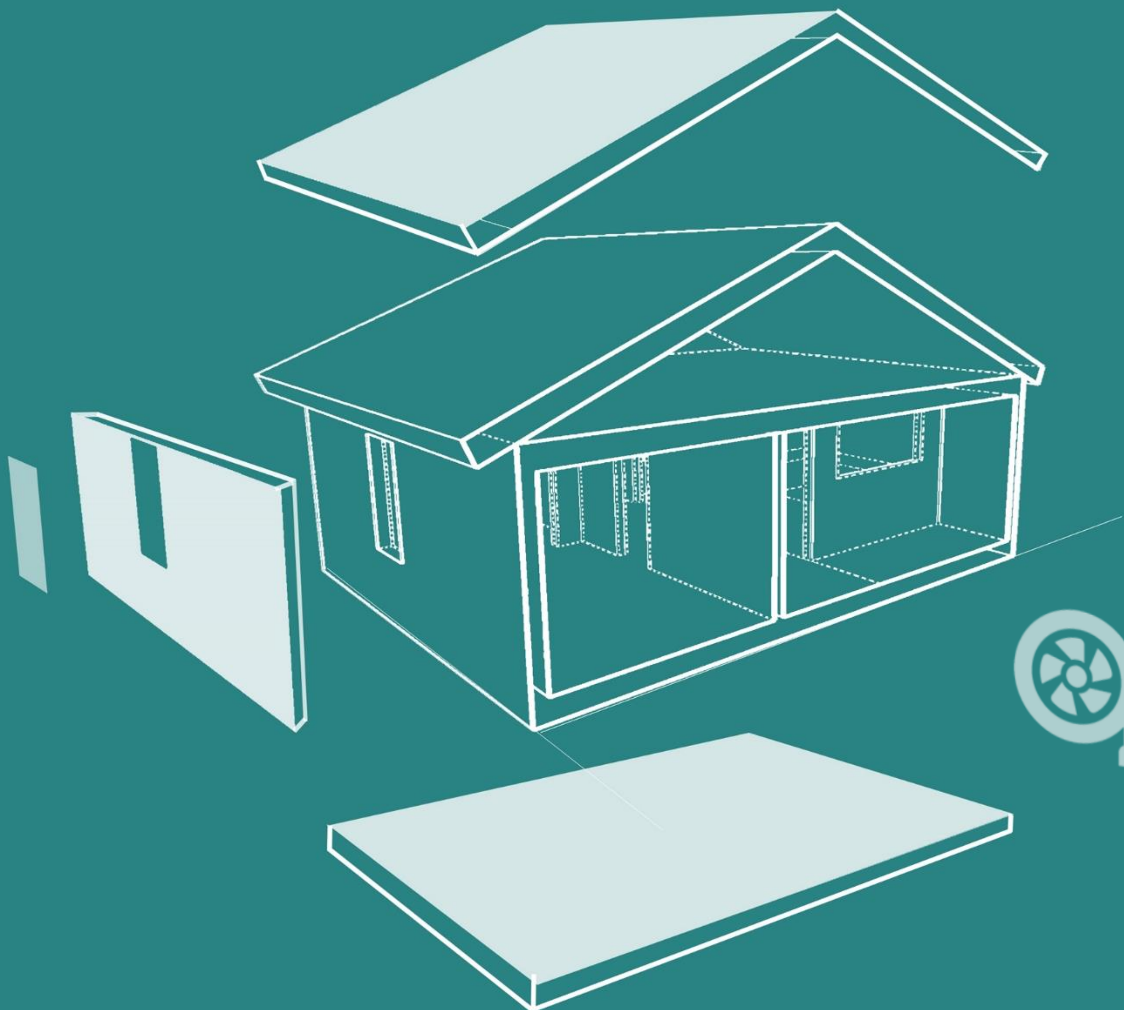

Assessing the Embodied Emissions of Building to the Energy Step Code

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Disclaimer

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This project was conducted under the mentorship of the City of Richmond staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of the City of Richmond or the University of British Columbia.

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List of Abbreviations

LCA	Life Cycle Assessment
WBLCA	Whole Building Life Cycle Assessment
NBC	National Building Code
BC	British Columbia
TEDI	Thermal Energy Demand Intensity
MEUI	Mechanical Energy Use Intensity
ACH_{50}	Air Changes per Hour at 50 pascal pressure difference
ESC	Energy Step Code
AEC	Annual Energy Consumption
EPS	Expanded Polystyrene foam insulation
XPS/XTPS	Extruded Polystyrene foam insulation
USI	U-Value of fenestration with SI units
RSI	R-Value with SI units
SHGC	Solar Heat Gain Coefficient
GHG	Greenhouse gases
GHGI	Greenhouse gas intensity
EC	Embodied carbon
OC	Operational carbon
BoM	Bill of materials
EPDs	Environmental Product Declarations
DSHW	Domestic Hot Water
CoV	City of Vancouver
MEQ	Mechanical Equipment Quantities
DMQ	Distribution Material Quantities
ECC_e	Embodied Carbon Content of Equipment
ECC_d	Embodied Carbon Content of Distribution
HVAC	Heating, Ventilation and Air Conditioning
ASHP	Air Source Heat Pump
EE	Embodied Emissions

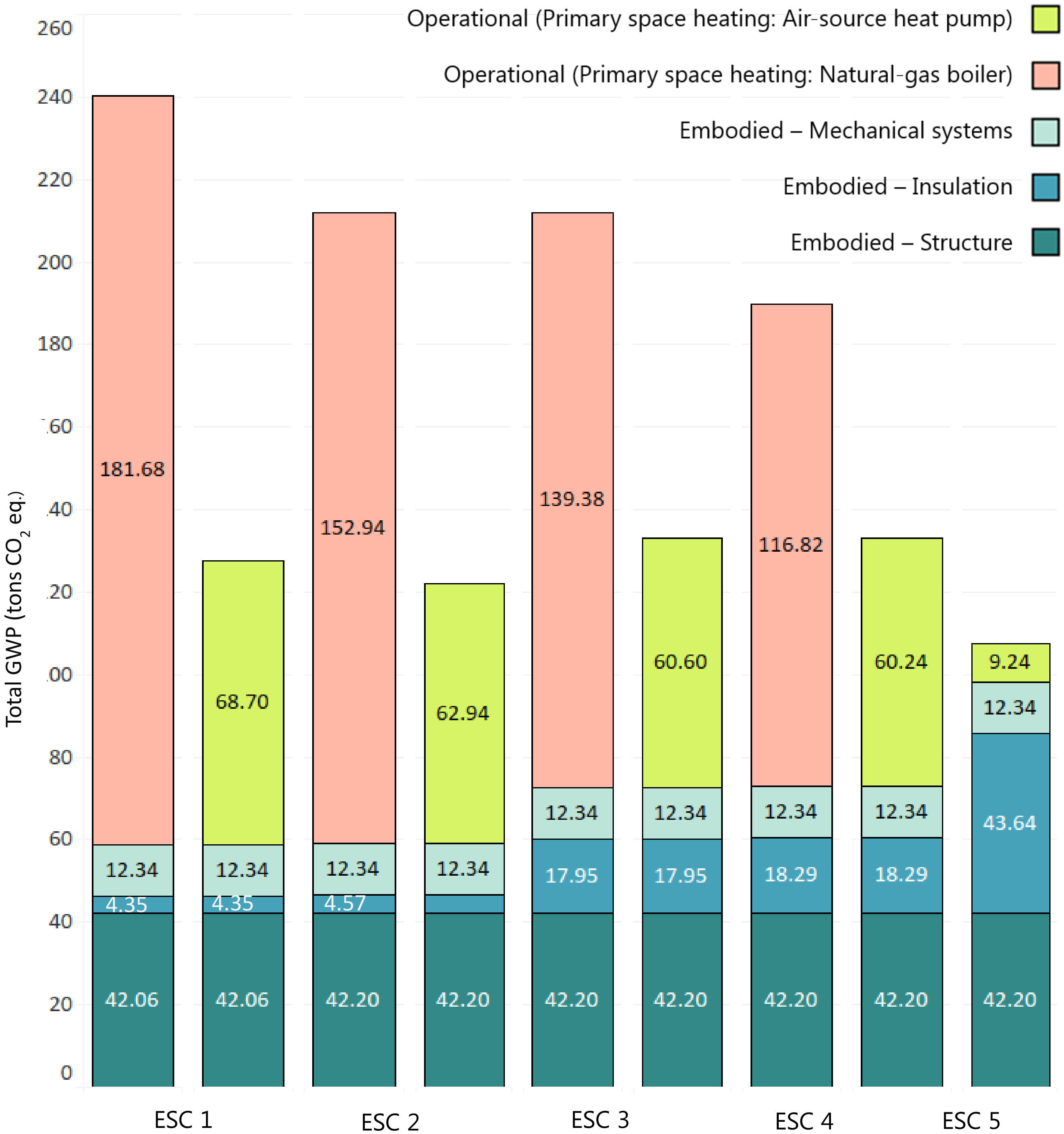
Executive Summary

The construction industry accounts for nearly 39% of energy-related carbon dioxide (CO_2) emissions in the world [1]. Out of this 39%, 28% is accounted for the operational emissions and the remaining 11% is for the embodied emissions throughout the building lifetime [1]. As the operational emissions decrease due to increased energy efficiency of the buildings and the proliferation of low-carbon energy systems, the embodied emissions become a larger portion of the total environmental footprint of the building sector. Transitioning to truly net-zero communities, therefore, requires increased attention to the embodied environmental impacts of buildings.

In British Columbia, the Energy Step Code has created considerable momentum in reducing the energy consumption of buildings. Many jurisdictions are using the Energy Step Code as a policy tool to also reduce operational emissions of the building sector. This research project was undertaken to evaluate the embodied emissions of single-family houses built to various levels of the Energy Step Code. Of particular interest were the conurbations of increased insulation to reduce the energy demand, and high-efficiency and low-carbon mechanical systems to reduce the operational emissions of the building.

Operational and embodied emissions of a typical single-family dwelling designed to meet the various tiers of the BC Energy Step Code were studied. A Step 1 two-storey house with a total floor area of 346.3 m^2 (heated floor area: 204.4 m^2) built in Richmond in 2019 was used as the baseline. Various upgrades were introduced to meet the performance requirements of Steps 2-5. The operational emissions of each design were calculated based on the annual energy demand estimated through modeling using HOT2000 [2]. The embodied emissions were estimated using a hybrid method entailing an Assembly Group whole-building life cycle analysis using the ATHENA *Impact Estimator for Buildings*, [3] and Bill of Materials calculations for the insulation materials and mechanical systems. The scope of the LCA was cradle-to-grave and a lifespan of 60 years was assumed for the house.

The figure below shows embodied and operational emissions of the studied Step 1-5 houses. For Steps 1-4, two scenarios for space heating equipment were considered: natural-gas boilers and air-source heat pumps. The Step 5 house is fully electrified (air-source heat pump for space and water heating). It was observed that the operational emissions are much lower if the house uses an air source heat pump which uses electricity as the fuel source, decarbonising the space heating and cooling, The embodied emissions from insulation increase considerably as we move from Step 1 to Step 5, because the higher-Step houses considered here entail more XPS which is a highly carbon-intensive insulation material.



It was concluded that while the Energy Step Code is not very effective in reducing the operational emissions of buildings, it can even have the unintended consequence of *increasing* the embodied emissions of buildings. The trade-off between the decrease in the operational emissions and the increase in the embodied emissions should be more closely studied and eliminated, in order to make it truly net-zero.

1. Introduction

The BC Energy Step Code has created considerable momentum in the move to reduce the energy consumption of buildings in the Province of British Columbia. Although the Energy Step Code focusses on energy efficiency, many communities in the province are leveraging the Step Code along with local environmental policies to reduce greenhouse gas emissions from buildings. However, such policies only address operational emissions.

As the operational emissions decrease due to increased energy efficiency of the buildings and the proliferation of low-carbon energy systems, the embodied emissions become a larger portion of the total environmental footprint of the building sector. Transitioning to truly net-zero communities, therefore, requires increased attention to the embodied environmental impacts of buildings. Moreover, the push for high-performance buildings enhances the use of construction materials, practices and mechanical systems that may have significant embodied emissions.

1.1 Objectives

The objective of this project is to assess the embodied emissions of buildings that have been designed and built to meet various performance targets of the Energy Step Code. The work includes:

- Establishing a benchmark by assessing the embodied emissions of typical, new single-family residential buildings in Richmond;
- Assessing the embodied emissions of various high-performance designs and low-carbon energy systems followed by comparison of the embodied emissions of improved designs and their projected operational emissions.

1.2 Scope and Limitations

The study is limited to new single-family houses. A typical design based on recent submissions to the City of Richmond was chosen as the baseline of the study. Upgrades were introduced to that baseline in order to meet the performance requirements of the various levels of the Energy Step Code. The environmental impacts of construction are not limited to the greenhouse gas emissions and their associated global warming effect. Life-cycle analysis also considers such effects as the acidification potential, eutrophication potential, ozone depletion, etc. Nevertheless, this study focuses on only the global warming potential of building materials, construction techniques and building energy systems. In particular, this study examines the embodied emissions of building materials (e.g. insulation) and mechanical systems (e.g. heat pumps) that are broadly used to increase the operational energy efficiency and reduce the operational GHG emissions of buildings.

2. Background

The buildings sector is growing at an unprecedented rate. More than 200 billion square meters of new construction are expected to be built in the next 40 years, adding the equivalent of Paris to the planet every single week. The building and construction industry, together, account for about 39% of energy-related carbon dioxide (CO_2) emissions in the world [1]. Out of this 39%, 28% is accounted for the operational emissions (energy required to heat, cool and light the building) and the remaining 11% is for the embodied emissions (material extraction, transportation, construction and demolition) throughout the building lifetime [1].

2.1 Operational vs Embodied Emissions

Operational emissions of a building are the GHG emissions released during the functioning or in-use phase of the building. These emissions arise from energy consuming activities including heating, cooling, ventilation and lighting of the building. *Embodied* emissions, on the other hand, correspond to the GHG emissions associated with the extraction, manufacturing and transportation of construction materials, as well as construction processes. Embodied emissions also account for major renovations during the lifetime of the building, where materials are added to a building, and the end-of-life demolition [2]. Embodied emissions are calculated and reported in terms of the global warming potential expressed as the equivalent CO_2 mass ($kgCO_2$ eq).

Embodied emissions can be evaluated in various stages of the supply chain: cradle to gate (factory), or cradle to site (of use), or cradle to grave (end of use). Figure 1 shows the emissions associated with various stages of a building's life cycle schematically. Embodied carbon depends on the material type, geographical location, manufacturing processes, building codes, and other construction practices. Most of the embodied carbon emissions occur at the early stages of a building's lifecycle [2]. Therefore, there is a significant potential to reduce the embodied emissions at during the initial phase of design.

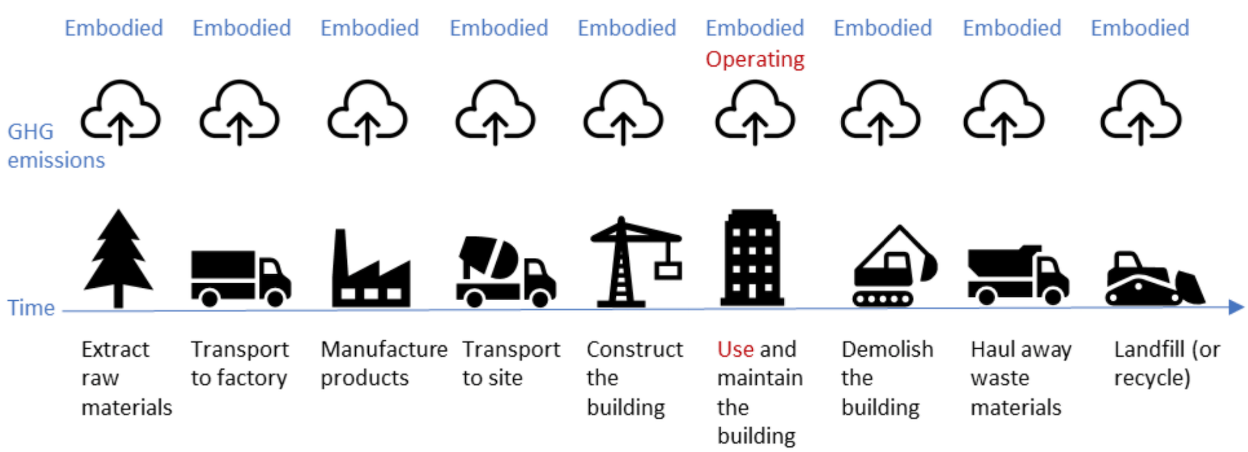


Figure 1: Emissions of a building during its Material Supply Chain [6]

2.2 Reducing Embodied Emissions

The reduction of operational emissions has been increasingly considered over the past twenty years through passive and hybrid design strategies. Embodied carbon emissions, on the other hand are being overlooked. Figure 2 shows that there is a huge potential to reduce the upfront carbon emissions if we build efficiently, which is crucial in addressing the climate change that we are witnessing.

