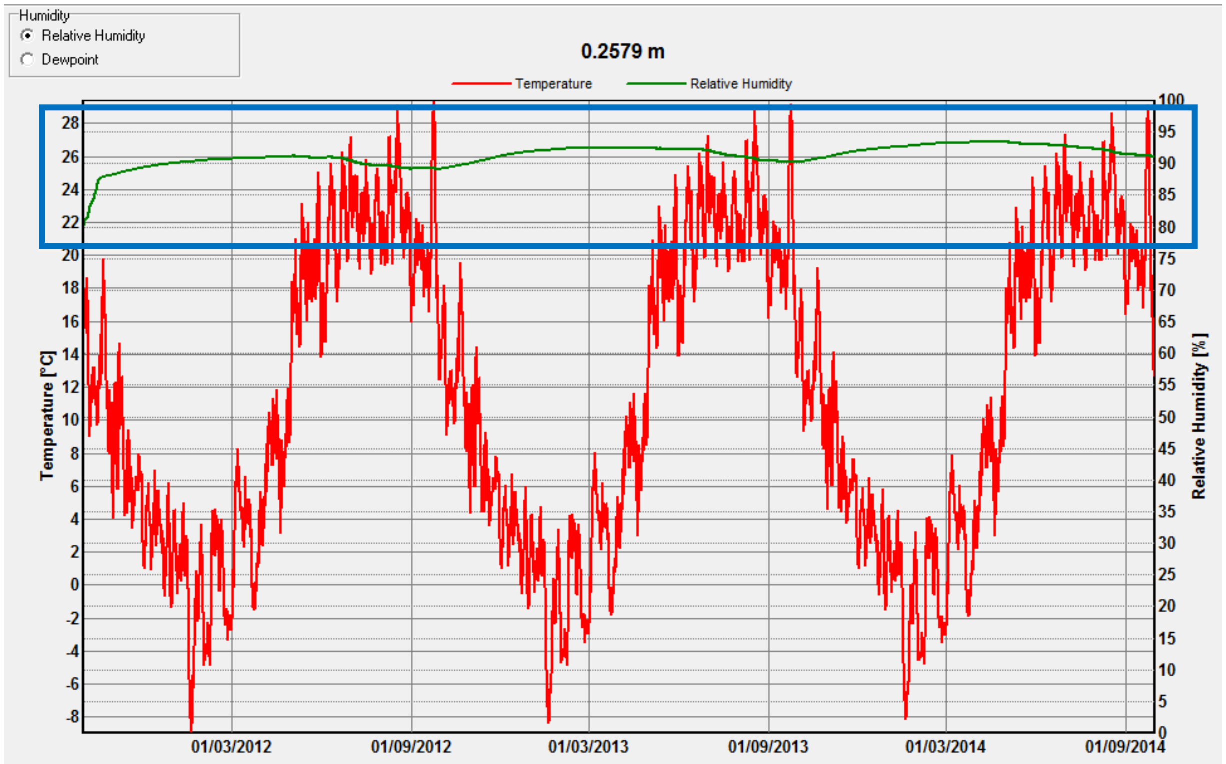


Figure 21- Brick SI Cellulose Closed- Cellulose/ Roxul Interface (SE)

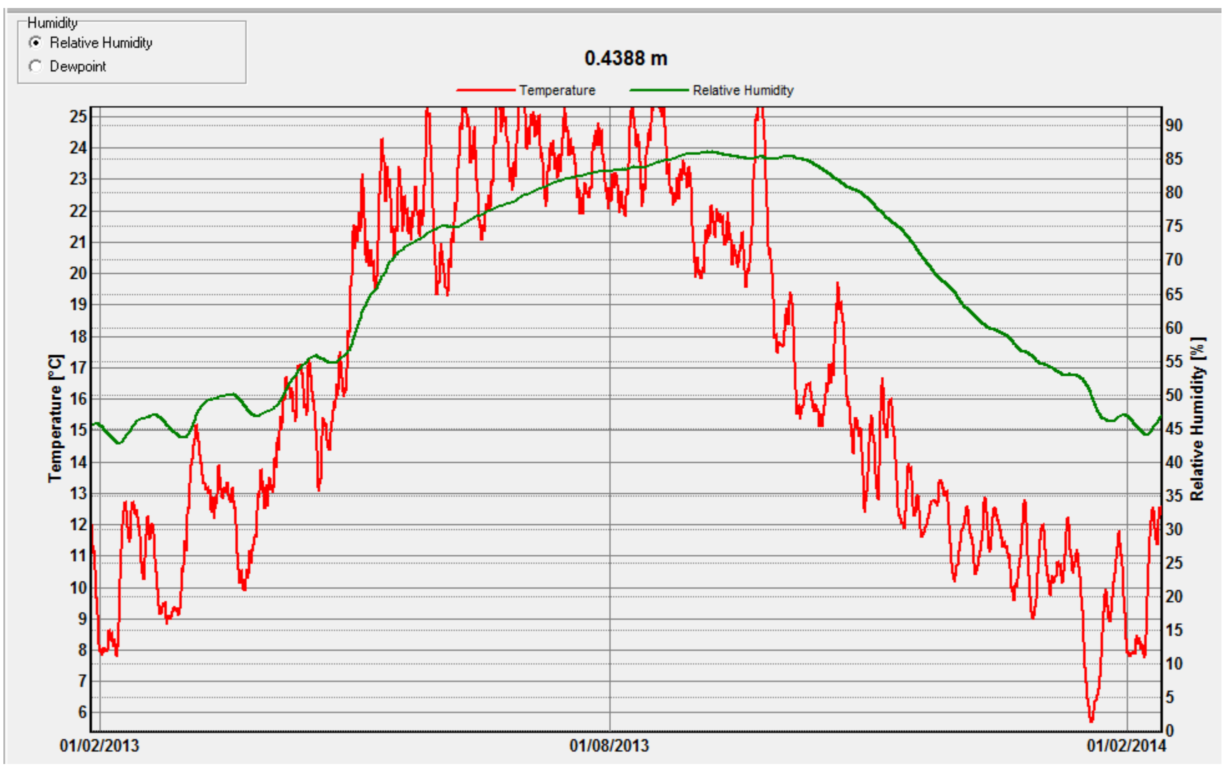


Figure 22- Brick SI Cellulose Closed- Centre of Cellulose Layer (Detailed) (SE)

Iterations

As with assembly #8, this assembly was first simulated without the Roxul rigid board nor the spunbonded polyethylene. Because this assembly already performs so poorly, the removal of these materials only increase the peak RH levels throughout the cellulose layer by about 5% (Figure 23).

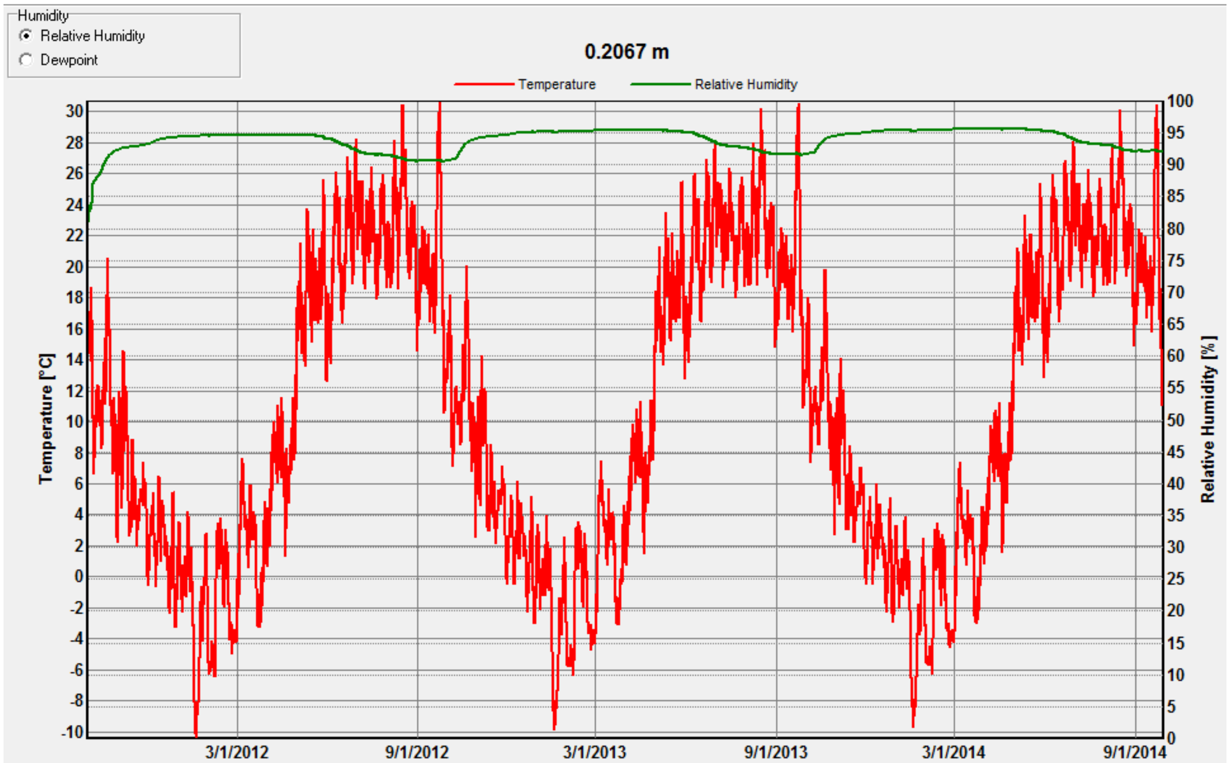
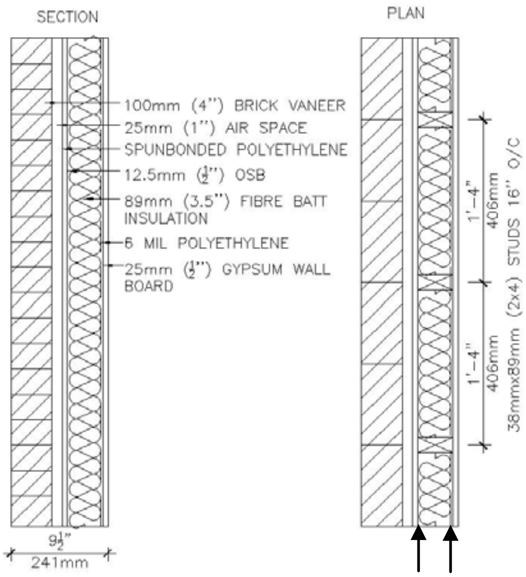


Figure 23- Brick SI Cellulose Closed No Roxul/ House Wrap- Cellulose/ Brick Interface (SE)

10. Existing Wood Frame



Insulation Thermal Resistance

RSI 2 $m^2 \cdot K/W$ (R 11.66 $ft^2 \cdot °F \cdot h/Btu$)

Assembly Thermal Resistance

RSI 2.6 $m^2 \cdot K/W$ (R 14.7 $ft^2 \cdot °F \cdot h/Btu$)

Effective Thermal Resistance

RSI 2.28 $m^2 \cdot K/W$ (R 12.9 $ft^2 \cdot °F \cdot h/Btu$)

General Note

This assembly will act as the control for the existing wood frame wall to be retrofitted which represents a large portion of the Toronto building stock. The existing assembly relies on 3.5 inches of fibreglass insulation, while studs create a direct thermal bridge from interior to exterior. Not until recently, this wall assembly has been the minimum code requirement of the OBC. The air barrier in this existing assembly is either the 6 mil poly or the house wrap, or both, but is only effective if installed properly. Poor workmanship around transitions can cause failure in the air barrier and create a leaky home.

Environmental Impact

Since this assembly acts as a baseline for the retrofit options, it does not include data on the environmental impact of the assembly because it contains only existing materials. All retrofit assemblies will have a table listing data for the eight environmental impact indicators. A comparative review between each assembly is developed in section 4.2.4 which provides a better understanding of the comparative magnitude of this data.

Moisture Performance

In most wood frame exterior walls, the most vulnerable layer of the assembly is the exterior sheathing, in this case the OSB. Low winter material temperatures and a vapour drive to the exterior, could cause condensation to build up on the interior side of the OSB, causing mould and rot. Hygrothermal analysis of the assembly in Wufi shows no concerning moisture issues. RH values in the OSB just exceed 80% in winter months (Figure 24), but not for more than 30 days above 5°C. Monitoring positions outboard of the poly show some RH spikes as high as 90% but only for short periods of time (Figure 25).

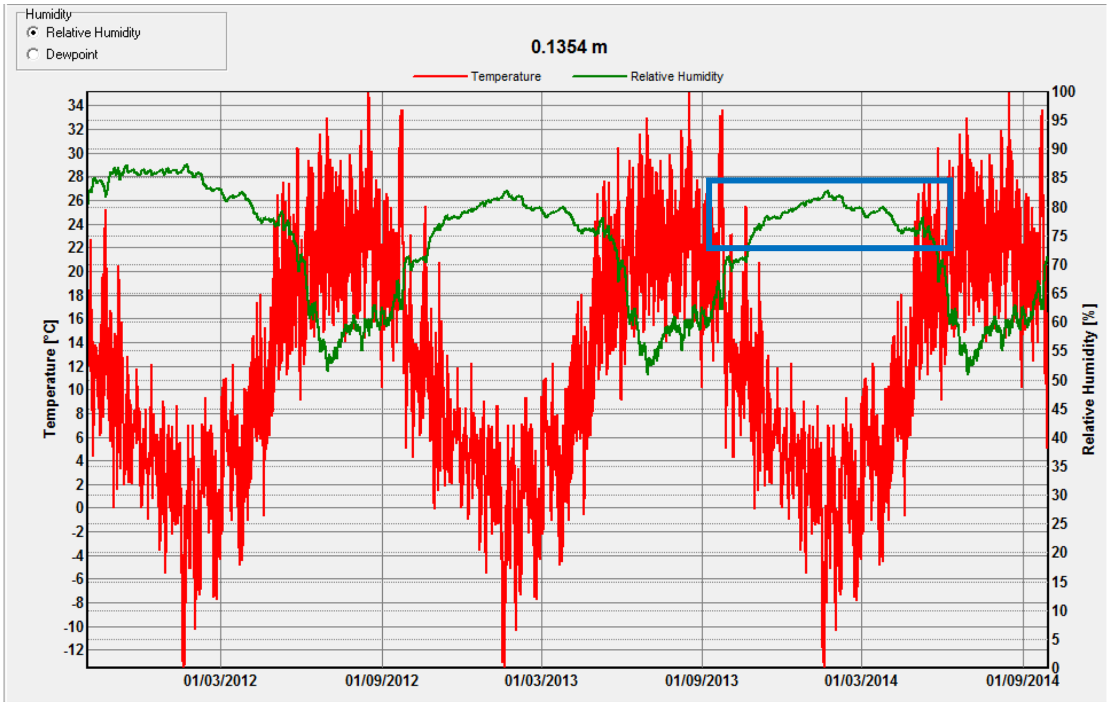


Figure 24- Existing Wood Frame- OSB/ Batt Interface (SE)

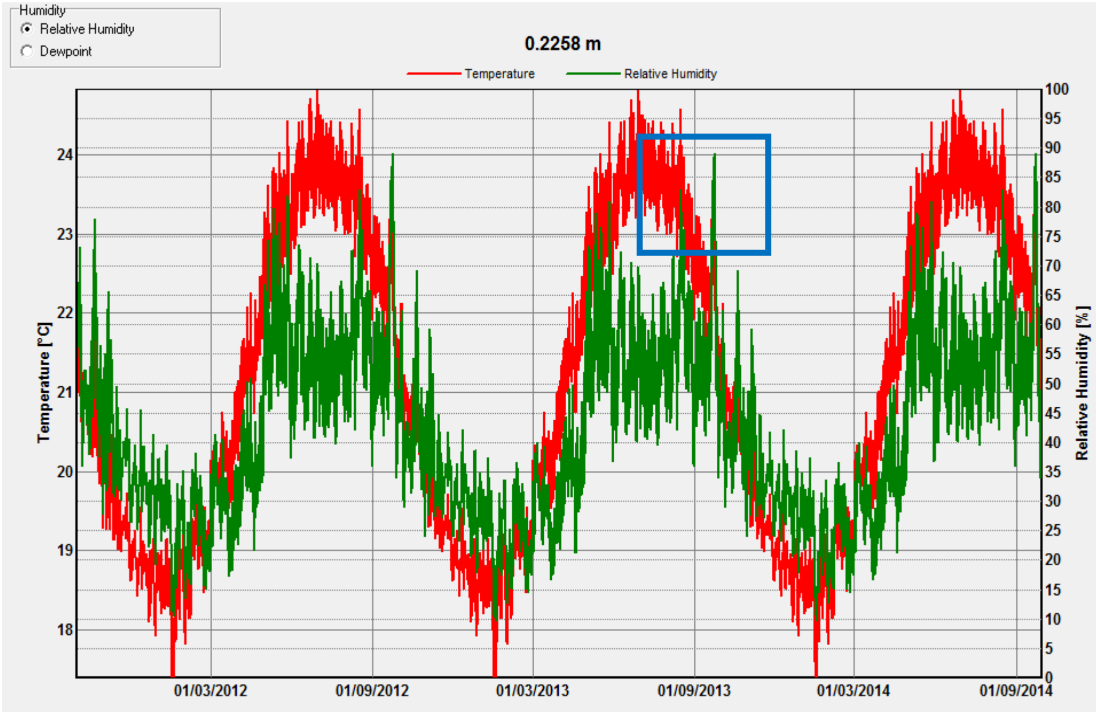
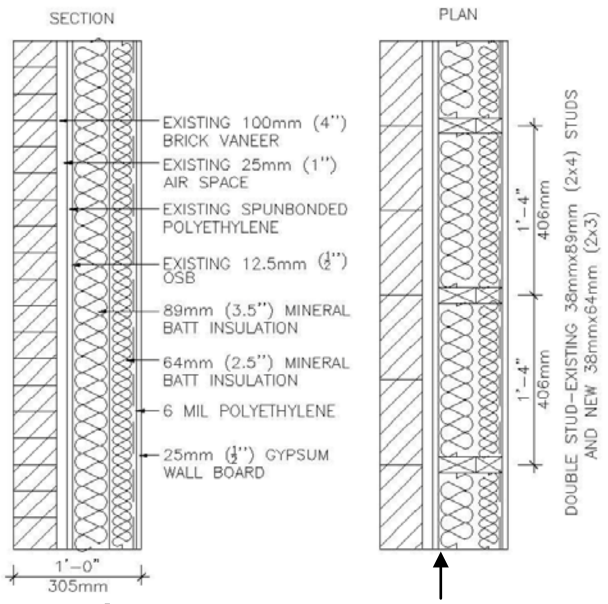


Figure 25- Wood Frame- Batt/ Poly Interface (SE)

11. Wood Frame 2006 OBC



Insulation Thermal Resistance

RSI 3.52 m²·K/W (R 20 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 4.08 m²·K/W (R 23.2 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 3.5 m²·K/W (R 19.9 ft²·°F·h/Btu)

General Note

The following retrofit aims to achieve the minimum thermal resistance required for the 2006 Ontario Building Code (RSI 3.35). The retrofit provides a slight thermal improvement over the existing assembly. As with the existing assembly the 6 mil poly should be utilized as the air barrier and installed properly to create a continuous air tight barrier.

Environmental Impact

The use of mineral batt insulation results in this retrofit having the highest impact in acidification, respiratory effect, eutrophication, and ozone depletion. As a result the retrofit can only be classified as an energy efficient upgrade.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
253.98	24.26	62.18	23.09	0.3	0.02	0.1	0.2

Moisture Performance

Similar to the existing assembly, hygrothermal analysis shows no pressing concern with moisture (Figure 26). RH values increase more during the winter months but are within ASHRAE 160P standards (Figure 27).

