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THE VIABILITY OF CONCRETE BLOCK AND BRICK FOR USE IN PASSIVE HOUSE AND NET ZERO BUILDINGS

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ABSTRACT

This paper explores both the Passive House also known as Net-zero Energy Buildings (NZEB) requirements and Net Zero Building (NZB) which aim for carbon neutrality to determine how concrete masonry and clay brick veneer can inherently meet these standards for a single-family home. This was accomplished by reviewing and describing the comprehensive requirements for these standards before illustrating how concrete block masonry can satisfy these requirements with a real-world case study of a single-family home utilizing concrete block backup wall with brick veneer located in Toronto Canada.

The walls of the single-family home of the case study involved a 15cm (6") concrete block backup wall sealed with a self-adhered air/vapour barrier, using 254 mm (10") of continuous extruded polystyrene (XPS), insulation and 90 mm clay brick veneer. The single-family home was drafted in Autodesk Revit using the MasonryIQ plugin for realistic representation of the masonry and the Cove.tool for the energy modeling of the home. The results were an Energy Use Intensity (EUI) of 159 kWh/m^2/yr. The current national benchmark for a single-family home is 250 kWh/m^2/yr meaning the case study was 57% more efficient than the national benchmark. The target for 2030 is 50 kWh/m^2/yr, which implies additional measures will be required to comply with future energy efficiency targets. One solution would be to reduce the glazing on the party walls (side walls of the home). This would increase the overall thermal performance of the home and reduce the heating demand. Less glazing is often preferable on the party walls for home lots with tight property as privacy is increased with less glazing.

After investigating the requirements of Net-Zero Building (NZB) that include life cycle analysis with cradle to grave assessments, concrete block's historically verified long-term benefits indicate that concrete block single-family homes will outperform wood-frame single family homes in the terms of resilience, cradle to grave and to cradle to cradle NZB total cost of ownership. This is all possible with concrete block while still meeting Passive House standards with only a marginal increase in wall thickness over wood-frame homes.

KEYWORDS: Construction, Concrete, Masonry, Block, Mass, Net-Zero Energy Building, PassiveHouse, Net-Zero Building, Lifecycle, Carbon,

1 INTRODUCTION

It is widely accepted that climate change is a significant challenge that humanity must address during this century. According to the World Meteorological Organization, the warmest 20 years recorded on earth were during the previous two decades, with the warmest four during 2015 to 2018. On average, global temperatures are now one degree Celsius higher than during the pre-industrial period. If not addressed, climate change could lead to much more difficult climatic circumstances such as irregular weather patterns, floods, storms as well as the melting of polar ice resulting in rising sea levels. By now, it is widely acknowledged by scientists and governments that high levels of Greenhouse Gasses (GHG) in the atmosphere are contribute to climate change, with carbon dioxide as one of the most common and abundant greenhouse gasses. There is significant discussion around solutions to slow down the rate of climate change and how to reduce carbon dioxide being emitted into our atmosphere.[1] Several approaches and measures are being taken to reduce Greenhouse Gasses (GHG) levels across various industries to address GHG related climate change. The two most common approaches include lowering the emissions that are released into the atmosphere and removing greenhouse gas emissions from the atmosphere all together, by planting more trees and using carbon capture technologies during industrial processes.[2]

This project will focus on the built environment. As urbanization and population density continue to increase, the projected numbers for the near future are startling. For example, by 2060, the world is projected to add 230 billion m^2, which is equivalent to 2.5 trillion ft^2, of buildings which is the equivalent of adding an entire New York City to the Earth every 34 days for the next 40 years[3]. Since 2014, the building industry in Canada consumes resources on average of $295 billion worth of material per year, and is forecasted to remain in the same range until 2023[4]. For these reasons, drastic changes and sustainable measures must be taken within the building industry to address the speed of urbanization in an environmentally aware fashion.

With respect to building materials, cement and concrete are often considered to be carbon intensive and not environmentally friendly. However, there are reductions and process changes that can be undertaken to eliminate the carbon footprint of concrete, and the industry is working together on a global scale to achieve these goals. The Global Cement and Concrete Association (GCCA) has recently committed to a Climate Ambition resulting in net zero cement by 2050; "Our Climate Ambition is our member companies' commitment to drive down the CO_2 footprint of their operations and products and aspire to deliver society with carbon neutral concrete by 2050. We will work across the built environment value chain to deliver this aspiration in a circular economy, whole life context".[5] In Canada, the Canadian Concrete Masonry Producers Association (CCMPA) is also doing their part to work towards net zero products. In 2020 alone, the association realized an almost complete conversion to Portland Limestone Cement (also referred to as GUL cement) in the manufacture of concrete block.

1 https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate

2 World Development Report, 2010

3 UN Environment, Global Status Report 2017

4 Statista, 2020. https://www.statista.com/study/60779/construction-in-canada/

5 https://gccassociation.org/climate-ambition/

Traditionally General Use (GU) was cement used to manufacture concrete block which is more carbon intensive than Portland Limestone Cement (PLC). Over 70% of concrete masonry units (CMU) produced in Canada are now being manufactured with PLC and this translates to a minimum 10% reduction in the carbon footprint of concrete block masonry in Canada.[6] In addition to these carbon reduction measures being explored on the materials side of concrete block masonry, a better understanding of how this type of construction can support sustainable and resilient building is needed.

This paper investigates the viability of concrete masonry for use in net-zero energy (Passive House buildings) and Net Zero Carbon Building (NZB). Chapters one through six describe the comprehensive requirements of Net Zero Energy Buildings (NEB) before illustrating how concrete block masonry can satisfy these requirements with a real-world case study in chapter seven.

2 PASSIVE HOUSE CONSTRUCTION

Before the viability of concrete block masonry as solution for Passive House and Net Zero buildings can be established, a review of the important definitions and requirements of these methods of building must be undertaken.

2.1 PASSIVE HOUSE STANDARD

Passive House is a widely known building standard that is implemented to achieve comfortable, low energy and environmentally aware designs. The standard was created in 1988 by Professor Bo Adamson of Lund University, Sweden, and Dr Wolfgang Feist of the Institute for Housing and the Environment who had a vision to create a comfortable and affordable house, with premium air quality and ventilation and reliable performance. After several research projects, the implementation of a pilot project was implemented in 1990; the Kranichstein PassiveHouse in Darmstadt, Germany. Six years later, in 1996, The Passive House Institute (PHI) was founded as an independent research organization[7]. Since 1996, Passive House techniques have become globally implemented (particularly in Europe and North America) as a building standard that focuses closely on optimizing energy gains and losses[8].

According to The Passive House Institute U.S.A., a passive building is one that demonstrates the following main five principles:

1. Continuous insulation: throughout its entire envelope with U-factor targets of 0.10 to 0.15 W/m^2-K after accounting for thermal bridging.
2. Airtight building envelope: that prevents infiltration of outside air and loss of conditioned, indoor air.
3. High-performance windows: (at least double or triple-paned windows, varies according to context, climate and building type).

[6] https://ccmpa.ca/2020/09/concrete-block-is-cutting-carbon-now/
[7] https://www.zehnderamerica.com/the-history-of-passive-house-how-the-passive-house-standard-was-born/
[8] https://www.phius.org/what-is-passive-building/the-history-of-passive-houses

4. Balanced heat and moisture recovery ventilation: with a minimal space conditioning system.
5. Managing solar gain: to maximize its use during winter and minimize it in summer.

The Passive House Building Standards can be applied to all building typologies, from single-family homes to apartment buildings, offices, and skyscrapers. Passive design strategy intricately models and balances a comprehensive and detailed set of factors including heat emissions from appliances and occupants to maintain comfort within the building with consistent indoor temperatures throughout both seasons of heating and cooling. Therefore, Passive House standard offers other significant long-term benefits besides energy efficiency, such as healthy and high-quality indoor air through the continuous mechanical ventilation of fresh filtered air. Other benefits include highly resilient buildings because of the comprehensive modeling and thus design and construction. Most importantly, it paves the way to creating Net Zero and Net Positive buildings by minimizing the loads that non-renewables are required to provide[9].

2.2 NET-ZERO STANDARD DEFINITIONS

While Passive House is certainly considered one of the most viable solutions in the conversation around sustainable building design, it does not yet account for embodied carbon. Given that Carbon Dioxide (CO_2) is an essential and inescapable inclusion when it comes to the topic of global[10] warming, it was decided that there would be merit in including a second sustainable building design that accounts for carbon as part of this investigation. As a result, Net Zero Building standards (NZB) were also examined. When discussing carbon in the built environment, there is a very important distinction that needs to be identified. A *Net Zero Carbon Building (NZB)* is one that reduces GHG emissions with the goal of balancing the emissions produced and emissions removed from our atmosphere. *Net Zero Energy Building (NZEB)* is one that produces as much energy as it uses over a course of one year and is by definition Passive House construction. Construction of Net Zero Buildings is becoming more feasible to execute with the advances taking place within construction technologies, as well as renewable energy systems and academic research. As the concept of Net Zero gains popularity, the previously broad definition continues to be refined but does not yet have a binding building standard or presence in the Canadian Building Codes[11]. At a high level, it is understood Net-Zero Energy Buildings combine exemplary building design to minimize energy requirements, as well as renewable energy systems that correspond to the remaining needs of energy reduction[12].

As a global response to the quickly accelerating conversation around developing Net Zero targets, the World Green Building Council (WorldGBC)[13] established a Net Zero Building Commitment to challenge businesses, cities, states and even regions to achieve net zero carbon in operation by 2030 and all buildings to be net zero carbon by 2050. The World Green Building Council is a member of the UN Global Compact that catalyzes the spread of

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[9] https://www.phius.org/what-is-passive-building/passive-house-principles

[10] https://www.nrdc.org/stories/greenhouse-effect-101

[11] https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/federal-actions-clean-growth-economy/homes-buildings.html

[12] https://www.wbdg.org/resources/net-zero-energy-buildings

[13] https://www.worldgbc.org/thecommitment

sustainable buildings for everyone, everywhere. Their goal is to realize the Paris Agreement[14] and UN Global Goals for Sustainable Development ambitions. A framework is provided by The Commitment to foster globally determined yet locally relevant solutions for buildings within an all-inclusive scale of specific portfolios to states or regional boundaries. As operational energy takes up the largest percentage of energy-related carbon emissions, it is the main focal point of WorldGBC. However, it is also acknowledged by the organization that 11% of energy related emissions are directly from building and construction, and include emissions from both the manufacturing of raw materials (often referred to as embodied carbon) and construction processes[15].