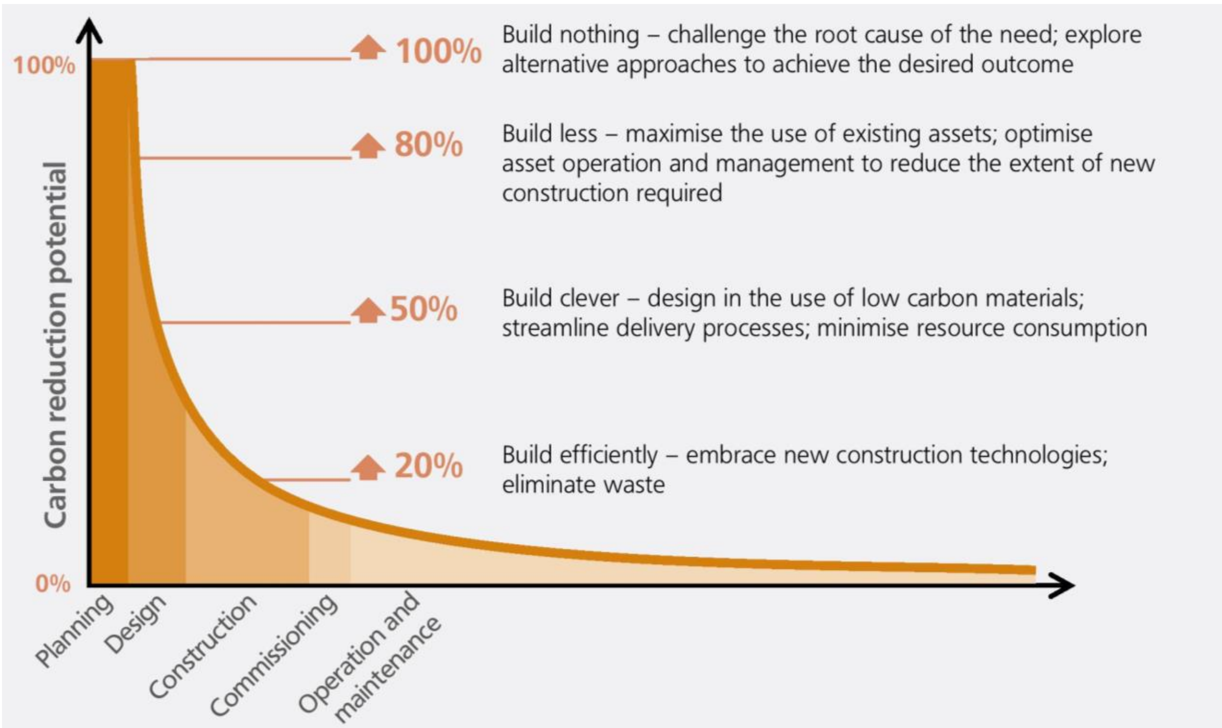


Figure 2: Opportunities to reduce embodied carbon emissions from stage of design process [3]

The initial step to reduce embodied emissions is to identify the "hot spots" i.e. materials or systems that contribute the most to a building's embodied emissions. These are quantified by carrying out a whole-building life-cycle assessment (WBLCA). See Section 2.3.

Several, e.g. [2] and [4], have examined the various aspects and urgency of the embodied carbon emissions of buildings, current industry practices, and strategies to reduce these emissions and formulating policies to address the embodied carbon emissions. A study carried out by the Urban Equation [2] analyzes the impacts embodied carbon by conducting a life cycle analysis of a typical Multi-Unit Residential Building located in Ottawa, ON, built to the standards of Ottawa Building Code and Toronto Green Standard. The key findings of the study include:

- The impact of embodied carbon on a building's total Life Cycle emissions becomes greater with the decrease of operational energy usage resulting from energy conservation measures.
- Increasing the thermal insulation of a building has a minimal impact on the embodied emissions of a building. [2]

Another research carried out at the Norwegian University of Science and Technology [4] studies embodied emissions in single-family house according to the current standards in Norway (TEK 17), using an LCA approach. The study examines various insulation types and thicknesses in search of the most effective combination for lowering the lifetime emissions of the building. The study also identifies the part of the building envelope where additional insulation is most efficient in reducing the lifetime greenhouse gas emissions of the building [4]. The key findings of the study are:

- Insulation is the third most carbon-intensive material in construction.
- The calculated GHG emissions vary inversely proportionally with the material quantities - more insulation leads to lower operational emissions, and overall lower lifetime emissions.
- Having more insulation increases the embodied emissions considerably but it generally does not outweigh the energy savings.
- The location of insulation in a specific structural component or assembly such as external wall, foundations, floor, roof, etc. has the largest impact on the lifetime emissions of the building.
- The operational emissions are most sensitive to the insulation thickness in the walls as the wall surface area is more than double than those of the roof and floor and thus allows for more heat transmission [4].

2.3 Whole-Building Life Cycle Assessment (WBLCA)

Life Cycle Assessment (LCA) is a framework for quantifying the potential environmental impacts of buildings and their individual components (foundation, walls, floor, roof, fenestration, etc.) throughout the different life cycle stages. LCAs are carried out in various stages which include resource extraction, manufacturing and prefabrication, transportation, onsite construction, operation, maintenance, demolition and disposal of buildings.

Whole-Building Life Cycle Assessments (WBLCA) is a holistic approach to carry out LCA for the entire building instead of an individual component. WBLCA measures all the flows between a building and the nature over its lifetime and then estimates the resulting impacts on air, land and water [5]. Undertaking WBLCA in initial design phases can help largely reduce the embodied carbon emissions in the following ways:

- Making informed material and design choices by selecting materials that have lesser carbon footprint (such as wood over concrete) or selecting locally sourced or recycled materials;
- Measuring the design decisions that are assumed to be "green" or "sustainable" by quantifying the overall impact environmental impacts for the final building design;
- Identifying and addressing the key "hot spots" in a building design which account for majority of carbon emissions in construction and operation phase;
- Assisting in providing compliance with green building policies and guidelines.

The present study includes carrying out WBLCA of a typical single-family house in Richmond to assess the overall embodied carbon emissions of existing design and possible upgrades.

2.4 The BC Energy Step Code

The BC Energy Step Code is a voluntary, performance-based energy efficiency standard that provides an incremental and consistent approach to build higher-efficiency buildings that go beyond the minimum requirements of the BC Building Code. The City of Richmond adopted the BC Energy Step Code in 2018. The current requirement for new single-family dwellings is compliance with Step 1 requirements. The City plans to adopt Step 3 for single-family houses in 2020.

Various municipalities, including the City of Richmond, are looking to leverage the BC Energy Step Code as a policy tool to achieve their targets and ambitions for reducing the emissions of the building sector. Nevertheless, since the Energy Step Code is concerned with energy efficiency, it does not guarantee deep reductions in the operational emissions of buildings, especially in the lower and intermediate Steps. As shown in a recent study [6], depending on the building energy system, even houses built to Steps 4 and 5 may have significantly high operational greenhouse gas emissions. See Figure 3. Furthermore, many of the energy conservation measures used to increase the energy efficiency of buildings, e.g. use of synthetic insulation materials and heat pumps, have significant embodied emissions. Therefore, the trade-off between the embodied emissions of the energy conversation measures used to meet the Energy Step Code performance criteria and the resulting reductions in the operational emissions is non-trivial and requires attention.

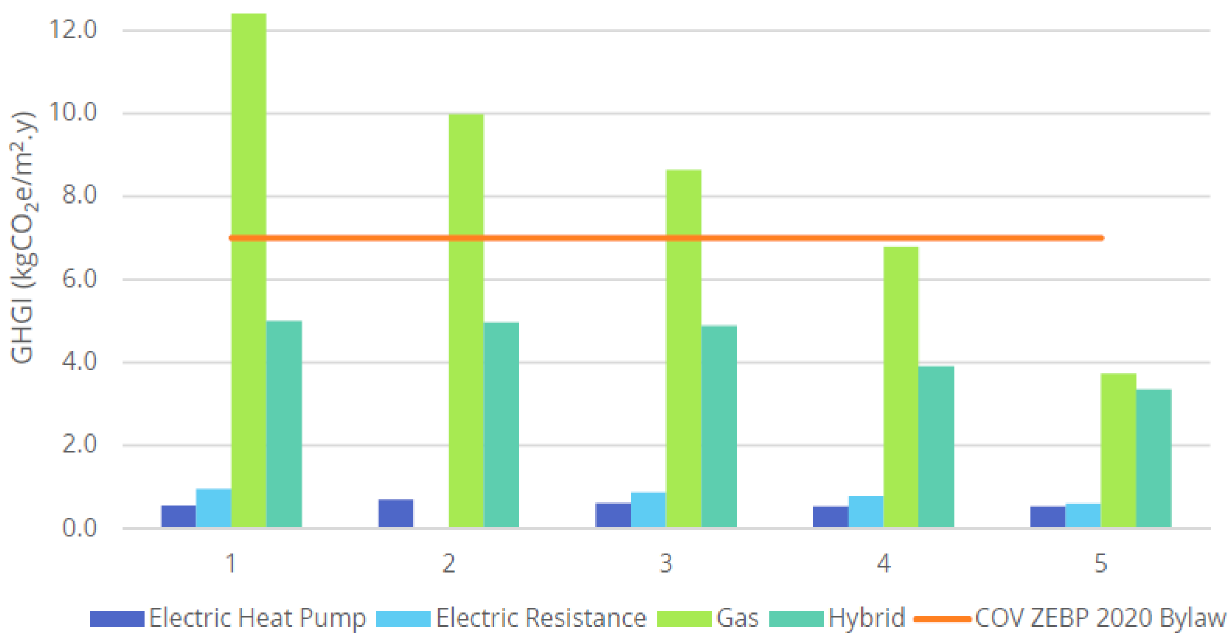


Figure 3: Operational GHG intensity of typical medium-size single-family dwellings built to various levels of the BC Energy Step Code [6]

3. Methodology

Operational and embodied emissions of a typical single-family dwelling designed to meet the various tiers of the BC Energy Step Code are studied. The baseline is a Step 1 house built in Richmond in 2019, as described in Section 3.3. Various upgrades were introduced to the baseline design to meet the performance requirements of the higher Steps.

Calculations used in the study

Embodied emissions

Structure | **Insulation**

- Whole Building LCA
- Athena Impact Estimator
- Assembly Method vs Hybrid Method

Mechanical System

- Calculation of GWP from equipment, distribution and refrigeration
- PhD. Thesis by Barbara Rodriguez for equipment & distribution
- CoV guideline for refrigerant

Operational emissions & compliance with the Energy Step Code requirements

- Energy Modeling
- HOT 2000
- Used file provided to the City as baseline

The operational emissions of each design were calculated based on the annual energy demand estimated through modeling using HOT2000 [7]. The software was also used to show compliance with the Energy Step Code by achieving the threshold values for key energy metrics i.e. TEDI, MEUI and ACH_{50}.

The embodied emissions were estimated separately for structure, insulation and mechanical systems. The embodied emissions for structure and insulation were quantified using a hybrid method entailing an Assembly Group whole-building life cycle analysis using the ATHENA *Impact Estimator for Buildings* [8] for the structure and Bill of Materials calculations for the insulation materials used in the structure, envelope, fenestration.. The scope of the LCA was a cradle-to-grave analysis and a lifespan of 60 years was assumed for the house. The LCA primarily draws on data from the Athena Sustainable Materials Institute's *Impact Estimator for Buildings* software [8] database, augmented with the Institute's secondary databases and the Environmental Product Declarations (EPDs) of the materials. Several other EPDs were used for calculation of the global warming potential of insulation using the hybrid method. See Section 3.3.4.

3.1 Description of the house

The subject of the study is a two-storey residence, representative of typical single-family houses in Richmond, BC. The house was constructed in 2019 and has the following details, as shown in Table 1.

Building type	Single family detached residence
Location	Richmond, BC
No. of floors	2
Area breakup	Ground Floor 165.97 m^2 Upper Floor 124.39 m^2 Garage 55.92 m^2
Building height	9.89 m
Overall building dimensions	9.75m x 17.5m
Expected lifetime	60 years

Table 1: Basic building information

The details of construction assemblies and drawings for the house have been attached as **Appendix A** and **B** of this report

3.1.1 **Object of Assessment:** The object of assessment of this study is a single-family residence and includes materials from the construction elements as stated in the **Appendix C**, as per the Uni-format. Table 2 below lists the broad inclusions and exclusions for the study. The construction elements assessed include structure, envelope, and interior partition materials. The interior material finishes for any of the surfaces are not included in the analysis. Other notable omissions include:

- Landscaping or hardscaping elements, site development features;
- Parking, pathway, boundary walls;
- Staircases;
- Electrical, plumbing, sanitary systems or equipment

HVAC and domestic hot water distribution systems have been included to incorporate embodied carbon emissions from the equipment and refrigerants used in the specific system type. This will be further detailed in the following.

Inclusions	
Foundations	Footing, slab on grade
Superstructure	Floor Roof Exterior Walls Exterior Windows Exterior Doors
Interior Construction	Partition walls, interior doors
Services &	HVAC

Exclusions	
Site Features	Boundary wall, landscaping, hardscaping
Interior Finishes	Wall, floor and ceiling finishes
Stairs	Stair construction and finishes
Services & Equipment	Conveying, plumbing, fire protection, electrical services
Furnishings	Fixed and movable furnishings

Table 2: Construction features and details included and excluded from the study

3.1.2 Assessment of System Boundary: The assessment system boundary defines which life cycle activities (undergone by the object of assessment) are to be included in the analysis. As illustrated in Figure 4, the system boundary according to EN 15978 is characterized by the temporal flow of the building life cycle – i.e. Product, Construction Process, Use and End of Life stages. The various processes that occur at each stage are grouped in "modules", labeled with alpha-numeric designation "A1" through "C4" [9]. Several industry EPDs were used to calculate GWP from insulation materials which use the same system boundary i.e. A1 to C4. The system boundary of this assessment is cradle-to-grave and includes the information modules shown as blue boxes in Figure 4.

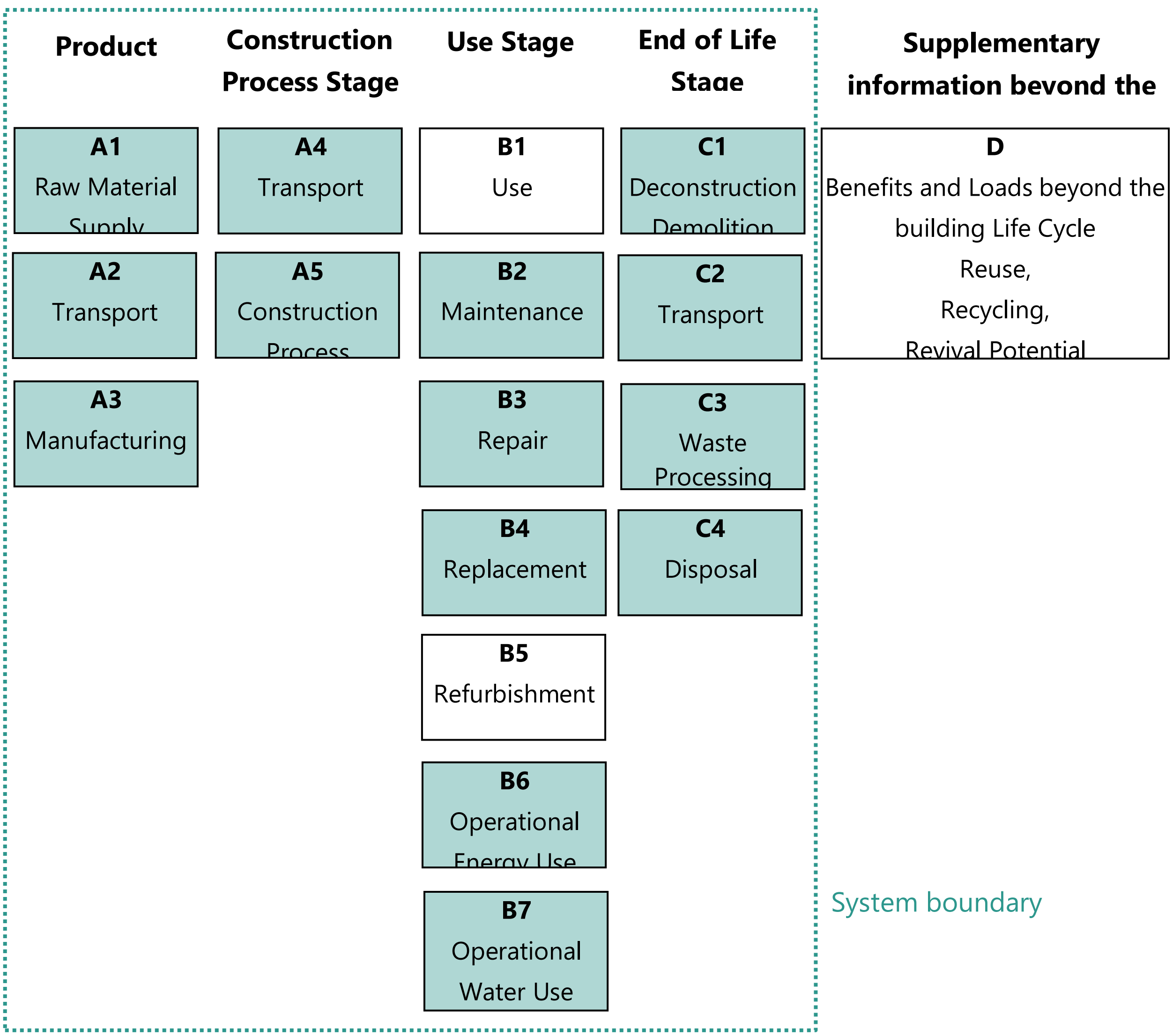


Figure 4: Assessment of System Boundary

3.1.3 Statement of scenarios used in the study: Figure 5 illustrates the five cases which were considered in the study, each pertaining to a Step. The study includes calculation of embodied and operational carbon emissions by making major and minor energy upgrades to the existing design such that the new model shows compliance with the performance requirements of the particular Step.

The project primarily involves a "sensitivity analysis" and identification of "hotspots" that majorly account for energy loss through the building. The research attempts at mitigating these "hotspots" by studying the impacts on embodied carbon emissions. The upgrades introduced at each Step are shown in the figure below.