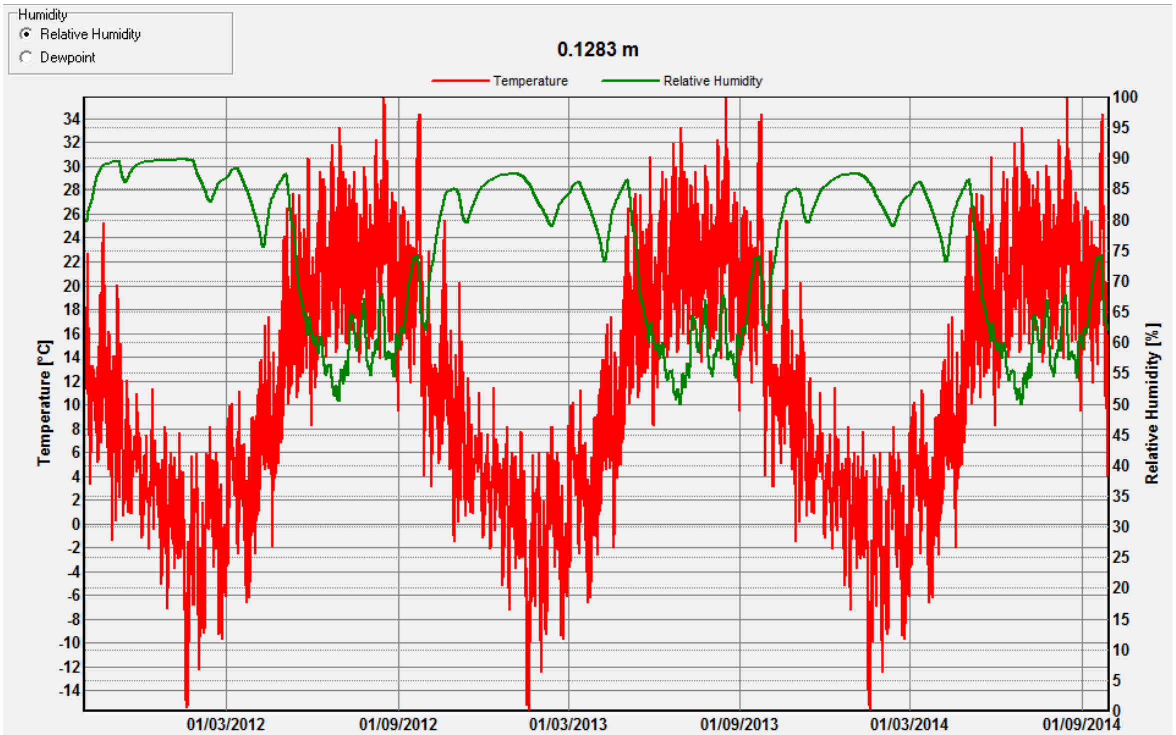


Figure 26- Wood Frame 2006 OBC- OSB/ Mineral Batt Interface (SE)

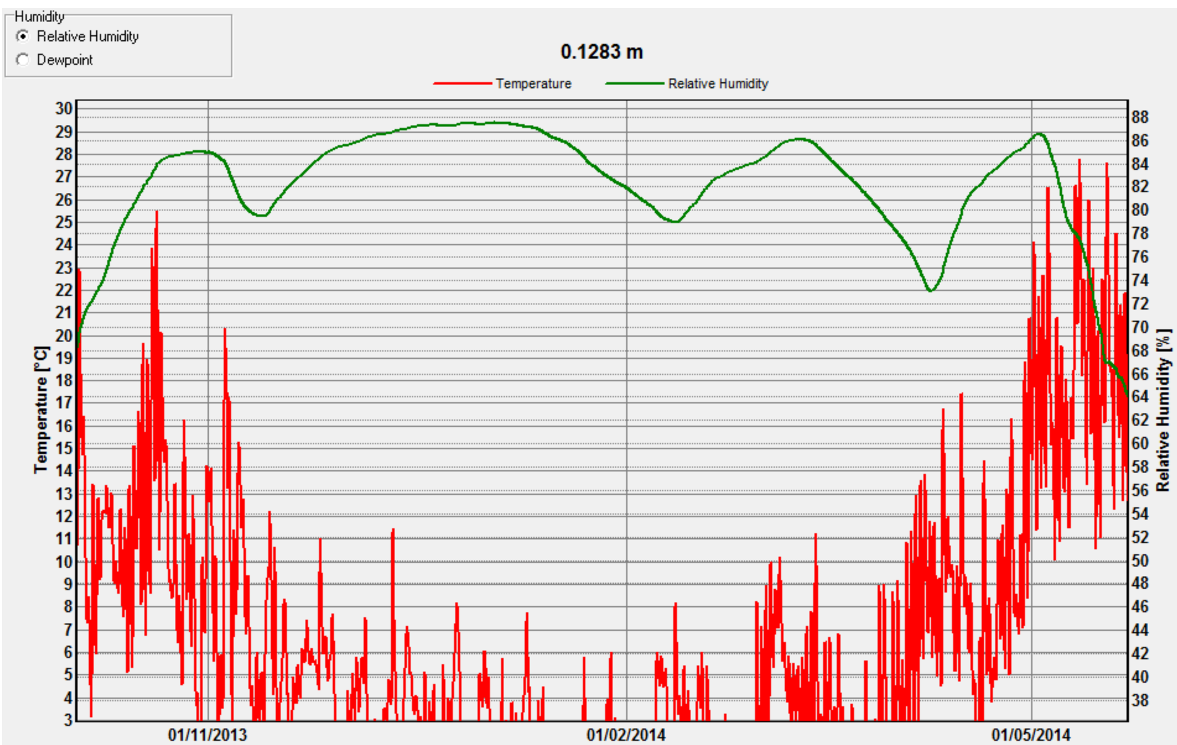
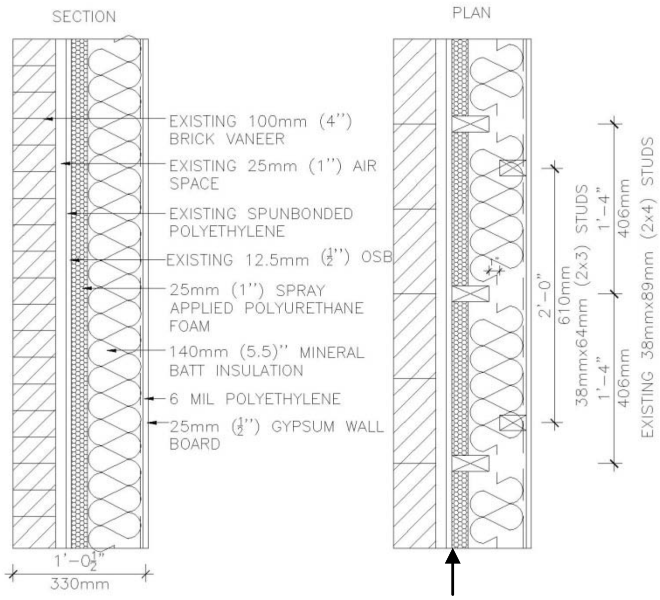


Figure 27-Wood Frame 2006 OBC- OSB/ Mineral Batt Interface (Detailed) (SE)

12. Wood Frame 2012 OBC



Insulation Thermal Resistance

RSI 4.17 m²·K/W (R 23.7 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 4.74 m²·K/W (R 26.9 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 4.25 m²·K/W (R 24.1 ft²·°F·h/Btu)

General Note

This retrofit aims to achieve the medium range thermal resistance required for the 2012 Ontario Building Code (RSI 4.23). The retrofit employs a layer of spray foam to achieve the required RSI value while trying to reduce the amount of indoor floor area imposed on. The spray foam acts as an excellent air barrier by providing a very airtight assembly by sealing any air passages through the wall. Long term air tightness can be achieved because spray foam does not crack and is permanently bound to the OSB.

Environmental Impact

As with assembly #11, the use of mineral batt insulation results in high impact in acidification, respiratory effect, eutrophication, and ozone depletion. The addition of the spray foam increases the impact in the other categories over the 2006 OBC upgrade. As such this retrofit is labelled as an energy efficient upgrade.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
322.26	31.72	59.03	23.28	0.3	0.02	0.1	0.3

Moisture Performance

Hygrothermal analysis shows no moisture issues on the northern exposure. During south-east exposure, monitoring positions show elevated RH values in the OSB, likely due to driving rain, sun driven moisture and a the fairly low diffusivity of the spray foam. Values fluctuate above 80% from November until approximately May (Figure 28). There may be a very slight potential for mould to occur in the OSB in the spring months. Values above 80% RH may or may not exceed a period of 30 days above 5°C (Figure 29) depending on the control of indoor moisture levels. It is important to note that the highest RH values occur in the outboard layers of the OSB.

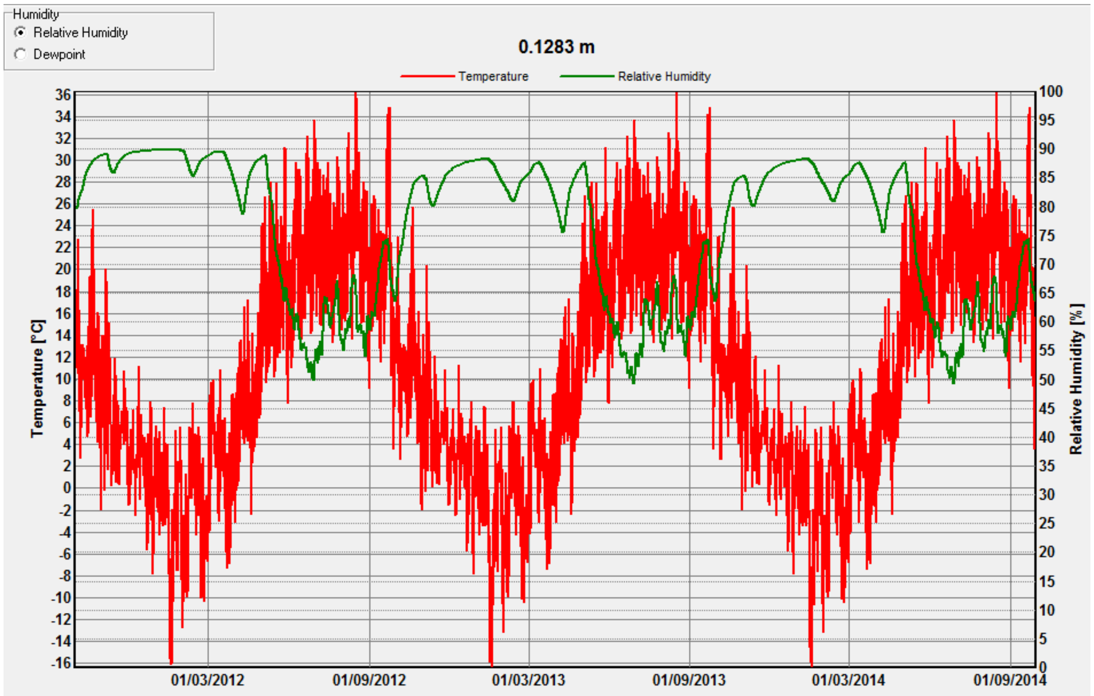


Figure 28- Wood Frame 2012 OBC- OSB/ Spray Foam Interface (SE)

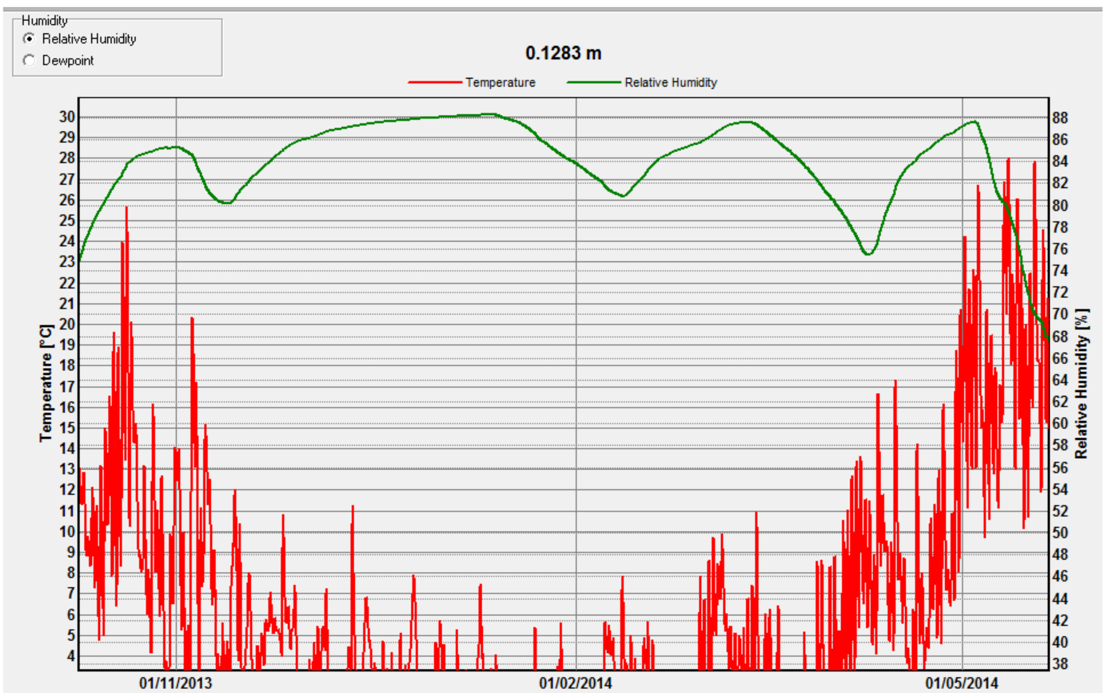


Figure 29- Wood Frame 2012 OBC- OSB/ Spray Foam Interface (Detailed) (SE)

Iterations

Another option which was explored for this retrofit included the removal of the 6 mil poly. Hygrothermal analysis shows no effect on the RH values of the OSB, but does show spikes in RH as high 90% (Figure 30) during winter months compared to the retrofit with the poly (Figure 31). This option may not be recommended if interior RH values are not regulated.

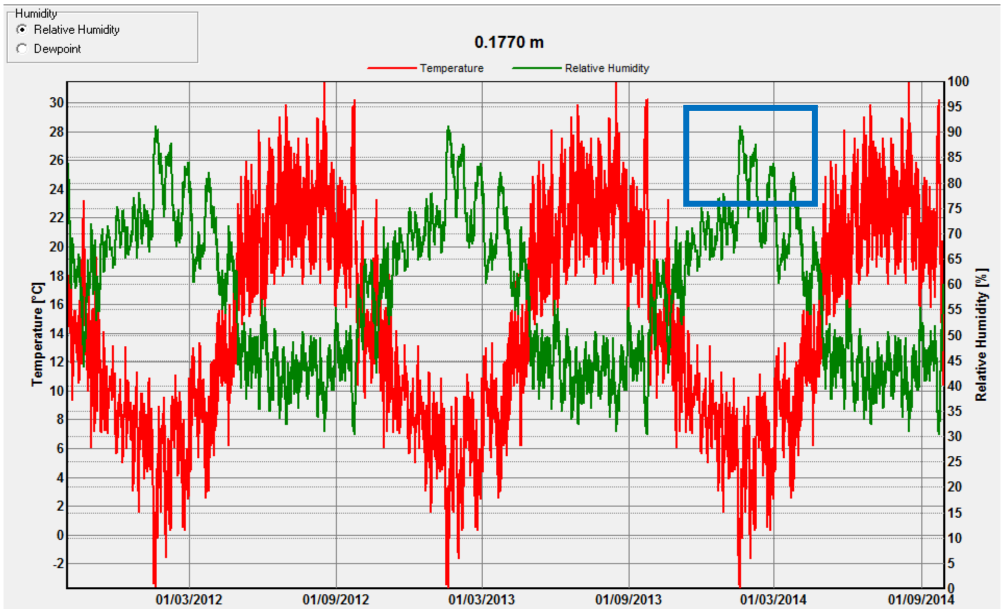


Figure 30- Wood Frame 2012 OBC No Poly- Spray Foam/ Mineral Wool Interface (SE)

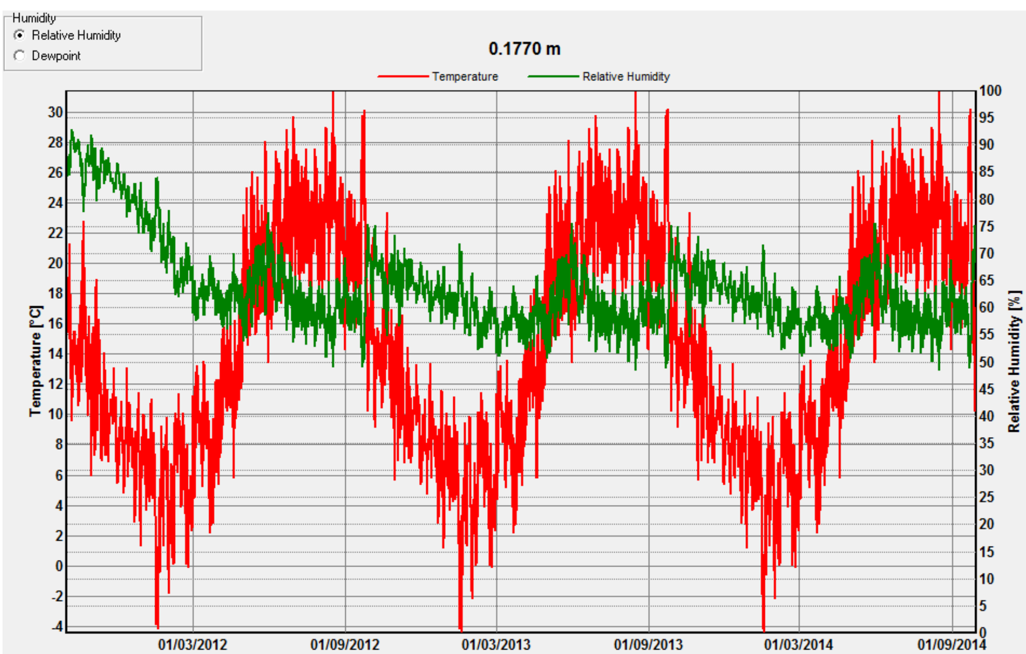
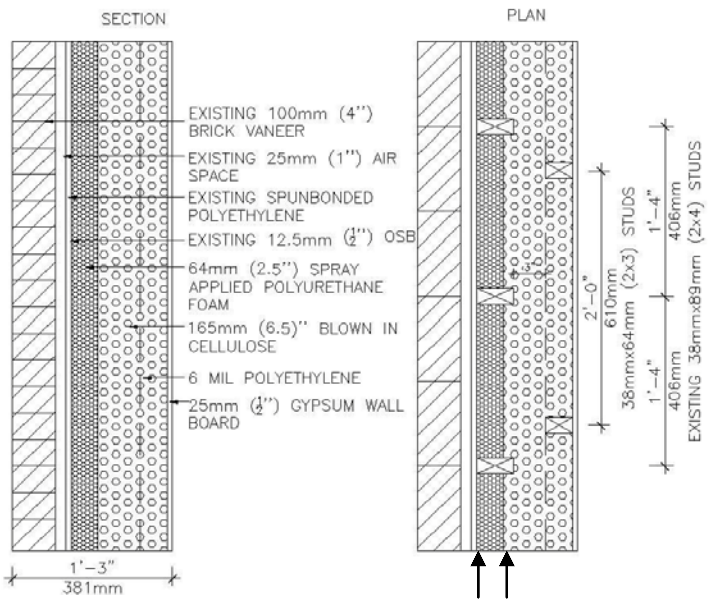


Figure 31- Wood Frame 2012 OBC- Spray Foam/ Mineral Wool Interface (SE)

13. Wood Frame Medium



Calculated Thermal Resistance

RSI 6.36 m²·K/W (R 36.1 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 6.92 m²·K/W (R 39.3 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 6.25 m²·K/W (R 35.5 ft²·°F·h/Btu)

General Note

This retrofit option provides a significant thermal resistance increase over building code standards. It employs both spray foam and cellulose insulation to achieve a high performing wall, while decreasing its environmental impact through significant use of cellulose insulation. The spray foam acts as an excellent air barrier by providing a very airtight assembly by sealing any air passages through the wall. Long term air tightness can be achieved because spray foam does not crack and is permanently bound to the OSB.

Environmental Impact

Becuase of the use of a significant amount of cellulose, this option has one of the overall lowest impacts of all the wood frame retrofits. Although this is the case, the affect and use of spray foam denies this retrofit the label of an environmental energy efficient upgrade.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
244.72	21.47	37.22	6.18	0.03	0.002	0.006	0.04

Moisture Performance

Similar to retrofit #12, Wufi analysis shows elevated RH values in the OSB, likely due to driving rain, sun driven moisture and lower diffusivity of the spray foam. Values fluctuate above 80% from November until approximately May. There may be a very slight potential for mould to occur in the OSB in the spring months. Values above 80% RH may or may not exceed a period of 30 days (Figure 32). It is important to note that the highest RH values occur in the outboard layers of the OSB. The cellulose in the assembly performs very well and shows no moisture concerns with RH values ranging from 30 to 70% with max RH occurring near the spray foam (Figure 33).