In North America, *Architecture 2030* is another prominent organization that works to rapidly transform the built environment and achieve NZEB. It is a non-profit research organization that issued the 2030 challenge back in 2006 in response to its research. To date, *Architecture 2030* has been widely adopted throughout North America. According to recent polls by the organization, the challenge is now being implemented by approximately 40% of all U.S architecture firms as well as 73% of the 20 largest architecture and engineering firms[16]. One of the core initiatives is the *ZERO code*. It could be described as a framework that provides code-adaptable language that legislates energy efficiency measures, on-site renewable energy production and off-site energy procurement, in support of the NZEB goal. Additional provisions that the new increased grid load from new buildings must be supplied by diverse renewable energy supplies are key aspects of the ZERO code. A requirement of less on-site or off-site renewable energy for energy efficiency buildings is also a feature of the ZERO code which has the ASHRAE Standard 90.1-2019 as its base. Implementation of the ZERO code can be achieved through building codes, zoning regulations, incentive programs and various other methods[17].

In Canadian, a Net-Zero Emissions Accountability Act was proposed and introduced in November 2020. Its goal was to formalize Canada's target to achieve net-zero emissions by the year 2050. The Net-Zero Emissions Accountability Act includes setting *legally-binding, five-year milestones of interim emissions reduction* as well as establishing an Advisory Body**.** The Advisory Body is an independent group of experts composed of fourteen individuals from across the country with a diverse range of expertise and backgrounds. Their role is to consult the Canadian government and citizens with guidance on the best pathways to achieving net-zero emissions by 2050. On a global level, Canada has joined over 120 countries in the net-zero by 2050 commitment. In addition, multiple Canadian provinces and cities made Net-Zero by 2050 commitments, including Toronto, Vancouver, Halifax and most recently Quebec. Prince Edward Island, Canada, has also pledged to be net-zero greenhouse emissions by 2040[18].

2.2.1 Operational vs. Embodied Carbon

As urbanization continues to accelerate with alarming speed, we continue to see the literal rise of large-scale construction projects across Canada. This is evident by the exponential increase in skyscrapers and high-rise structures built throughout the last decade in every major Canadian city. However, this rapid progression in the building industry is accompanied by a heavy environmental price tag which is frequently measured in carbon emissions.

[14] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[15] UN Global Goals for Sustainable Development

[16] https://architecture2030.org/

[17] http://zero-code.org/

[18] https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html

At this point it is useful to define and differentiate two of the more commonly measured forms of carbon when examining the built environment; specifically, operational carbon and embodied carbon.

Operational carbon or emissions are the ones produced during the in-use operation of a building throughout the lifetime of a building from occupancy until demolition or vacancy. Today, nearly ⅓ of Canadian GHG emissions are directly caused by buildings making them a prime target for reduction strategies.[19]

Embodied carbon includes the measure of impacts that arise from the extraction, processing, transportation, and fabrication of construction materials, and is also referred to as embodied energy. Embodied carbon contributes an estimated 11% to the building industry's total GHG emissions [20]. According to Carbon Trust (2006), the embodied carbon emissions are generally linked with construction raw material extraction (quarrying or mining), manufacturing and transportation to site, on-site construction processes as well as building maintenance, repair, and refurbishment. End of life and decommissioning, including demolition, recycling and landfill, are also considered within the embodied carbon emissions. Depending on the calculations, other GHGs could be included as well[21].

The primary purpose of this paper is to investigate the viability and inclusion of concrete masonry in sustainable building design – namely Passive House and Net Zero standards – we will focus solely on the embodied carbon aspect of the built environment.

To this point we have established that embodied carbon is defined as the total primary energy consumed, carbon released, or emissions apart from the operational emissions. When designing a Net-Zero building with carbon neutral objectives, understanding how to accurately measure embodied carbon is essential to achieving this goal. A popular, and widely accepted, methodology for measuring embodied carbon (and therefore achieving a Net-Zero building) is called a Life Cycle Assessment (LCA); defined by the Architectural Institute of America (AIA) as "one of the best mechanisms for allowing architects and other building professionals to understand the energy use and other environmental impact associated with all the phases of a building's life cycle: procurement, construction, operation, and decommissioning." [22]

A recent study conducted by the International Institute of Sustainable Development (IISD) study, *Emission Omissions: Carbon Accounting Gaps in the Built Environment,*[23] confirmed that Life Cycle Assessment (LCA) is the best methodology for analyzing the carbon cycle in the built environment and thus reducing emissions. However, given the constantly developing definition around Net-Zero standards, the article importantly highlights that while LCAs are generally accepted, IISD research found that LCA tools can still have problematic deficiencies or gaps. For example, in some industries, LCAs overlook significant sources of carbon, and such gaps could result in misdirected or wasted efforts to reduce GHG's. The above research by the IISD called for increased transparency in carbon accounting, and the quantification of the existing assumptions about embodied carbon in various industries such as wood, steel, and

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[19] Environment and Climate Change Canada, 2019

[20] https://www.worldgbc.org/thecommitment

[21] Carbon Trust (2006)

[22] https://www.aia.org/resources/7961-building-life-cycle-assessment-in-practice

[23] IISD, Emission Omissions: Carbon accounting gaps in the built environment, 2019.

concrete building products. For example, one of the largest gaps addressed within the study is that current LCAs for forestry products entirely omit emissions from "biogenic carbon". These carbon omissions were found to represent up to 72% of the life-cycle emissions of wood products. Conversely, the study highlighted the carbon accounting transparency being demonstrated by the concrete industry. While at first glance identifying these "carbon accounting gaps" seems relatively simple, it is imperative to understand the material lifespan parameters of the LCA that is being utilized.

The LCA spectrum has three distinct thresholds where carbon can be measured and when comparing carbon emissions of various building materials, it is imperative that all materials be measured and accountable to the same threshold.

These boundaries can be defined as:

- Cradle to Gate:
- Cradle to Grave:
- Cradle to Cradle:

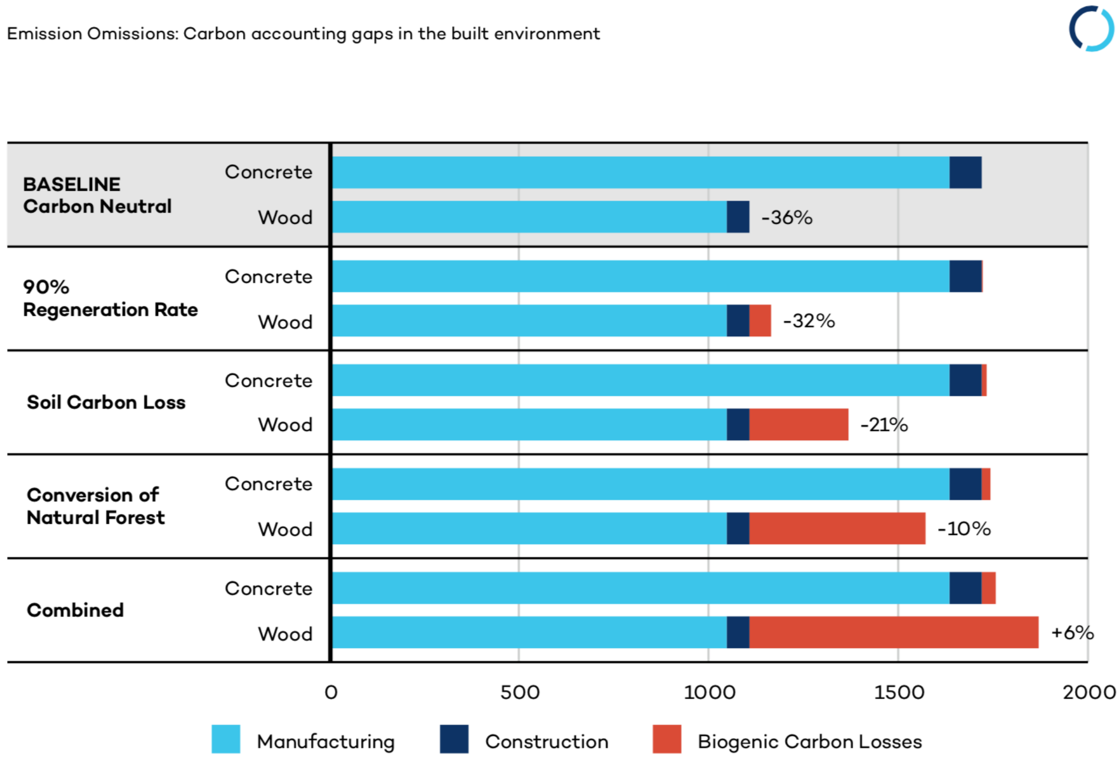

Figure ES1. Whole-building cradle-to-gate lifecycle greenhouse gas emissions: Alternative wood and concrete building construction considering four different forest management scenarios

Note: The functional unit is the whole building, based on a concrete and wood building design that has similar operational and service efficiency.

FIGURE 1: Whole-building cradle-to-gate lifecycle greenhouse gas emissions

Included in the IISD findings, the above graph demonstrates an LCA study comparing alternative design construction for a wood and concrete mid-rise residential building. The study has been conducted as a comparison between two structural frame versions of similar buildings. This LCA compares the life-cycle emissions for concrete and wood construction, however because the measure is using "cradle to gate" boundaries, biogenic emissions are not calculated within the LCA of wood, meaning that concrete further exceeds net timber lumber in terms of GHG and GWP. Despite this omission, as shown in the chart, at the total combined calculations concrete still has less emission intensity by 6%. Based on the above and the findings of the IISD study, a "cradle to gate" LCA can clearly be problematic because it results in inequitable comparison of carbon accounting between building materials, setting various materials at a respective advantage or disadvantage. Specifically, in the conversation around concrete, the manufacturing process is transparently carbon intensive which weighs heavily on the carbon footprint in this particular type of LCA.