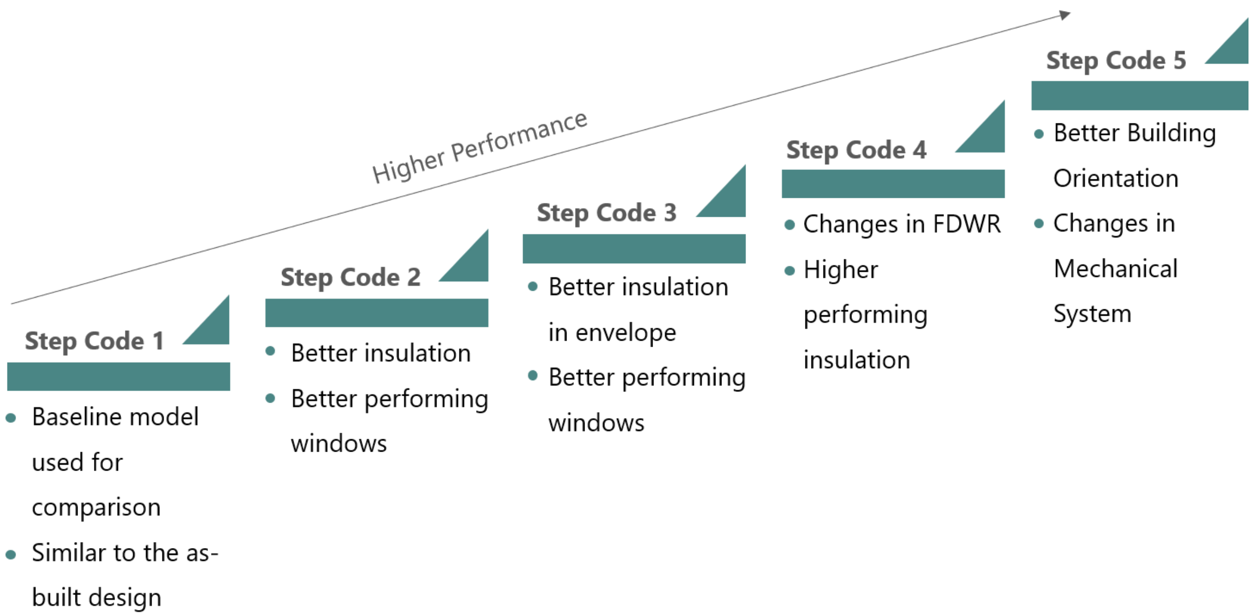


Figure 5: Types of energy upgrades for each Energy Step Code level ("Step")

3.1.4 Modeling the baseline case (Step 1 house): The baseline case was modelled according to the As-built specifications, reported to the City at the time of Final Inspection of the house. The input parameters for this case are the same as the construction details of the existing building. The performance of the building was reported while obtaining the building permit, as per the compliance of the Energy Step Code Level 1. The HOT 2000 file submitted to the City was used as the baseline for creating the energy model files for all the cases. Embodied emissions were calculated through a whole-building LCA with Athena Impact Estimator and the Hybrid method, as described in Section 3.3.4. Table 3 lists the key construction assemblies incorporated in the HOT2000 model.

Exterior Walls	Wood stud 2 x 6 @ 16" O.C. gyp board and sheathing	R 20 Batt Insulation
Roof / Ceilings	Attic: truss 24" O.C.	R 40 Batt Insulation
Slab on Grade	4" Concrete Slab	2.5" XPS under slab full area
Floors Over Unheated Spaces	Cantilever: 9 1/2" TJI @ 16" O.C.	R 31 Batt Insulation
Fenestration & Doors	Windows: Double glazed, vinyl, argon, low-e coating Doors: Fiberglass polystyrene core	USI – 1.77 SHGC – 0.40

Table 3: Key construction details modelled for the Baseline (Step 1) Case

3.2 Building Energy Model: HOT2000

HOT2000 is a building energy simulation tool for low-rise residential buildings. HOT2000 calculations are based on the Modified Bin Method. The software is developed by Natural Resources Canada (NRCan) to support the EnerGuide Rating System, ENERGY STAR for New Homes, and R-2000 residential energy efficiency initiatives [7].

3.2.1 **Main energy characteristics of Step 1-5 houses:** Table 4 lists the input values for insulation, glazing and mechanical system types in that were used to achieve compliance with Steps 1 to 5. For Step 1 to 4 houses, two options for mechanical systems were considered. Option 1 uses natural gas for both space heating ang domestic hot water. Option 2 uses an electric air source heat pump for space heating and cooling and a natural-gas boiler for domestic hot water. The requirements for Step 5 house could only be met with a fully electric system for space heating and cooling and domestic hot water. Additionally, in order to achieve Step 5, the number of windows on the east facade had to be reduced by two.

Energy Efficiency Level	ESC 1	ESC 2	ESC 3	ESC 4	ESC 5
Roof Insulation	R 40 Loose Filled	R 56 Blown Cellulose	R 60 Blown Cellulose	R 60 Blown Cellulose	R 60 Blown Cellulose
Floor Insulation	R 31 Batt	R 31 Batt	R 31 Batt	R 31 Batt	R 31 Batt

Wall Insulation	R 20 Batt	R 28 Batt	R 28 Batt + 1″ EPS	R 28 Batt + 2″ EPS	R 28 Batt + 2″ XPS
Slab on Grade Insulation	2.5″ EPS	3″ EPS (RSI 2.32)	3″ XPS (RSI 2.85)	3″ XPS (RSI 2.85)	3″ XPS (RSI 2.85)
Glazing	USI: 1.77 SHGC: 0.53	USI: 1.43 SHGC: 0.40	USI: 1.35 SHGC: 0.40	USI: 1.20 SHGC: 0.40	USI: 1.00 SHGC: 0.40
Mechanical Systems	**Option 1**: Natural gas condensing heater + central split AC + natural gas condensing boiler for DSHW				**Primary:** Electricity; Air Source Heat Pump (heating & cooling) **Secondary:** Natural Gas Induced Draft Boiler
	Option 2: Air source heat pump (heating & cooling) + natural gas condensing boiler for DSHW				

Table 4: Input parameters for changes made in HOT 200 file

3.2.2 **Energy metrics obtained from HOT 2000**: Minor and major energy upgrades were made to the baseline energy model to meet the Energy Step Code requirements of each level. These changes were then modelled in Athena Impact Estimator to calculate the final embodied emissions. The final energy metric values obtained for each house have been listed below in Table 5 and 6 for both the options mentioned above in Table 4. Note that the intensity metrics were calculated based on the heated floor area of 204.39 m^2 (total floor area: 346.28 m^2) and the requirements of a Step5 house could only be met using a fully electrified heat pump.

Energy Metrics (Option 1)	**EnerGuide Reference House**	**ESC 1**	**ESC 2**	**ESC 3**	**ESC 4**	**ESC 5 (fully electrified)**
Air leakage rate (ACH_{50})	2.5	3.1	2.9	2.4	1.5	1
TEDI (kWh/m^2/yr)	54	53	42	36	26	16

% better ERS than < reference house	0%	19%	32%	37%	45%	43%
MEUI (kWh/m^2/yr)	108	87	73	68	59	62
Annual Electricity Consumption (GJ/year)	104.6	89.7	79.3	75.2	68.6	70.3
Electricity Consumption (kWh/yr)	8660.0	9277.7	9220.8	9019.8	9192.9	13117.7
Natural gas consumption (m^3/yr)	1699.8	1509.9	1304.1	1147.5	952.2	4.5
GHG (kg/yr)	3178	3028	2549	2323	1947	154
GHGI (kg/m^2yr)	16	15	12	11	10	1

Table 5: Energy metric values for Step 1- 4 houses using natural gas condensing heater + central split AC + natural gas condensing boiler for DSHW and fully electrified Step 5 house

Energy Metrics (Option 2)	**ESC 1**	**ESC 2**	**ESC 3**	**ESC 4**	**ESC 5 (fully electrified)**
Air leakage rate (ACH_{50})	3.1	2.9	2.4	1.5	1
TEDI (kWh/m^2/yr)	53	42	36	26	16
% better ERS than < reference house	28%	35%	37%	40%	43%
MEUI (kWh/m^2/yr)	67	58	56	51	62
Annual Electricity Consumption (GJ/year)	75	67.9	66	62.8	70.3
Electricity Consumption (kWh/yr)	15474.5	13931.3	13455.7	12660.2	13117.7
Natural gas consumption (m^3/yr)	502.7	461.7	454.1	446	4.5
GHG (kg/yr)	1145	1049	1029	1004	154
GHGI (kg/m^2yr)	6	5	5	5	1

Table 6: Energy metric values for Step 1-4 houses using air source heat pump (heating & cooling) + natural gas condensing boiler for DSHW and fully electrified Step 5 house

3.3 WBLCA: Athena Impact Estimator

There are multiple ways to conduct LCAs using various software that are available. For the purposes of this study, *Athena Impact Estimator* [8] was used to assess the embodied emissions of the building. Embodied emissions due to the mechanical systems were estimated separately, based on the methodology and data available in the thesis. [13]

3.3.1 **Whole-building LCA using the Assembly Method:** The existing building design was modelled in Athena Impact Estimator with the closest matches available in the software library. Only material assemblies listed in **Appendix B** were taken into consideration. Certain approximations and assumptions were made since the exact matches are not available in the software database. The detailed input summary table has been reproduced in **Appendix D**.

For the purpose of this study, the Assembly Method for WBLCA was used chosen over the Bill of Materials method because:

- Assembly Method is easier to comprehend for obtaining ball-park results
- This Assembly Method is more flexible and provides ease of making changes in the assembly and envelope options by selecting the closest match from the available options

However, there were certain limitation in the software and the Assembly Method, which have been discussed below.

3.3.2 **Approximations and Assumptions:** Certain assumptions had to be made to approximate the actual design and construction details as the available options in Athena Impact Estimator. Key material assumptions are listed below:

- Strength of concrete is 3600 psi, but it is assumed as 4000 psi as the closest match found in the software
- Floor assembly did not provide an option to input insulation material. Hence, the insulation in floor was input as "extra material".
- R 30 batt insulation has been added for floor assemblies as the closest match available, instead of R 28 batt insulation which was used in the baseline design.
- Details of asphalt roof shingles with perforated roofing and felt were excluded (details not available)
- Athena Impact Estimator software does not provide an option to input glazing properties of the windows (i.e. U-value, SHGC). All windows were modeled as double-glazing with vinyl clad wood window frame.
- The insulation options available for floor and roof were only in multiples of 10 (R 20, R 30, R 40) for batt insulation and ranges (R 10-20, R 21-30, R 31-R 40) for blown cellulose insulation. Hence, to add intermediate values for insulation such as R 22 or R 24 batt, closest match was

selected (R 20) as the material option and the thickness of was selected as per the actual insulation.

3.3.3 Insulation values in Athena Impact Estimator: The changes mentioned in table 7 were made in the LCA model to assess the higher-Step houses. The assembly options available in the HOT2000 and ATHENA are not the same. Hence, the closest approximation was made to pick from the available material options.

Energy Efficiency Level	ESC 1	ESC 2	ESC 3	ESC 4	ESC 5
Roof Insulation	(R 31-40) 15″ Loose Fill	R 56 Blown Cellulose 15.5″	R 60 Blown Cellulose 16.5″	R 60 Blown Cellulose 16.5″	R 60 Blown Cellulose 16.5″
Floor Insulation	R 30 Batt	R 30 Batt	R 30 Batt	R 30 Batt	R 30 Batt
Wall Insulation	R 20 Batt 6″	R 30 Batt 7.7″	R 30 Batt 7.7″ + 1″ EPS	R 30 Batt 7.7″ + 2″ EPS	R 30 Batt 7.7″ + 2″ XPS
Slab on Grade Insulation	2.5″ EPS	3″ EPS	3″ XPS	3″ XPS	3″ XPS

Table 7: Input parameters for changes made in Athena Impact Estimator for all the Step Code Level houses

3.3.4 The "Hybrid" Method: Based on discussions with several industry experts and research, it was determined that the global warming potential values for insulation materials (especially EPS and XPS) are significantly underestimated in the Athena Impact Estimator's database.

To get more precise results for the overall embodied emissions, a hybrid method was adopted which included separate calculations for the embodied emissions of the structure and the insulation materials. For the global warming potential of the structure, a "stripped-down" model was constructed in Athena Impact Estimator using the assembly method. This "stripped-down" model had structural assemblies same as that of the existing building design, but without any insulation material. The results obtained from the "global warming potential" report generated by the software gibe as the total embodied emissions of the structure.

The LCA models made for each house as per the inputs detailed in section 3.3.3, table 7 were used to obtain the total quantity of the insulation materials used in the house. These values were generated in terms of mass value (ton) from the "Bill of Materials" report generated by the software for key insulation materials. Industry EPDs and compilations were then used to calculate the total global warming potential from insulation types specifically. Table 8 shows a sample calculation for the Step 1 house.

Material	Mass Value (1") Ton	Mass Value (Kg)	Density (kg/m^3)	Resistivity (R/inch)	Resistivity (RSI/m)	Emission factor from EPDs ($kgCO_2/m^2/RSI$)	GWP
Blown Cellulose R40 Loose filled	0.4765	476.5	48	3.7000	25.53	0.70	177.40
Expanded Polystyrene 2.5" R10	0.2282	228.2	46.4	3.9000	26.91	2.49	329.54
FG Batt R 20	0.5725	572.5	16	3.3000	22.77	4.64	3780.38
FG Batt R30 Walls	0.0089	8.9	16	3.3000	22.77	4.64	58.76
Total GWP from Insulation Materials ($kgCO_2$)							4346.10

Table 8: Sample "hybrid" method calculation for insulation materials of the Step 1 house

The values obtained for the structure (from the stripped-down model) and insulation (from the hybrid method) were added to obtain the overall global warming potential of the houses. Details of the final calculations for all houses can be found in **Appendix E.**

3.3.5 **Mechanical systems:** For high-level calculations of the embodied emissions of the mechanical systems an existing dissertation [10] was used. This dissertation expands on preliminary studies of embodied carbon in building systems in commercial office buildings by providing a new simplified method to assess the embodied emissions across the life cycle of heating, ventilation, air conditioning and refrigerant systems. This simplified method separates the embodied emissions of mechanical systems to three components: mechanical equipment, distribution systems and refrigerants, as shown in the equation below.

$$\text{Total GWP } [kgCO_2 \text{ eq. }/m^2] = GWP_{equipment} + GWP_{distribution} + GWP_{refrigerant} \quad (1)$$

GWP of equipment and distribution: Equation 2 shows the model for the GWP of equipment, where mechanical equipment quantities (MEQs) represent the total weight of unitary equipment such as boilers or chillers, that are typically a composite of different materials. Similarly, in Equation 3 the distribution material quantities (DMQs) represents a single material that can be quantified individually (copper piping, galvanized sheet metal).

$GWP_{equipment}$ [$kgCO_2$ eq./m^2] = MEQ [kg_m /m^2] * ECC_e [$kgCO_2e/kg_m$] (2)

$GWP_{distribution}$ [$kgCO_2$ eq./m^2] = DMQ [kg_m /m^2] *ECC_d [$kgCO_2e/kg_m$] (3)

The typical ranges of material quantities (kg/m^2) and embodied carbon ($kgCO_2/m^2$) given in [10] were used over a lifespan of 15 years for the mechanical system types mentioned in Table 10. Results are shown in Table 9 and 10. See **Appendix E** and **Appendix G** for further details.

Equipment	**Weight (kg)**	**Heated Floor Area (m^2)**	**MEQ (kg/m^2)**
Central split system	53.9775	204.39	0.26
Viessman Heating Boiler	36	204.39	0.18
Total MEQ			**0.44**
Equipment	**Weight (kg)**	**Heated Floor Area (m^2)**	**DMQ (kg/m^2)**
PEX Piping for in-floor hydronic heating loops	55.9	204.39	0.27
Ducting for Exhaust Equipment	46.8	204.39	0.23
Total DMQ			**0.49**

Table 9: MEQ and DMQ calculations

The final values obtained for each of the equations have been listed below:

Building Type	**System Type**	**MEQ** [kg/m^2]	**ECC_e** [$kgCO_2$ eq. /kg_m]	**Total equip.** [$kgCO_2$ eq. /m^2] for 15 years	**Total equip.** [$kgCO_2$ eq. /m^2] for 60 years
Standard	Packaged rooftop heat pump	0.44	3.16	1.264	5.05
		DMQ [kg/m^2]	**ECC_d** [$kgCO^2$eq./kg_m]	**Total dist.** [kgCO2 eq./m^2] for 15 years	**Total dist.** [kgCO2 eq./m^2] for 60 years
		0.49	2.72	1.35	5.4

Table 10: Total GWP from equipment and distribution

Refrigerant: Section 6.1 of the City of Vancouver guideline for rezoning [11] lists the following equation for GWP of refrigerants:

$GWP_{refrigerant}$ [$kgCO_2$ eq./m^2a] = [GWP_r * Rc * (0.02 * L + 0.1)] / (L * A) (4)

The parameters used in Equation 4 and the results are shown in Table 11.

GWP (R410a)	$kgCO_2/kg$	1890
R	kg	3.38
Lifetime	a	15
Leakage rate	-	0.02
End of life leakage	-	0.1
A	m^2	204
Refrigerant charge	lb/TON	2.5
Capacity	TON	3.0
E_r (annual)	$kgCO_2/m^2/a$	0.83
E_r x 60 (lifetime)	$kgCO_2/m^2$	50.04

Table 11: Total GWP from refrigerant as per section 6.1 of CoV guidelines for rezoning over a lifespan of 60 years

The total GWP from equipment, distribution and refrigerant was estimated at 60.49 $kgCO_2$ eq./m^2 for a period of 60 years and the heated floor area of 204.39 m^2. Note that the same figure was used for all the Step Code houses.

Total GWP (HVAC) = 5.05 + 5.4 + 50.04 = 60.49 $kgCO_2$ eq. /m^2

4. Results and Discussion

4.1 Embodied and operational emissions

4.1.1 **Embodied emissions (Athena vs Hybrid Method): Figure 6** shows the embodied emissions of structure and insulation using the two different methods: Assembly Method and Hybrid Method for Step 1-5 houses over a period of 60 years. The difference in values increases considerably especially in higher Step Code houses because these houses use more amount of XPS insulation.