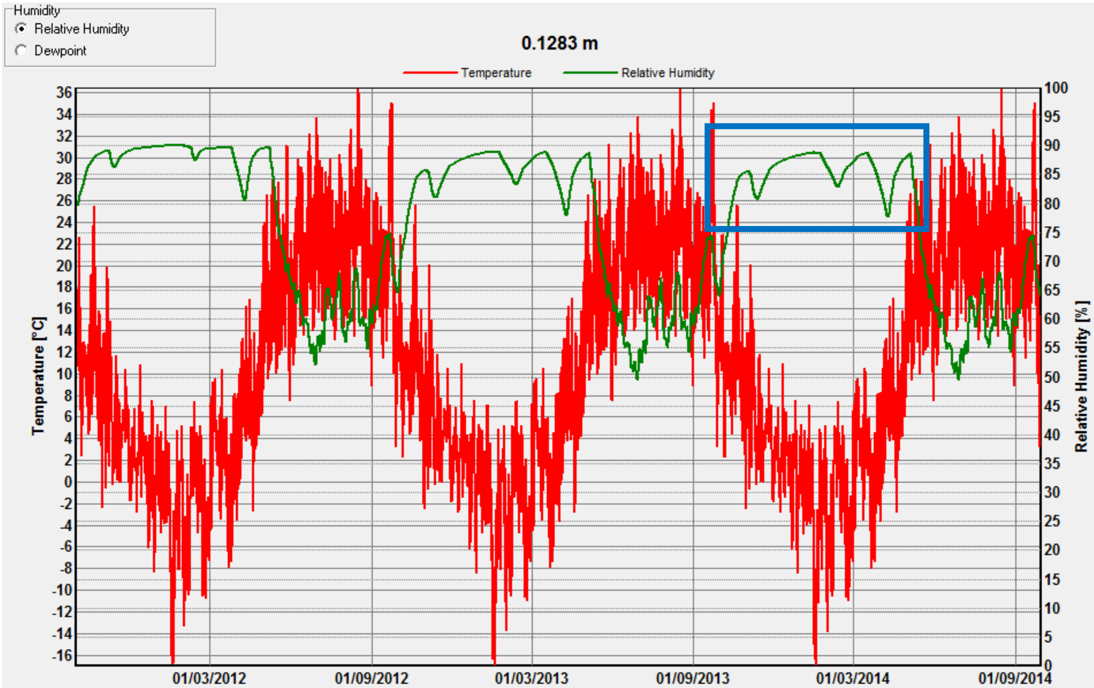


Figure 32- Wood Frame Medium- OSB/ Spray Foam Interface (SE)

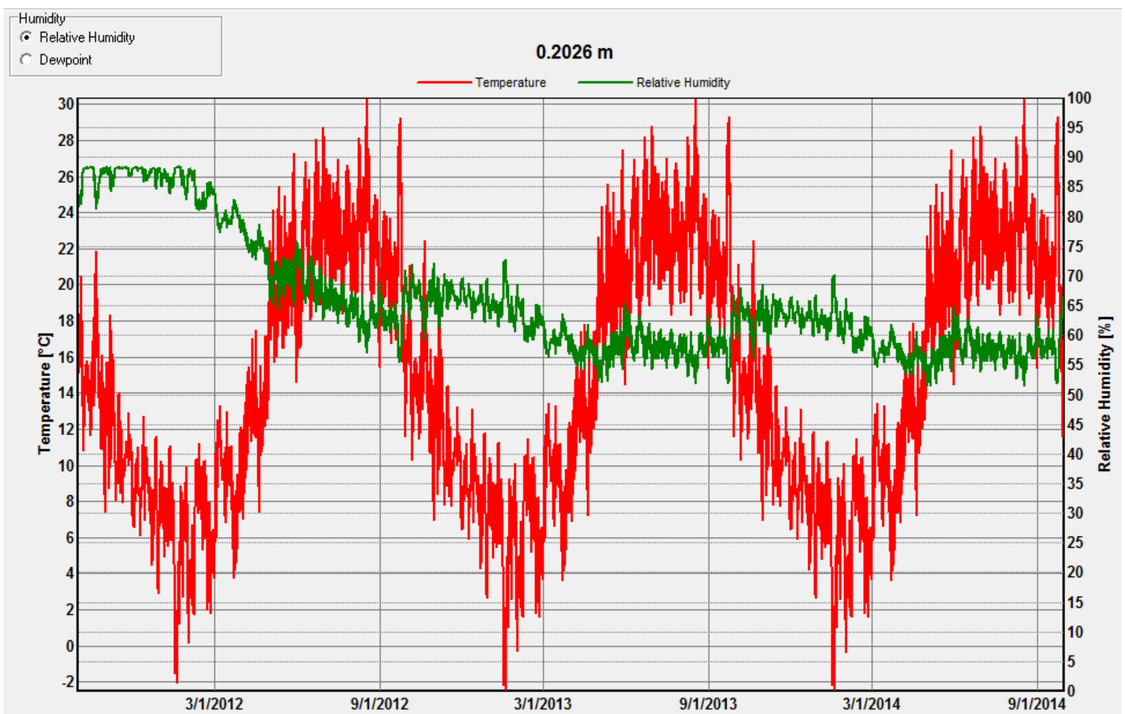


Figure 33- Wood Frame Medium- Spray Foam/ Cellulose Interface (SE)

Iterations

The following iteration of the assembly was simulated without a 6 mil vapour retarder. Without the poly, the total final moisture content of the assembly is slightly reduced from 1.26 kg/m^2 to 1.19 kg/m^2 (both started at 2.45 kg/m^2). RH levels of the OSB is not reduced, while RH levels of the cellulose increase at the spray foam interface during winter months when outdoor vapour drive is prominent. Although these levels are increased, they never raise above 80% (Figure 34). As a result it is possible to employ this retrofit without the 6 mil poly.

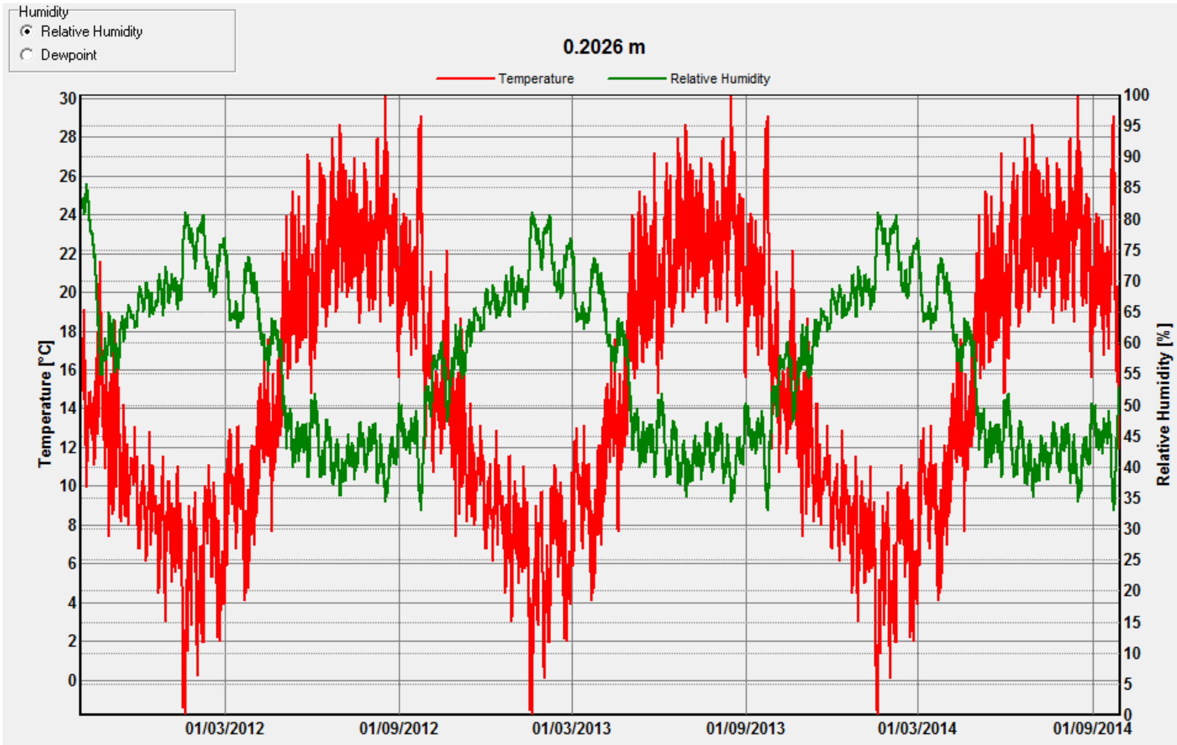
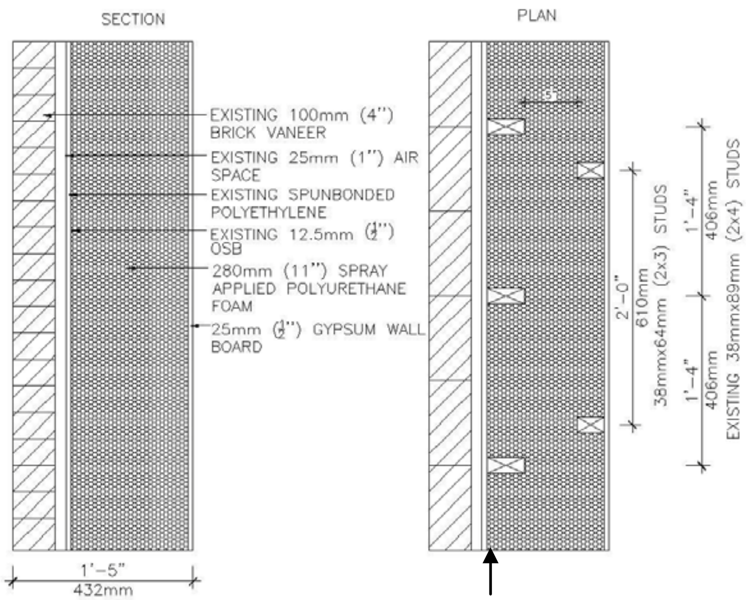


Figure 34- Wood Frame Medium No Poly- Spray Foam/ Cellulose Interface (SE)

14. Wood Frame Super Insulated Interior Spray Foam



Insulation Thermal Resistance

RSI 10.37 m²·K/W (R 58.9 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 11.03 m²·K/W (R 62.6 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 10.11 m²·K/W (R 57.4 ft²·°F·h/Btu)

General Note

This super insulated retrofit option employs a significant amount of spray foam to achieve Passive Haus EnerPHit guide required thermal resistance of RSI 10 and a virtually air tight wall assembly. As a result of such high insulation value, there is a significant loss off floor area due to the increased wall thickness over other retrofit options. The spray foam acts as an excellent air barrier by providing a very airtight assembly by sealing any air passages through the wall. Long term air tightness can be achieved because spray foam does not crack and is permanently bound to the OSB.

Environmental Impact

Because of the reliance of such a large thickness of spray foam insulation, the environmental effects of this retrofit are significant and thus this is one of the highest impact retrofits in the research and can only be categorized as an energy efficient upgrade. The highest impacts occur in fossil fuel consumption, global warming, and acidification.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
693.19	72.59	42.93	16.66	0.07	0.005	0.01	0.1

Moisture Performance

As with the other retrofits which use spray foam on the OSB, RH values within the OSB on south-east exposures boarder the ASHRAE 160P standard (Figure 35), and a small potential for mould is possible. It is important to note that the highest RH values occur in the outboard layers of the OSB.

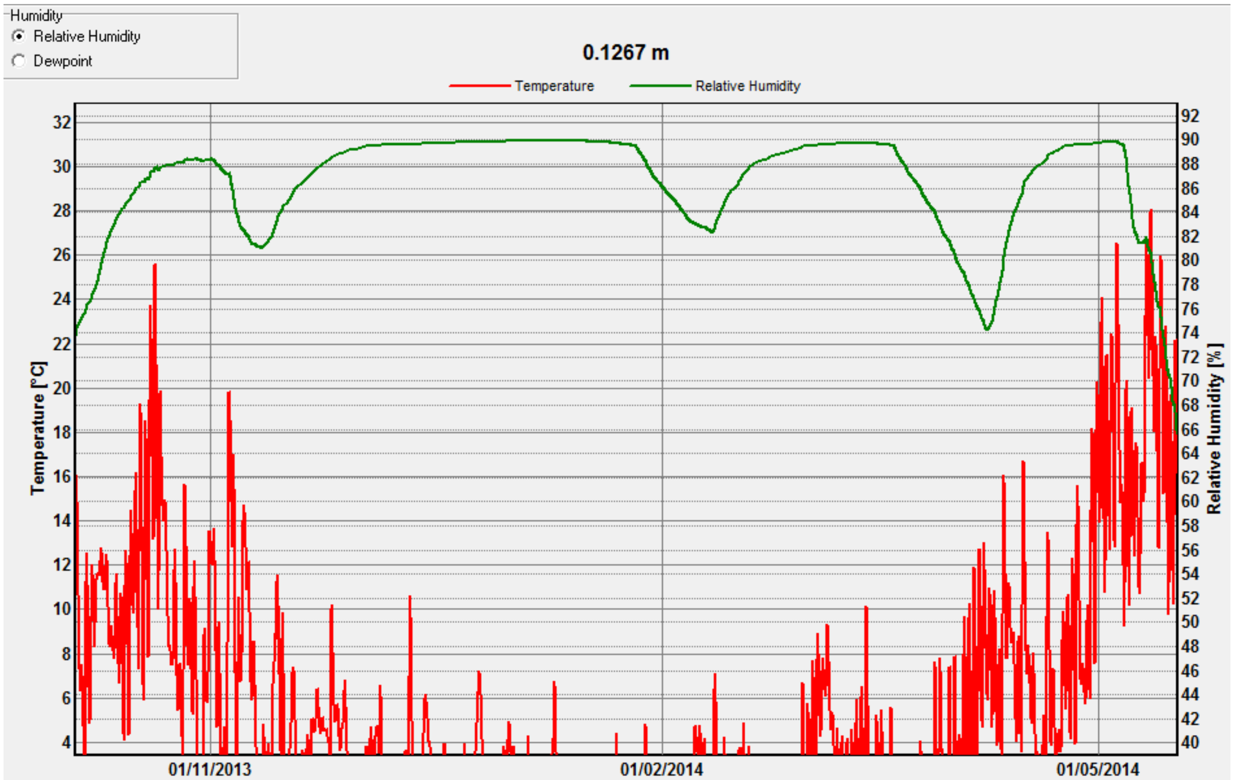
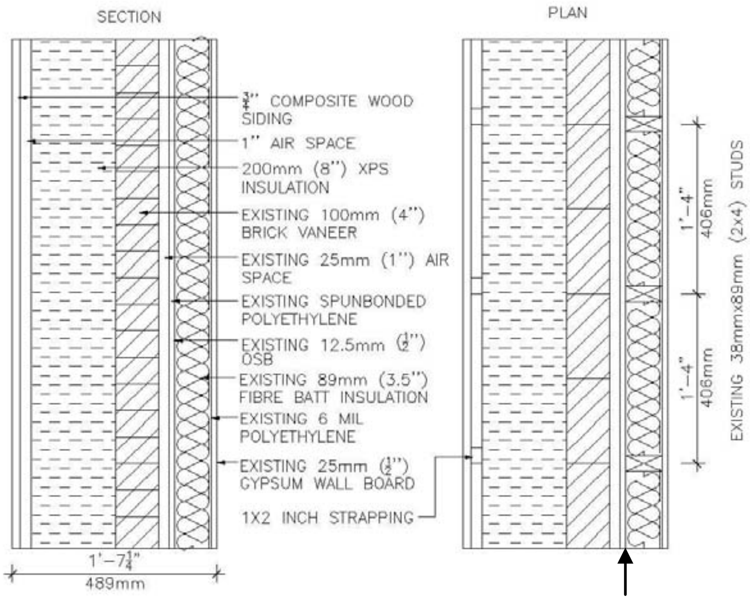


Figure 35- Wood Frame SI Interior Spray Foam- OSB/ Spray Foam Interface (Detailed) (SE)

15. Wood Frame Super Insulated Exterior Insulation



Insulation Thermal Resistance

RSI 10.11 m²·K/W (R 57.4 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 11.03 m²·K/W (R 62.6 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 10.7 m²·K/W (R 60.8 ft²·°F·h/Btu)

General Note

This super insulated retrofit option employs a significant amount of exterior XPS insulation to achieve Passive Haus EnerPHit guide required thermal resistance of RSI 10. Exterior insulation significantly reduces any thermal bridging and if transitions between boards are taped properly, can act as the air barrier as well. The drawback of such a retrofit is that the exterior of the brick will be covered up, which may not be preferred by the homeowner. Because of the reliance of such a large thickness of XPS insulation, the environmental effects of the retrofit are significant.

Environmental Impact

As with the use of spray foam insulation, the significant use of XPS has a profound effect on the impact of this retrofit and therefore is categorized as an energy efficient upgrade only. XPS shows the highest impact in fossil fuel use, global warming, resource use and smog potential.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
683.97	35.41	86.29	15.15	0.07	0.008	0.002	0.6

Moisture Performance

By placing rigid insulation on the exterior of the brick, any moisture that is able to get behind the cladding will drain and be vented away. It was decided after simulations of the "Brick PH Exterior Insulation" assembly, that spunbonded polyethylene on the exterior of the XPS is not needed. If the joints are sealed and taped properly, the spunbonded polyethylene may not necessarily be required. RH values from the exterior of the brick to the interior drywall never exceed 70% RH and follow the pattern of the indoor moisture levels (Figure 36).

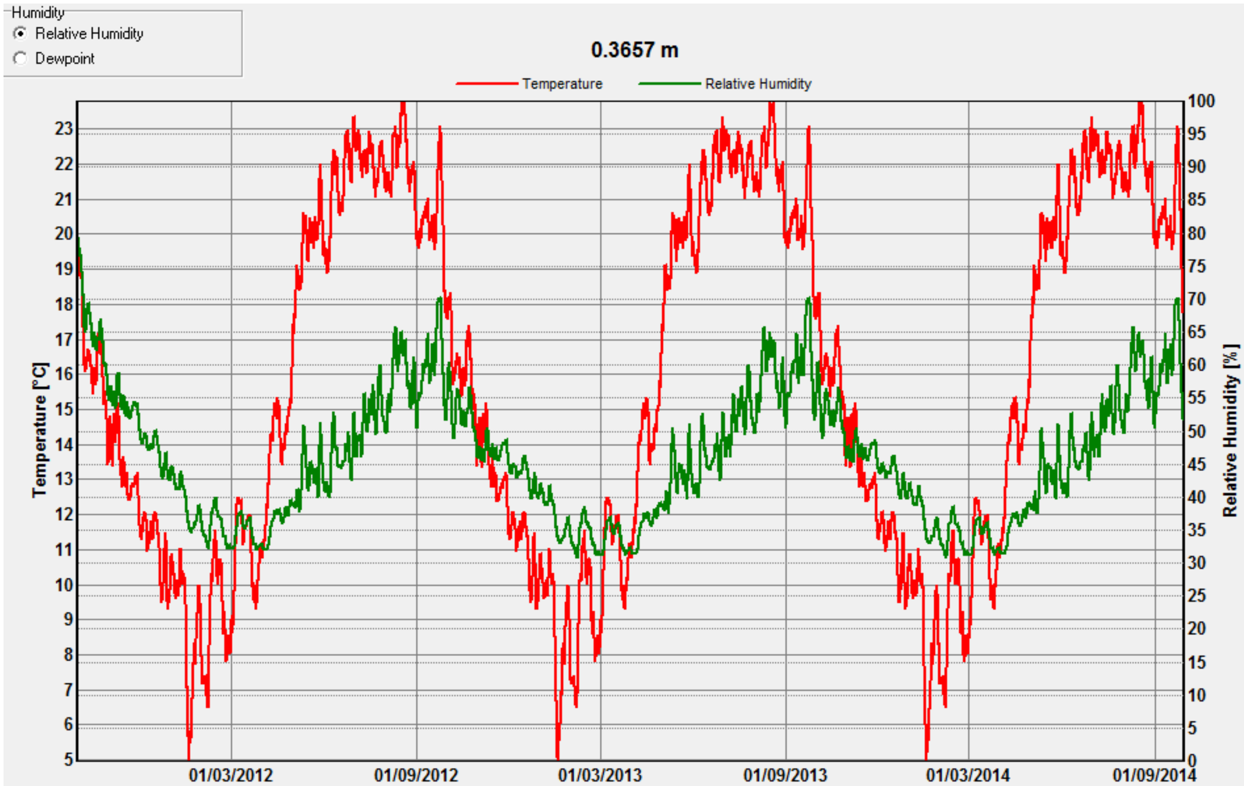
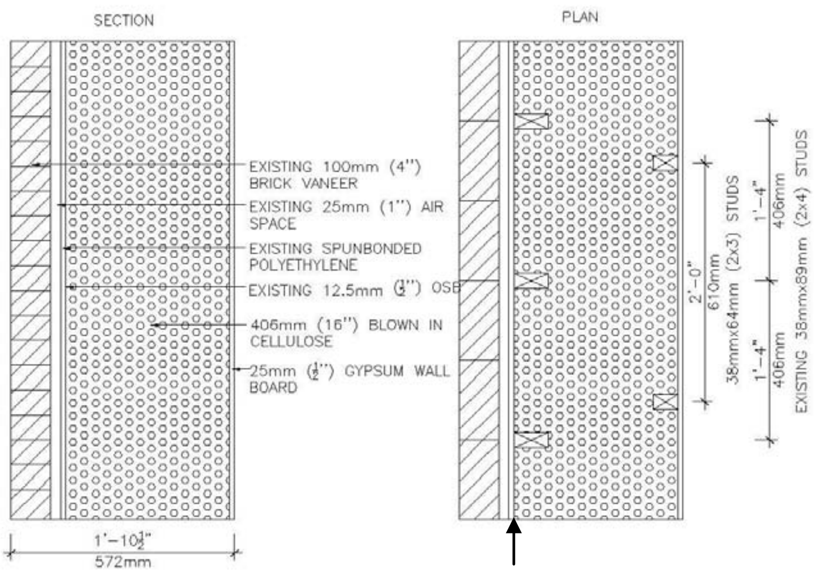


Figure 36- Wood Frame SI Exterior Insulation- OSB

16. Wood Frame Super Insulated Cellulose Diffusion Open



Insulation Thermal Resistance

RSI 9.86 m²·K/W (R 56 ft²·°F·h/Btu)

Assembly Thermal Resistance

RSI 10.5 m²·K/W (R 59.6 ft²·°F·h/Btu)

Effective Thermal Resistance

RSI 10.08 m²·K/W (R 57.2 ft²·°F·h/Btu)

General Note

This super insulated retrofit option utilizes blown in cellulose as the major insulating value to achieve Passive Haus EnerPHit guide required thermal resistance of RSI 10. Because the RSI value of cellulose is lower per unit of thickness than spray foam or XPS insulation, this retrofit option takes up more interior area than the other retrofits. This retrofit must utilize the interior drywall as the air barrier in the assembly and thus transitions between windows and subfloors must be detailed accordingly. The advantage of using cellulose on the other hand, is that the environmental effect of the assembly is usually significantly lower in each impact category.