Although the above IISD study clearly demonstrated concrete operating at a 6% less carbon intense footprint then alternate building materials, even within the cradle-to-gate LCA boundaries, the cement and concrete industries realize that there is much more work to be done in the production process in order to achieve the goal of Carbon Neutral 2050.

It is common knowledge that in order to produce concrete significant carbon dioxide emissions are released during the production of cement. The IISD study outlines the two basic stages comprising the cement production process: the production of clinker from raw materials and later the transformation of clinker into cement. In stage one, raw materials—predominantly limestone, (but also small quantities of clay, shale, sand and sometimes industrial waste to ensure the correct balance of chemicals) are ground and heated in kilns to a temperature of 1,450°C. As a result, limestone is decomposed into calcium oxide and carbon dioxide in a process called calcination. During the calcination process around 526 kgCO2/t clinker is released. (Environment and Climate Change Canada, 2017b, Appendix A6.2). In 2016, global production of cement was 4.2 billion tonnes, with most of this production accounted for by China. In the same year, almost 12 million tonnes of cement were produced by Canada, less than 1 percent of the global total. In stage two, clinker is ground with other mineral components to produce cement; gypsum is used to control the setting properties. Other additives are sometimes used to adjust other characteristics such as permeability. Portland cement (the most widely used cement type) contains 95% clinker with the remainder being gypsum.[24]

To date, the largest carbon reduction in concrete production that has been realized is the substitution of a lower-carbon Portland Limestone Cement (PLC) in place of standard limestone cement (GU). This claim is quantified in an article published by Rediscover Concrete defining Portland-Limestone Cement (Contempra™) (PLC). In this article, the substitution of PLC for standard Limestone Cement (GU) results in a reduction of CO2 emissions by 10%. By that rate, if all cement consumed in Canada were to be replaced by Portland-limestone, at least 1 million tonnes of GHG would be saved per year. This is equivalent to avoiding the consumption of 347 million liters of gasoline or planting 23 million trees annually. Another advantage of using Portland-limestone is that it still produces concrete with the same level of strength and durability as of concrete produced with ordinary Portland Cement. Portland-limestone cement is now referenced in the National Building Code through the CSA A.23.1 standard. Following recent successful sulphate testing programs, the new CSA A3001-13 and A23.1-14 Standards now provide specifications for the use of Portland-limestone cement in sulphate exposure environments. Using Portland-Limestone cement represents a momentous milestone in the industry's progressive efforts in reducing its environmental footprint. Throughout the last ten years, GHGs were reduced by 15%. The

[24] IISD, Emission Omissions: Carbon accounting gaps in the built environment, 2019.

transition from coal to lower carbon fuels taking place today could lead to an additional reduction of at least 20% in GHGs emissions[25].

To further support the drive towards alternative lower carbon fuels and net-zero, the Canadian cement industry is working closely with governments and stakeholders to promote the shift. A recent article in Construction Canada, "The Path to Zero: Concrete's role in Decarbonizing the Built Environment" written by Adam Auer, VP of Sustainability for the Cement Association of Canada, Auer argues; "

Overall, across the cement and concrete industries there are many short and mid-term goals being actively implemented to accelerate the drive to net-zero concrete. For example, another massive carbon reduction is anticipated by switching from coal and petcoke to lower carbon fuels for kilns. According to the International Energy Agency, based on the trials of leading jurisdictions, promising reductions of almost 50% after using alternative fuels were achieved. Low carbon fuels (LCF) that are derived from the waste stream (construction and demolition waste, agricultural waste, and non-recyclable plastics) are considered to be among the best alternative fuels to be used. These recovered fuels play an important role in the circular economy as well. Virgin fossil fuels are displaced with recovered material that would be otherwise destined for landfill or incineration. Cement manufacturing also has a distinctive advantage of being able to recover/recycle the mineral and metal contents of waste materials, which in turn reduces pressure on virgin sources. As climate change has emerged lately as a top priority for governments across Canada, LCF is being considered more closely as a GHG reduction strategy. The modernization of waste management policies and practices are also taking place at the same time[26].

In addition to the carbon reductions being achieved in the cement manufacturing processes, there are also great strides being made in concrete masonry and concrete block (CMU). For example, a proven method of reducing GHG during the process of CMU production takes place within the new transformative technologies such as Carbon Capture. Carbon Capturing can help transform concrete from a "carbon emitter" into a "carbon sink". Extensive investments are being made into the Carbon Capture technologies field.[27] Furthermore, innovations such as carbonated concrete, where concrete is cured using carbon dioxide instead of water are expected to reduce GHG emissions by 70% once the commercialization phases of such technologies are complete.[28] Curing concrete blocks at the time of manufacture using carbon dioxide can increase the uptake of carbon dioxide by the cement in the concrete block through "pre-carbonation", though concrete block that is not cured with carbon dioxide will also absorb carbon dioxide throughout its life through weathering carbonation. Either process results in an approximate absorption and storage of approximately 0.23 kg of CO2 per 20cm block unit.

While all of the above-mentioned methods are considered as short-term and easily actioned, in order to accurately account for concrete carbon emissions, the IISD suggests the consideration of cradle-to-grave LCA instead of cradle-to-gate LCA. The road is being paved for a confident inclusion of concrete mass, block, and masonry in the Net Zero Energy Building Standards. Reaching the goal would be much faster and accurate if existing carbon accounting

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[25] http://rediscoverconcrete.com/assets/files/revised-contempra-fact-sheet_v2.pdf

[26] https://www.iea.org/publications/freepublications/publication/Cement.pdf

[27] http://rediscoverconcrete.com/en/sustainability/reducing-our-footprint.html

[28] S. Ghoshal, F. Zeman, 15 - Carbon dioxide (CO2) capture and storage technology in the cement and concrete industry, 2010

gaps within the industry are addressed. As per the IISD, further studies into concrete carbonation rates would also help inform LCA analysis.

A recent study conducted at the University of Windsor, Canada entitled; Masonry Construction as a Solution for Healthy and Resilient Buildings: a Life Cycle Thinking Based Evaluation[29] has been looking into cradle to grave life-cycle assessments for interior walls constructed using concrete block, steel studs with gypsum walls and wood studs with gypsum walls. The study concluded that a concrete block-masonry wall's environmental performance is superior in the "cradle to grave" system boundary, which is an accurate and close representation of reality. In their study, the concrete block-masonry wall performed 89% better than the steel stud gypsum wall, which was the second-best. The environmental performance of the wood stud gypsum wall was the best among the three options until the construction phase (cradle to gate system boundary). This technique of using cradle to grave system boundaries considers more impacts like, global warming potential, nutrification, smog, natural resource depletion and water intake. Not all of these aspects are considered with the cradle to gate approach, which can result in significant inaccuracies to the broader image of different building materials and net-zero energy inclusion and viability[30]. Additionally, when a cradle-to-cradle analysis is implemented, there are several ways in which concrete outperforms and outlasts various other building materials; included but not limited to, overall lifespan, maintenance costs, carbon sequestering and recyclability.

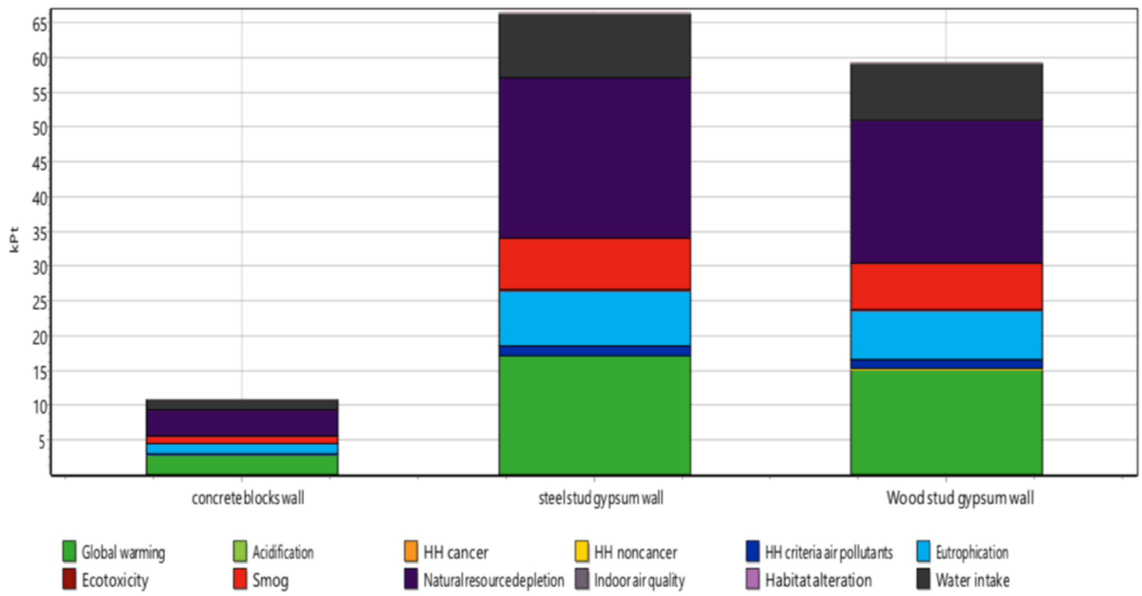

FIGURE 2: Cradle to Grave LCA of interior walls

In conclusion, although concrete block masonry is often dismissed as an overly carbon intensive product, there is transparent, objective, and quantifiable data that demonstrates the contrary. Based on these recent studies it is certain that concrete block masonry is less carbon intensive than other building materials in both cradle-to-gate and a cradle-to-grave life cycle analysis. Additionally, cement and concrete continue to actively drive towards process improvement and achieving Net-Zero by 2050. Concrete block is a product which has made

[29] Patel & Ruparantha, MASONRY CONSTRUCTION AS A SOLUTION FOR HEALTHY AND RESILIENT BUILDINGS: A LIFE CYCLE THINKING BASED EVALUATION, 2021

[30] Iyyanki V. Muralikrishna, Valli Manickam, Chapter Five - Life Cycle Assessment, 2017.

significant strides in its embodied carbon reduction and continues to pursue carbon elimination and sequestering in the manufacturing process. Given both these current carbon reductions and CMU and the commitment to achieving Net-Zero, CMU is an ideal candidate for a building material of choice in sustainable building design.