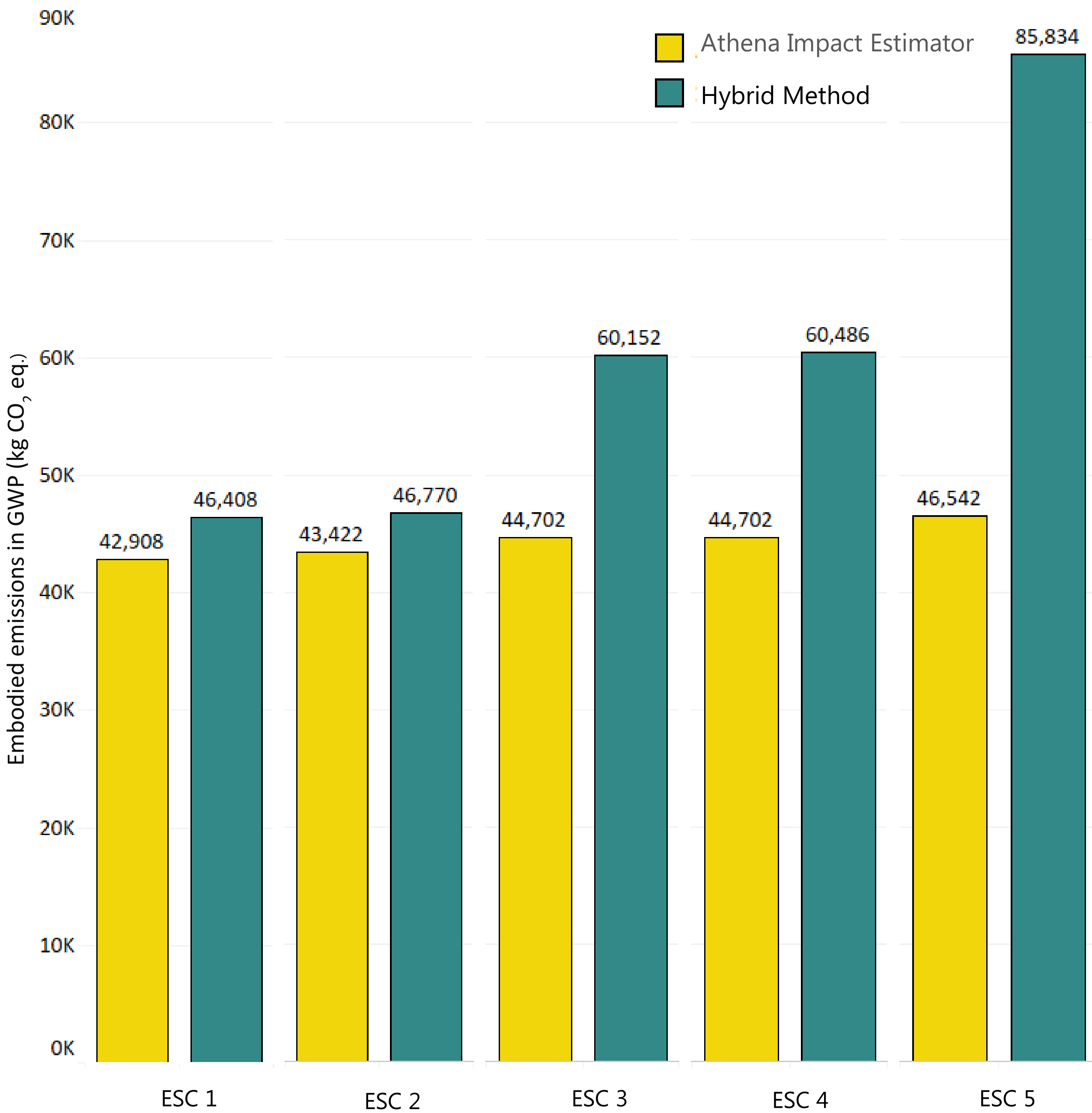


Figure 6: Embodied emissions (structure + insulation) of Step 1-5 houses over a period of 60 years using Assembly and Hybrid Methods

4.1.2 Total embodied vs operational emissions: Figure 7 shows the embodied and operational emissions of the studied Step 1-5 houses as per **Appendix F**. For Steps 1-4, two scenarios for space heating equipment were considered: natural-gas boilers and air-source heat pumps. The Step 5 house is fully electrified (air-source heat pump for air conditioning and water heating). It was observed that the operational emissions are much lower if the house uses an air source heat pump. The embodied emissions from insulation increase considerably as we go from Step 1 to 5.

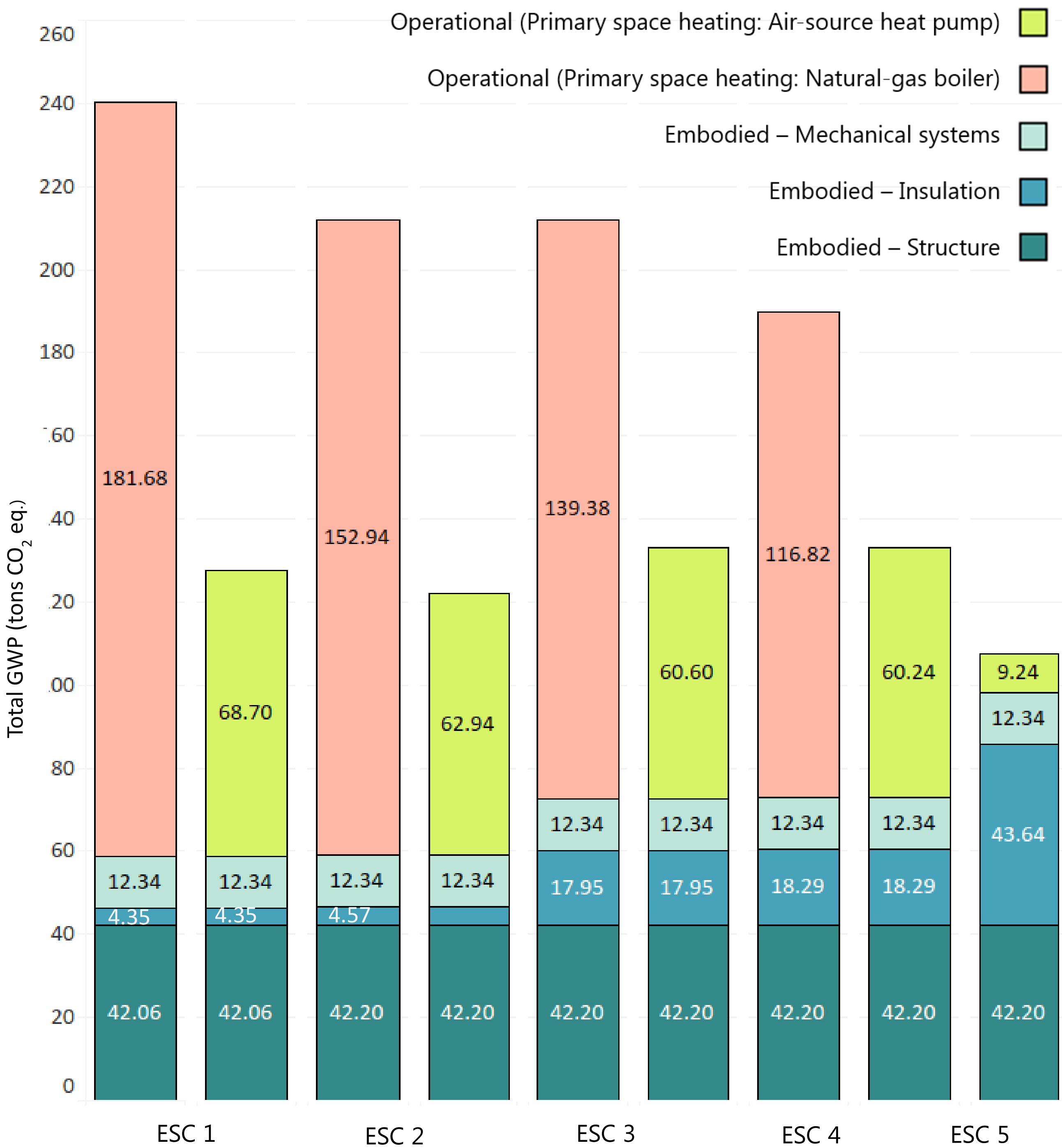


Figure 7: Total emissions of Step 1-5 houses over a period of 60 years

4.1.3 **Normalised embodied vs operational emissions: Figure 8** shows the total embodied and operational emissions of the Step 1-5 houses normalized by the heated floor area (204.4 m^2). Note the operational emissions for Step 2, 3 and 4 houses are the same. This is because the space heating is virtually decarbonized with the use of electricity as the primary fuel source and by changing the space heating load, the total emissions from water heating does not change.

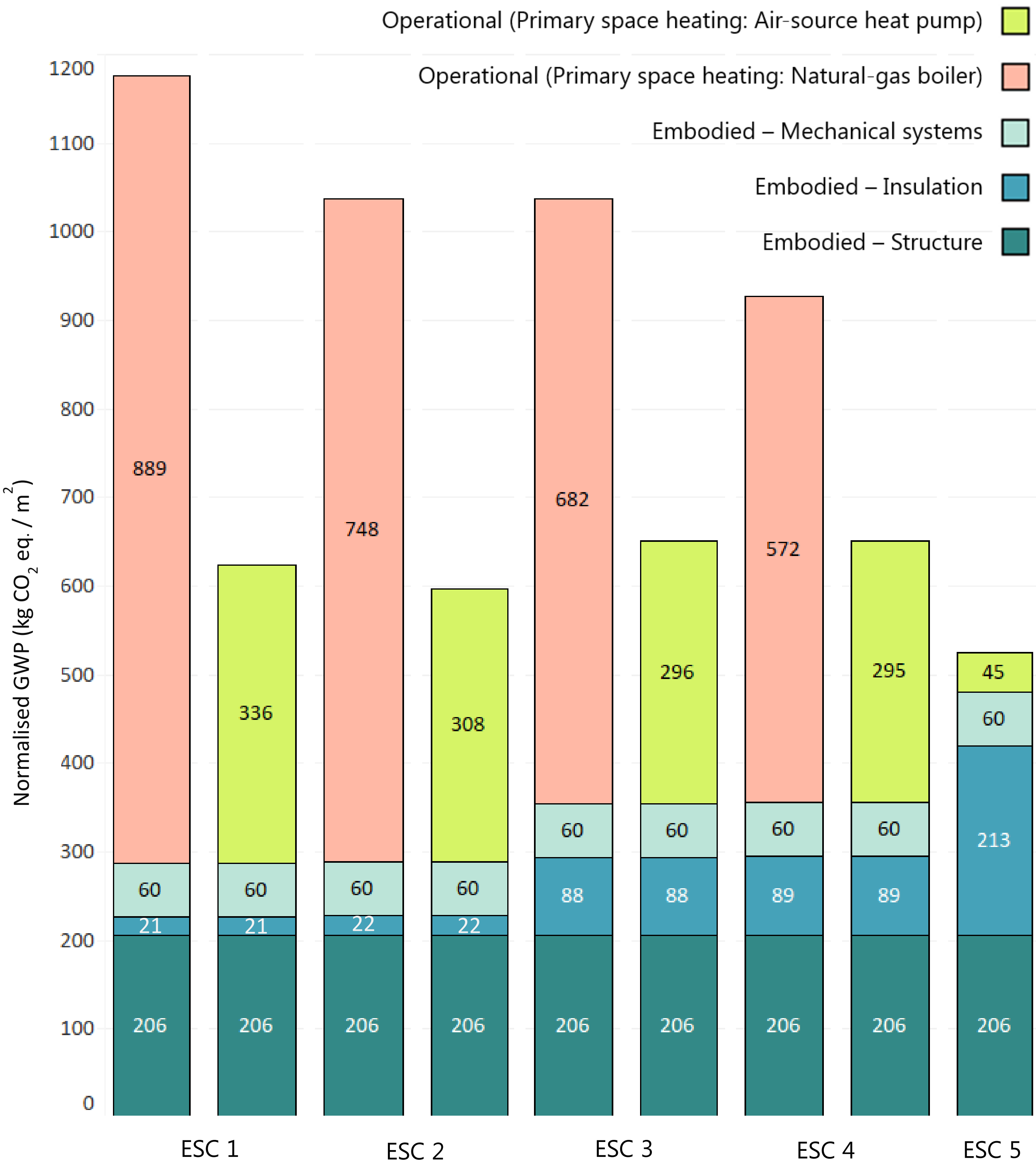


Figure 8: Total emission intensity (per unit heated floor area) of Step 1-5 houses over a period of 60 years

4.1.4 Embodied emissions from structure, insulation and mechanical systems: **Figure 9** shows the contribution of the structure, insulation materials and mechanical systems to the embodied emissions at the two ends of the Energy Step Code ladder: Step 1 and Step 5. Note the significant increase in both the absolute and relative contribution of the insulation materials to the embodied emissions when comparing the Step 1 and Step 5 houses.

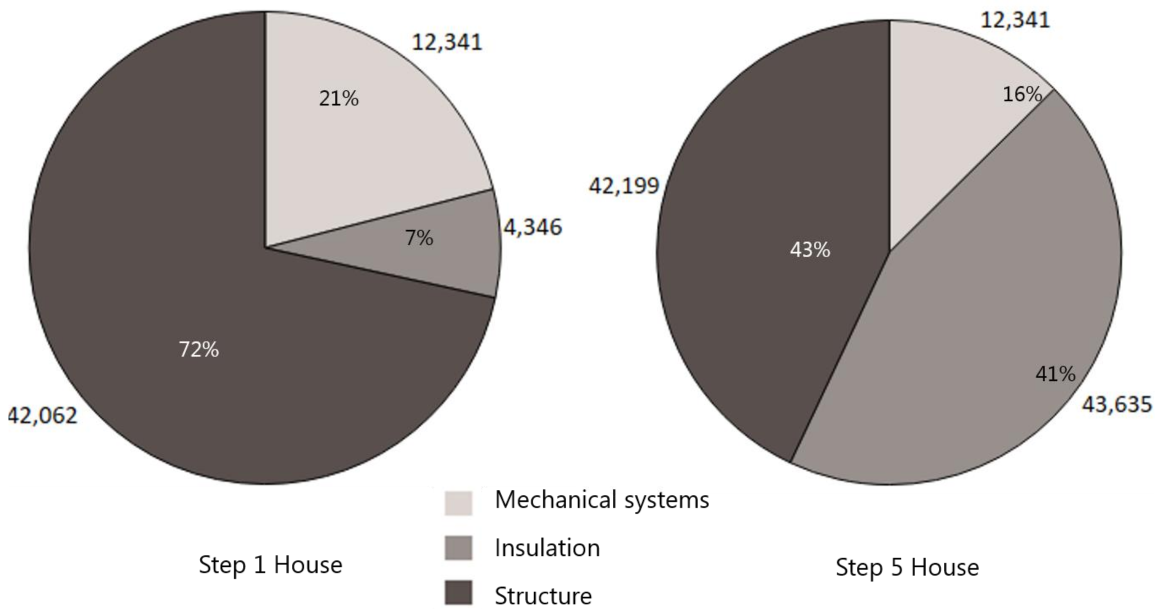


Figure 9: Breakdown of embodied emissions [kg CO_2 eq.] for Step 1 and Step 5 houses (60 yrs.)

4.1.5 Embodied emissions from various components of mechanical system: **Figure 10** shows the contribution of the various components of the mechanical systems to the embodied emissions. Note the very large contribution of the refrigerant.

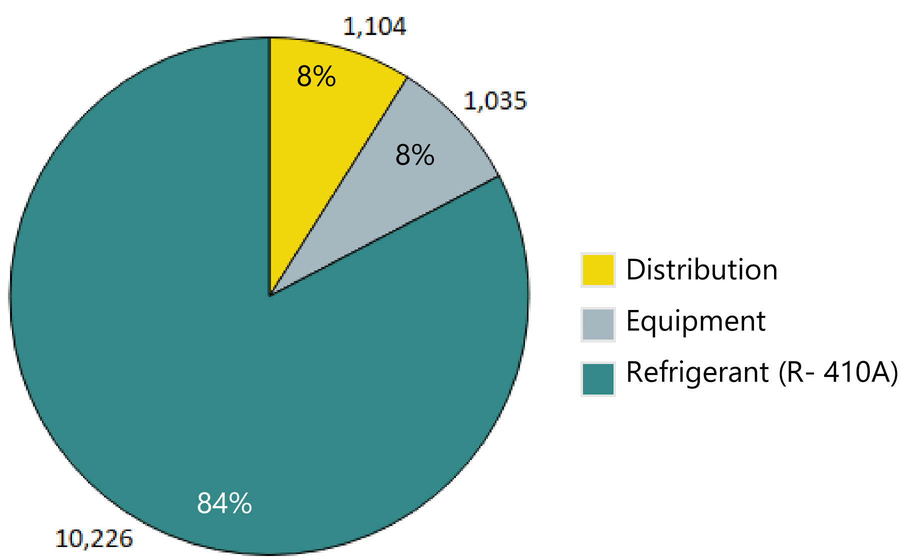


Figure 10: Breakdown of embodied emissions of mechanical systems emissions [kg CO_2 eq.] (60

4.1.6 Embodied emissions of various envelope assemblies: **Figure 11** shows the embodied effects from individual assemblies, i.e. walls, roof, and foundation. Floors, beams and columns were excluded from the presentation as no changes were made to these assemblies for Step 1-5 houses.

The maximum change is observed in wall assemblies as the global warming potential increases from 17,429 kg CO_2 eq. in the baseline (Step 1) case to 20,055 kg CO_2 eq. in the Step 5 house. Note that this figure includes contribution from both external and internal walls, however, changes in insulation and structure were made only in the external walls. Major modifications were changes in insulation, changing wood stud size from 2″ x 6″ to 2″ x 8″ and removing two windows on the eastern façade for Step Code 5 house. The change in foundation is considerably less, as the global warming potential increases from 18,703 kg CO_2 eq. in the baseline case to 19,446 kg CO_2 eq. in the Step 5 house, causing a difference of about 743 kg CO_2 eq. Similarly, the change in roof assembly is lesser as the difference observed is of about 266 kg CO_2 eq. between the baseline case and the Step 5 house.