Environmental Impact

The advantage of using cellulose insulation is that the environmental effect of the assembly is significantly lower in all impact categories. Since the impact is significantly lower than all other brick retrofits and the entire insulation value is provided by cellulose, this retrofit is labelled as an environmental energy efficient upgrade.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
109.06	7.1	42.17	3.17	0.02	0.001	0.007	0.02

Moisture Performance

Hygrothermal analysis of the assembly shows expected high RH levels in the OSB and exterior layer of cellulose in the winter during both south-east and north exposures. RH levels in the OSB during north exposure exceed 80% RH for slightly less time. Although, RH levels in both the

OSB and cellulose exceed 80% from about January to middle of May, the graphs show that these levels don't last longer than 30 days above 5°C (Figure 37 & Figure 38). Although ASHRAE standard 160P is met, there is still a small potential for mould growth to occur if indoor moisture levels are not regulated.

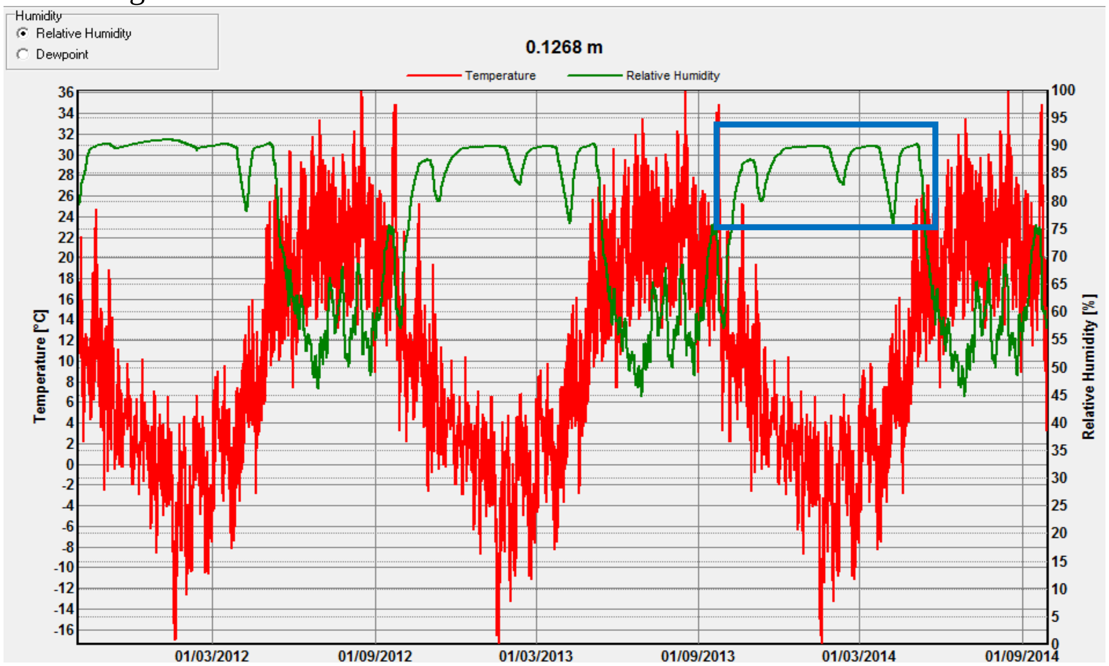


Figure 37- Wood Frame SI Cellulose Open- Centre of OSB (SE)

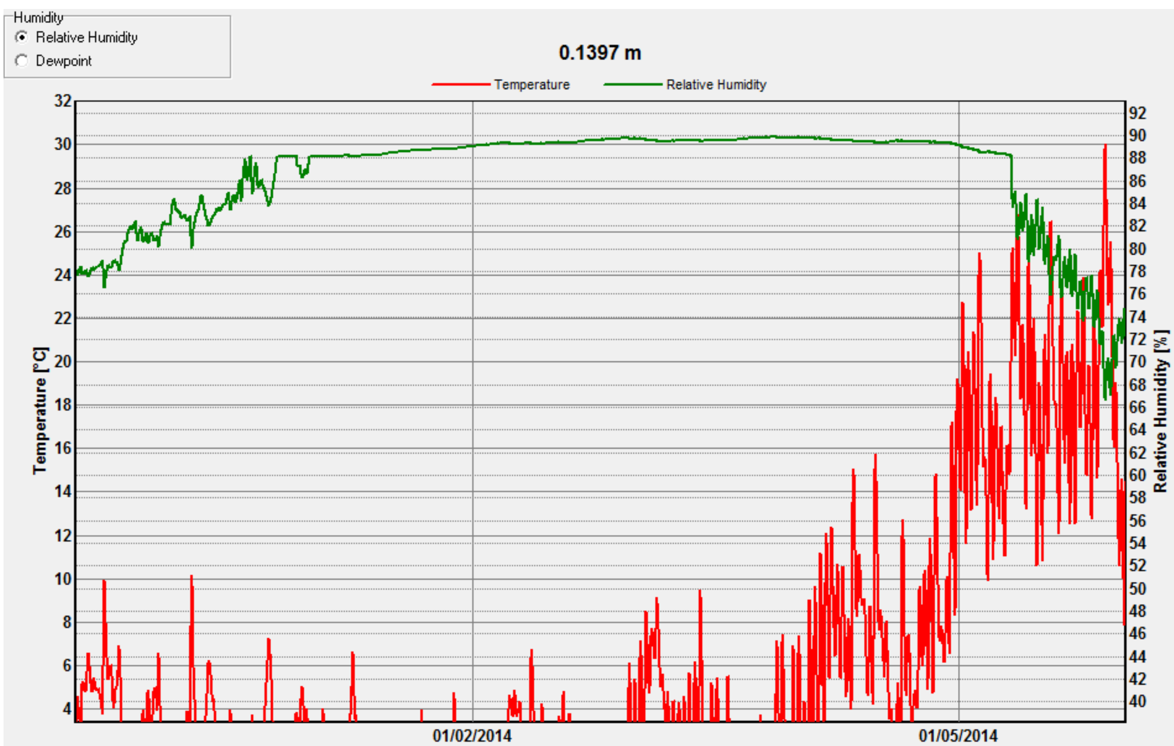


Figure 38- Wood Frame SI Cellulose Open- Cellulose/ OSB Interface (Detailed) (SE)

Iterations

Another possible option for the retrofit is similar to that done with the solid brick cellulose retrofit. A simulation was run with a 2" layer of the Roxul rigid board against the OSB to observe the effect it has on the RH levels of the cellulose. The simulation shows minimal effect on the OSB, but does result in a noticeable decrease in RH of the exterior side of the cellulose (Figure 39). This option will increase the environmental effect of the retrofit, but may be recommended if interior moisture levels are not regulated.

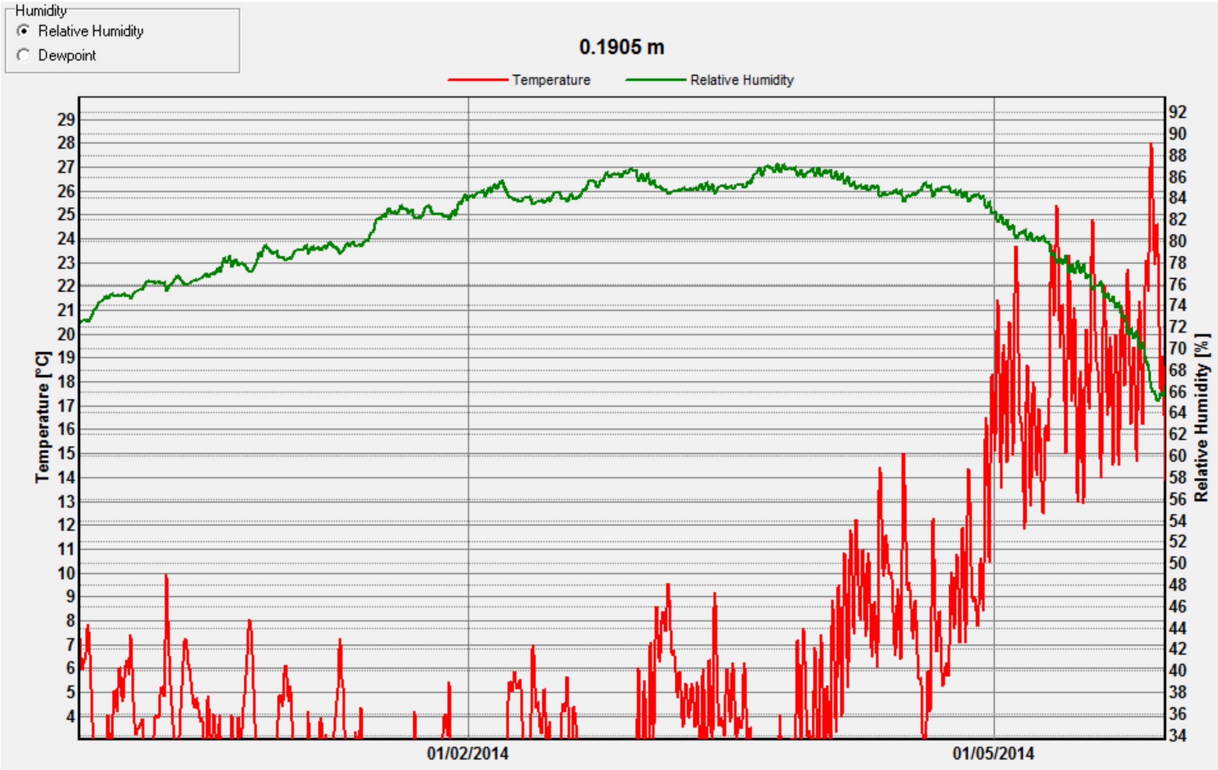
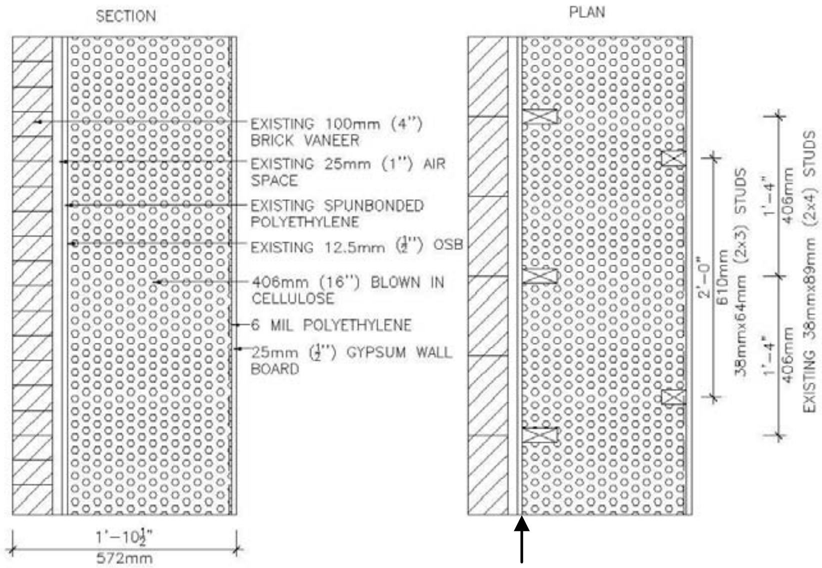


Figure 39- Wood Frame SI Cellulose Open w/ Roxul- Cellulose/ Roxul Interface (Detailed) (SE)

17. Wood Frame Super Insulated Cellulose Diffusion Closed



Insulation Thermal Resistance

RSI 9.86 m^2·K/W (R 56 ft^2·°F·h/Btu)

Assembly Thermal Resistance

RSI 10.5 m^2·K/W (R 59.6 ft^2·°F·h/Btu)

Effective Thermal Resistance

RSI 10.08 m^2·K/W (R 57.2 ft^2·°F·h/Btu)

General Note

This option is the same as retrofit #16 but has a 6 mil poly vapour retarder outboard of the drywall. The retrofit aims to determine whether a vapour retarder interior of the insulation will improve or worsen the moisture performance of the wall assembly. In this retrofit either the poly or the drywall can be utilized as the air barrier, in either case, each was be detailed properly to create an effective barrier.

Environmental Impact

As with assembly #16, the use of cellulose insulation, which creates the lowest impact in all categories, results in an environmental energy efficient upgrade.

Fossil Fuel (MJ)	Global Warming (kg CO2)	Resource Use (kg)	Acidification (mol of H)	Respiratory Effect (kg PM2.5)	Eutrophication (kg N)	Ozone Depletion (mg CFC11)	Smog (kg Nox)
121.33	7.31	42.42	3.43	0.02	0.001	0.007	0.02

Moisture Performance

During both north and south-east exposure hygrothermal analysis of the assembly shows very similar RH values in the OSB as in assembly #16 (Figure 40). It is in the cellulose where moisture levels begin to differ. In both exposures, the outer portion of the cellulose experiences slightly lower RH values (although still above 80%) during the winter months (middle of November until about beginning of May). The graphs show that these levels don't last longer than 30 days above 5°C (Figure 41). The major difference that is noticed with the 6 mil vapour retarder is the increased RH levels of the cellulose during the warmer months, when vapour drive is directed indoors. Levels do not reach concern but peak about 15% higher than assembly #16 (75% compared to 60%).

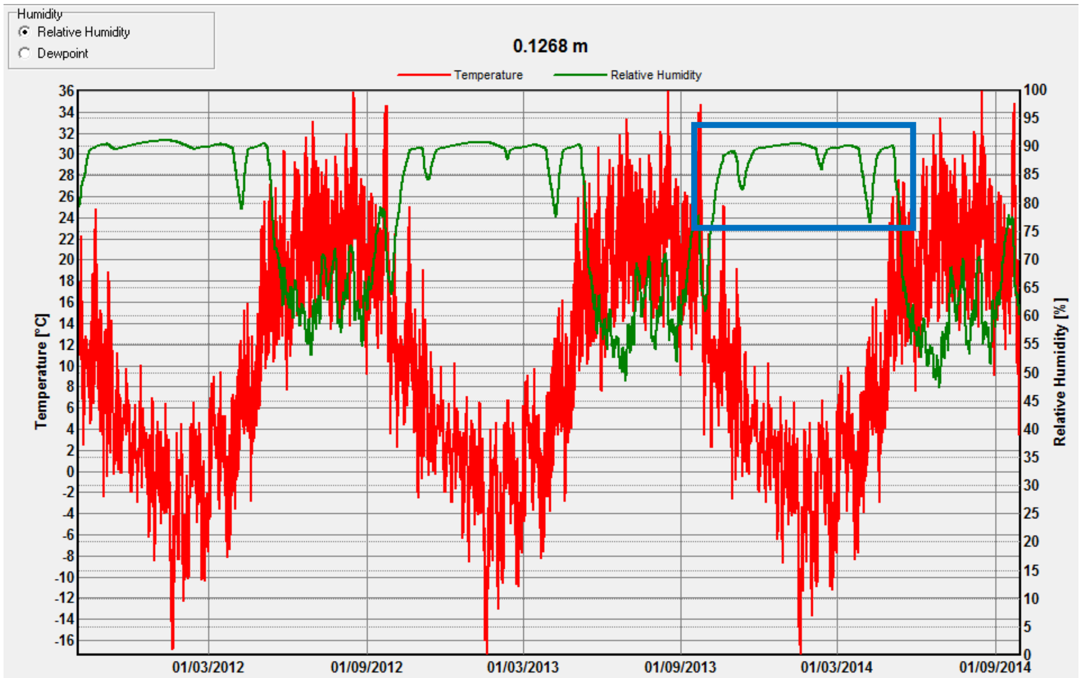


Figure 40- Wood Frame SI Cellulose Closed- OSB (SE)

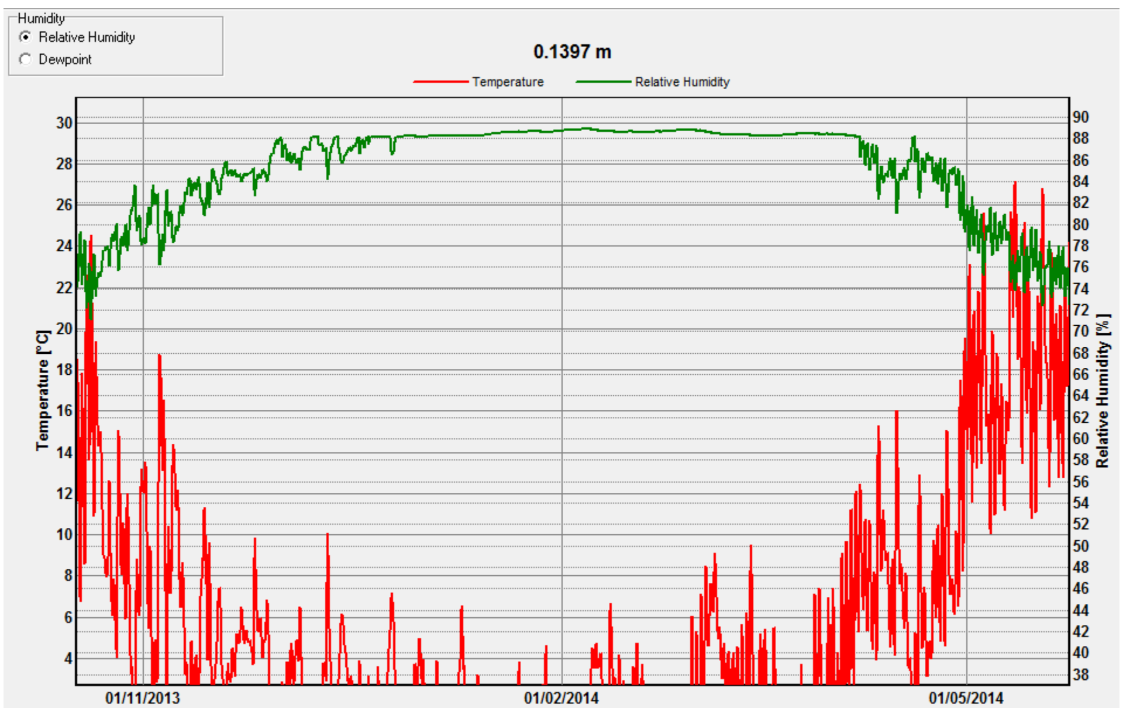


Figure 41-Wood Frame SI Cellulose Closed- Cellulose/ OSB Interface (Detailed) (SE)

Iterations

As with assembly # 16, the Roxul rigid board was added inboard of the OSB to analyze the effect on cellulose moisture levels. As with assembly #16, the Roxul has no effect on the OSB but significantly reduces the RH levels of the cellulose. At the interface with the Roxul, the RH levels in the cellulose are reduced to just above 80% during the winter (Figure 42). This option significantly reduces any chance of mould growth but increases the environmental effect of the retrofit. This option may be recommended if interior moisture levels are not regulated.