3 THERMAL PERFORMANCE

In addition to the accelerating conversation around carbon, energy and thermal performance requirements, these topics are growing and taking an increasingly significant position in building codes throughout North America, This is evidenced by their inclusion in both Passive House and Net Zero building standards as well as the NECB 2017, BC step code, and ASHRAE standards.[31] Understanding and meeting the requirements has also become increasingly crucial for building designers as buildings constructed in provinces that have adopted NECB 2017 or step codes must comply with the requirements in these standards. Consequently, it has become generally accepted amongst this community that important decisions need to be made at the onset of the design process to create cost-effective, energy efficient, and comfortable buildings that comply with the energy codes in effect where the building is to be constructed. Such decisions include construction and building materials, basic enclosure assembly design and window area. Designing a building that follows Net-Zero and Passive House Standards requires consideration of the thermal performance of its roofs and walls (especially exterior) and may involve creating a balance between the thermal mass of the selected building material and thermal insulation.

3.1 THERMAL MASS

For the purposes of this paper, the term Thermal Mass can be defined as the ability of a specific material to absorb and store heat energy. Materials are either high or low thermal mass materials. High (or heavy) thermal mass materials like concrete, or water, or stone, require a lot of heat energy to change their internal temperature and hence, the temperature on its other side. Low mass materials, like timber and steel, when exposed to heat energy, change their temperature rapidly. In the building sector, the general effect of thermal mass is used to regulate more stable interior temperatures.[32]

In order to understand thermal mass, it is important to note that heat is transferred within a building enclosure by three modes: convection (air leakage), conduction, and radiation. Bulk convection (air leakage) is controlled by the airtightness of the building envelope, which will be discussed later in this paper. For opaque assemblies (solid walls and roofs), the conduction and radiation modes are grouped together.

3.1.1 Thermal Mass & Net-Zero Energy Buildings

An enclosure with high thermal mass will absorb and release heat daily on a year-round basis. Such a feature is usually used to minimize cooling and heating loads that are required during summer and winter respectively. On warm summer days, (concrete block/ masonry) walls and concrete floors with high thermal mass will steadily absorb heat at their surface and store it

[31] Straube, J. & Hall B., Assessing thermal performance and resiliency of contemporary buildings, 2019.

[32] https://www.basalite-cmu.com/insulation-vs-thermal-mass

until exposed to the cooler air of the night. At this point, heat will begin to migrate back to the surface and be released. In this way, heat moves in a wave-like motion, alternately being absorbed, and released in response to the change in day and night-time conditions. This ability to respond naturally to changing conditions helps stabilize the internal temperature and provides a largely self-regulating environment, reducing the risk of overheating and the need for mechanical cooling.[33] Thermal mass, therefore, supports the concept of NZEB, since the thermal performance of a building is optimized through the usage of concrete block and/or masonry with minimal support from HVAC systems in heating or cooling seasons.

3.1.2 Thermal Mass and Passive House Standards

Thermal mass of concrete block and masonry walls has the ability to capture and recycle heat gains from south facing windows (known as passive solar design), along with those from lighting, people, appliances etc. As the temperature drops overnight, this is slowly released back into the building, helping keep it warm and reducing the need for supplementary heating. Whilst lightweight buildings are also capable of doing this to a limited degree, the extent to which free heat gains can be recycled increases with the level of thermal mass present. This complies directly with principle number five of the Passive House Standards; Managing solar gain to maximize its use during winter and minimize it in summer. This is also now recognized in SAP, which is the compliance tool for Part L1A of the Building Regulations, which deals with the conservation of fuel and power in new dwellings.[34] Carefully calculating FWDR and selecting the optimum glazing in accordance to the climate and context follows Passive House Standards; Employment of high-performance windows (at least double or triple-paned windows, varies according to context, climate and building type).

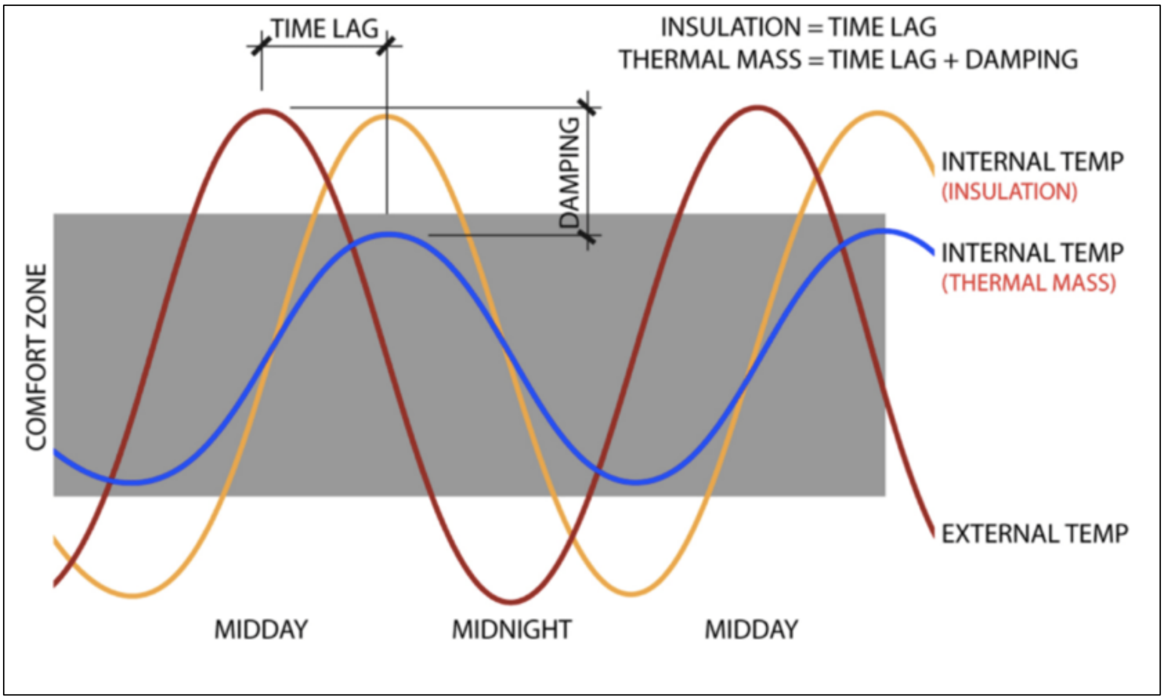

FIGURE 3: Basic principles of temperature comfort, insulation and thermal mass [35]

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[33] https://www.concretecentre.com/Performance-Sustainability/Thermal-Mass/Thermal-Mass-in-Summer.aspx

[34] https://www.concretecentre.com/Performance-Sustainability/Thermal-Mass/Thermal-Mass-in-Winter.aspx

[35] https://www.basalite-cmu.com/insulation-vs-thermal-mass

There are two common measures of a building's envelope assemblies to control heat flow via conduction/radiation: the U-value(Thermal Transmittance) and the R-value (Thermal Resistance). Both of these measures assume that the assembly is airtight so that heat transfer by convection can be ignored.

3.2 Thermal Bridging

The ability for a material to resist heat flow is measured according to the R-value and is inversely proportional to the thermal transmittance U-value. Therefore, the lower the U-value, the better the thermal resistance of the assembly and the better the thermal performance of the assembly (higher insulation value). The U-value of the construction is derived from the values of the individual layers. A low energy building needs low heat losses and hence a low U-value.[36]

There are many different definitions of R-value. The definition applied depends on the code, code official, and the different needs of energy modelers and designers. However, the most important distinctions between different definitions involve how thermal bridging is considered. There are several types of R-values reported in the industry or demanded by codes. Some of them are:

- The Rated or Labelled R-value which is the value printed on the package or technical data sheet along with the thickness intended for use.
- The Installed R-value, or nominal R-value is simply the rated R-value of the insulation products in their installed condition (e.g. compressed batt insulation or not). The contribution of other materials is ignored.
- The Assembly R-value or Center-of-Cavity is calculated by assuming the assembly is one-dimensional and simply adding the thermal resistance of all layers (e.g. in a concrete double-wythe insulated "sandwich" panel, the outer concrete, insulation, inner concrete, air films).
- The Whole-wall R-value, (Rww) includes the clear-fieldR-value (Rcw) plus the thermal impact of conductive penetrations (e.g. floors) and any additional framing or fasteners at openings (e.g. windows and doors), and the effects of thermal bridges at changes in plane and other interfaces (e.g. foundation-to-above-grade wall, wall-to-roof, balconies, etc.) but excludes window area. For simplicity, sometimes the clear-field R-value is used when the whole-wall R-value should be (i.e. thermal bridging is ignored), but this approach can significantly over-estimate the thermal performance of many commercial enclosure systems.
- The Overall R-value (Roverall) measures the performance of an entire enclosure type (such as wall or roof) and includes the combined effect of whole-wall R-value (Rww) plus the heat loss through windows, doors, and curtain walls. It is important for understanding overall building performance and is implicit to the simple trade-off methods used to demonstrate compliance.

Unfortunately, there is no single accepted definition for R-value of a building envelope assembly and a single R-value definition is not used as a term in all of the major energy standards, it varies depending on both the user of the term and the context.