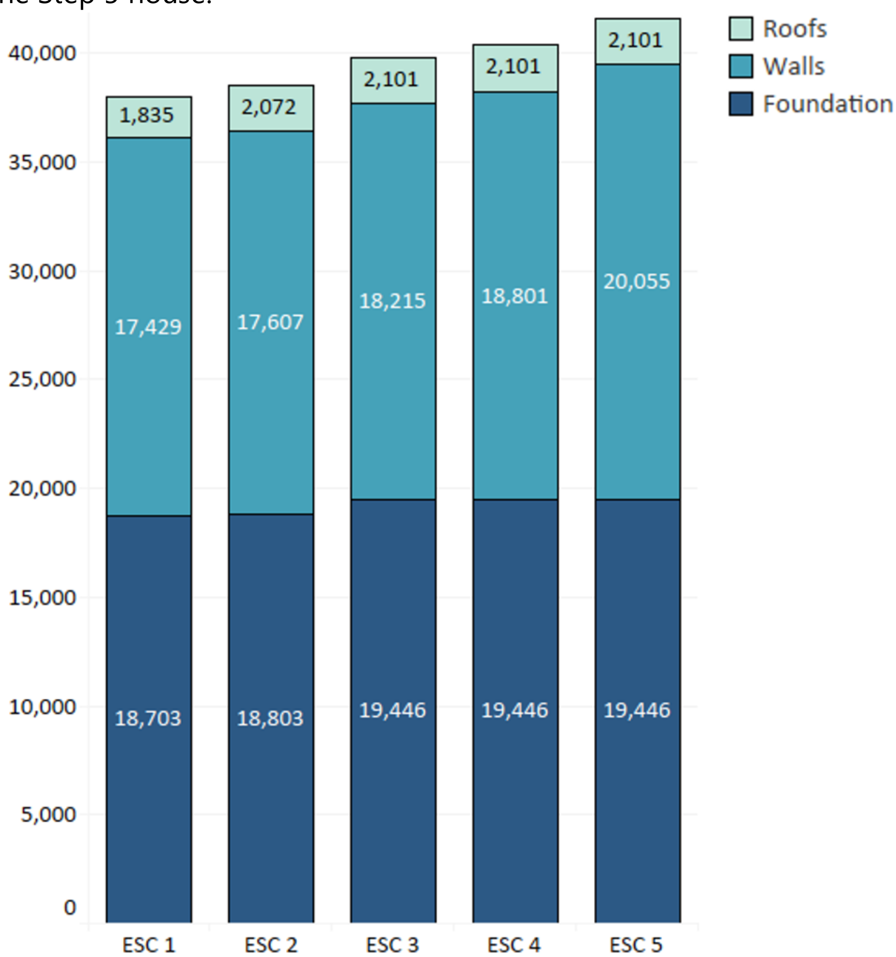


Figure 11: Total embodied emissions as per the “assembly group effects” results obtained from Athena Impact Estimator for foundation, walls, floor over a period of 60 year

4.2 Hot Spots of the Structure

The figure below shows the percentage component of the embodied emissions of the structure of the baseline building design (Step 1) and the highest-performing upgraded design (Step 5). Note that these results are from the "assembly group effects" report generated by Athena Impact Estimator and hence includes the insulation materials as modelled in the software, GWP of which is underestimated.

It can be seen that foundations account for almost 43% of the total global warming potential as they are made of concrete which has the highest embodied emissions among the key building materials. The walls have significant impact too, about 40% owing to the amount of insulation used in walls.

From the comparison between the two charts, it can be observed that the change in distribution of global warming potential over the structural assemblies is very minimal. The contribution of foundation decreases by 1.7% only as we move to the Step Code Level 5 house. Whereas the embodied emissions from wall increases by 2.5% in a Step Code Level 5 house. Note that the total embodied emissions of two the houses are different, as shown in Section 4.1.

Energy Step Code level 1 (baseline case) **Energy Step Code level 5**

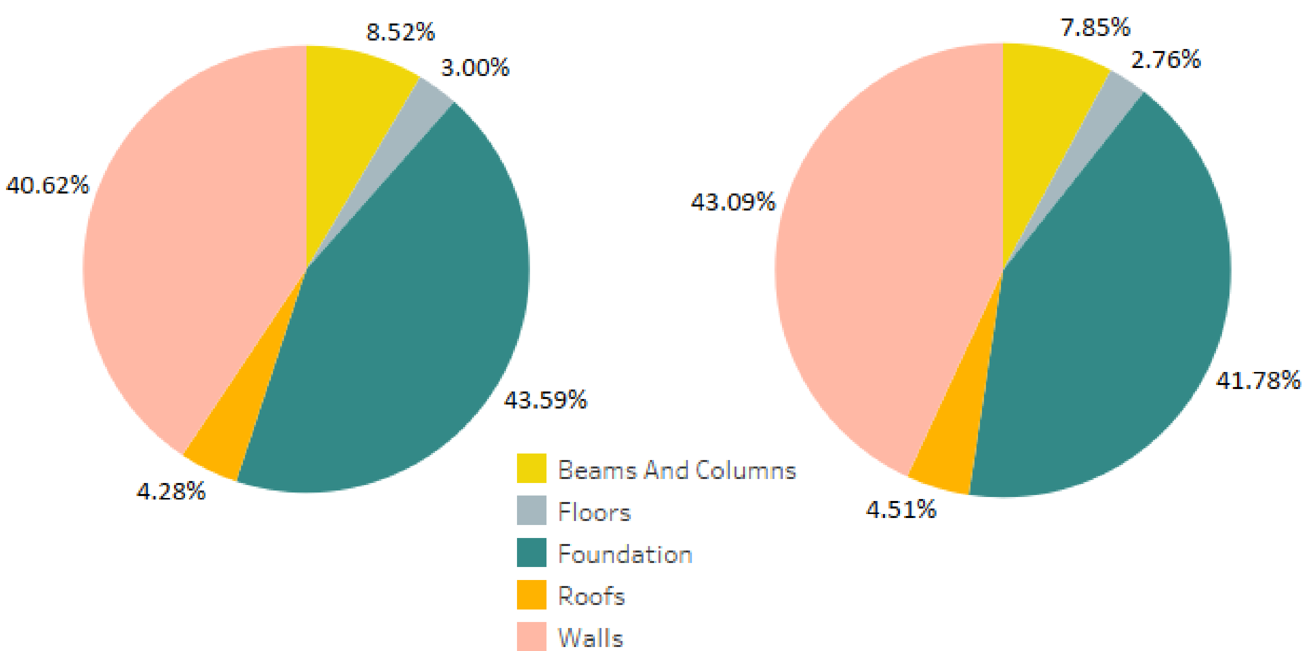


Figure 12: The distribution of the embodied emissions of the "stripped" house for the Step 1 (LEFT) and Step 5 (RIGHT) cases

5. Summary of Results

Embodied and operational emissions – As we go up the Step Code ladder, the embodied emissions increase by only 5.5% from Step Code 1 to Step Code 5 house, but the operational emissions become almost negligible in a Step 5 house. Nevertheless, for a Step 5 house to be truly net-zero, embodied emissions which account for almost 90% of the total emissions in the most energy efficient house must also to be addressed.

Embodied emissions from structure, insulation and mechanical systems – The contribution of structure towards the total global warming potential remains between 70% to 74% in Step 1 to Step 5 house while mechanical systems account for around 24% of the total global warming potential. Although the contribution of insulation is as little as 1.5% in the Step 1 house, it increases to more than 7% at Step 5.

Insulation material – The case studies presented here entail uses significant amounts of XPS which is a highly carbon-intensive material. The use of XPS was intentional to represent realistic practices in the industry and demonstrate the potential increase of the embodied emissions due to insulation. Compliance with various Steps could have been achieved using other insulation materials.

Operational emissions from various mechanical systems – Compliance with the Energy Step Code can be achieved with various mechanical systems, each having different operational emissions. The fuel source and amount of refrigerant used for these systems will have significant impact on the overall embodied emissions of the HVAC systems. We saw that the use of electricity for space heating and cooling considerably reduced the total GWP, while the use of natural gas for domestic hot water still had considerable impact on the total GWP. The Step 5 house is fully electrified which brings the total operational emissions to nearly net-zero; yet, the house has significant embodied carbon emissions.

Sensitivity analysis – Focusing on the contributions of the structural assemblies, foundation and walls are the key hotspots, accounting for about 85% of the total global warming potential, when contribution from mechanical system is excluded. The amount of concrete used for the foundation and the insulation in external walls have a major effect on the overall global warming potential. Thus, these two components should be handled sensitively while making material and design choices in the initial planning phase of designing the house.

The maximum change was observed in the wall assemblies, 15% from baseline to the Step 5. This is followed by the change in contribution from the roof which is about 14.5%. The percentage change in foundation is considerably lower, about 4%.

Discrepancy in results – There are ambiguities about the relevance and accuracy of some of the assumptions and values used in the Athena Impact Estimator. To cross check the results, an alternative approach was used where the ATHENA estimates for the contribution of the structure were retained, but the contribution of insulation materials were estimated based on material quantities and the environmental product declaration. It was observed that the final results generated by Athena Impact Estimator could be underestimated by as much as 15% for the Step 1 house and 30% for the Step 5 house.

6. Recommendations

Based on the results summarized above, the following observations and recommendation are made:

- While the Energy Step Code is not very effective in reducing the operational emissions of buildings, it can even have the unintended consequence of *increasing* the embodied emissions of buildings. The trade-off between the decrease in the operational emissions and the increase in the embodied emissions should be more closely studied.
- A building is truly carbon-neutral only when both its embodied and operational emissions have been eliminated. As the operational emissions of buildings are reduced, the contribution of the embodied emissions become even more significant. In a Step 5 single-family dwelling, for instance, the embodied emissions can account for up to 60% of the total emissions of the house.
- Due to the increased amounts of insulation used, embodied emissions of a Step 5 house can be significantly higher the embodied emissions of a comparable Step 1 house. This can be mitigated by attention to *Environmental Product Declarations*, and specifically the embodied global warming potential, of construction materials and use of natural and low-carbon insulations.
- Refrigerants are the primary source of embodied emissions of mechanical systems. With the increasingly popularity of heat pumps (due to their low operational emissions in BC), more attention must be paid to the embodied emissions of refrigerants.
- It is important to collect data on the embodied emissions of buildings. Such data can and should inform policy at the municipal, provincial and federal levels. The data can be reported in the form of embodied and operational carbon emissions for the existing design as well as other options which include different mechanical systems and materials for insulation specifically. It is useful to report the embodied and operational greenhouse gas emissions on both total and normalized (per unit floor area) bases.

7. Way Forward

- Similar analysis for larger buildings such as multi-unit residential building, offices, commercial and public buildings.

- Trying alternate tools and methodologies other than Athena Impact Estimator for carrying out WBLCA which can give more reliable results.

- Trying out various insulation options and materials that could be used to meet the targets of the Energy Step Code and study their impact on embodied carbon emissions.

- Assessing material quantities and global warming potential for equipment, distribution and refrigerant more precisely and separately for each Step Code house.

- Experimenting with different mechanical systems for Energy Step Code compliance such as air-to-water and ground-source heat pump, electric-resistance heating, hybrid mechanical systems, and studying their effects on embodied and operational carbon emissions.

8. References

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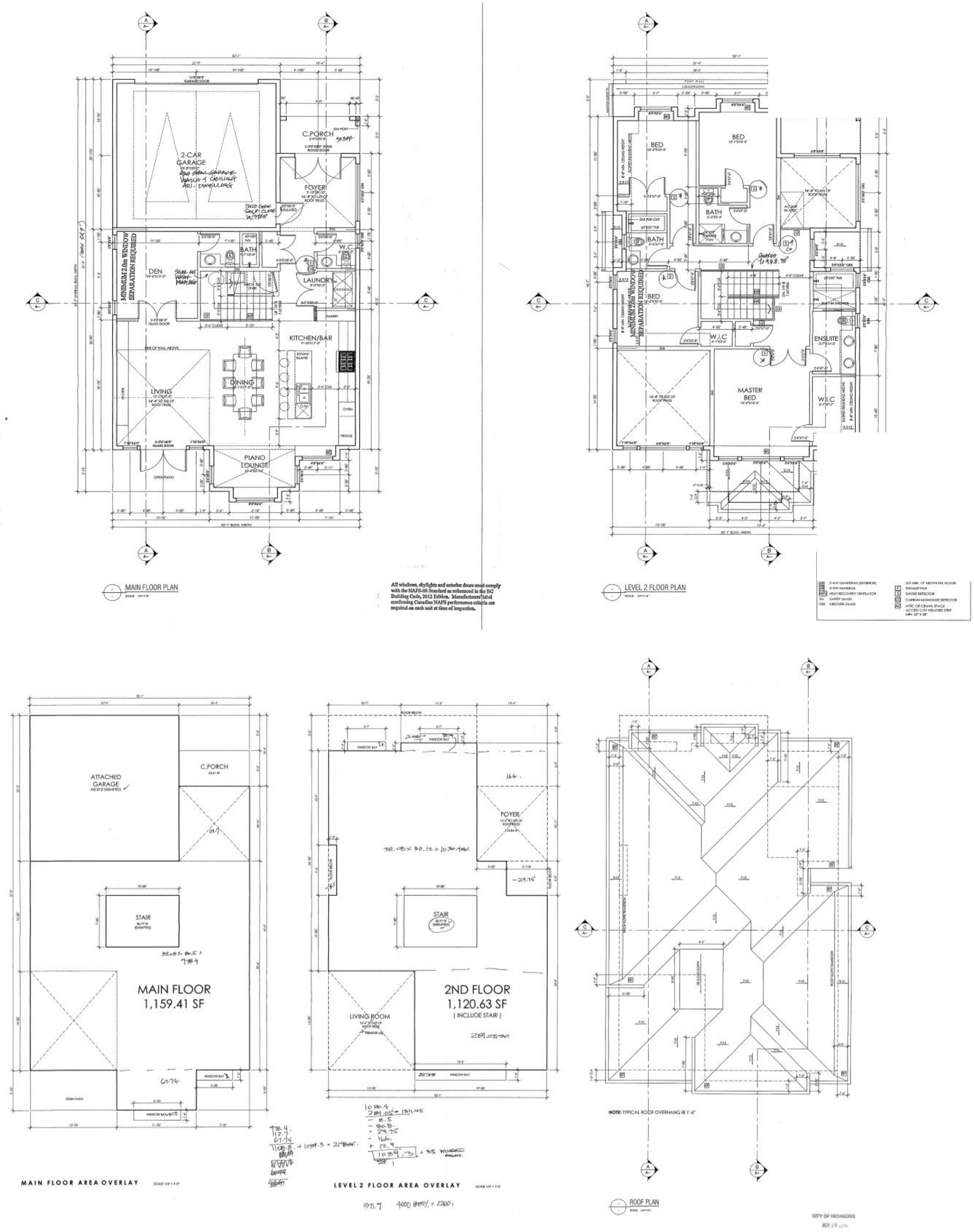
9. Appendices

9.1 Appendix A - Construction assemblies and envelope details

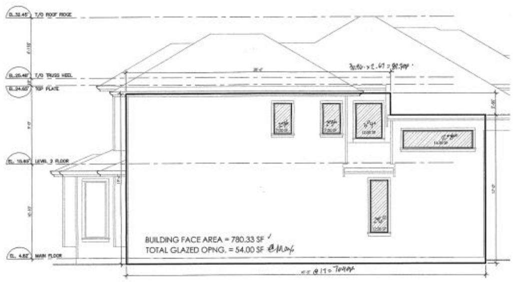
Construction Assembly		**Description**
Exterior Walls	W1A	Exterior Wood Framed Wall with Stone Veneer
	W1B	Exterior Wood Framed Wall with Fibre Cement
	W3	Exterior Wood Framed Wall with Stucco
Interior Walls	W2	Interior Wood Framed Wall at Garage
	W4	Typical Interior Wood Framed Wall
Roof	R1	Typical Truss Roof with 24" O.C. Engineered Roof Truss with 14.5" Glass Fibre Loose Fill Insulation
	R2	Typical Truss Roof with 24" O.C. Engineered Roof Truss with no insulation
Floor	F1	4" Slab on Grade at a Heated Space with R12 XPS insulation
	F2	4" Concrete Slab with 10 Mil UV Poly over undisturbed soil
	F3	Cantilevered Wood Framed Bay over Exterior Space
	F4	Wood Framed Floor over unconditioned garage
	F5	Typical Interior Wood Framed Floor
	F6	Typical Interior Wood Framed Floor over unconditioned garage
Foundation and Footing	SF1	Strip Footing 1
	SF2	Strip Footing 2
	F1	Pad Footing 1
	F2	Pad Footing 2
Columns and Beams		LVL / PSL
Doors		Fibreglass polystyrene core
Windows		Vinyl Clad Wood Window Frame Double Pane with Argon Filling

9.2 Appendix B - Drawings



(WEST) FRONT ELEVATION SCALE 1/4" = 1'-0"

(EAST) REAR ELEVATION SCALE 1/4" = 1'-0"



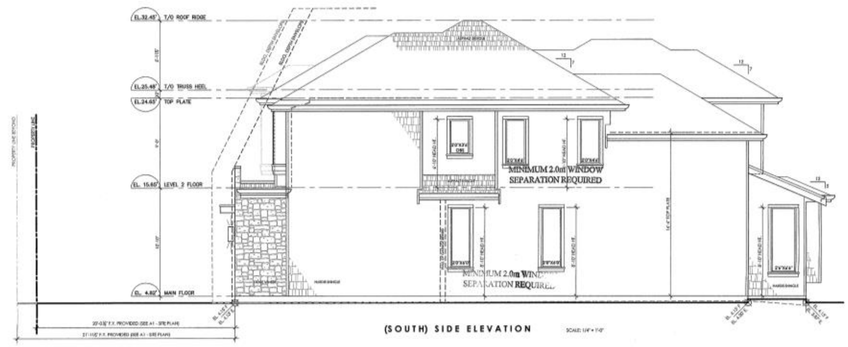
NORTH BUILDING FACE KEY PLAN SCALE 1/4" = 1'-0"

SOUTH BUILDING FACE KEY PLAN SCALE 1/4" = 1'-0"