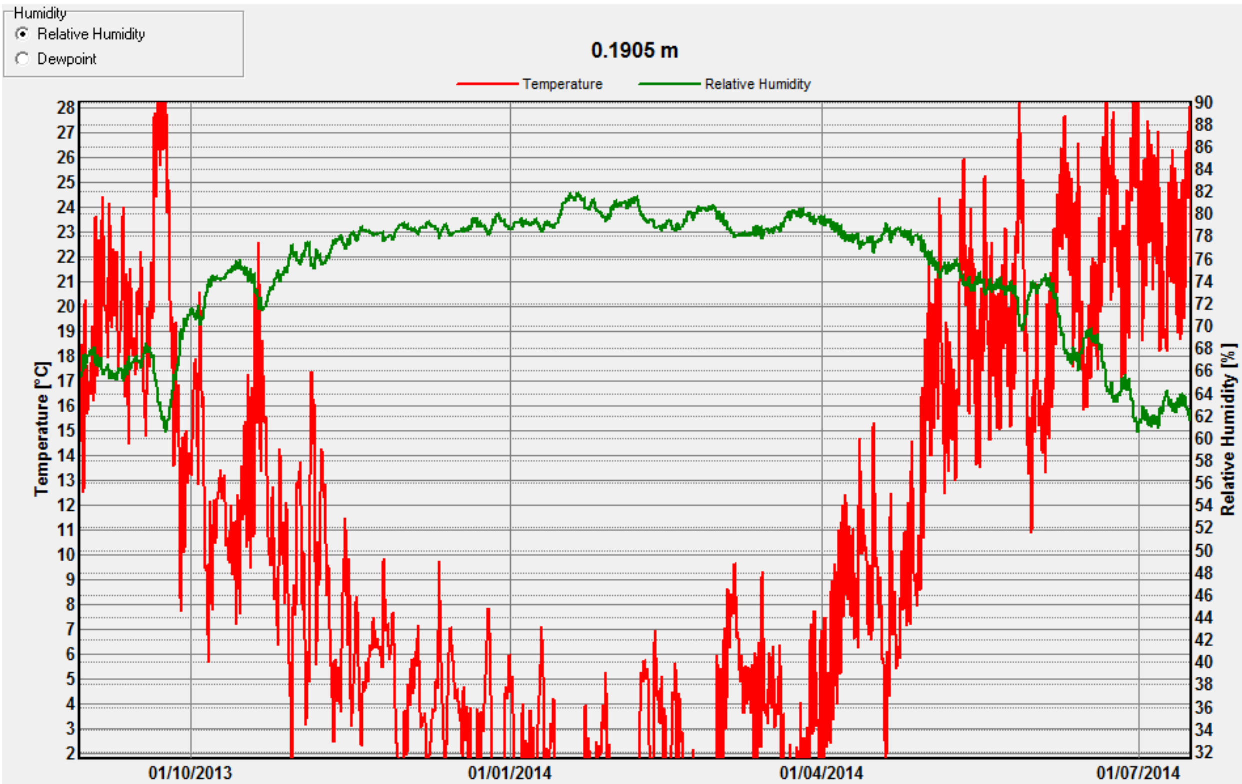


Figure 42- Wood Frame SI Cellulose Closed w/ Roxul- Cellulose/ Roxul Interface (Detailed) (SE)

4.2 Discussion

The following section of the research uses the information compiled and compares the assemblies against one another in four categories: thermal control, durability as it pertains to moisture, constructability, and overall environmental impact. These four categories are essential to analyzing retrofit options in a truly sustainable manner.

4.2.1 Thermal Control

If a database of sustainable renovation techniques is to be developed, it is obvious that the thermal resistance of each assembly must be established. The greater the thermal resistance of a wall assembly, the less heat that is lost or gained through the wall, and thus less energy is required to heat or cool a home. Figure 43 shows the predicted thermal resistance of each assembly while Figure 44 shows the simulated effective thermal resistance.

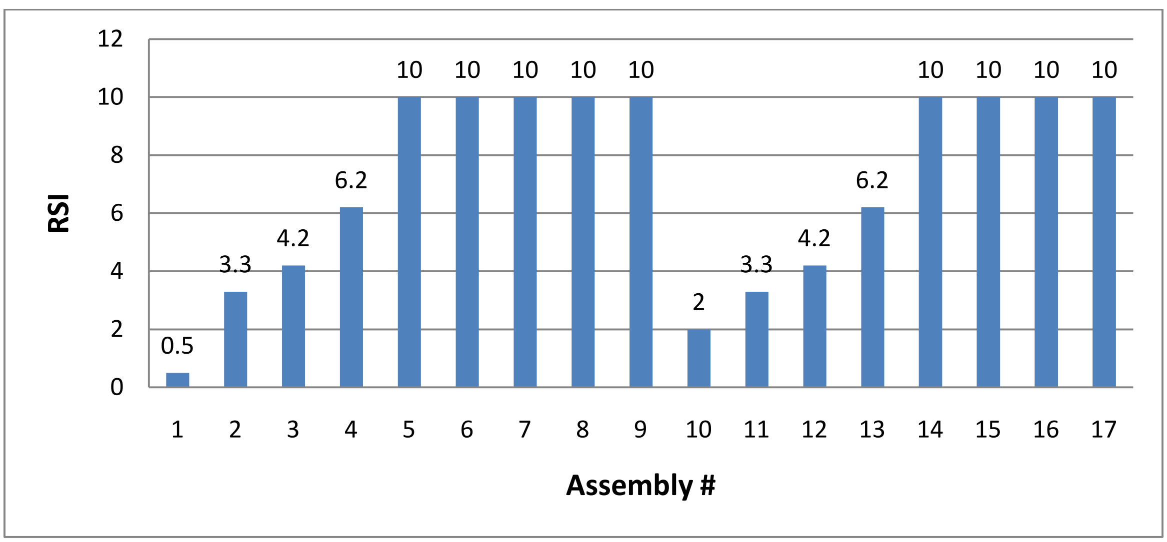


Figure 43- Wall Assembly Predicted RSI Values

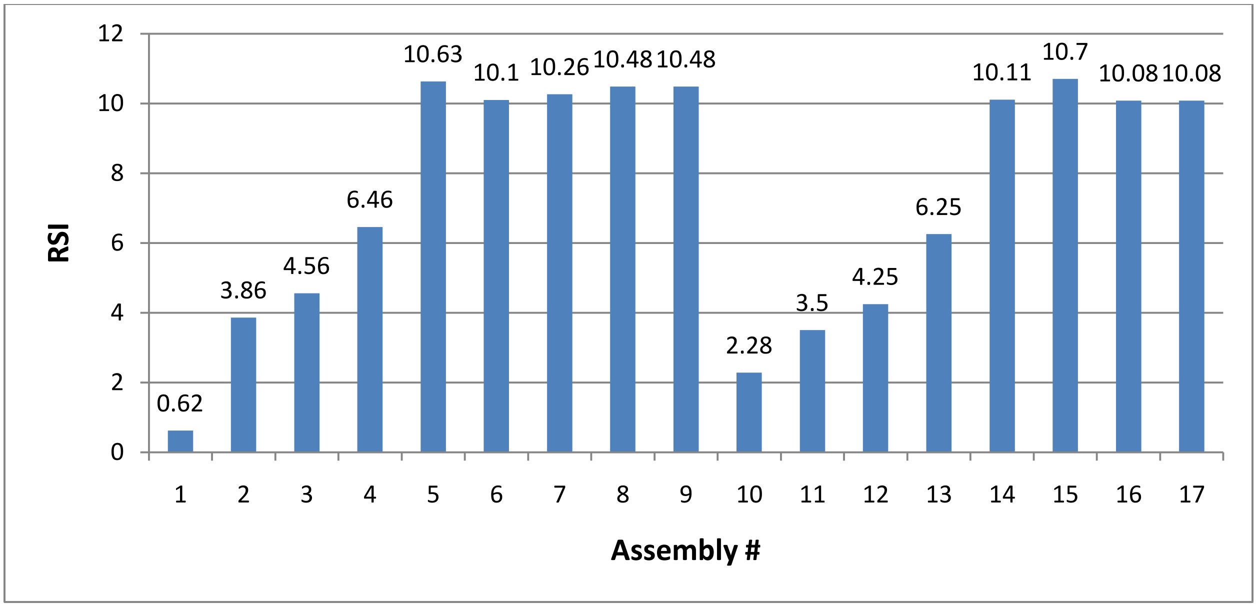


Figure 44- Wall Assembly Simulated RSI Values

As the database begins to grown, multiple assemblies will have similar RSI values but may be constructed of different materials. For this reason, along with comparing each assembly's RSI values, the total thickness of each retrofit should be compared. Depending on preference, or space restrictions, it is essential that home owners, designers and builders have access to this information to make an informed decision. Figure 45 compares the thickness of each retrofit.

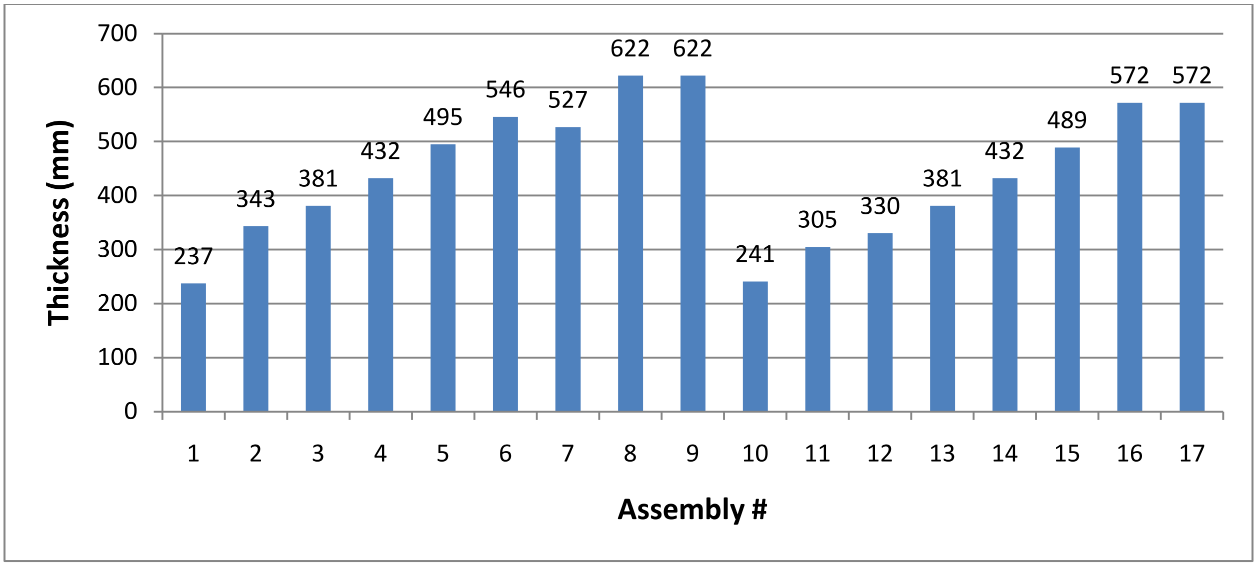


Figure 45- Assembly Thickness

As the Figure shows, assemblies with similar RSI values (ie 5-9 and 14-17) can have a variety of thicknesses, usually depending on the type of insulation used. Foam products provide a higher RSI value per inch and thus require less thickness to produce the same RSI value as a cellulose wall.

4.2.2 Durability as it Pertains to Moisture

The moisture performance of each retrofit option was explored and presented in the two page breakdown of each assembly in Section 4.1. Overall it is evident that the assemblies which have the best moisture control were those that employ exterior insulation. Placing the insulation outboard of the existing structure keeps the structure warm and dry (solid brick) and free of any moisture issues. The brick is no longer able to absorb rain and thus significantly reduces the moisture content of the entire assembly. In the existing wood frame construction, the absorptive brick cladding also no longer receives moisture from rain. In both existing assemblies, the exterior insulation acts as the drainage plane of the assembly, any moisture getting behind the cladding is drained and vented out, while the XPS nearly eliminates sun driven moisture due to its low diffusivity. The exterior insulation also significantly reduces thermal bridging of the interior studs, increasing the overall effectiveness of the retrofit.

All interior retrofits which utilized spray applied polyurethane foam or XPS experience high RH values at the exterior interface of the insulation during approximately winter/ spring months. The solid brick retrofits experienced the highest RH values due to its high absorbtivity, water retention and solid construction. In each case these values do not pose a problem because any moisture will be localized, controlled and water will not be able to collect and run down onto the floor penetration. Also neither brick nor spray foam is a mould sensitive material. With regards to the wood frame construction retrofits using spray foam, all show similar results and conform to the ASHRAE 160p standard. Further research is required to verify this concern with field data.

The assemblies which designers, contractors and home owners may have most concern with, in terms of moisture performance, are the assemblies which utilize cellulose insulation. Because cellulose insulation is rarely used in wall assemblies and is usually thought of as attic insulation, there is hesitation in the construction industry to implement cellulose into wall assemblies. A review of the simulations carried out in the research show that the cellulose insulation used in the existing wood frame wall meet ASHRAE 160p standards on moisture levels. It is important to note that interior RH values must be regulated to ensure mould potential is reduced. For example, the average yearly RH value simulated was 35%. Figure 46 and Figure 47 show the effect an increase of only 10% on the average yearly RH has on the moisture levels of the cellulose. Peak RH values are slightly increased but last significantly longer during winter months, increasing the risk of mould growth.

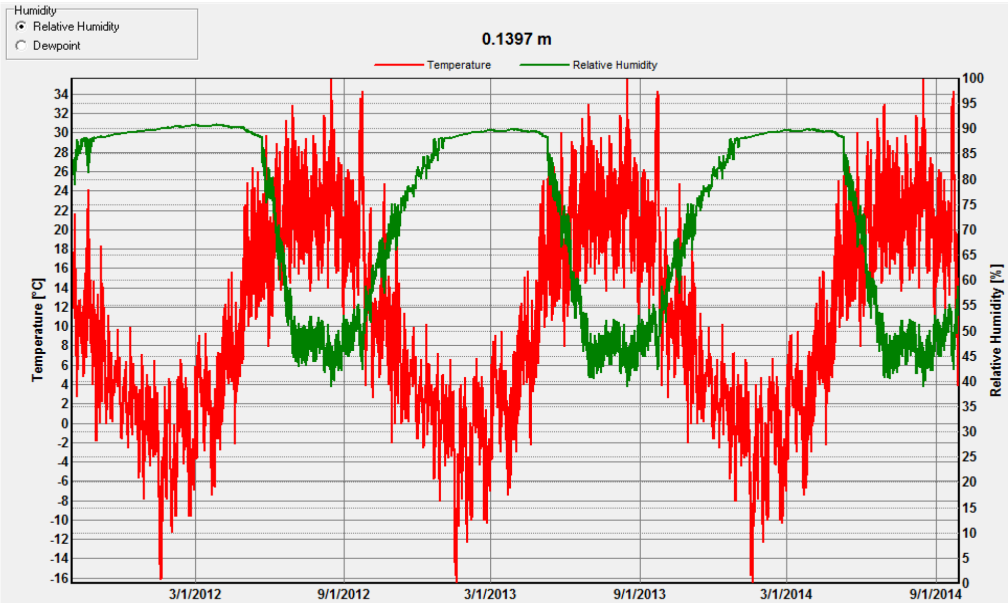


Figure 46- Wood Frame PH Cellulose Open- Cellulose/ OSB Interface (SE) (35% RH)

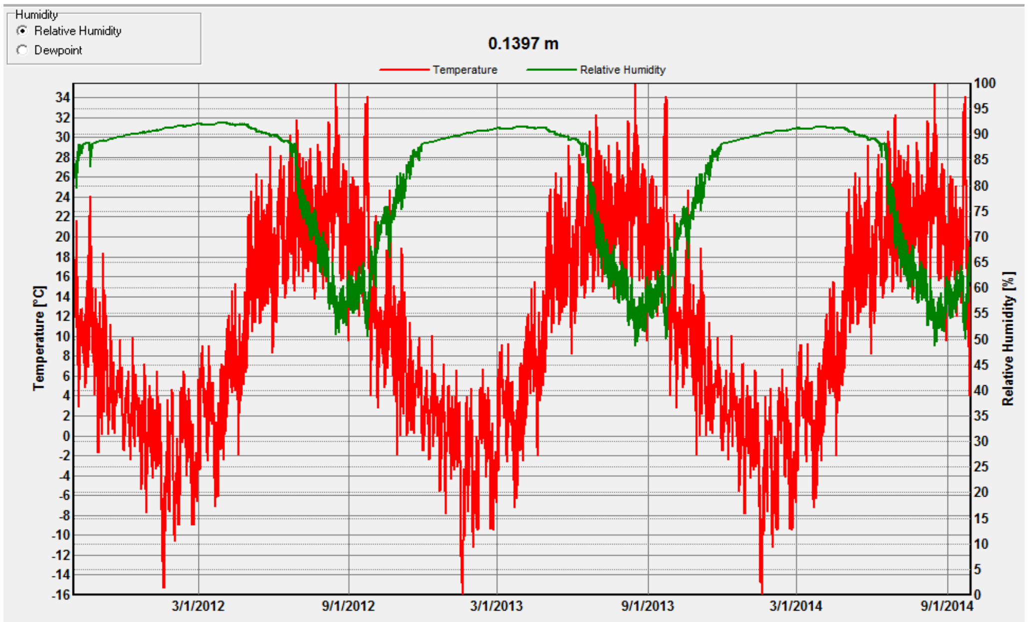


Figure 47- Wood Frame PH Cellulose Open- Cellulose/ OSB Interface (SE) (45% RH)

With the solid brick construction the research concludes that further investigation and field studies are needed to determine if the high RH levels in the cellulose can be reduced and whether this retrofit is a viable option for solid brick masonry walls. On the other hand it is clear that in all solid brick retrofits, with or without cellulose, the application of a 6 mil poly vapour retarder can result in dangerous moisture build ups within the wall assembly.

One issue which affects solid brick construction retrofits, and which has not yet been addressed, is increased freeze thaw cycles of the exterior layer of the brick. Increases in freeze thaw cycles can be an issue of concern with interior insulation of a solid brick assembly. Freeze thaw can only occur when the brick is essentially saturated and temperatures are well below zero [14]. The addition of interior insulation will lower the temperature gradient across the wall and reduces the difference in temperature from the brick to the exterior air and results in reduced drying potential of the brick. As a result, the moisture content of the brick will increase but not necessarily to unsafe levels [14]. Although insulation may increase the moisture content of the brick to some degree, reducing wetting at critical areas of a wall (window sills, and at grade), can often reduce wetting far more than the reduction in drying caused by insulating the brick [14]. This is a subject of further research and long term field studies and is beyond the scope of this research.

4.2.3 Constructability

This section of the research provides a brief comparative discussion concerning the physical construction of the retrofits. Information on the constructability of retrofits allows home owners, designers and builders to better understand the scope of work involved with their sustainable retrofit.

On a basic level, each retrofit which employs interior insulation utilizes the same construction technique; a second stud wall is built up away from either the existing exterior studs or the solid brick and is then insulated and finished with drywall. These types of retrofits are fairly easy to implement but have the drawback of interior finish deconstruction, disturbing interior living space during construction, and loss of interior floor area. More disruption is also required when spray foam or cellulose insulation is utilized, and occupants are required to leave their homes temporarily due to indoor health issues.

Exterior insulation retrofits for both solid brick construction and wood frame brick veneer walls is a straight forward procedure and usually does not require deconstruction; exterior insulation can be placed over the brick along with the exterior cladding. The retrofit has the advantage of an undisturbed interior but requires the existing exterior brick finish to be covered up, possibly discouraging such a retrofit.

It is clear that this section is a currently a general overview and simple discussion of a more complex category and therefore further information, by building science professionals and contractors, of the constructability of individual assemblies is necessary and would provide a more in depth analysis and discussion on individual retrofits and may be added in as a section in the two page assembly breakdowns.

4.2.4 Environmental Impact

The two page assembly breakdown of each retrofit provided a quick quantitative look at eight environmental impacts of each retrofit. This section of the research now provides a comparative review of the retrofits through those eight impact categories. Unlike many retrofit programs, which usually only focus on energy efficiency, a sustainable retrofit database should also provide home owners, designers and builders with a clear understanding of the environmental impacts between retrofit options in order to make a sustainable home upgrade decision. By comparing the retrofits with one another it will allow a better understanding of the magnitude of their environmental impact.