Although R-value uses traditional inch-pound (IP or I-P) units, it remains the most common means of communicating thermal resistance. Canadian codes and standards usually employ

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[36] Straube, J. & Hall B., Assessing thermal performance and resiliency of contemporary buildings, 2019.

metric (SI) units. To differentiate the metric (SI) from the traditional (IP) unit's metric, thermal resistance is reported as RSI and the two can be easily converted.

$$\text{R-value } (ft^2\text{-}^oF\ h/Btu) = RSI * 5.678$$
$$RSI\ (m^2\text{-}K/W) = \text{R-value} / 5.678$$

Also, any of these R-values might also be reported as a U-value (U = 1/R)

The U-value is commonly used to describe the overall thermal transmittance of an assembly and is defined simply as:

$$U = 1 / RT$$ [37]

When heat moves through an enclosure, it flows through more than just the center of the assembly Additional heat will bypass the insulation and flow through more conductive areas such as steel or concrete that penetrate the insulation layer. Such penetrations, labeled as thermal bridges, are inevitable in the construction of building envelope assemblies and energy codes increasingly require designers to account for them when judging compliance of an assembly with codes and standards.[38] If unaccounted for, thermal bridges (even of minimal R-values for single bridges) can result in an accumulated and considerable heat transfer which can result in reduced thermal performance of enclosures, resulting in rapid heat loss and requiring additional energy consuming compensations. This is often referred to as a cold bridge. Thermal bridges can be estimated by several different calculation techniques to provide the U-value of the total wall system including thermal bridges .[39]

Computer-based finite-element thermal models of two (2D) or three dimensions (3D) are generally preferred over thermal testing of envelope assemblies. However, the more accurate 3D finite element thermal modeling software products that are commercially available are still both very expensive to purchase and computationally intensive. As a result, only small sections of the envelope can be realistically modeled and often, the cost of project-specific analysis may not be justified for early-stage design or small projects. Other simpler hand calculation methods, such as the parallel path and zone method can and have been used for years to assess thermal bridging in enclosures but are less accurate than their 3D finite thermal model counterparts. Steel stud and wood stud backup walls often use the parallel path method. This method uses an area-weighted U-value based on different possible heat flow paths usually with significantly different thermal performance and is analogous to electricity flowing through resistors configured in a parallel circuit. With wood or steel stud backup walls thes insulation within the stud cavity has a higher thermal resistance than the studs which act as thermal bridges.The heat transfer can take a path through the stud or through the insulation as it moves through the assembly and is an example where there are two thermal resistors in parallel. Thus, the aggregated thermal resistance of the stud and cavity insulation can be calculated into a single R-value (and resulting U-factor) using the parallel path method. The thermal bridging phenomenon is illustrated in Figure 5 where thermal bridging of the wood-stud wall and floor framing has melted the frost and created damp, dark,areas beside the white frost at locations of the wall and floor framing.

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37 Straube, J. & Hall B., Assessing thermal performance and resiliency of contemporary buildings, 2019.

38 Christian & Kosny, Thermal performance and wall ratings, 1995

39 Straube, J. & Hall B., Assessing thermal performance and resiliency of contemporary buildings, 2019.

FIGURE 4: Thermal bridging of a wood-stud wall evidenced by dark areas on white frost at locations of the wood framing.[40]

Other examples include a concrete block wall where the heat can flow through the webs or the cells, or a wall and a penetrating balcony. They are typically calculated separately, and their RSI-values weighted in proportion to their relative area.[41]

In masonry assemblies, thermal bridging typically occurs at locations such as shelf angles which support the weight of the masonry veneer and masonry ties that laterally tie the veneer to the back-up wall. These locations are in addition to the linear thermal bridges encountered in all wall systems regardless of material such as at-grade transitions, floor transitions, roof transitions, corner transitions and window and door transitions. Occasionally stainless steel or a similar material is chosen for such shelf angles and masonry ties as stainless steel is more resistant to corrosion and has ⅓ the conductance of structural steel. However, stainless steel is significantly more expensive and does not resist thermal bridging as well as plastics or glass fibre reinforced polymers (GRFP) which better manage heat loss which is unwanted within low-energy buildings.[42] However, GFRP stand-offs and other composite materials are currently being explored for wall ties and shelf angles/standoffs in full bed masonry wall systems. These materials are engineered to introduce structural breaks in the assembly that provide a barrier to thermal transfer while maintaining structural performance. Not only do

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[40] Photograph Courtesy of Alberta Masonry Council.

[41] World Bank, World Development Report, 2010.

[42] https://www.constructioncanada.net/thermal-bridging-at-brick-ties/

these materials offer premium thermal performance, most deliver exceptional fire resistance, structural performance, and durability.[43]

3.3 Windows and Thermal Performance

Other aspects that significantly influence the thermal performance of a wall are openings for fenestration and doors. Accurate thermal performance, and code compliance, requires the designer to also consider the influence of windows and curtain walls on heat flow through the total vertical enclosure. Window and curtain wall required R-values are significantly lower than the R-values required of opaque walls. Heat flows preferentially through lower thermal resistance components like windows and doors, much more heat is transmitted through these components and thermal bridging to the opaque wall also occurs at the interface of the wall and windows or door. Because windows and doors are typically poor thermal performers, the number of windows in a wall greatly affects the overall thermal performance and is assessed by examining the ratio of windows and doors to the opaque wall. This ratio of windows and doors to opaque walls is often referred to as the Window to Wall Ratio (WWR) or Fenestration and Door to Wall Ratio or FDWR. FWDR is a key component of the NECB's trade-off method. Figure 6 demonstrates the remarkable impact of WWR (FWDR) for a system with a clear-field R-value of 20 and high-performance double-glazed aluminum windows. The overall enclosure R-value drops from R-9.4 to R-4.5 as the WWR (FWDR) increases from 20 to 60%. This is further illustrated in Figure 5 where using a higher WWR (FWDR), from 40% and higher, offers very little gain in thermal performance even after doubling the opaque wall insulation (i.e. the R-10 and R-20 lines approach each other). These examples reinforce how the reduction of window area can significantly increase the overall performance of a wall. Increasing the opaque wall area by reducing the number of windows can also be used to deliver equivalent thermal performance for a wall system that uses less insulation to a wall system with higher opaque wall insulation and more windows. As a result, the combination of high thermal performance windows and lower FWDRs is most often the lowest cost approach to energy efficiency and thermal comfort[44].

[43] https://ferocorp.com/wp-content/uploads/2021/02/FERO-Technical-Brochure-Ties-FAST-Digital-Version.pdf

[44] Straube, J. & Hall B., Assessing thermal performance and resiliency of contemporary buildings, 2019.

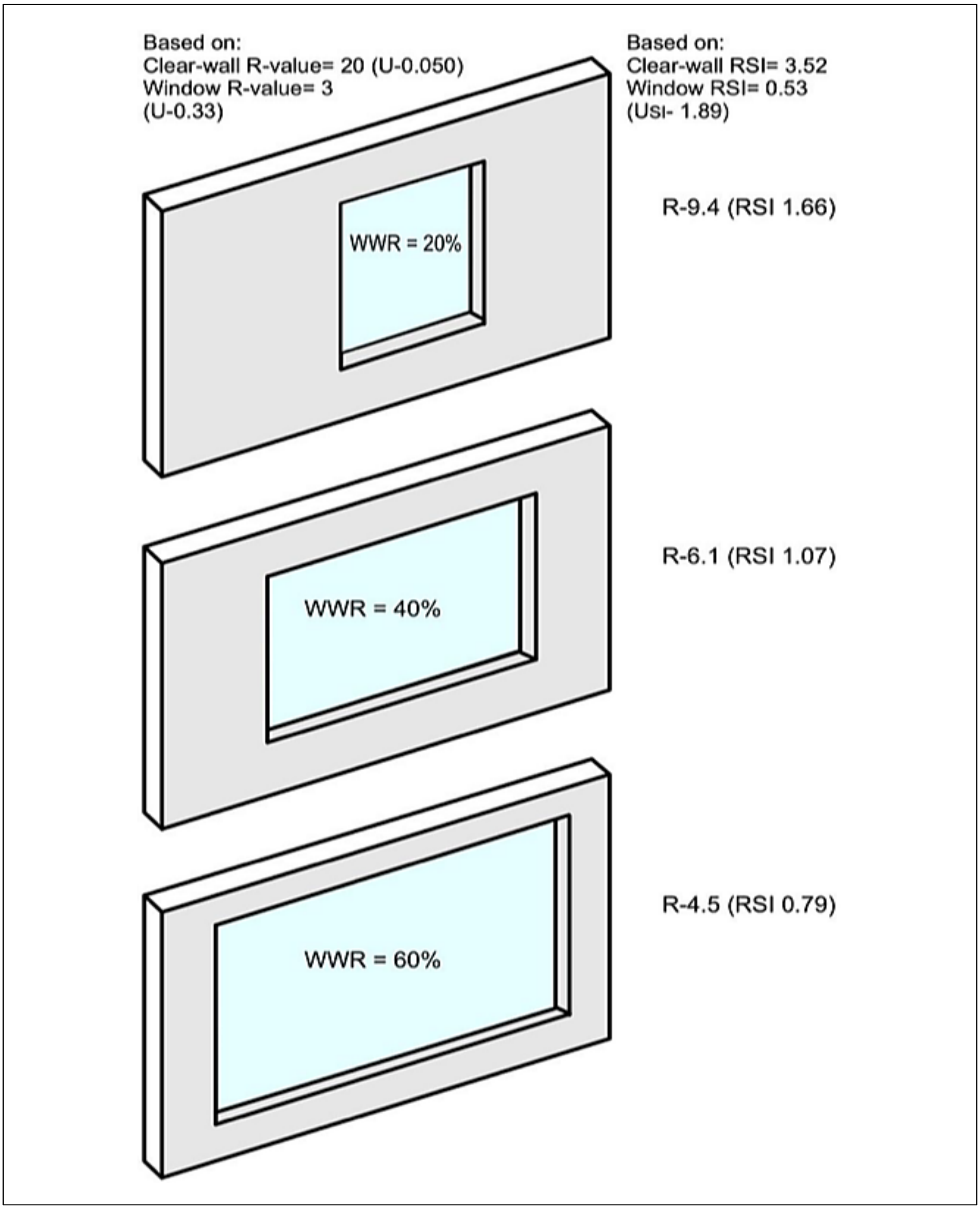

FIGURE 5: Impact of FWDR (WWR) on the overall thermal performance of a wall assembly

3.4 Surface Emissivity and Solar Reflective Index (SRI)

In addition to horizontal heat transfer through walls, solar heat is also gained through vertical flow through roofs. Roofs play an important role in heat gain or loss in a building especially since warm air rises carrying heat. For heat to be stored or released from an exposed soffit, for example, it must pass between the surface and occupied space below, and although heat moves relatively quickly through concrete, it is generally more limited at its surface, which acts to some extent as a thermal bottle neck. Soffits encourage turbulent air flow across the roof structure and increase convective heat transfer. Soffits are needed to vent an attic space and prevent the accumulation of unwanted moisture. Alternatively, building envelopes that place the roof insulation outside of the attic space do not require venting and soffits and are typically easier to make airtight. This produces a much more energy efficient roof envelope system.