SPATIAL CALCULATION

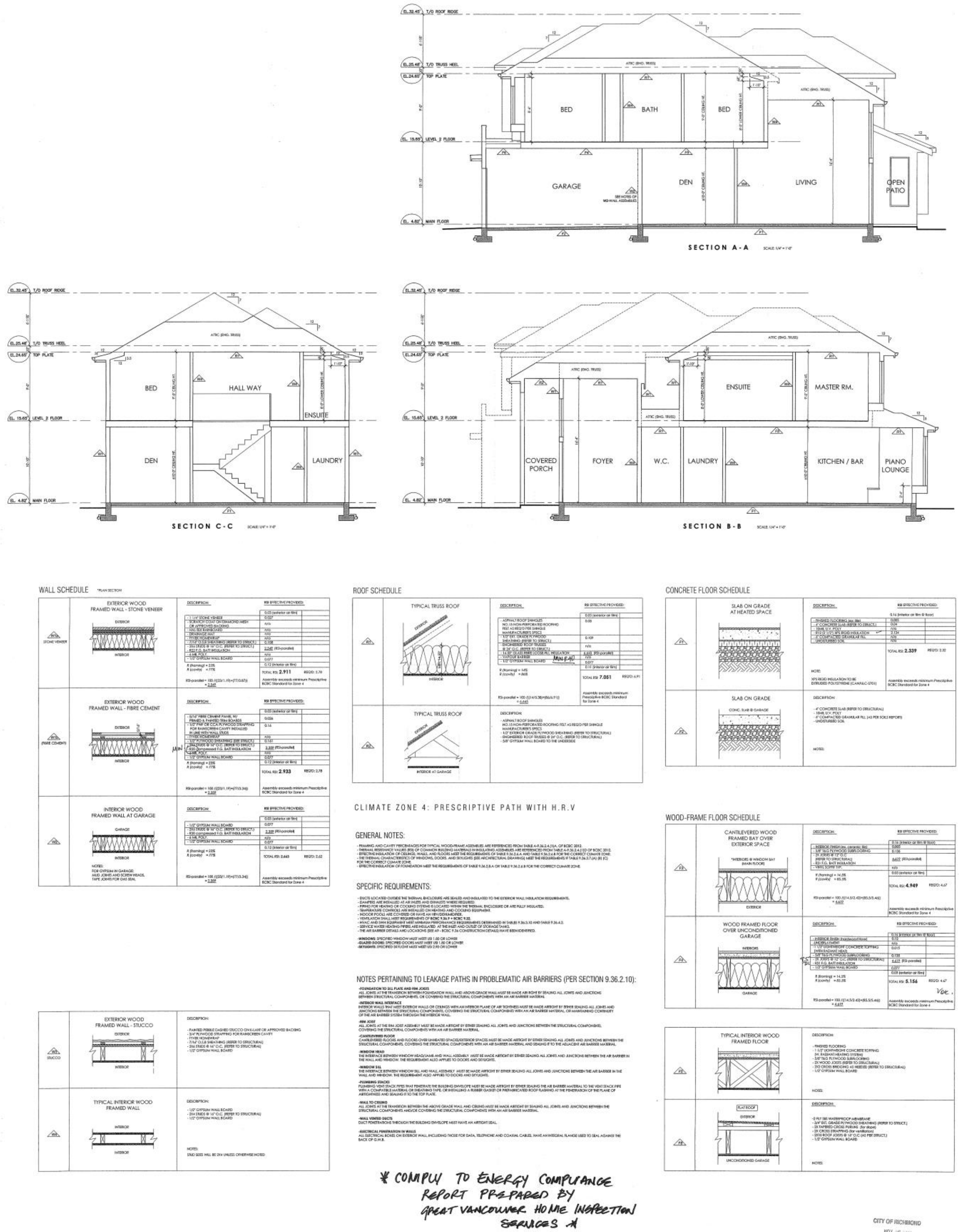
	NORTH (L.D)	SOUTH (L.D)
AREA OF BUILDING FACE	780.33 SF (72.49 SM)	707.81 SF (65.76 SM)
LIMITING DISTANCE	3.98 (1.21 m)	3.90 (1.21 m)
SPRINKLERED	N/A	
% GLAZING PERMITTED	7.69%	7.89%
% GLAZING PROPOSED	54.0 SF (6.92%)	49.0 SF (6.92%)
FIRE RESISTANCE RATING (REQUIRED)	NOT REQUIRED	NOT REQUIRED
TYPE OF CONSTRUCTION (REQUIRED)	COMBUSTIBLE OR NONCOMBUSTIBLE	COMBUSTIBLE OR NONCOMBUSTIBLE
TYPE OF CONSTRUCTION (PROPOSED)	COMBUSTIBLE	COMBUSTIBLE
TYPE OF CLADDING (REQUIRED)	COMBUSTIBLE OR NONCOMBUSTIBLE	COMBUSTIBLE OR NONCOMBUSTIBLE
TYPE OF CLADDING (PROPOSED)	NONCOMBUSTIBLE	NONCOMBUSTIBLE

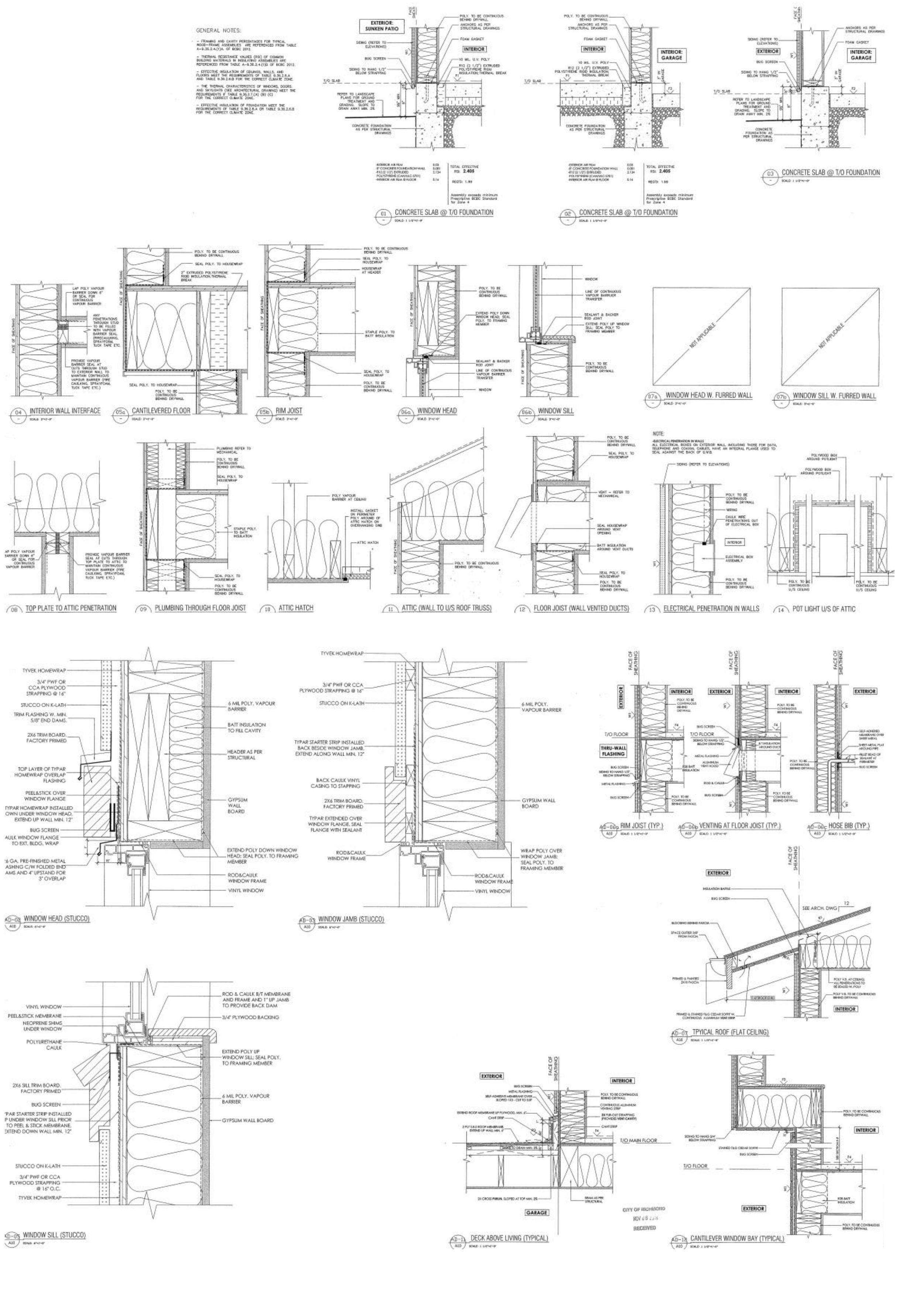
CALCULATIONS CONFORM TO B.C.B.C. TABLE 9.10.15.4



(SOUTH) SIDE ELEVATION SCALE 1/4" = 1'-0"

(NORTH) SIDE ELEVATION SCALE 1/4" = 1'-0"


SECTION A-A
BED
BATH
BED
GARAGE
DEN
LIVING
OPEN PATIO
SECTION C-C
BED
HALL WAY
ENSUITE
DEN
LAUNDRY
SECTION B-B
ENSUITE
MASTER RM.
COVERED PORCH
FOYER
W.C.
LAUNDRY
KITCHEN / BAR
PIANO LOUNGE
WALL SCHEDULE
ROOF SCHEDULE
CONCRETE FLOOR SCHEDULE
WOOD-FRAME FLOOR SCHEDULE
CLIMATE ZONE 4: PRESCRIPTIVE PATH WITH H.R.V
GENERAL NOTES:
SPECIFIC REQUIREMENTS:
NOTES PERTAINING TO LEAKAGE PATHS IN PROBLEMATIC AIR BARRIERS (PER SECTION 9.36.2.10):
* COMPLY TO ENERGY COMPLIANCE REPORT PREPARED BY GREAT VANCOUVER HOME INSPECTION SERVICES *
CITY OF RICHMOND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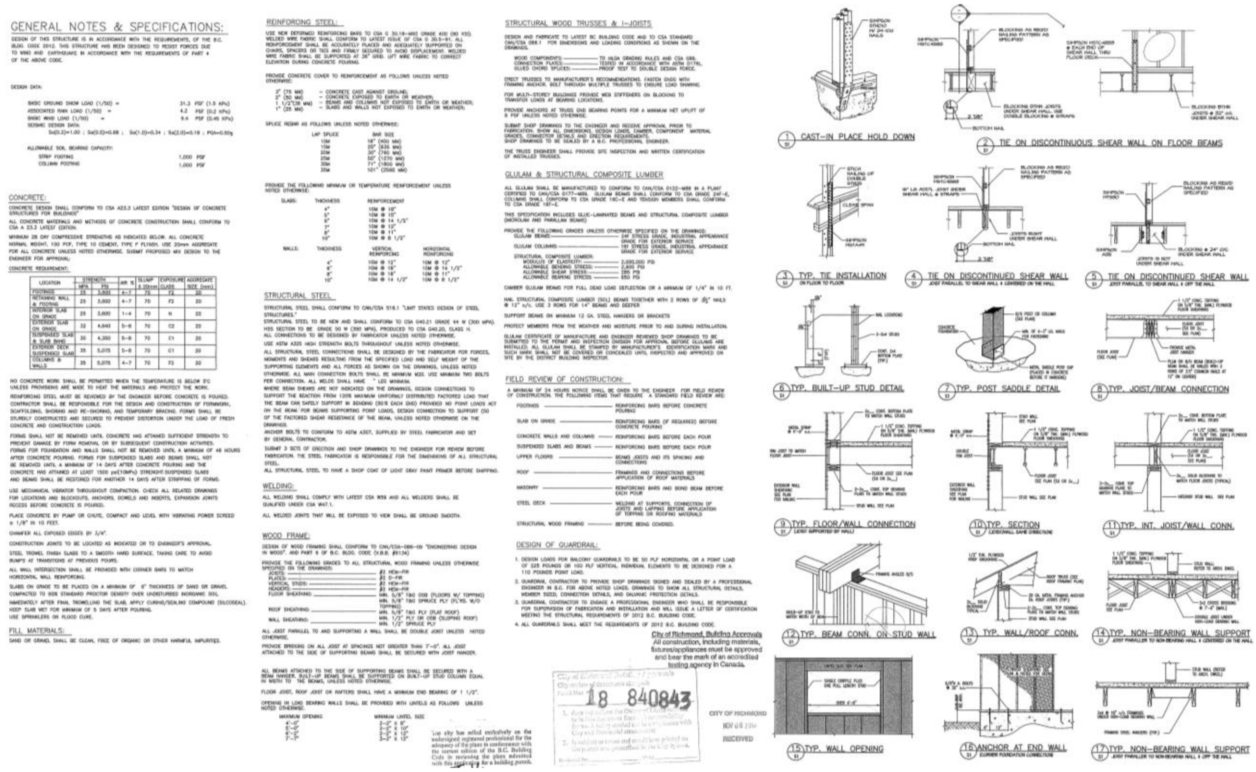
CONCRETE SLAB @ T/O FOUNDATION
CONCRETE SLAB @ T/O FOUNDATION
INTERIOR WALL INTERFACE
CANTILEVERED FLOOR
RIM JOIST
WINDOW HEAD
WINDOW SILL
WINDOW HEAD W. FURRED WALL
WINDOW SILL W. FURRED WALL
TOP PLATE TO ATTIC PENETRATION
PLUMBING THROUGH FLOOR JOIST
ATTIC HATCH
ATTIC (WALL TO U/S ROOF TRUSS)
FLOOR JOIST (WALL VENTED DUCTS)
ELECTRICAL PENETRATION IN WALLS
POT LIGHT U/S OF ATTIC
WINDOW HEAD (STUCCO)
WINDOW JAMB (STUCCO)
RIM JOIST (TYP.)
VENTING AT FLOOR JOIST (TYP.)
HOSE BIB (TYP.)
TPYICAL ROOF (FLAT CEILING)
WINDOW SILL (STUCCO)
DECK ABOVE LIVING (TYPICAL)
CANTILEVER WINDOW BAY (TYPICAL)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CONCRETE:
FILL MATERIALS:
REINFORCING STEEL:
STRUCTURAL STEEL:
WELDING:
WOOD FRAME:
STRUCTURAL WOOD TRUSSES & I-JOISTS
GLULAM & STRUCTURAL COMPOSITE LUMBER
FIELD REVIEW OF CONSTRUCTION:
DESIGN OF GUARDRAIL:
CAST-IN PLACE HOLD DOWN
TIE ON DISCONTINUOUS SHEAR WALL ON FLOOR BEAMS
TYP. TIE INSTALLATION
TIE ON DISCONTINUED SHEAR WALL
TIE ON DISCONTINUED SHEAR WALL
TYP. BUILT-UP STUD DETAIL
TYP. POST SADDLE DETAIL
TYP. JOIST/BEAM CONNECTION
TYP. FLOOR/WALL CONNECTION
TYP. SECTION
TYP. INT. JOIST/WALL CONN.
TYP. BEAM CONN. ON STUD WALL
TYP. WALL/ROOF CONN.
TYP. NON-BEARING WALL SUPPORT
TYP. WALL OPENING
ANCHOR AT END WALL
TYP. NON-BEARING WALL SUPPORT
City of Richmond, Building Approvals
18 840843
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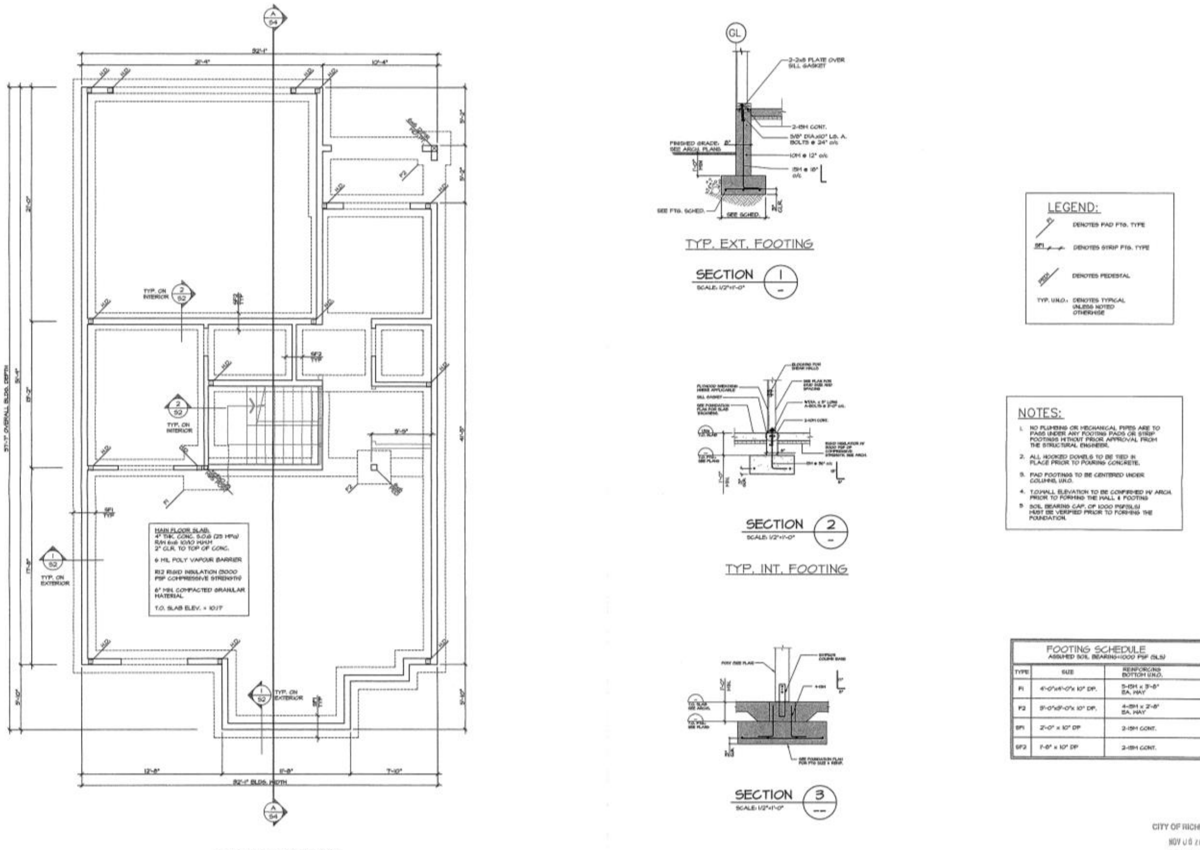
FOUNDATION PLAN
SCALE: 1/4"=1'-0"
TYP. EXT. FOOTING
SECTION 1
SCALE: 1/2"=1'-0"
LEGEND:
NOTES:
SECTION 2
SCALE: 1/2"=1'-0"
TYP. INT. FOOTING
FOOTING SCHEDULE
SECTION 3
SCALE: 1/2"=1'-0"
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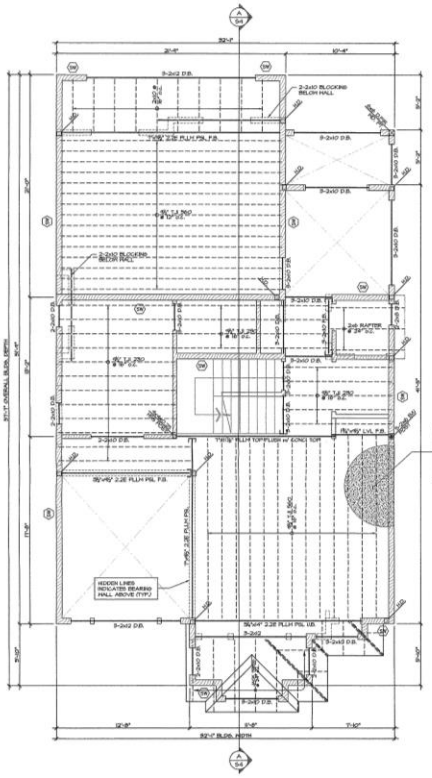
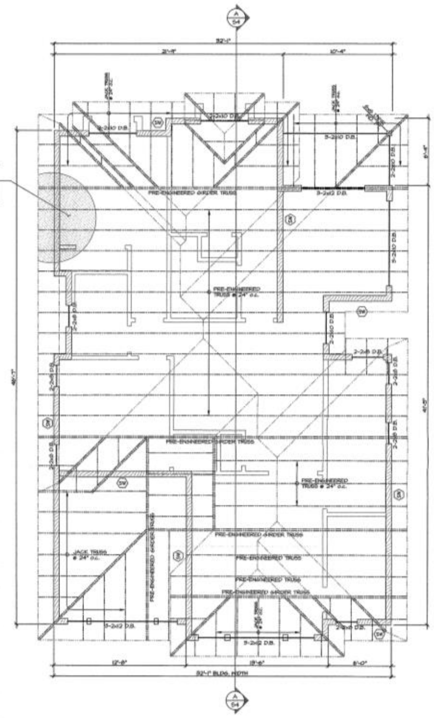