The following graphs compare the assemblies in each of the eight impact categories.

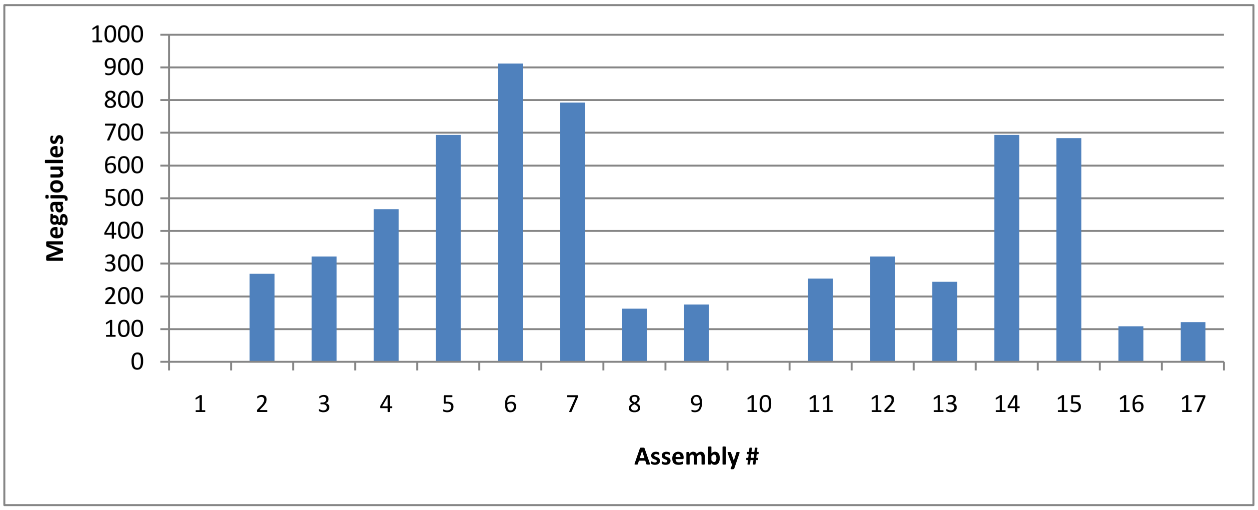


Figure 48- Fossil Fuel Consumption

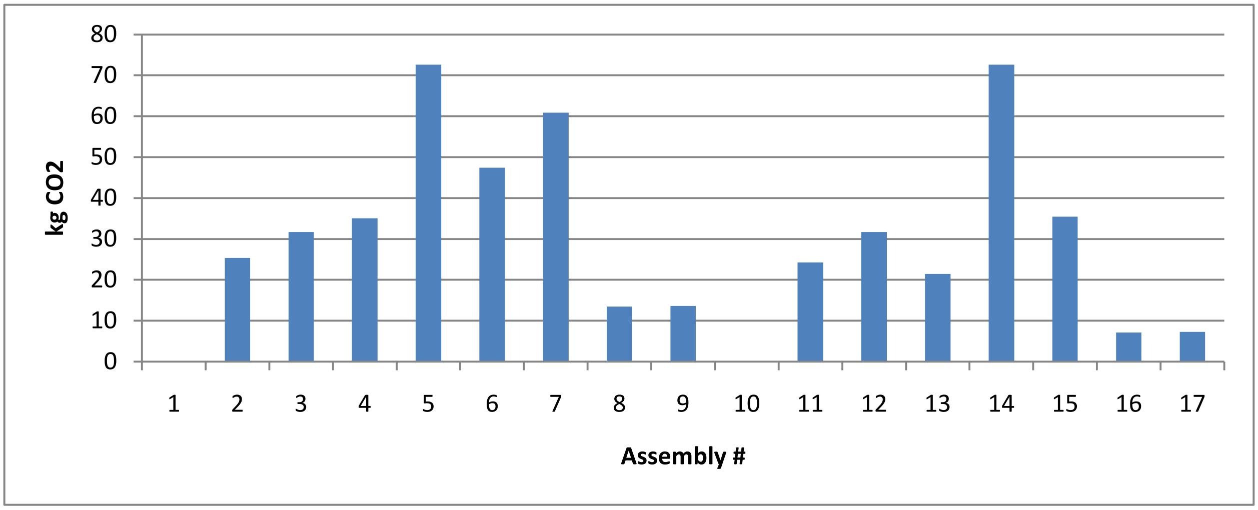


Figure 49- Global Warming Potential

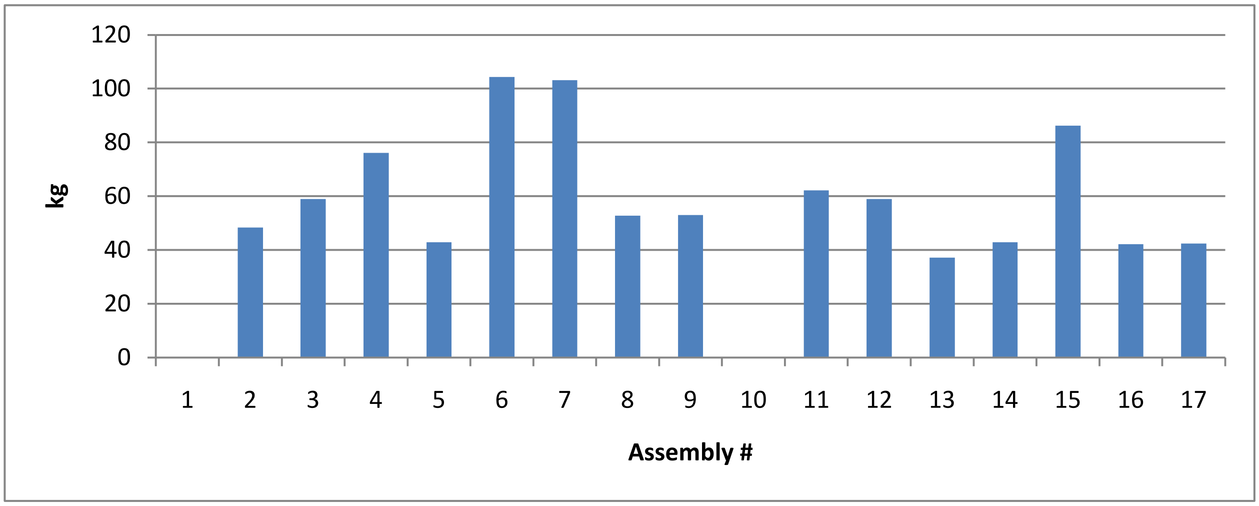


Figure 50- Resource Use

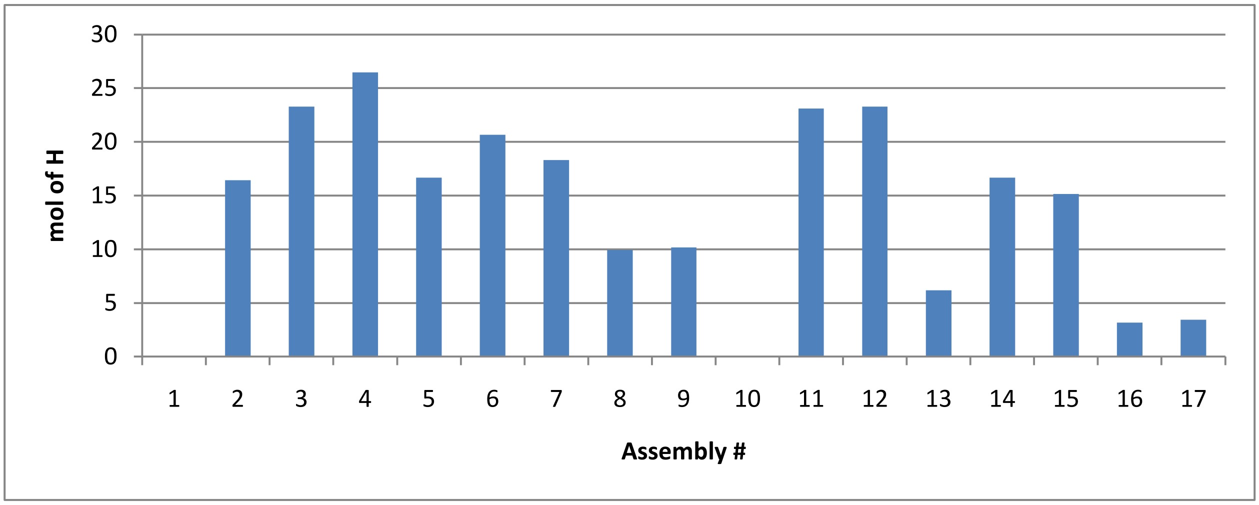


Figure 51- Acidification Potential

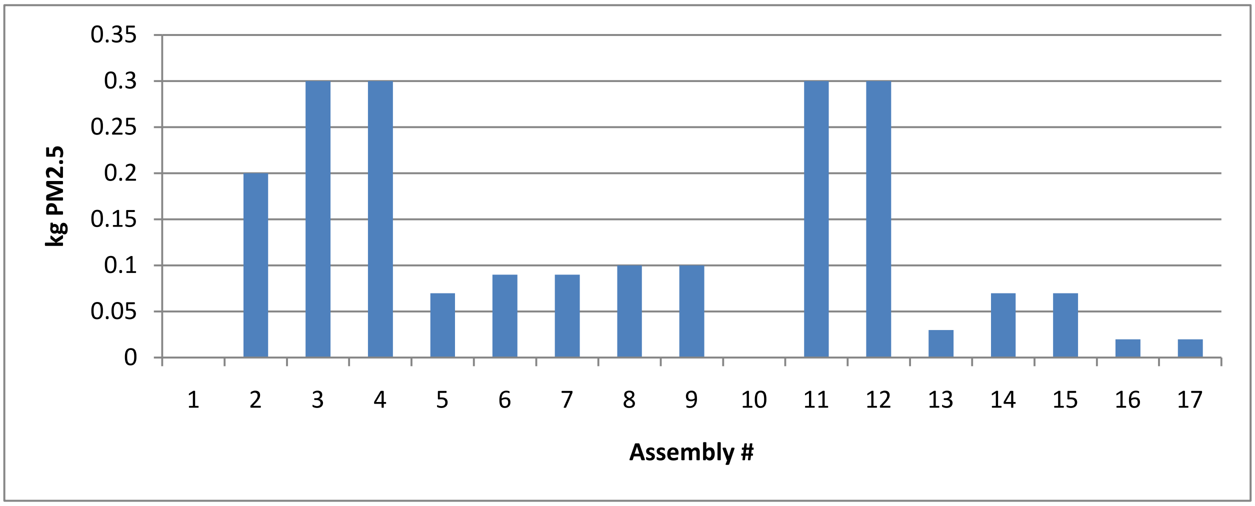


Figure 52- Respiratory Effect Potential

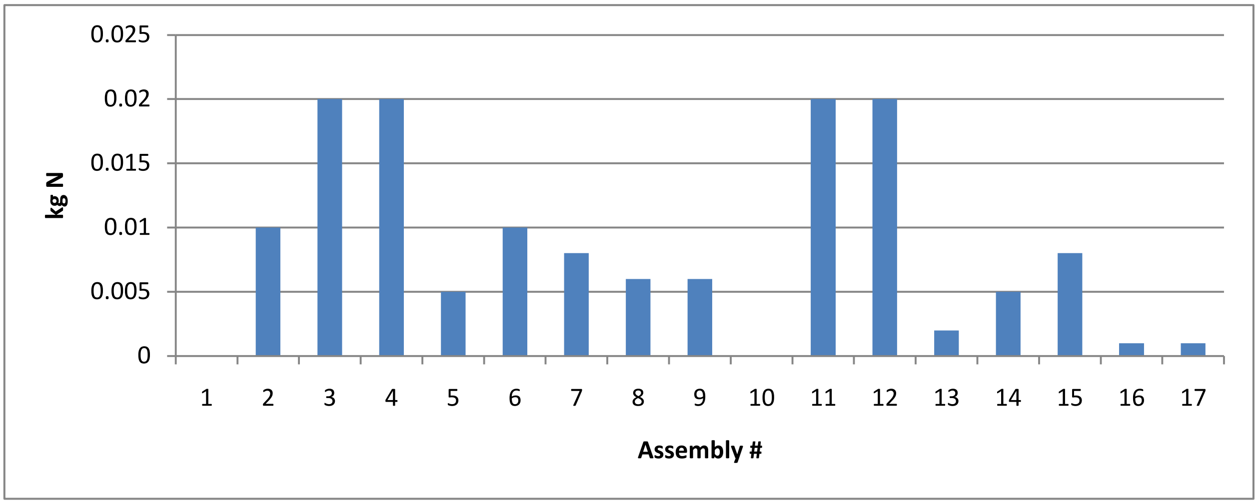


Figure 53- Eutrophication Potential

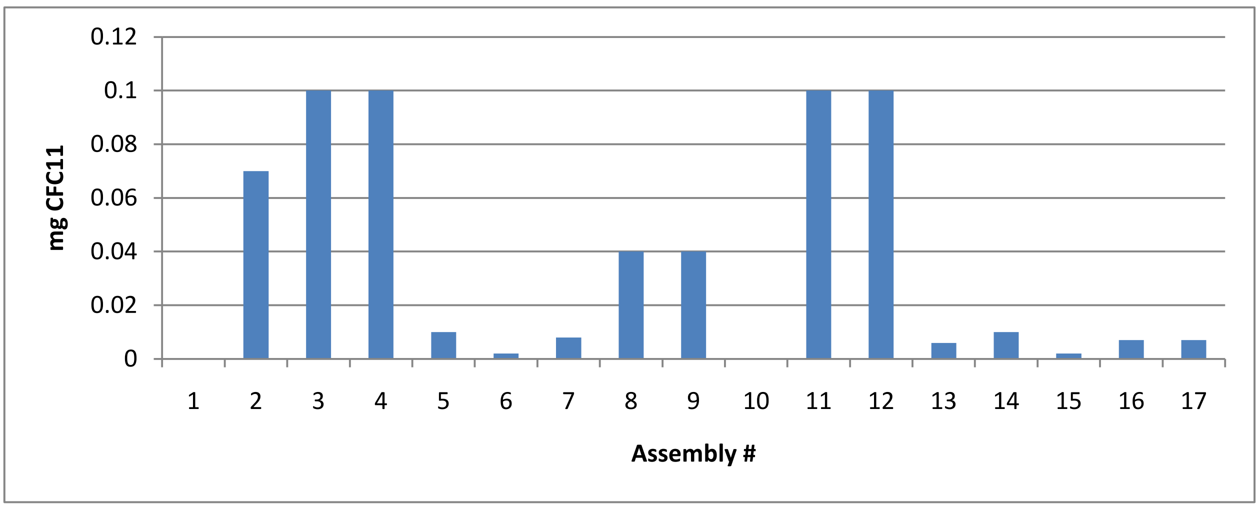


Figure 54- Ozone Depletion Potential

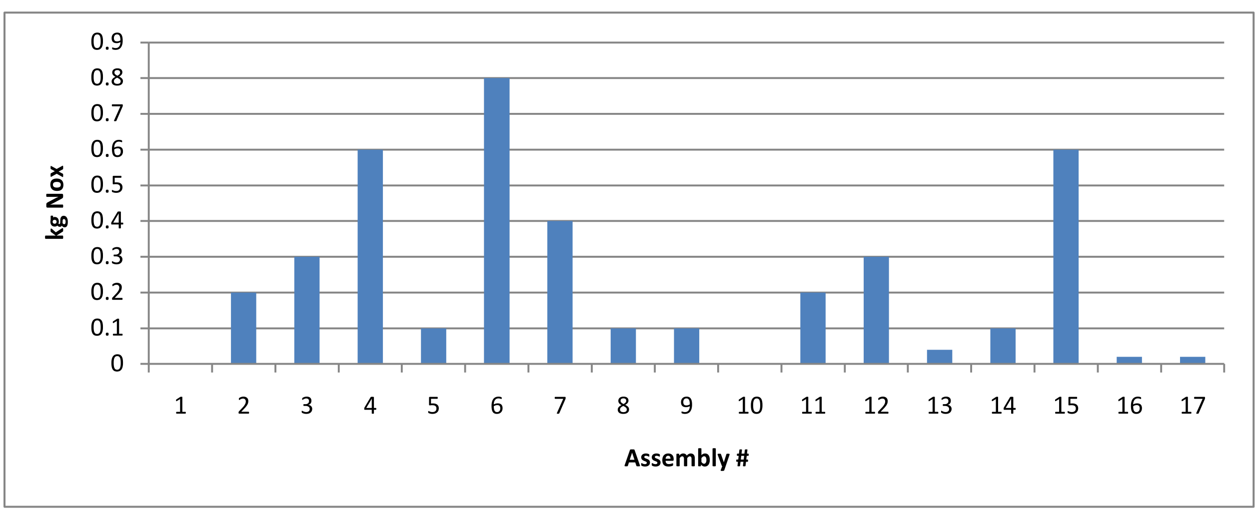


Figure 55- Smog Potential

There are two characteristics that can affect the environmental impact of a retrofit: RSI value (insulation thickness); and insulation material used. It is obvious that if two retrofits use the same materials, yet one has a higher RSI, the one with the higher RSI will have the higher environmental impact because of its increased use of insulation. Since almost all retrofits use similar building materials, it is usually the type of insulation which will determine the major difference in environmental impact. In some cases increased insulation levels may be the contributor to the environmental impact, while in other cases the type of insulation material used will be the contributor.

Among this group of retrofits, insulation choice seems to be the dominant contributor in the impact categories. The Figures show that those retrofits which employ a majority of cellulose insulation have the lowest values in most of the impact categories. With wood frame retrofits, assemblies 16 and 17, which use only cellulose insulation and have an RSI 10 value, have the lowest values in each impact category of any retrofit. Because cellulose insulation requires little energy to manufacture and is made up of 80% recycled paper, it is one of the most ecologically friendly insulation materials [38].

With the other retrofits, depending on the insulation used, some had a greater impact in one category while having a lower impact in others. The retrofits that employ mineral batt insulation had the highest impact in smog potential, ozone depletion potential, eutrophication potential, respiratory effect potential, and acidification, while retrofits which employ foam based insulation like XPS and polyurethane had the highest impact on fossil fuel consumption, global warming effect, and resource use.

Therefore, from an environmental standpoint, it would be difficult to label any retrofit using a significant amounts of foam based products or even mineral products, sustainable. Assembly 13, which employs a small amount of spray foam in conjunction with a significant portion of cellulose, provides a much lower environmental impact then an all foam retrofit, while still benefiting from the positive qualities of spray foam (ie air sealing, high RSI/ inch etc). As a database of a variety of retrofits eventually emerges, it will make it easier to understand the environmental impact of a retrofit, whether the retrofit is sustainable, and what types/ combination of insulations may result in a more sustainable retrofit.

4.2.4.1 Further Development

The one issue with the environmental impact data collected, is whether a weighting factor should be attributed to each category. Should some environmental impact categories be weighted greater than others? This could affect the overall environmental impact of retrofits and significant research is needed on the subject and should be incorporated into the creation of a sustainable retrofit database.

5 Further Research

The research completed has provided a foundation for a proposed framework to analyse existing and proposed construction assemblies in order to develop a database of sustainable renovation techniques for retrofitting existing buildings. There is now a call for research to continue to develop such a database as well as expand upon some of the sections developed thus far.

Using the framework proposed here, modeling of the multitude of other assemblies and retrofit options across the GTA, from foundation walls to roof assemblies, is required to develop the database. Further research and data collection is required on material properties such as chemical composition, long-term off-gassing characteristics, and existence of known allergens through a review of manufacturer's literature and product specification in addition to data published by the Athena Institute. Three-dimensional analysis of heat and moisture may be seen as an asset to such a database and an area of further research.

With respect to retrofits, field studies and further investigation is critical to improving the understanding of the effects interior retrofits have on freeze thaw cycles of solid brick masonry, as well as determining whether cellulose insulation is a viable material in brick masonry wall retrofits.

The proposed framework is by no means complete and was limited by the time frame of the research and therefore the development of a sustainable renovation database will need to incorporate other factors and research that were not able to be proposed and developed here.