The rate of heat transfer through radiation is determined by another factor called surface emissivity. Emissivity describes how shiny or matte a surface is and is measured by a factor ranging between 0 and 1. Emissivity is an important characteristic because matte surfaces, such as that of concrete, have a high emissivity level of between 0.85-0.95, making them very good at absorbing and emitting radiant heat. In contrast to this, relatively shiny surfaces such as galvanized steel have a much lower emissivity of around 0.22-0.28 that limits radiant heat flow. Since heat transfer to and from the soffit is typically about 2/3 radiant and 1/3 convective, a low surface emissivity has a significant impact on overall performance.

The Solar Reflectance Index (SRI) is a measure of the solar reflectance and emissivity of materials that can be used as an indicator of how hot they are likely to become when solar radiation is incident on their surface. The lower the SRI, the hotter a material is likely to become when exposed to solar radiation. Cool Metal roofs, with both high reflectivity and high emissivity, offer significant savings in reducing cooling loads. By definition, cool roofs reflect much of the solar radiation, and that which is absorbed is re-radiated by virtue of high emissivity. This is beneficial in predominantly warm climates like the southern US. However, in Canada, heating load predominates, even in the warmest cities. Thus, energy savings in Canada can be achieved by selecting materials with low infrared emissivity. Pre-painted, asphaltic and membrane roofs have high emissivity and therefore re-radiate much of absorbed infrared solar radiation at night - a detriment in winter when absorption heat should be retained to reduce heating loads. A 55% Aluminum-Zinc roof combines the benefit of high reflectivity, which reduces summer cooling load, with the benefit of low emissivity, which reduces winter heating loads[45]. A concrete block or masonry wall that is left unfinished and uncovered provides better performance in terms of thermal mass than other materials and adding a layer of finishes (such as paint) for aesthetic reasons typically has negligible impact on thermal mass properties of a block wall.

3.5 THERMAL INSULATION

Thermal insulation is the process of heat transfer reduction between objects in thermal contact, or within a range of radiative influence. To achieve lower system thermal conductivity, thermal insulation elements are made from low thermal conductivity materials. Thermal insulation can be achieved with specially engineered methods or processes, as well as with suitable object shapes and materials. In the building sector, the term “Insulation” is used to describe a familiar material used to restrict the transfer of low temperatures through a buildings’ envelope and into the interior. Insulation materials are typically measured in R-value. Essentially, insulation “lags" the time it takes for an outside climate to enter a building through the building envelope. By using adequate thermal insulation materials, surface temperatures are then controlled for personnel protection and comfort. Temperature control is facilitated and vapor flow and water condensation on cold surfaces can be prevented by the appropriate placement of a vapour barrier in contact with the warm side of the insulation. Appropriately selected levels of thermal

[45] https://www.designingbuildings.co.uk/wiki/Solar_Reflectance_Index_in_the_built_environment

insulation increase the operating efficiency of heating, ventilating, cooling, plumbing and other various power systems and hence, reduce emissions of pollutants to the atmosphere.

3.5.1 Insulation Types

There are three main types of insulation: Fibrous Insulation, Cellular Insulation, and Granular Insulation. Fibrous insulation is typically composed of small diameter fibers finely, dividing the air space. They may or may not be bonded together and are usually made of Silica, rock wool, slag wool or alumina silica fibers. The most common fibrous insulations are glass fiber and mineral wool. These products usually have their fibers bonded together with organic binders, reinforcing the structural integrity of the insulation. Cellular Insulation, as indicated by its name, is composed of small individual cells separated from each other. The cellular material may be glass or foamed plastic such as extruded polystyrene (closed cell), polyisocyanurate, or elastomeric. Granular Insulation is made of small nodules which may contain voids or hollow spaces. It is different from cellular insulation, as gas transfers between these gaps. Granular Insulation can be produced in various forms such as loose / pourable form or rigid (when combined with binders, fibers or undergo chemical reactions). Calcium silicate, cellulose and expanded polystyrene are well-known examples of granular insulation.

The diverse uses of insulation in the building sector results in a variety of forms to meet specific functions and applications. Methods of installation are determined by both the form and type and insulation. The most widely used forms of insulation used are:

- Rigid Boards and Blocks.
  All types of insulation (fibrous, cellular, and granular) can be produced in solid forms, creating the previously mentioned material forms.

- Flexible Sheets and Preformed shapes.
  Usually produced by cellular and fibrous types of insulation.

- Flexible Blankets
  Usually produced by fibrous types of insulation

- Cements (insulating and finishing).
  Produced from fibrous and granular insulations and cement, they may be of the hydraulic setting or air-drying type.

- Foams.
  Poured or froth foam used to fill irregular areas and voids. Spray used for flat surfaces.[46]

LOW TEMPERATURE RANGE (15°C to -75°C)

Due to its large geographical area, Canada has an extensive variety of climates (Figure 6). There are rainforests on Vancouver Island, marine environments on the east and west coasts, mountainous regions in Alberta and British Columbia, desert conditions in the badlands of Alberta, semi-arid climates on the prairies of Alberta, Saskatchewan and Manitoba, high humidity climates near the great lakes in Ontario, and arctic/tundra in the territories.

[46] http://tiac.ca/wp-content/uploads/2015/12/TIAC_Guide_English_2013-Section-02.pdf

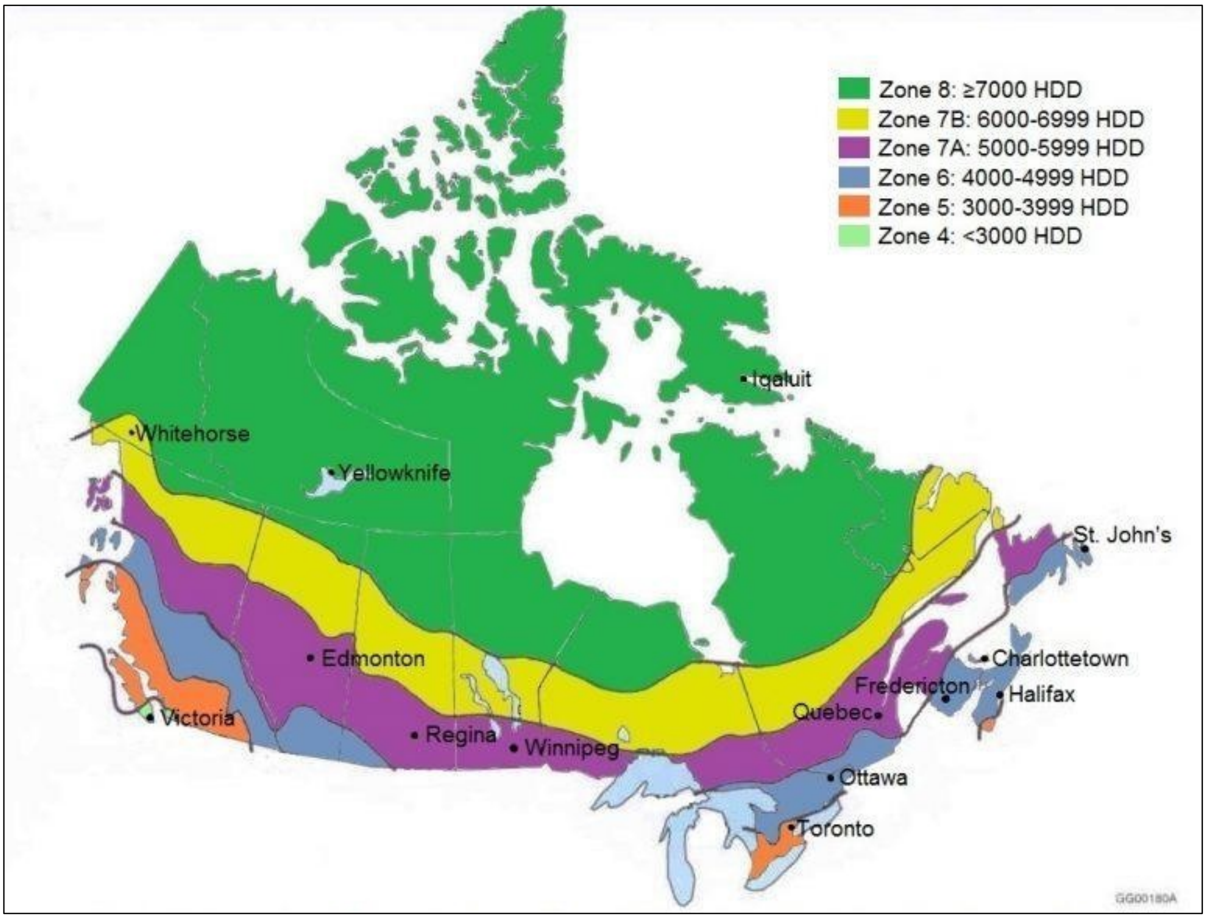

FIGURE 6: Climate Zones in Canada

The northern two-thirds of the country has a climate of very cold winters and short, cool summers. The central southern area of the interior plains has a typical continental climate—very cold winters, hot summers, and relatively sparse precipitation. Southern Ontario and Quebec have a climate with hot, humid summers and cold, snowy winters. On the other side, on the west coast, all of Canada has a winter season with below freezing average temperatures and with constant snow cover.[47] Generally, Canada is known to fall under the low temperature category, which ranges between (15°C to -75°C) most of the year.

The predominant design challenges that face installations in low-temperature regions are moisture penetration and operating efficiency. For below ambient applications, insulations are preferred to have a low level of moisture absorption. In addition, vapour barriers are extensively used, but in practice it is difficult to achieve the perfect vapour barrier particularly in residential buildings that use non-self-healing polyethylene vapour barriers on the interior of the structural wall. The pressure of the vapor flow from the warm outside surface to the cooler inside surface is such that, even with waterproof insulation, vapor may diffuse through the material, enter through unsealed joints or cracks, and condense, and cause damage in the form of corrosion with steel stud backup walls and mold and rot in wood-stud backup walls.

- Refrigeration (0°C through -75°C)

[47] https://www.britannica.com/place/Canada/Climate

Water vapour that breaches the vapour-barrier will not only condense but may freeze as well. The built-up frost and ice will likely cause deterioration in all types and forms of insulation systems.

- Cold and chilled water (15°C through 0°C)

Within this temperature range, water vapor will condense, causing corrosion on structural steel elements and mold and rot on wood elements. Failure of the insulation assembly is also possible if the insulation is not hydrophobic.