SECOND FLOOR FRAMING OVER MAIN FLOOR WALLS

SCALE: 1/4"=1'-0"



ROOF FRAMING OVER 2ND FLOOR WALLS

SCALE: 1/4"=1'-0"

SPECIFIED LOADS:		
LIVE LOAD	21.4	PSF
DEAD LOAD	12	PSF
NET ROOF UPLIFT	8	PSF

NOTES

1. ALL BUILT-UP BEAMS TO BE 2-2x10 D.B. TYP. U.N.O.
2. IF NO SPECIFIC BUILT-UP POST IS DENOTED BESIDE A BEAM, IT IS IMPLIED THAT THE FOLLOWING IS REQUIRED
   - 2 CRIPPLE + 1-FULL HEIGHT
   - OR 3 FULL HEIGHT FOR FLUSH BEAMS
3. USE SPF # 2 OR BETTER GRADE FOR WALL STUDS
4. PROVIDE SOLID BLOCKING BETWEEN JOISTS UNDER ALL BEARING WALLS.
5. PROVIDE EITHER SOLID BLOCKING @ 36" o.c. OR ADDITIONAL FLOOR JOISTS CENTRED UNDER NON LOAD BEARING WALLS RUNNING PARALLEL WITH JOISTS.
6. 5/8" PLYWOOD SHEATHING TO BE PLACED OVER FLOOR JOISTS W/ 2½" NAILS @ 6" O/C

LEGEND

⊗	DENOTES BUILT-UP POSTS OVER BEAMS OR WALLS (SEE FLOOR ABOVE).
F.B.	DENOTES FLUSH BEAM
D.B.	DENOTES DROP BEAM
U.B.	DENOTES UPSTAND BEAM
T.S.	DENOTES 1.1E TIMBERSTRAND LSL
PLLH	DENOTES 2.2E PARALLAM PSL FOR BEAMS, 1.8E FOR POSTS
U.N.O.	DENOTES UNLESS NOTED OTHERWISE
T.O.W.	DENOTES TOP OF WALL
----	DENOTES FLOOR JOIST / PRE-ENGINEERED ROOF TRUSSES
═	DENOTES LOAD BEARING WALL EXTERIOR = 2x6 STUD @ 16" o.c. INTERIOR = 2x4 STUD @ 16" o.c.
(SW)	DENOTES SHEARWALL (SEE SHEARWALL SCHEDULE BELOW)
CONT.	DENOTES CONTINUOUS, CONTINUOUS BEAMS CANNOT BE CUT OVER BEARING WALLS.
⊓	DENOTES LOCATIONS OF JOIST OR BEAM HANGER (HANGER TYPE TO BE SPECIFIED BY JOIST/BEAM SUPPLIER U.N.O.)
	DENOTES PAD FTG. TYPE
SF1	DENOTES STRIP FTG. TYPE
E.W.	DENOTES EACH WAY
BOTT.	DENOTES BOTTOM
HD	DENOTES HOLD DOWN SEE DETAILS 1-5 ON PAGE S1

SHEAR WALL SCHEDULE

ALL FLOORS	- SHEATING: 1/2" PLYWOOD SHEATHING (CSA O121)
	- PANELS PLACED HORIZONTAL OR VERTICAL
(SW)	- ALL PANEL EDGES TO BE BLOCKED SOLID (2x4 SOLID BLOCKING EITHER PLACED ON EDGE OR PLACED FLAT WITH NAILS BENT OVER)
	- ALL PANEL EDGES TO BE NAILED WITH 3" 10d COMMON OR 10d POWER DRIVEN NAILS SPACED AT: 4" O/C TYP. U.N.O. 2" O/C WHERE (SW) SHOWN
	- ALL INTERIOR SUPPORTS TO BE NAILED WITH 2½" NAILS @ 12" o/c

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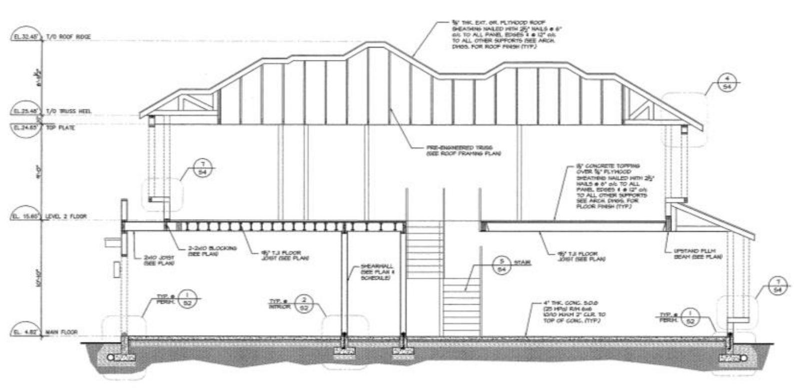
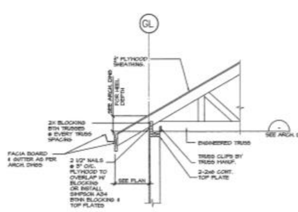


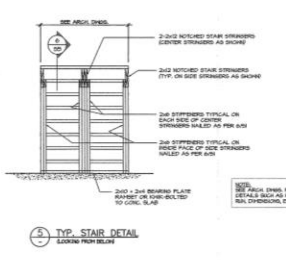
CROSS SECTION A-A

SCALE: 1/4"=1'-0"

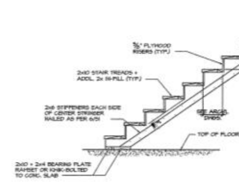


TYP. TRUSS BEARING @ EXTERIOR WALL

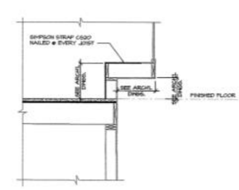
SECTION 4



5 TYP. STAIR DETAIL



6 SECTION



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9.3 Appendix C – Uni Format

ASTM Uniformat II Classification for Building Elements (E1557-97)

Level 1 Major Group Elements		Level 2 Group Elements		Level 3 Individual Elements	To be included or not
A	SUBSTRUCTURE	A10	Foundations	A1010 Standard Foundations A1020 Special Foundations A1030 Slab on Grade	Yes Yes Yes
		A20	Basement Construction	A2010 Basement Excavation A2020 Basement Walls	Yes Yes
B	SHELL	B10	Superstructure	B1010 Floor Construction B1020 Roof Construction	Yes Yes
		B20	Exterior Enclosure	B2010 Exterior Walls B2020 Exterior Windows B2030 Exterior Doors	Yes Yes Yes
		B30	Roofing	B3010 Roof Coverings B3020 Roof Openings	Yes Yes
C	INTERIORS	C10	Interior Construction	C1010 Partitions C1020 Interior Doors C1030 Fittings	Yes Yes No
		C20	Stairs	C2010 Stair Construction C2020 Stair Finishes	No No
		C30	Interior Finishes	C3010 Wall Finishes Floor C3020 Finishes C3030 Ceiling Finishes	No No No
D	SERVICES	D10	Conveying	D1010 Elevators & Lifts D1020 Escalators & Moving Walks D1090 Other Conveying Systems	No No No
		D20	Plumbing	D2010 Plumbing Fixtures D2020 Domestic Water Distribution D2030 Sanitary Waste D2040 Rainwater Drainage D2090 Other Plumbing Systems	No No No No No
		D30	HVAC	D3010 Energy Supply D3020 Heat Generating Systems D3030 Cooling Generating Systems D3040 Distribution Systems D3050 Terminal & Package Units	Yes Yes Yes Yes Maybe Maybe

				D3060 Controls & Instrumentation D3070 Systems Testing & Balancing D3090 Other HVAC Systems & Equipment	Maybe Yes
		D40	Fire Protection	D4010 Sprinklers D4020 Standpipes D4030 Fire Protection Specialties D4090 Other Fire Protection Systems	No No No No
		D50	Electrical	D5010 Electrical Service & Distribution D5020 Lighting and Branch Wiring D5030 Communications & Security D5090 Other Electrical Systems	No No No No
E	EQUIPMENT & FURNISHINGS	E10	Equipment	E1010 Commercial Equipment E1020 Institutional Equipment E1030 Vehicular Equipment E1090 Other Equipment	No No No No
		E20	Furnishings	E2010 Fixed Furnishings E2020 Movable Furnishings	No No
F	SPECIAL CONSTRUCTION & DEMOLITION	F10	Special Construction	F1010 Special Structures F1020 Integrated Construction F1030 Special Construction Systems F1040 Special Facilities F1050 Special Controls Instrumentation	No No No No No
		F20	Selective Building Demolition	F2010 Building Elements Demolition F2020 Hazardous Components Abatement	No No

9.4 Appendix D – Input Summary Table for WBLCA of baseline

1	GENERAL INFORMATION ON THE HOUSE				
	Parameter	**Input Value**	**Unit**	**Ref**	**Comments**
1.1	Building Height	32.45	Feet	Section A-A Pg 8	Total height to the tip of the roof is considered
1.2	Building Life Expectancy	60	years	standard	Average lifespan of a house
1.3	Gross Floor Area	3727.41	Sq ft	Area Calc. Pg 2	(includes 2102.46 Ground Floor area, 1554.25 Upper Floor and 601.67 garage)
2	**OPERATING ENERGY CONSUMPTION**				
	Parameter	**Input Value**	**Unit**	**Ref**	**Comments**
2.1	Electricity Consumption per year	8999	kWh	Baseline House Energy Data	Excel file provided by Sepehr on May 20,2020
2.2	Natural Gas consumption per year	1452.7	m3	Baseline House Energy Data	Excel file provided by Sepehr on May 20,2021
3	**FOUNDATIONS**				
	Parameter	**Input Value**	**Unit**	**Ref**	**Comments**
3.1	Strip Footing SF1 (Assembly)	Length: 199.91' Width: 2' Thickness: 10" Rebar: 143lbs/yd3 Concrete: 4000 psi	Feet Feet Feet lbs/yd3 psi	Foundation Plan: Pg 13 Length: Perimeter Width: in table Thickness: in table	Rebar: Assumption for the mid value, three values given in Athena signify low/med/high ranges Concrete Strength: 3600 psi (given on pg12) 4000 psi approximation
3.1.1	Strip Footing SF1 (Envelope)	Vapor Barrier: Polyethylene 6mil Insulation: Polystyrene 76.2mm	mil mm	Details on Pg10 HOT200 PCR	Polystyrene Expanded is the closest approximation to EPS provided in the HOT2000 reports

3.2	Strip Footing SF2 (Assembly)	Length: 129' Width: 1.6666' Thickness: 10" Rebar: 143lbs/yd3 Concrete: 4000 psi	Feet Feet Feet lbs/yd3 psi	Foundation Plan: Pg 13 Length: Perimeter Width: in table Thickness: in table	Rebar: Assumption for the mid value, three values given in Athena signify low/med/high ranges Concrete Strength: 3600 psi (given on pg12) 4000 psi approximation
3.2.1	Strip Footing SF2 (Envelope)	Vapor Barrier: Polyethylene 6mil Insulation: Polystyrene 76.2mm	mil mm	Details on Pg10 HOT200 PCR	Polystyrene Expanded is the closest approximation to EPS provided in the HOT2000 reports
3.3	Pad Footing F1 (Assembly) Qty: 1 in number	Length: 4' Width: 4' Thickness: 10" Rebar: 143lbs/yd3 Concrete: 4000 psi	Feet Feet Feet lbs/yd3 psi	Foundation Plan: Pg. 13 Length: in table Width: in table Thickness: in table	Rebar: Assumption for the mid value, three values given in Athena signify low/med/high ranges Concrete Strength: 3600 psi (given on pg12) 4000 psi approximation
3.3.1	Pad Footing F1 (Envelope)	Vapor Barrier: Polyethylene 6mil Insulation: Polystyrene 76.2mm	mil mm	Details on Pg10 HOT200 PCR	Polystyrene Expanded is the closest approximation to EPS provided in the HOT2000 reports
3.4	Pad Footing F2 (Assembly) Qty: 2 in number	Length: 3' Width: 3' Thickness: 10" Rebar: 143lbs/yd3 Concrete: 4000 psi	Feet Feet Feet lbs/yd3 psi	Foundation Plan: Pg 13 Length: in table Width: in table Thickness: in table	Rebar: Assumption for the mid value, three values given in Athena signify low/med/high ranges Concrete Strength: 3600 psi (given on pg12) 4000 psi approximation

3.4.1	Pad Footing F2 (Envelope)	Vapor Barrier: Polyethylene 6mil Insulation: Polystyrene 76.2mm	mil mm	Details on Pg10 HOT200 PCR	Polystyrene Expanded is the closest approximation to EPS provided in the HOT2000 reports
3.5	Slab on Grade (Assembly)	Length: 57.583' Width: 32.083' Thickness: 8" Concrete: 4000 psi	Feet Feet Feet Inches psi	Length: of house Width: of house Thickness: in table	Rebar: Assumption for the mid value, three values given in Athena signify low/med/high ranges Concrete Strength: 3600 psi (given on pg12) 4000 psi approximation
3.5.1	Slab on Grade (Envelope)	Vapor Barrier: Polyethylene 6mil Insulation: Polystyrene 76.2mm	mil mm	Details on Pg10 HOT200 PCR	Polystyrene Expanded is the closest approximation to EPS provided in the HOT2000 reports
4	**WALLS**				
	Parameter	**Input Value**			
4.1	**Ground Floor: Wall Name**	**Garage Wall: South Façade**	**Garage Wall: West Façade**	**Garage Wall: Interior**	**Entrance Wall**
	Length	20.97	20.75	43	10.33
	Height	10.83	10.83	10.83	10.83
	Used Assembly Components	Wood Stud Load Bearing; Kiln Dried; Plywood Sheathing 16 o.c. Stud Spacing	Wood Stud Load Bearing; Kiln Dried; Plywood Sheathing	Wood Stud Load Bearing; Kiln Dried; Plywood Sheathing 16 o.c. Stud Spacing 2 x 6" Stud Thickness	Wood Stud Load Bearing; Kiln Dried; Plywood Sheathing 16 o.c. Stud Spacing 2 x 6" Stud Thickness

		2 x 6" Stud Thickness	16 o.c. Stud Spacing 2 x 6" Stud Thickness		
	Windows: Number	0	0	0	0
	Windows: Area	0	0	0	0
	Windows: Frame Type	0	0	0	0
	Windows: Glazing Type	0	0	0	0
	Door: Number (32' x 7')	0	6	1	2
	Door: Type	0	Solid Wood Door	Solid Wood Door	Solid Wood Door
	Envelope	Glass Mat Gyp Panel 0.5" Fiber Cement Siding Fiberglass Batt R20 - 75mm Polyethylene 6 mil	Glass Mat Gyp Panel 0.5" Fiber Cement Siding Fiberglass Batt R20 - 75mm Polyethylene 6 mil	Glass Mat Gyp Panel 0.5" Fiber Cement Siding Fiberglass Loose Fill Cavity R22 - 75mm Polyethylene 6 mil	Glass Mat Gyp Panel 0.5" Fiber Cement Siding Fiberglass Batt R20 - 75mm Polyethylene 6 mil

4.2	**First Floor: Wall Name**	**North Façade**	**East Façade**	**South Façade**	**West Façade**
	Length	53.33'	35.08'	48.91'	44.25'
	Height	10.83'	10.83'	10.83'	10.83'
	Used Assembly Components	Wood Stud Load Bearing; Kiln Dried; Plywood Sheathing 16 o.c. Stud Spacing 2 x 6" Stud Thickness	Wood Stud Load Bearing; Kiln Dried; Plywood Sheathing 16 o.c. Stud Spacing 2 x 6" Stud Thickness	Wood Stud Load Bearing; Kiln Dried; Plywood Sheathing 16 o.c. Stud Spacing 2 x 6" Stud Thickness	Wood Stud Load Bearing; Kiln Dried; Plywood Sheathing 16 o.c. Stud Spacing 2 x 6" Stud Thickness
	Windows: Number	5	3	3	3
	Windows: Area	49	120	25	78
	Windows: Frame Type	Vinyl Clad Wood Window Frame Double Pane	Vinyl Clad Wood Window Frame Double Pane	Vinyl Clad Wood Window Frame Double Pane	Vinyl Clad Wood Window Frame Double Pane
	Windows: Glazing Type	Double Glaze Hard Coated Argon	Double Glaze Hard Coated Argon	Double Glaze Hard Coated Argon	Double Glaze Hard Coated Argon
	Door: Number	0	0	0	0