The framework and eventually a large database will benefit from a table which provides a quick overview of the assemblies to help simplify and breakdown the decision making process for home owners, designers, and builders, that is currently lacking in the research. A purely visual example of such a table is illustrated on the following page and incorporates the four key comparative categories: thermal performance, hygrothermal performance, constructability, and environmental effect. Other categories, such as cost, may be added as research continues. To develop such a table, there is then a need to develop a numerical ranking system for each category with assemblies being ranked from 1-5; 1 being poorest performing, and 5 being the best performing. By providing such a table it will allow a decision making process for homeowners to unfold:

1. Do I want an interior or exterior retrofit?

2. Do I want to lose interior living space?

3. Which categories are most important to me? etc.

Table 3- Proposed Assembly Comparative Overview

Assembly	Thermal	Moisture	Constructability	Environmental Effect	AVG
BRICK **Interior Retrofit**					
2)Brick 2006 OBC	2	3	4	3	**3**
3)Brick 2012 OBC	2.5	3	4	3.5	**3.25**
etc.					
Exterior Retrofit					
6)Brick SI Exterior	5	5	4	1	**3.75**
etc.					
WOOD FRAME **Interior Retrofit**					
11) WF 2006 OBC	2	4	4	3	**3.25**
12) WF 2012 OBC	2.5	4	4	3	**3.38**
etc.					
Exterior Retrofit					
16) WF SI Exterior	5	5	4	1	**3.75**
etc.					

Once a general decision of which retrofits may be applicable to a project through this quick overview, a more detailed summary of each retrofit can now be accessed in the two page assembly breakdown.

As mentioned previously, the development of an environmental ranking of impact categories will be a major field of research to be undertaken in order for a truly sustainable database to be possible. Once this is accomplished, a limitation arises in which home owners, or others without a building science background, may not be able to make a connection between an impact indicator and the assembly; essentially not understand what exactly is being affected from a certain retrofit. Therefore the eventual database developed may require a method or index to help homeowners or designers better understand how these environmental indicators connect to the environmental impact of their retrofit and what exactly these impacts entail.

The research also limits itself to the four comparative categories (thermal performance, hygrothermal performance, constructability, environmental impact), but the development of a sustainable renovation database requires a look at other factors that were beyond the scope and time frame of the research. An important factor not addressed, cost of retrofits, would unquestionably need to be incorporated into such a database and plays a large role in the retrofit decision. Depending on the budget of the project, certain retrofit options may not be a viable or desired option for some homeowners. This factor may not only address the initial cost of retrofits, but also look at the payback periods of a retrofit, an area of significant importance continually being researched and studied today.

The proposed framework is a step towards the development of a sustainable renovations database and is by no means perfect, but the limitations addressed as well as those that may be recognized by others, give way to and stimulate further research on the subject.

6 Conclusions

It is clear from the literature and past research, that the need for a comprehensive framework for sustainable renovation applicable to Canadian homes is evident. This major research project has propsed a framework to organize and analyze existing assemblies and proposed retrofits in order to establish a foundation for a database that will allow a true evaluation of sustainable renovations. It defines, quantifies and evaluates the outcomes of the application of retrofits in a much more sustainably comprehensive manor by addressing the fundamental criteria that define sustainability:

- Energy performance (reduction of consumption over efficiency)
- Occupant health and comfort (thermal, environmental sensitivity)
- Hygrothermal performance (durability and moisture management)
- Indoor air quality (air changes per hour, off-gassing, contaminant existence)
- Material choice (embodied energy, chemical composition, sourcing and shipping)

The objectives set out by the research were addressed and completed as follows:

(1)The research first developed a list of existing and proposed retrofit assemblies which provided a model for the types of assemblies to be included in such a database. This list included two baseline existing assemblies (solid brick and wood frame) which represented a significant portion of the GTA housing stock. Also included were a total of 15 retrofit options employing both interior and exterior retrofit options, as well as a variety of insulation materials (i.e mineral batt, spray applied polyurethane foam, extruded polystyrene, and cellulose).

(2) Once a list was established a review of the material properties and environmental impact indicators was gathered for each assembly which provided data on the environmental effect of retrofit options in 8 impact categories developed by the Athena Institute. Evaluating the environmental impact of a retrofit is an integral part of the proposed framework. By collecting numerical data in eight environmental impact categories, designers, builders and home owners can easily indentify to what degree a retrofit option is environmentally friendly over other options as well as determining which impact categories were affected most by certain insulation

materials. Other information on material properties such as chemical composition, long-term off-gassing characteristics, and existence of known allergens should be included in the database, and is an area for further research which will provide added understanding of the impacts these retrofits have on the environment. It is clear through the research and corresponding literature [25] that the significant use of high impact insulation materials such as petroleum and mineral based products may not fit the title of a sustainable retrofit and that it is time the construction industry begins to look towards intensive implementation of lower impact materials such as cellulose.

(3) A system for simulating the thermal and hygrothermal properties of the retrofits using computer software in order to assess a retrofits thermal resistance and moisture performance was proposed. This provided data on the RSI values of the retrofitted walls as well as an indication of the effect of any thermal bridging inherent in the retrofits. Unlike many retrofit programs, the framework also provided a detailed analysis of the moisture performance of a retrofit. Hygrothermal performance analysis provided an indication of any possible moisture related issues that may result from a retrofit and is a key area of research, especially in cold climate regions. With respect to the assemblies simulated in the research, it is evident that exterior insulated retrofits outperform interior insulation, and that regulation of interior RH levels is crucial when insulating with mould sensitive materials.

(4) Once the previous objectives were completed, the data and information was organized and presented in a two page breakdown for each assembly, which would allow designers, contractors and home owners easy access to: the construction of the assembly, thermal and hygrothermal properties, and environmental impact data for each retrofit. The assemblies were then compared to one another in four key categories: thermal performance, hygrothermal

performance, constructability, and environmental effect, in order to analyze the assemblies in a sustainable manner.

Although the research has fulfilled the objectives it had set out, research and development on the framework is by no means complete and the limitations and further research required was established.

The framework is one of the first steps towards a sustainable renovation index, and a step towards a new way of addressing home retrofits. As the time comes to upgrade our current inefficient housing stock, and climate change becomes an ever more present force in our environment, it is the responsibility of academics, professionals, and government to develop this much needed database.

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Appendix A- List of the preliminary wall and roof assemblies

Load Bearing Brick Walls

Existing

Basement Wall

- 8-12’’ double or triple wythe brick masonry . Unfinished, not damp proofed or insulated.

Exterior Wall 1

- 8’’ double wythe brick masonry, unfinished

Exterior Wall 2

- 8’’ double wythe brick masonry
- lathe and plaster finish on 1.5’’ strapping with no vapour, air barrier and insulation

Half Story Sloped Roof

- gabled roof and side attic space and knee walls. Knee wall often uninsulated.

FlatRoof

- built up roofing
- protection board
- 2’’ rigid insulation
- 5/8’’ sheathing
- 10’’ rafters
- plaster and lathe interior finish.

Energy Efficient Retrofit

Basement Wall Retrofit 1

- 8-12’’ double or triple wythe brick masonry . Unfinished, not damp proofed or insulated.

- 2’’ XPS insulation
- 2 x 6 inch studs 24’’ o/c with fibreglass batt insulation
- ½’’ gypsum wall board

Basement Wall Retrofit 2

- 8-12’’ double or triple wythe brick masonry . Unfinished, not damp proofed or insulated.
- 2’’ spray applied closed cell polyurethane foam
- 2 x 4 inch studs 24’’ o/c with spray applied closed cell polyurethane foam
- ½’’ gypsum wall board

Basement Wall Retrofit 3

- 8-12’’ double or triple wythe brick masonry . Unfinished, not damp proofed or insulated.
- Two layers 2" foil-faced polyisocyanurate insulation
- 2 x 6 inch studs 24’’ o/c with fibreglass batt insulation
- ½’’ gypsum wall board

Exterior Wall 1

- 8’’ double wythe brick masonry, unfinished
- Can be treated as the Basement Wall Assembly retrofits

Exterior Wall 2

- 8’’ double wythe brick masonry
- lathe and plaster finish on 1.5’’ strapping with no vapour, air barrier and insulation
- Can be treated as the Basement Wall Assembly retrofits

Wood frame Construction

2 x 4/ 2x6 Construction

Basement Wall

- 8-10’’ Concrete, uninsulated

Basement Wall 2

- 8-10’’ concrete
- 2 x 3 inch framing 16’’ o/c with fibreglass batt insulation
- 6 mil polyethylene
- ½’’ gypsum wall board

Exterior Wall 1

- 3.75’’ brick veneer
- 1’’ airspace
- spunbond polypropylene
- exterior sheathing (plywood/OSB)
- 2 x4 inch studs 16’’ o/c with fibreglass batt insulation
- 6 mil polyethylene
- ½’’ gypsum wall board

Exterior Wall 2

- 3.75’’ brick veneer
- 1’’ airspace
- spunbond polypropylene
- exterior sheathing (plywood/OSB)
- 2 x6 inch studs 16’’ o/c with fibreglass batt insulation
- 6 mil polyethylene

Exterior Wall 3

- Vinyl/ composite wood siding,
- spunbond polypropylene
- exterior sheathing (plywood/OSB
- 2 x4 inch studs 16’’ o/c with fibreglass batt insulation
- 6 mil polyethylene

- ½’’ gypsum wall board

Exterior Wall 4

- Vinyl/ composite wood siding,
- spunbond polypropylene
- exterior sheathing (plywood/OSB
- 2 x6 inch studs 16’’ o/c with fibreglass batt insulation
- 6 mil polyethylene
- ½’’ gypsum wall board

Roof

Vented Attic space

- 10’’ ceiling joists with 6-8’’blown cellulose insulation
- 6 mil poly polyethylene
- ½’’ gypsum wall board

Cathedral Ceiling

- Asphalt Shingles
- 5/8’’ exterior sheathing
- 10’’ vented rafters with 5.5’’ fibreglass batt insulation
- 6 mil poly polyethylene
- ½’’ gypsum wall board

<u>Energy Efficient Retrofit</u>

Basement Wall Retrofit

- 8-10’’ Concrete
- 2’’ XPS insulation

- 2 x 6 inch studs 24’’ o/c with fibreglass batt insulation

Exterior Wall 1Retrofit

- 3.75’’ brick veneer
- 1’’ airspace
- spunbond polypropylene
- exterior sheathing (plywood/OSB)
- new 3” spray foam insulation
- new 6 mil polyethylene
- new ½’’ gypsum wall board

Exterior Wall 2 Retrofit

- 3.75’’ brick veneer
- 1’’ airspace
- spunbond polypropylene
- exterior sheathing (plywood/OSB)
- 2 x6 inch studs 16’’ o/c with new 3.5’’ spray foam and fibreglass batt insulation
- ½’’ gypsum wall board

Exterior Wall 3

- Vinyl/ composite wood siding,
- spunbond polypropylene
- exterior sheathing (plywood/OSB
- 2 x4 inch studs 16’’ o/c with fibreglass batt insulation
- New 3.5” spray foam
- New ½’’ gypsum wall board

Exterior Wall 4

- Vinyl/ composite wood siding,
- spunbond polypropylene
- exterior sheathing (plywood/OSB
- 2 x6 inch studs 16’’ o/c with new 3.5 inch spray foam and fibreglass batt insulation
- 6 mil polyethylene
- ½’’ gypsum wall board

Energy and Environmentally Efficient Retrofits

The following section will list some envelope retrofit options/ materials used to improve energy efficiency while minimizing health and environmental impacts.

- Brick -1.5’’ spray applied closed cell polyurethane foam, 2 x 6 inch studs 24’’ o/c with blown in cellulose, 6 mil, gypsum wall board
- Wood frame- Double stud wall with only cellulose insulation
- Blue jean insulation
- Air krete- can be used in foundation walls, mold resistant
- Icynene
- Water blown foam insulation
- Any blown in cellulose insulation within attic space can fall into this category

Appendix B- Detailed assembly material breakdown

Existing Solid Brick Construction

1. Existing (RSI 0.65-R 3.7)

- 200mm (8’’) double wythe brick
- 25mmx38mm (1x2) furring w/ lathe and plaster finish

2. 2006 OBC (RSI 3.3-R 19)

- Existing 200mm (8’’) double wythe brick
- 38mm (1.5’’) spray applied closed cell polyurethane foam
- 38mmx64mm (2x3)stud wall offset 1’’ from spray foam c/w 89mm(3.5’’) mineral batt insulation
- 12.5 mm (1/2’’)Gypsum Wall Board

3. 2012 OBC (RSI 4.2-R 24)

- Existing 200mm (8’’) double wythe brick
- 25mm (1’’) spray applied closed cell polyurethane foam
- 38mmx64mm (2x3) stud wall offset 115mm (4.5’’) from brick c/w 140mm (5.5’’) mineral batt insulation
- 12.5 mm (1/2’’)Gypsum Wall Board

Energy Efficient Upgrades

4. Medium (RSI 6.2-R 35)

- Existing 200mm (8’’) double wythe brick
- 76mm (3’’) XPS
- 38mmx140mm (2x6) stud wall c/w mineral batt insulation
- 12.5 mm (1/2’’)Gypsum Wall Board, latex paint as vapour retarder

5. Passive Haus- Interior Spray Foam (RSI 10-R 57)

- Existing 200mm (8’’) double wythe brick
- 216mm (8.5’’) spray applied closed cell polyurethane foam
- 38mmx64mm (2x3) stud wall c/w spray applied closed cell polyurethane foam
- 12.5 mm (1/2’’)Gypsum Wall Board

6.Passive Haus- Interior/Exterior Insulation (RSI 10-R57)

- Composite wood siding
- 25mm (1’’) airspace
- 100mm (4’’) XPS
- Existing 200mm (8’’) double wythe brick
- 76mm (3’’) spray applied closed cell polyurethane foam
- 38mmx89mm (2x4) stud wall c/w spray applied closed cell polyurethane foam
- 12.5 mm (1/2’’)Gypsum Wall Board

7. Passive Haus- Exterior Insulation (RSI 10-R57)

- Composite wood siding
- 25mm (1’’) airspace
- Spunbonded polyethylene
- 254mm (10’’) XPS
- Existing 200mm (8’’) double wythe brick
- Existing 25mmx38mm (1x2) furring w/ lathe and plaster finish

Environmental Energy Efficient Upgrades

8. PH Cellulose (Diffusion Open) (RSI 10-R57)

- Existing 200mm (8’’) double wythe brick
- Spunbonded polyethylene
- 50mm (2’’) Roxul Drainage Board
- 241mm (11.5’’) blown in cellulose insulation
- 38mmx64mm (2x3) stud wall c/w blown in cellulose insulation
- 12.5 mm (1/2’’)Gypsum Wall Board

9. PH Cellulose (Diffusion Closed) (RSI 10-R57)

- Existing 200mm (8’’) double wythe brick
- Spunbonded polyethylene
- 2’’ Roxul Drainage Board
- 241mm (11.5’’) blown in cellulose insulation
- 38mmx64mm (2x3) stud wall c/w blown in cellulose insulation
- 6 mil polyethylene
- 12.5 mm (1/2’’)Gypsum Wall Board

Existing Wood Frame Construction

10. Existing (RSI 2-R 12)

- 100 mm (4’’) Brick veneer
- 25mm (1’’) airspace
- Spunbonded polyethylene
- 12.5mm (1/2’’) exterior sheathing (plywood/ OSB)
- 2x4 inch stud wall c/w fibreglass batt insulation
- 6 mil polyethylene

- 12.5 mm (1/2’’)Gypsum Wall Board

<u>11. 2006 OBC (RSI 3.3-R 19)</u>

- Existing 100 mm (4’’) Brick veneer
- Existing 25mm (1’’) airspace
- Existing Spunbonded polyethylene
- Existing 12.5mm (1/2’’) exterior sheathing (plywood/ OSB)
- Existing 38mmx89mm (2x4) stud wall c/w new mineral batt insulation
- 38mmx64mm (2x3) stud wall c/w mineral batt insulation
- 6 mil polyethylene
- 12.5 mm (1/2’’)Gypsum Wall Board

<u>12. 2012 OBC (RSI 4.2-R 24)</u>

- Existing 100 mm (4’’) Brick veneer
- Existing 25mm (1’’) airspace
- Existing Spunbonded polyethylene
- Existing 12.5mm (1/2’’) exterior sheathing (plywood/ OSB)
- Existing 38mmx89mm (2x4)stud wall with new 25mm (1’’) spray applied closed cell polyurethane foam on sheating
- 38mmx64mm (2x3) stud wall offset 1’’ from 2x4 wall; entire cavity from foam filled with 140mm (5.5’’) mineral batt insulation
- 6 mil polyethylene
- 12.5 mm (1/2’’)Gypsum Wall Board

Energy Efficient Upgrades

13. Medium(RSI 6.2-R 35)

- Existing 100 mm (4’’) Brick veneer
- Existing 25mm (1’’) airspace
- Existing Spunbonded polyethylene
- Existing 12.5mm (1/2’’) exterior sheathing (plywood/ OSB)
- Existing 38mmx89mm (2x4) stud wall with new 64mm(2.5’’) spray applied closed cell polyurethane foam on sheathing
- 6 mil polyethylene on exterior side of 2x3 wall
- 38mmx64mm (2x3) stud wall offset 76mm (3’’) from 2x4 wall; entire cavity from foam filled with 165mm (6.5’’)blown in cellulose
- 12.5 mm (1/2’’)Gypsum Wall Board, latex paint as vapour retarder

14. Passive Haus- Interior Spray Foam (RSI 10-R 57)

- Existing 100 mm (4’’) Brick veneer
- Existing 25mm (1’’) airspace
- Existing Spunbonded polyethylene
- Existing 12.5mm (1/2’’) exterior sheathing (plywood/ OSB)
- Existing 38mmx89mm (2x4)stud wall c/w new spray applied closed cell polyurethane foam on sheathing
- 127mm (5’’) spray applied closed cell polyurethane foam on sheathing
- 38mmx64mm (2x3) stud wall c/w spray applied closed cell polyurethane foam
- 12.5 mm (1/2’’)Gypsum Wall Board

15. Passive Haus- Exterior and Interior Insulation (RSI 10-R 57)

- Composite wood siding
- 25mm (1’’) airspace

- 200mm (8’’)XPS
- Existing 100 mm (4’’) Brick veneer
- Existing 25mm (1’’) airspace
- Existing Spunbonded polyethylene
- Existing 12.5mm (1/2’’) exterior sheathing (plywood/ OSB)
- Existing 38mmx64mm (2x4) stud wall c/w fibreglass batt insulation
- Existing 6 mil polyethylene
- Existing 12.5 mm (1/2’’)Gypsum Wall Board

Environmental Energy Efficient Upgrades

16. PH Cellulose (Diffusion Open) (R57)

- Existing 100 mm (4’’) Brick veneer
- Existing 25mm (1’’) airspace
- Existing Spunbonded polyethylene
- Existing 12.5mm (1/2’’) exterior sheathing (plywood/ OSB)
- Existing 38mmx89mm (2x4) stud wall c/w new blown in cellulose
- 267mm (10.5’’) blown in cellulose
- 38mmx64mm (2x3) stud wall c/w blown in cellulose
- 12.5 mm (1/2’’)Gypsum Wall Board

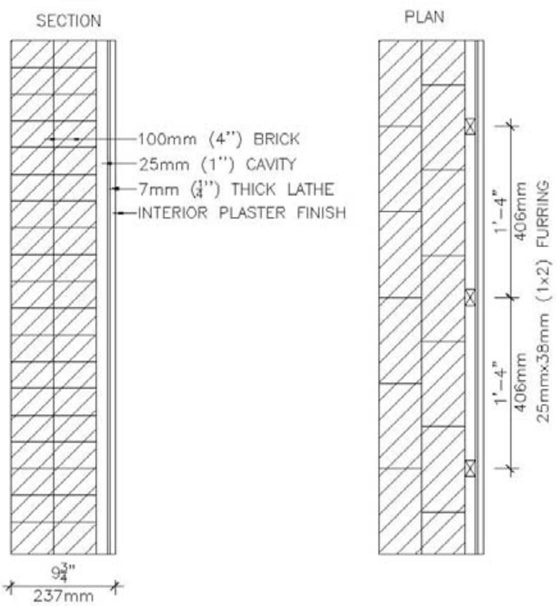
17. PH Cellulose (Diffusion Closed) (R57)

- Existing 100 mm (4’’) Brick veneer
- Existing 25mm (1’’) airspace
- Existing Spunbonded polyethylene
- Existing 12.5mm (1/2’’) exterior sheathing (plywood/ OSB)
- Existing 38mmx89mm (2x4) stud wall c/w new blown in cellulose
- 267mm (10.5’’) blown in cellulose