There are several types of insulation that are generally used within this temperature range. For instance, Cellular Glass, Elastomeric Foamed Plastic, Fiberglass, Mineral/ stone fiber and Cotton insulation.[48]

3.5.2 Thermal Insulation and Passive House

A key feature of a passive house is that they incorporate very high requirements for insulation. One of the first requirements of Passive House is the employment of continuous insulation throughout a building's entire envelope with zero to minimal thermal bridging. This reduces the amount of heat lost through the building fabric to a minimal level. Heavily insulated buildings better mitigate the effects of thermal bridges compared to lightly insulated buildings. This can be an important consideration for the refurbishment of existing buildings. When the Passive House requirements of thermal insulation are met in an enclosure's design, heating requirements are reduced to a minimum even on the coldest days. Hence it is possible to adequately heat the dwelling by just preheating the fresh air entering the rooms, thereby reducing energy usage. [49]

The U-value of a Passive House wall needs to be quite low to achieve this level of energy performance. For typical buildings, U-values of Passive House walls should range between 0.10 and 0.15 W/m^2-K; depending on the climate, these figures may be somewhat higher or lower.

Passive House certified thermal insulation materials are currently available on the market. Specific brands of Mineral Wool insulation are commonly used in passive house practices as they provide exceptional thermal performance and are also non-combustible and moisture resistant. The R-value of mineral wool insulation products do not change over time. The production process of mineral wool does not use blowing agents, which can off-gas and result in lower thermal performance. They do not expand or contract with the variance of temperatures within the enclosure. As a result, the wall's thermal performance remains consistent because of the dimensional stability of mineral wool products.

Other considerations with Passive House design include fire resistance and life safety. Mineral wool insulation is exceptionally resilient to fire and has a melting point of approximately 1177°C (2150°F). Additionally, it does not contribute to flame spread and does not add to the emission of toxic smoke even when directly exposed to fire. As a result, mineral wool

[48] https://www.leafscore.com/eco-friendly-living-products/the-best-materials-for-eco-friendly-insulation/
[49] https://www.phius.org/what-is-passive-building/passive-house-principles

insulation products act as a critical line of defense against fire, keeping occupants safe as well as reducing property damage in the event of a fire[50].

4 BUILDING ENVELOPE

A Building's Envelope is defined as the collection of components that divide a conditioned space from unconditioned space, including the outside air, or the ground, or when separating conditioned spaces meant to be conditioned to temperatures that differ by more than 10ºC.

The complexity of constructing walls to current Canadian building codes can be illustrated by a list of functional requirements that must be satisfied. According to the science of building envelopes, there are at least 13 distinct aspects to be fulfilled in order to construct a successful building envelope.[51] First, it must offer the necessary structural integrity in reaction to imposed building loads, such as seismic, wind, occupancy and self-weight. Structural design is addressed in Part 4 of the National Building Code of Canada (NBCC) The structure can be a mix of frame member sizes, sheathing types, and structural reinforcement as needed. The wall assembly must also provide complete rain and weather protection of the interior space from the exterior environment. With respect to the needs of the interior environment, thermal insulation is necessary to manage heat flow, air barriers are required to restrict undesired air movement, and vapor barriers are required to prevent airborne moisture from entering the back-up wall assembly. Other factors that are also considered include building codes, regulations and standards govern material performance requirements including, in some circumstances, fire safety, sound attenuation and moisture management. Part 5 of the NBCC relates to Environment Separation while Part 3 addresses fire safety. The owner and the design team will also have requirements with respect to the wall system's economics, final aesthetic, and other factors such as wall thickness, and usable interior space. In residential construction, a framed wall assembly, typically wood-stud, is used to construct the structural wall, while a variety of insulation, membrane, and cladding products can be used to complete the envelope. These components and materials must act in concert to fulfill all of these various criteria and will have a direct influence on the short-term and long-term comfort of the inhabitants, the building's energy usage, maintenance frequency and requirements and the quality of the indoor environment[52].

4.1 BUILDING ENVELOPE PERFORMANCE AND EFFICIENCY

The primary functions of a successful building envelope are as structural integrity, water resistance, air tightness, condensation resistance, movement allowance, thermal control energy efficiency, sound transmission attenuation, fire safety, maintainability, constructability, durability, aesthetics, and economical value[53]. These functions are described in detail below.

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50 http://tiac.ca/wp-content/uploads/2015/12/TIAC_Guide_English_2013-Section-02.pdf

51 https://www.wbdg.org/guides-specifications/building-envelope-design-guide/building-envelope-design-guide-introduction

52 (Arsenault, 2015) https://continuingeducation.bnpmedia.com/courses/certainteed-insulation/the-science-behind-building-envelope-design-in-framed-wall-assemblies/2/

53 https://www.wbdg.org/guides-specifications/building-envelope-design-guide/building-envelope-design-guide-introduction

Structural Integrity

First and foremost, a building envelope should support its own weight and transfer lateral stresses to the building frame if the wall or the main exterior wall frame in other words, is not part of the main building structure.

Water Resistance

The capacity of the envelope to manage moisture transport is the most essential aspect of its regulation. Moisture is a significant threat to a building's general integrity and must be considered. Moisture is the number one cause for envelope failure and poor building performance and sometimes structural damage. Moisture affects any structure from above (roof), below (basement/floor), and on the sides (walls). To prevent undesired transfer from inflicting significant harm, each component must be addressed. It is necessary in all climates, but it is especially important in cold and hot-humid regions.

Air Tightness

Resisting excessive air infiltration is crucial to creating a successful building envelope. Controlling air flow is critical for reducing energy consumption, maintaining indoor air quality, preventing condensation, and providing comfort. Air movement control encompasses flow through the enclosure or via components of the building envelope itself, as well as into and out of the interior area. For example, when a home is referred to as drafty, we're referring to the regulation of air flow and the heat that is carried away by the air flow. As a result, air tightness is one of the main principles of the Passive House Standards.

Condensation Resistance

Under service circumstances, condensation resistance on interior surfaces is required.

Movement Allowance

A building envelope has to allow for differential movement that could be caused by moisture, seasonal or diurnal temperature variations, and structural movement. This is usually achieved by including movement joints, especially around openings in the envelope i.e.; windows and doors.

Thermal Control/ Energy Conservation

The envelope should reduce thermal transfer through radiation, convection and conduction to reduce the energy consumption and emissions from the HVAC systems.

Sound Transmission Attenuation

The building envelope should account for the attenuation of sound as this contributes to occupant comfort. A Sound Transmission Class exceeding STC = 50 is desirable to reduce sound transmission particularly in multi-family residential buildings, hotels, hospitals, and schools.

Fire Safety

The building envelope should provide rated resistances to fire and flame spread, and smoke.

Maintainability

The building envelope components should be selected so they reduce the frequency and magnitude and cost of repairs and maintenance, as well as facilitate the maintenance, repair, and replacement of components.

Constructability
Allowing for appropriate clearances, alignments, and sequencing to allow for the integration of several components throughout construction utilizing accessible components and attainable craftsmanship.

Durability
The building envelope should provide functional and aesthetic characteristics that remain intact for a prolonged time.

Aesthetics
Meeting the aesthetic expectations of the design and lasting throughout the building's lifetime.

Economical Value
The building envelope should be as economical as possible considering not only initial cost but also the cost of maintenance over the service life of the building.

The intended level (or standard) to which the system must be constructed for each of the aforementioned functional needs is referred to as building performance. For example, what movement dimensions must be accommodated, and what is the system's projected useful life, or durability. The majority of these tasks are also applicable to fenestration and the roof, and a few are also valid for below-grade construction. The design of the structure is expected to be thoroughly measured and carried out to guarantee that there are no exposed edges, cracks between the windows and walls, or flaws between the roof and the walls or between the walls and the base. It's all part of the building envelope idea. Each layer of the enclosure has its own unique obstacles. For instance, roofs are bombarded by heat, rain and hail, walls on the other hand are contented with wind and rain. Below-grade superstructure, foundations are always surrounded by wet, damp earth along with seismic and lateral loads.

Building envelopes are often characterized as either "tight" or "loose." A loose building envelope allows for more natural air transmission, which improves indoor air quality and perhaps eliminates the need for artificial ventilation. However, a loose building envelope can create a draftier interior space, and make temperature regulation more difficult and expensive and carbon intensive to operate. Therefore, a loose building envelope typically contradicts NZEB and passive house objectives.

A tight building envelope provides better control over the internal air quality, temperature, humidity, and energy usage. To achieve a tight shell for a building, energy-efficient windows and doors, lower FDWRs, additional insulation, and extensive use of sealants are required. This typically results in a more pleasant building for its residents, with less energy waste when it comes to heating and cooling. Tight envelopes are also less likely to produce mold or mildew resulting from moisture intrusion, which can assist extend the life of building components. The disadvantage of a narrower building envelope is that it needs more expensive mechanical ventilation systems since it restricts the amount of natural ventilation that may occur. Without an efficient building envelope, cooling and heating sources are continuously battling the outside elements to condition the interior space. This is not only costly, but it can translate into significant reliance on mechanical systems. For instance, if the building design allows for leaks and draughts, a building where the air conditioning system has been turned off for a long period would take longer to cool when the air conditioning system is turned on. .[54]

Some techniques were discovered to be extremely useful in producing tight and efficient building envelopes based on fieldwork with home builders throughout the country performed by the National Association of Home Builders (NAHB) Research Center under the Department of Energy (DOE)'s "Building America Program". One of the recurring outcomes from these studies is that a successful building envelope is one that is well ventilated. With wood-framed homes, water can condense on the interior of a roof, allowing moisture to seep into the insulation and reduce its efficiency while also fostering rot mold and mildew. These conditions may damage the rafters and framework of the structure, rendering it structurally unsafe as well as create respiratory issues from mold for the occupants. With appropriate ventilation and placement of insulation, air and vapor barriers, condensation is managed. This helps to keep the integrity of the thermal insulation and roof space for a much longer period of time. Another method of ventilation works in tandem with insulation by releasing heat that would otherwise be forced back down into the structure during the hotter months. The quantity of ventilation required will be determined mostly by the amount of roof space to be covered. Installing vents in high and low areas of the roof (e.g., soffit vents and ridge vents) increases air movement and reduces the possibility of moisture buildup.[55]