	Door: Type	0	0	0	0
	Envelope	Glass Mat Gyp Panel 0.5" Fiber Cement Siding Fiberglass Batt R20 - 75mm Polyethylene 6 mil	Glass Mat Gyp Panel 0.5" Fiber Cement Siding Fiberglass Batt R20 - 75mm Polyethylene 6 mil	Glass Mat Gyp Panel 0.5" Fiber Cement Siding Fiberglass Batt R20 - 75mm Polyethylene 6 mil	Glass Mat Gyp Panel 0.5" Fiber Cement Siding Fiberglass Batt R20 - 75mm Polyethylene 6 mil
5	**FLOORING**				
	Parameter	**Input Value**	**Unit**	**Ref**	**Comments**
5.1	Typical Interior Floor: Wood Joist	Floor Width: 51' Span: 16.07' Decking Type: Plywood Live Load: 75psf Decking Thickness: 5/8"	Feet Feet Text Text Inches	Floor Schedule Pg. 9	
5.1.1	Typical Interior Floor: Envelope	Glass Mat Gyp Panel 0.5"	Inches	Floor Schedule Pg. 9	

5.2	Floor between garage and interior space : Wood Joist	Floor Width: 21.76' Span: 16.07' Decking Type: Plywood Live Load: 75psf Decking Thickness: 5/8"	Feet Feet Text Text Inches	Floor Schedule Pg. 9	
5.2.1	Flooring: Envelope	Glass Mat Gyp Panel 0.5" Insulation: R30 FG Batt	sqft as extra materials Area : 21.76 x 16.07 = 349 sqft	Floor Schedule Pg. 9	Closest approximation to FG R31 insulation; Added along with cantilever bay floor
5.3	Floor between garage and exterior space : Wood Joist	Floor Width: 21.9' Span: 5.1666' Decking Type: Plywood Live Load: 75psf Decking Thickness: 5/8"	Feet Feet Text Text Inches	Floor Schedule Pg. 9	
5.3.1	Flooring: Envelope	Glass Mat Gyp Panel 0.5"	Inches	Floor Schedule Pg. 9	
5.4	Cantilevered floor Bay 1 @ W facade: 5'7" x 1'6" Bay 2 @ W	Floor Width: 7.1' Span: 5' Decking Type: Plywood	Feet Feet Text Text Inches	Floor Schedule Pg. 9	Closest approximation to FG R31 insulation; Added along with floor between garage and interior

	façade 5'7" x 1'4" Bay 3 @ E façade 13'6" x 1'6" Total Area = 35.822 sqft	Live Load: 75psf Decking Thickness: 5/8" Insulation: R30 FG Batt			
6	**ROOFING**				
	Parameter	**Input Value**	**Unit**	**Ref**	**Comments**
6.1	Upper floor roof Assembly: Light Frame Wood Truss	Roof Width: 46.58' Span: 32.08' Live Load: 50 psf Truss Type : Parallel (mostly) Decking Type: Plywood Decking Thickness: 1/2"	Feet Feet Feet psf Inches	Roof Schedule Pg. 9	Confused about exact envelope materials and available in Athena
	Envelope	Fiberglas Loose Fill Open Blow 368.02mm Polyethylene 6 mil Gyp Regular 1/2"	inches	Roof Schedule Pg. 9	Confused about exact envelope materials and available in Athena; excluded asphalt roof shingles with perforated roofing and felt (details not available)
6.2	Roof between Garage and Exterior	Roof Width: 21.75' Span: 5.166'	Feet Feet Feet psf Inches	Roof Schedule Pg. 9	

		Live Load: 50 psf Truss Type : Parallel (mostly) Decking Type: Plywood Decking Thickness: 1/2"			
	Envelope	Gyp Board 5/8"		Roof Schedule Pg. 9	Confused about exact envelope materials and available in Athena; excluded asphalt roof shingles with perforated roofing and felt (details not available)
7	**COLUMNS AND BEAMS**				;
7 a	Ground Floor: Columns and Beams	Number of Columns: 17 Number of Beams: 17 Bay size: 12' Supported Span: 21' Supported Area: 2102.4 sqft Column Height: 10.8' Supported Element: Floor Live Load: 50psf Column		Second Floor and Roof Framing Pg 14	excluded asphalt roof shingles with perforated roofing and felt (details not available)

		Type: LVL/PSL Beam Type: LVL/PSL			
7b	Upper Floor: Columns and Beams	Number of Columns: 15 Number of Beams: 12 Bay size: 12' Supported Span: 21' Supported Area: 1554.2 sqft Column Height: 9' Supported Element: Roof Live Load: 50psf Column Type: LVL/PSL Beam Type: LVL/PSL		Second Floor and Roof Framing Pg 15	Not sure about the numbers and dimensions

9.5 Appendix E – Resources and Calculation for Hybrid Method

9.5.1 Table for calculation of GWP from insulation materials using hybrid method

ESC 1							
Material	Mass Value (1") Ton	Mass Value Kg	Density from GB Table (kg/m^3)	Resistivity (R/inch)	Resistivity (RSI/m)	Emission factor from EPDs ($kgCO_2/m^2/RSI$)	GWP ($kgCO_2$)
Blown Cellulose R40 Loose filled	0.48	476.50	48.00	3.70	25.53	0.70	177.41
Expanded Polystyrene 2.5" R10	0.23	228.20	46.40	3.90	26.91	2.49	329.54
FG Batt R 20	0.57	572.50	16.00	3.30	22.77	4.64	3,780.39
FG Batt R30 Walls	0.01	8.90	16.00	3.30	22.77	4.64	58.77
Total GWP from Insulation in kg CO_2 (ESC 1)							4,346.11
ESC 2							
Material	Mass Value (1") Ton	Mass Value Kg	Density from GB Table (kg/m^3)	Resistivity (R/inch)	Resistivity (RSI/m)	Emission factor from EPDs ($kgCO_2/m^2/RSI$)	GWP ($kgCO_2$)
Blown Cellulose R56	1.43	1,434.91	48.00	3.70	25.53	0.70	534.24
Expanded Polystyrene 3" R12	0.25	246.60	46.40	3.90	26.91	2.49	356.11
FG Batt R30 Walls	0.56	557.44	16.00	3.30	22.77	4.64	3,680.91
Total GWP from Insulation in kg CO_2 (ESC 2)							4,571.26
ESC 3							

Material	Mass Value (1") Ton	Mass Value (kg)	Density from GB Table (kg/m^3)	Resistivity (R/inch)	Resistivity (RSI/m)	Emission factor from EPDs ($kgCO_2/m^2/RSI$)	GWP ($kgCO_2$)
Blown Cellulose R60	1.54	1,541.70	48.00	3.70	25.53	0.70	573.99
Expanded Polystyrene 1" R4	0.24	240.70	46.40	3.90	26.91	2.49	347.59
Extruded Polystyrene 3" R 15 60 psi	0.41	407.40	80.00	5.00	34.50	75.99	13,350.78
FG Batt R30 Walls	0.56	557.40	16.00	3.30	22.77	4.64	3,680.68
Total GWP from Insulation in kg CO_2 (ESC 3)							17,953.04
ESC 4							
Material	Mass Value (1") Ton	Mass Value (kg)	Density from GB Table (kg/m^3)	Resistivity (R/inch)	Resistivity (RSI/m)	Emission factor from EPDs ($kgCO_2/m^2/RSI$)	GWP ($kgCO_2$)
Blown Cellulose R60	1.54	1,541.70	48.00	3.70	25.53	0.70	573.99
Expanded Polystyrene 2" R8	0.47	472.10	46.40	3.90	26.91	2.49	681.76
Extruded Polystyrene 3" R 15 60 psi	0.41	407.40	80.00	5.00	34.50	75.99	13,350.78
FG Batt R30 Walls	0.56	557.40	16.00	3.30	22.77	4.64	3,680.68
Total GWP from Insulation in kg CO_2 (ESC 4)							18,287.21
ESC 5							

Material	Mass Value (1") Ton	Mass Value (kg)	Density from GB Table (kg/m^3)	Resistivity (R/inch)	Resistivity (RSI/m)	Emission factor from EPDs (kgCO_2/m^2/RSI)	GWP (kgCO_2)
Blown Cellulose R60	1.54	1,541.70	48.00	3.70	25.53	0.70	573.99
Expanded Polystyrene 2" R8	0.01	9.00	46.40	3.90	26.91	2.49	13.00
Extruded Polystyrene 3" R 15 60 psi	1.20	1,201.30	80.00	5.00	34.50	75.99	39,367.43
FG Batt R30 Walls	0.56	557.40	16.00	3.30	22.77	4.64	3,680.68
Total GWP from Insulation in kg CO_2 (ESC 5)							43,635.10

9.5.2 Source for Emissions factor

Image showing Emission factor in GWP values from standard EPDs for various insulation materials

	Data Source	Insulation Type	Global Warming Potential A-C (kgCO2e/m2)											
			R-5	R-10	R-15	R-20	R-25	R-30	R-35	R-40	R-45	R-50	R-55	R-60
	Dow Styrofoam EPD 2014	XPS (HFC) - Styrofoam	83.9	167.8	251.7	335.7	419.6	503.5	587.4	671.3	755.2	839.2	923.1	1,007.0
	Owens Corning Foamular EPD 2018	XPS (HFC) - 100 psi	91.2	182.3	273.5	364.7	455.8	547.0	638.2	729.3	820.5	911.7	1,002.8	1,094.0
	Owens Corning Foamular EPD 2018	XPS (HFC) - 60 psi	66.9	133.8	200.6	267.5	334.4	401.3	468.2	535.0	601.9	668.8	735.7	802.5
	Owens Corning Foamular EPD 2018	XPS (HFC) - 40 psi	54.7	109.4	164.1	218.8	273.5	328.3	383.0	437.7	492.4	547.1	601.8	656.5
HFC	Owens Corning Foamular EPD 2018	XPS (HFC) - 25 psi	47.1	94.2	141.3	188.4	235.5	282.5	329.6	376.7	423.8	470.9	518.0	565.1
	Owens Corning Foamular EPD 2018	XPS (HFC) - 15 psi	39.5	79.0	118.6	158.1	197.6	237.1	276.7	316.2	355.7	395.2	434.8	474.3
	Jackson EPD 2015 (Germany CML)	XPS (HFO)	12.3	24.7	37.0	49.4	61.7	74.1	86.4	98.8	111.1	123.5	135.8	148.1
	SPFA Industry Average EPD 2018	Spray Foam (HFC) - 2K-LP	31.5	63.0	94.5	126.0	157.4	188.9	220.4	251.9	283.4	314.9	346.4	377.9
	SPFA Industry Average EPD 2018	Spray Foam (HFC) - Closed Cell	17.8	35.5	53.3	71.1	88.9	106.6	124.4	142.2	160.0	177.7	195.5	213.3
	SPFA Industry Average EPD 2018	Spray Foam (HFO) - Closed Cell	3.7	7.3	11.0	14.7	18.3	22.0	25.7	29.3	33.0	36.6	40.3	44.0
HFO	SPFA Industry Average EPD 2018	Spray Foam (HFC) - Roofing	23.3	46.6	69.9	93.2	116.5	139.8	163.1	186.4	209.7	233.0	256.3	279.6
	SPFA Industry Average EPD 2018	Spray Foam (HFO) - Roofing	4.4	8.7	13.1	17.5	21.9	26.2	30.6	35.0	39.3	43.7	48.1	52.5
	EPS-IA Industry Avg. 2017	EPS	2.2	4.4	6.6	8.8	11.1	13.3	15.5	17.7	19.9	22.1	24.3	26.5
	BASF Neopor 2018	GPS - Neopor	1.5	3.0	4.6	6.1	7.6	9.1	10.7	12.2	13.7	15.2	16.8	18.3
Other	PIMA Industry Avg. 2015	Polyiso - Roof	2.5	4.9	7.4	9.9	12.3	14.8	17.3	19.7	22.2	24.7	27.1	29.6
	PIMA Industry Avg. 2015	Polyiso - Wall	2.0	4.1	6.1	8.2	10.2	12.3	14.3	16.3	18.4	20.4	22.5	24.5
	NAIMA Industry Avg. 2013	Mineral Wool Loose Fill	1.3	2.5	3.8	5.0	6.3	7.5	8.8	10.0	11.3	12.5	13.8	15.0
	NAIMA Industry Avg. 2018	Mineral Wool Board - Light Density	3.5	7.0	10.6	14.1	17.6	21.1	24.7	28.2	31.7	35.2	38.8	42.3
	NAIMA Industry Avg. 2018	Mineral Wool Board - Heavy Density	8.0	15.9	23.9	31.9	39.8	47.8	55.7	63.7	71.7	79.6	87.6	95.6
	CIMA/CIMAC Industry Avg. 2019	Cellulose Loose Fill	0.6	1.2	1.9	2.5	3.1	3.7	4.3	5.0	5.6	6.2	6.8	7.4

Source: Priopta, retrieved from https://www.dropbox.com/s/pum1qowzfc55sa3/Priopta%20%20Embodied%20Carbon%20Presentation%20%28July%2015%2C%202020%29.pdf?dl=0

9.5.3 Source for Resistivity (R/inch)

Image showing Resistivity (R/inch) for various insulation materials

Insulation Material	R-value R/inch	Density lb/ft³	Emb. E MJ/kg	Emb. Carbon $kgCO_2/kg$	Emb. Carbon $kgCO_2/ft^2 \cdot R$	Blowing Agent (GWP)	Bl. Agent kg/kg foam	Blowing Agent GWP/ bd-ft	Lifetime GWP/ $ft^2 \cdot R$
Cellulose (dense-pack)	3.7	3.0	2.1	0.106	0.0033	None	0	N/A	0.0033
Fiberglass batt	3.3	1.0	28	1.44	0.0165	None	0	N/A	0.0165
Rigid mineral wool	4.0	4.0	17	1.2	0.0455	None	0	N/A	0.0455
Polyisocyanurate	6.0	1.5	72	3.0	0.0284	Pentane (GWP=7)	0.05	0.02	0.0317
Spray polyurethane foam (SPF) – closed-cell (HFC-blown)	6.0	2.0	72	3.0	0.0379	HFC-245fa (GWP=1,030)	0.11	8.68	1.48
SPF – closed-cell (water-blown)	5.0	2.0	72	3.0	0.0455	Water (CO_2) (GWP=1)	0	0	0.0455
SPF – open-cell (water-blown)	3.7	0.5	72	3.0	0.0154	Water (CO_2) (GWP=1)	0	0	0.0154
Expanded polystyrene (EPS)	3.9	1.0	89	2.5	0.0307	Pentane (GWP=7)	0.06	0.02	0.036
Extruded polystyrene (XPS)	5.0	2.0	89	2.5	0.0379	HFC-134a[1] (GWP=1,430)	0.08	8.67	1.77

1. XPS manufacturers have not divulged their post-HCFC blowing agent, and MSDS data have not been updated. The blowing agent is assumed here to be HFC-134a.

Source: retrieved from https://www.buildinggreen.com/blog/global-warming-potential-insulation-materials

9.6 Appendix F – Cumulative results for all emissions

Step Code House	Heated Area [m2]	GHG [kg/yr] (HOT2000)	GHGI [kg/m2/yr]	GHGI*60 [kg/m2]	Total GHGI in 60 years
Ref House	204.00	3178	16	935	190680
Step 1	204.00	3028	15	891	181680
Step 2	204.00	2549	12	750	152940
Step 3	204.00	2323	11	683	139380
Step 4	204.00	1947	10	573	116820
Step 5 (fully electrified)	204.00	154	1	45	9240
Step 1 + ASHP	204.00	1145	6	337	68700
Step 2 + ASHP	204.00	1049	5	309	62940
Step 3 + ASHP	204.00	1010	5	297	60600
Step 4 + ASHP	204.00	1004	5	295	60240

Step Code House	EE *60 [kg/m^2]	EE (Structure)	EE (Insulation)	EE Mech Sys.	EE (Mechanical Sys) per sqm	EE (Hybrid Method)	Total EE (Hybrid + Mech)	EE (Athena)	Difference %
Step 1	227	42062.01	4346	12340.98	60.495	46408.0	46468.505	42907.66	7.54
Step 2	229	42199.12	4571.26	12340.98	60.495	46770.38	46830.875	43421.73	7.16
Step 3	295	42199.12	17953.04	12340.98	60.495	60152.16	60212.655	44702.41	25.68
Step 4	297	42199.12	18287.21	12340.98	60.495	60486.33	60546.825	45288.25	25.13
Step 5 (fully electrified)	421	42199.12	43635.1	12340.98	60.495	85834.22	85894.715	46542.34	45.78

EE – embodied emissions

9.7 Appendix G – GWP from HVAC Systems

9.7.1 DMQ Calculation

Outer Radius	Inner Radius	Length	Pie	Outer vol (cubic inch)	Inner vol (cubic inch)	Total Vol (cubic inch)
3"	2.95"	60"	3.147	1699.38	1643.20605	56.17395
3"	2.95"	72"	3.147	2039.256	1971.84726	67.40874
3"	2.95"	96"	3.147	2719.008	2629.12968	89.87832
2"	1.95"	144"	3.147	1812.672	1723.17132	89.50068
3"	2.95"	12"	3.147	339.876	328.64121	11.23479
3"	2.95"	60"	3.147	1699.38	1643.20605	56.17395
Total Vol in cubic inch						370.3704
Total vol in m3						0.006
density (kg/m$^{3)}$						7800
Mass (v x d) in kg						**46.8**

9.7.2 GWP from various HVAC Component

Component	Value
Refrigerant	50.03
Equipment	5.065
Distribution	5.4
Total	60.495