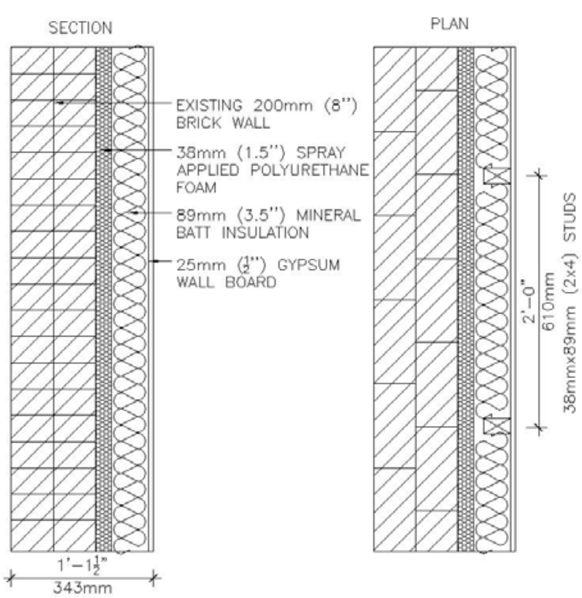
- 38mmx64mm (2x3) stud wall c/w blown in cellulose
- 6 mil polyethylene
- 12.5 mm (1/2'')Gypsum Wall Board

Appendix C- Plan and Section Drawings for each Assembly

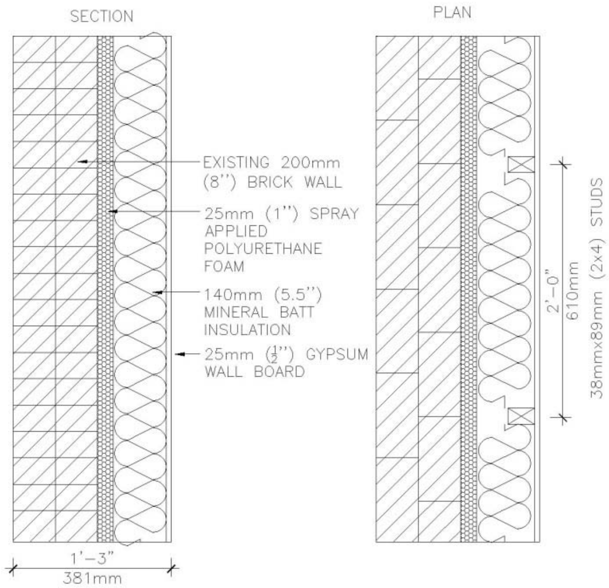
1. Existing Brick



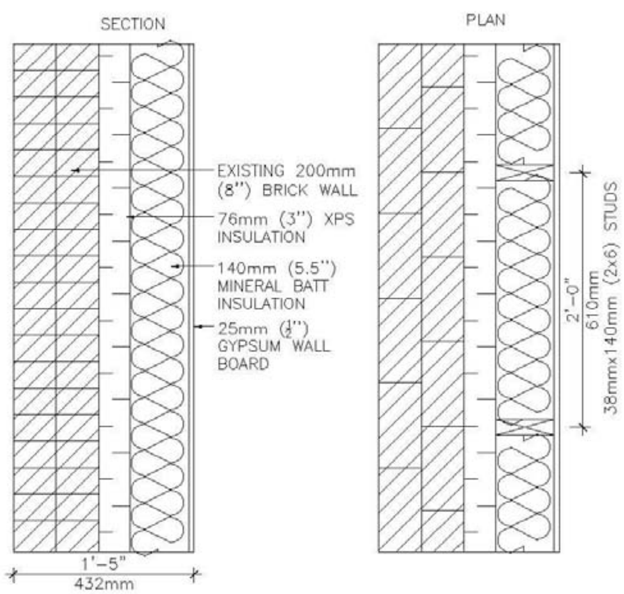
2. Brick 2006 OBC



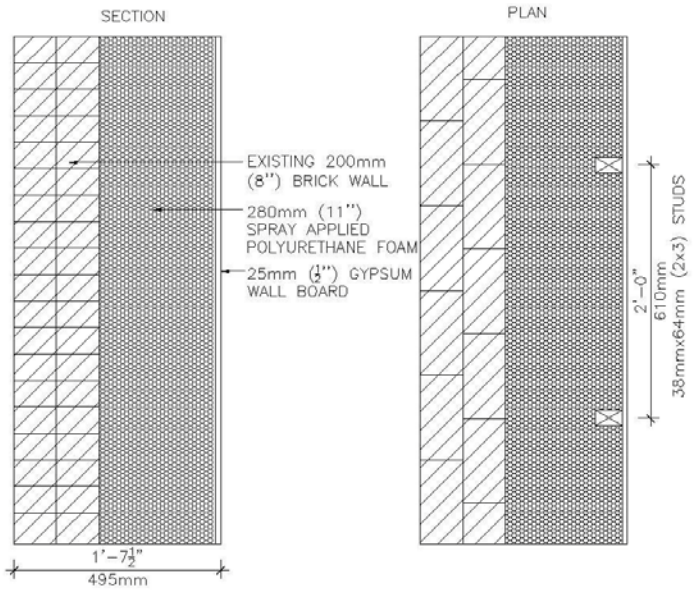
3. Brick 2012 OBC



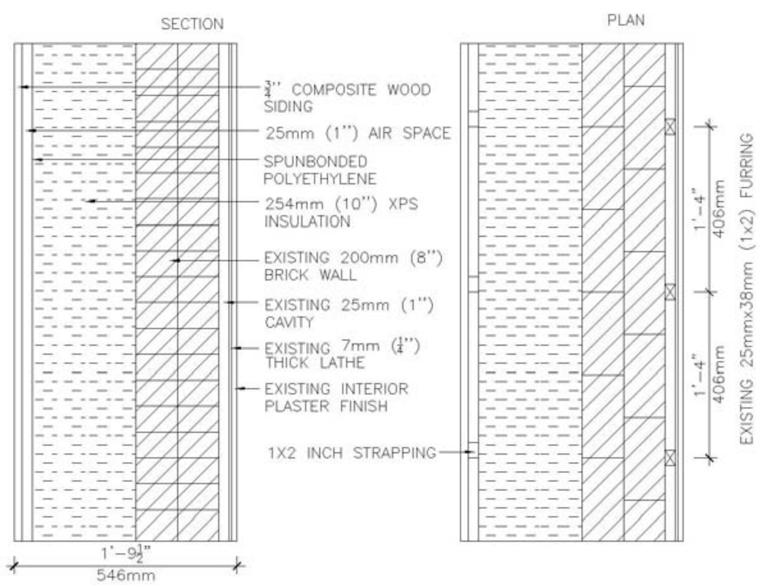
4. Brick Medium



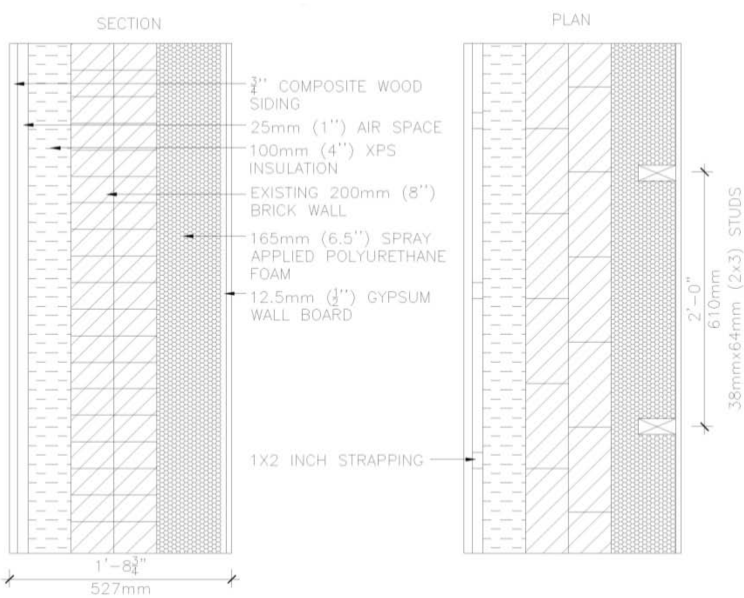
5. Brick Passive Haus Interior Spray Foam



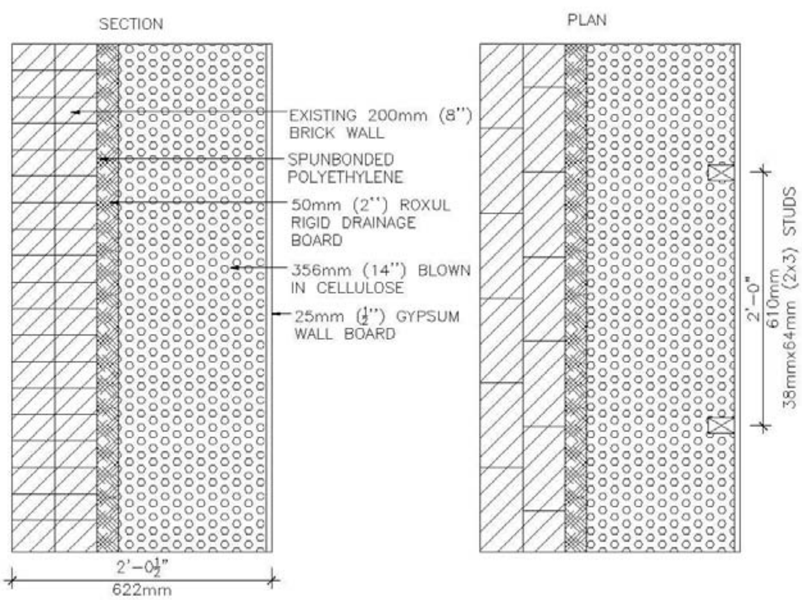
6. Brick Passive Haus Exterior Insulation



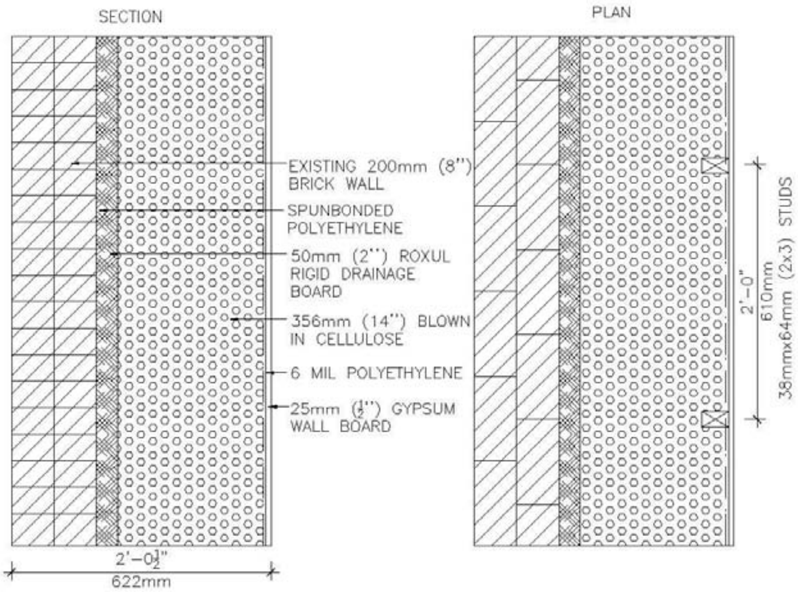
7. Brick Passive Haus Interior/ Exterior Insulation



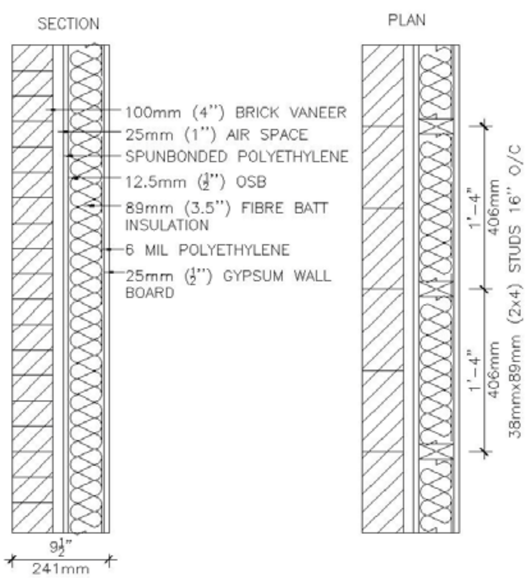
8. Brick Passive Haus Cellulose Diffusion Open



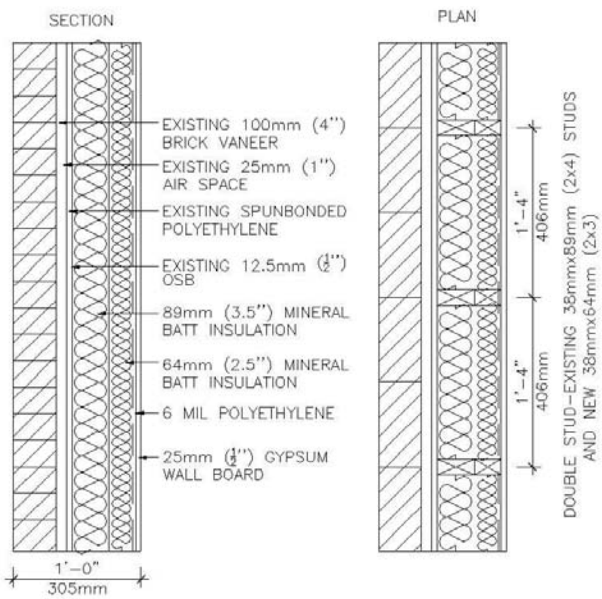
9. Brick Passive Haus Cellulose Diffusion Closed



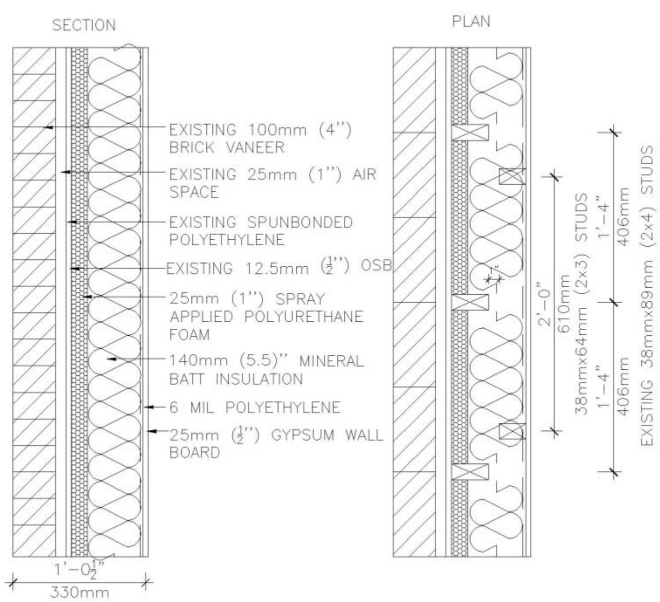
10. Existing Wood Frame



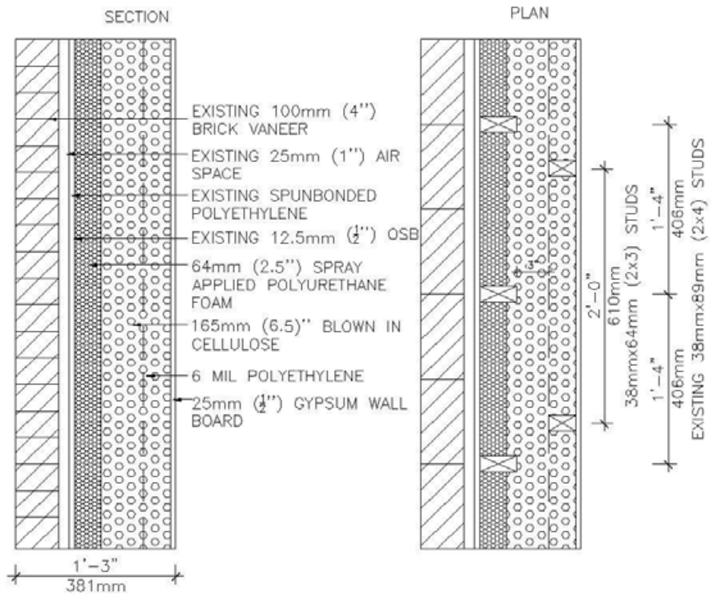
11. Wood Frame 2006 OBC



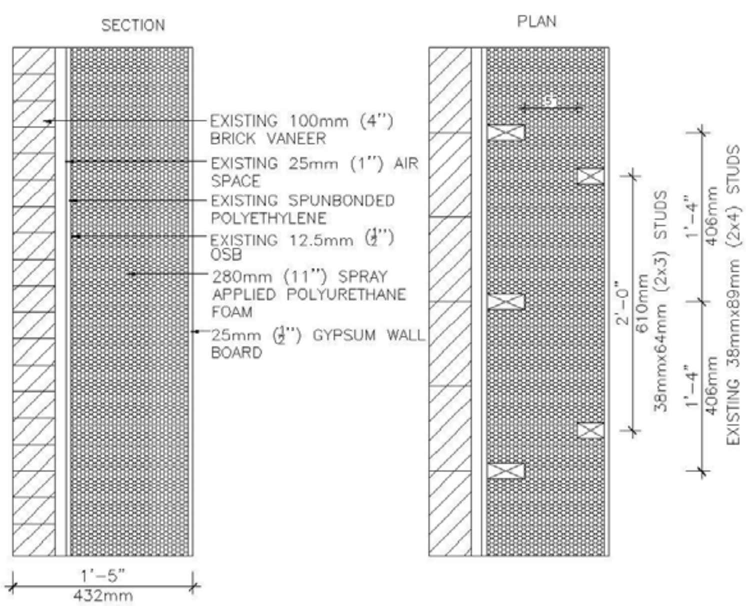
12. Wood Frame 2012 OBC



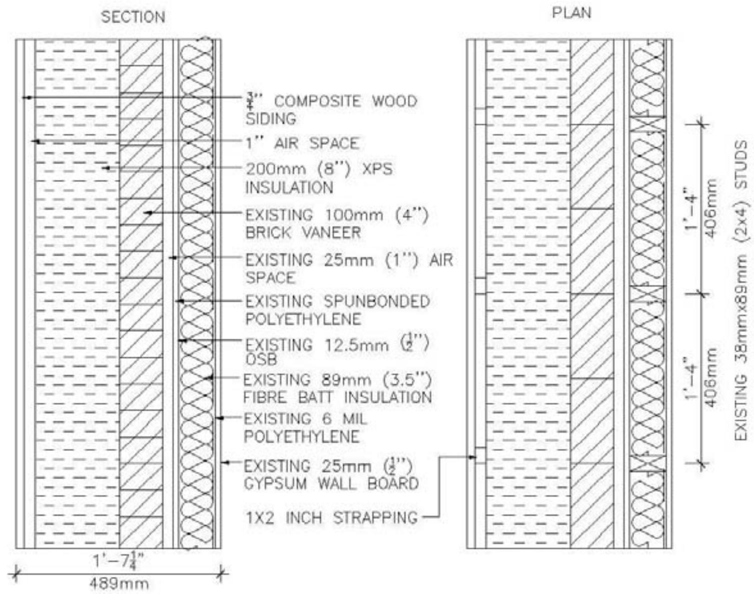
13. Wood Frame Medium



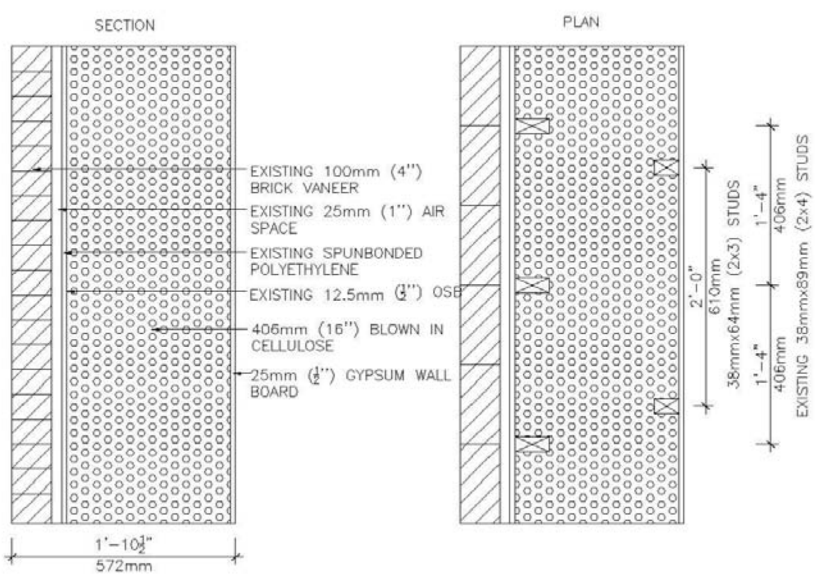
14. Wood Frame Passive Haus Interior Spray Foam



15. Wood Frame Passive Haus Exterior Insulation



16. Wood Frame Passive Haus Cellulose Diffusion Open



17. Wood Frame Passive Haus Cellulose Diffusion Closed