4.2 AIR TIGHTNESS

One of the most significant purposes of the building enclosure and, in certain circumstances, the interior walls is the restriction of air flow by the air barriers system. Water, vapor, heat energy, and airborne pollutants are all transported through air. As a result, uncontrolled air leakage can cause moisture problems due to condensation and bulk water infiltration, excessive heat loss, which causes discomfort and energy waste, and poor indoor air quality, which impacts occupant health and comfort. Airtightness is the elimination of any unintentional gaps and cracks, holes, splits, and tears through which air can travel into and out of the building's "conditioned" area (heated or cooled space). Such gaps, cracks, can account for up to 50pc of all heat losses via a building's exterior envelope and can be caused by bad construction design, poor craftsmanship, or the use of incorrect or inappropriate materials. It is crucial to understand that an airtight building does not mean it is hermetically sealed, but rather that inadvertent air leakage has been controlled and minimized.[56]

Airtightness is significant in various aspects of a building, like heat, moisture, comfort and human health. Airtightness is crucial for preventing heat loss because it allows for less uncontrolled air flow in and out of the structure. Less heat loss also means that the heating system will function more efficiently, lowering the heating expenses as well as energy usage. It also helps to maintain thermal comfort (ie. insulating better in winter and reducing overheating in the summer). Energy savings are an essential aim of creating airtight enclosures, and they are a driving force for the introduction of enhanced air tightness regulations for buildings. As for moisture, water vapor is transported by air movement or diffusion. Most of the time, air movement is the primary moisture transfer method. Condensation can occur as a result of moisture transfer in an enclosure, particularly when relatively warm, moist air flows towards a cooler surface. As moisture from rain or snow is pushed in by air leakage caused by

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[54] https://www.probuilder.com/11-tips-mastering-building-envelope-design

[55] https://build.com.au/building-envelopes-draughts-and-ventilation

[56] https://passivehouseplus.ie/magazine/guides/the-ph-guide-to-airtightness

the moving air, it can also cause bulk water to enter the enclosure. When an air barrier material is required, its location is important for moisture management and therefore wall durability. First, air movement can transport a substantial quantity of moisture into or through a building assembly, and second, the air barrier can function as a vapor retarder. It is important to recognize that an air barrier is intended to regulate the passage of air into and out of the building envelope, whereas a vapor retarder is intended to limit the diffusion of water vapor through building materials and subsequent condensation. Because a vapor retarder may also hinder drying, the necessity for one varies according to climate, building type, and building usage. Moisture collection in the enclosure might cause mold and hence health hazards. The spread of smells, noise, pollutants, and pests is further aided by air leakage over the building perimeter and across interior building zones. Poor airtightness implies that there is minimal control over where the air comes from and how much penetration happens, as well as the path the air takes to reach the area, all of which have an influence on the interior air quality. It can enhance health by preventing allergens from being transported into the building through air leakage, and it can also result in improved sound insulation within the building. Compartmentalization is also an essential aspect of cross-fire safety. A well-designed mechanical ventilation system combined with an airtight building enclosure may provide a high-performance solution that increases durability, decreases heat loss, and improves air quality. [57]

As previously mentioned, air barrier systems are sometimes designed as a part of the building envelope to reduce air leakage. Alternatively, the thermal envelope can also be designed and detailed to function as an air barrier system. Current building codes (ref. 4) do not specify quantitative air barrier standards, but rather mandate that the outside envelope be sealed to prevent air infiltration/exfiltration through both commercial and residential building envelopes. However, the 2012 International Energy Conservation Code (IECC) (ref. 5) and certain local governments have implemented performance criteria for commercial building air leakage management. The 2012 IECC specifies three levels of compliance for air barrier materials, air barrier assemblies, and the entire structure. These commercial air barrier requirements are only applicable to climate 4 to 8 buildings. . One of the following compliance criteria can be:

- At a pressure difference of 1.57 lb/ft2 (0.02 L/s-m2 at 75 Pa), a building material intended to function as an air barrier must have an air permeance of less than 0.004 cfm/ft2 or,
- An air barrier assembly, such as a concrete masonry wall assembly, must have an air leakage rate of less than 0.04 cfm/ft2 at a pressure difference of 1.57 lb/ft2 (0.2 L/s-m2 at 75 Pa), or,
- At a pressure difference of 1.57 lb/ft2 (2.0 L/s-m2 at 75 Pa), a building must have an air leakage rate of less than 0.4 cfm/ft2.[58]

Multi-wythe concrete masonry assemblies provide a number of alternatives for meeting the commercial building air leakage criteria stated above. There are various proprietary air barrier materials and accessories available in addition to the presumed alternatives. Most air barrier materials are coatings that are typically placed on the cavity side of the backup wythe. But also, certain spray-applied insulation and rigid insulation, with sealed connections, can be utilized as an air barrier.[59]

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[57] BC Housing, Achieving Airtight Buildings, 2017.

[58] NCMA, TEK 6-14A, Revised 2011.

[59] NCMA, TEK 6-14A, Revised 2011.

4.2.1 CODES AND STANDARDS

When coatings such as paint or block filler are called for, they can be applied to either the interior or exterior side of the concrete masonry, so any masonry architectural finishes need not be compromised. These Standards include:

- National Building Code for Canada (NBC) 2020
- National Energy Code for Buildings (NECB) 2020
- ASHRAE

While the NECB does not specify airtightness, it does provide a suggested air leakage rate of 0.25 L/(sm2), which corresponds to "a typical infiltration rate at 5 Pa," according to Section A-8.4.3.4.(3) of the code. This suggested pace is covered in further detail in Chapter 0.[60] The International Building Code (IBC) 2012 does not address whole-building airtightness directly, although it does require that structures be designed in compliance with the International Energy Conservation Code (IECC) 2012.[61]

4.3 ACOUSTICS

The frequency and strength of sound are determined by vibrations conveyed through air or other media. Hertz is the unit of measurement for frequency (the number of vibrations or cycles per second) (Hz). Decibels (dB), a relative logarithmic intensity scale, are used to quantify the intensity of the sound. Each 20 dB increase in sound corresponds to a tenfold increase in pressure. This logarithmic scale is especially suited for sound since the human ear perceives sound in a logarithmic manner. A 10 dB increase in sound level, for example, is perceived by the ear as twice the loudness. The speed of sound through a specific medium, such as a party wall, is affected by both its density and stiffness. All solid materials have an inherent vibration frequency. If a solid's inherent frequency is close to or equal to the frequency of the sound that impacts it, the solid will vibrate in sympathy with the sound, which will be transmitted through the solid. The effect is most noticeable in light, thin, or flexible walls or barriers. If the partition is heavy (high inertia) and stiff, as is the case with concrete masonry walls, the vibration is significantly reduced or damped. In addition to this, the natural frequency of vibration for concrete masonry walls is relatively low, so only low-frequency noises will produce sympathetic vibration. As a result, concrete masonry is particularly good in reducing sound transmission of typical sounds experienced in the occupancy of residential buildings.

Reduction of sound transmission to adjacent dwellings or occupied spaces is desirable as it enhances occupants comfort and is a consideration in Net-Zero Building Standards.

Concrete masonry is an ideal noise control material in two ways. First, it efficiently inhibits airborne sound transmission by diffusing incidents throughout a wide frequency range. Second, concrete masonry effectively absorbs noise, reducing the intensity of the disturbance. Concrete masonry has been utilized effectively in a variety of applications ranging from party walls to hotel separation walls and even highway sound barriers due to these properties. The surface roughness and porosity of the material under consideration have the greatest influence on sound absorption values. More porous and open-textured surfaces absorb more sound and, as a result, have a higher value. That means that painting a concrete brick wall covers small surface holes, lowering the wall's sound absorption value.[62]

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[60] RDH, Study of Part 3 Building Airtightness, 2015.

[61] International Energy Conservation Code. International Code Council, 2012.

[62] NCMA TEK 13-1C, Revised 2012.

4.3.1 BUILDING CODE REQUIREMENTS

The International Building Code (ref. 4) includes provisions for regulating sound transmission through internal partitions separating adjacent dwelling units and separating dwelling units from nearby public spaces such as halls, corridors, staircases, or service areas. When evaluated in accordance with ASTM E90, partitions fulfilling the aforementioned purposes must have a sound transmission class of at least 50 dB for airborne noise. When field tested, an STC of 45 must be obtained. To preserve the STC, penetrations and holes in these partitions must be sealed, lined, or otherwise treated. The International Residential Code (ref. 5) has comparable standards but requires walls and floor/ceiling components separating dwelling units to have a minimum STC value of 45 dB when evaluated in accordance with ASTM E90.

4.3.2 MINIMIZING SOUND TRANSMISSION

Sound insulation is achieved, for example, between residential units, by constructing walls to reduce sound transmission. The efficacy of this method is largely determined by wall weight rather than surface roughness. In general, the heavier the concrete masonry wall, the better it will prevent sound transmission. The previously described sound transmission class (STC) grade indicates how well a specific wall stops sound transmission across a wide frequency range. The Standard Method for Determining the Sound Transmission Class Rating for Masonry Walls is used to calculate STC ratings for concrete masonry walls. Sound may readily pass through any hole in a wall. For instance, a poorly fitted hallway door, as well as gaps surrounding ducts, pipes, and electrical outlets that are inadequately fitted or sealed, are common sources of sound leakage. A 0.007 in. (0.178 mm) broad crack along the top of a 1212 ft (3.8 m) wall will enable the same amount of transmitted sound as a 1 in.2 (645 mm^2) hole. As a result, it is critical to seal any cracks, seams, and gaps in order to retain the acoustical integrity of the wall. This circles back to the significance of designing a tight building envelope to ensure users' comfort.

The nature of sound and how it travels in the atmosphere is also worth considering when considering building layout and design. Sound moves most efficiently in straight lines. When sound energy changes direction, part of it is absorbed and some is diffused, lowering the amount of energy that is transferred. With that in mind, simple design choices like offsetting hallway doors or separating windows would decrease the amount of sound transmission through spaces.

In cases of unavoidable wall penetrations, like HVAC installations and electrical boxes, it is advised to seal around it completely with joint sealant. In practice, these gaps are usually filled with foam, cellulose fiber or mineral wool. As the significance of thermal insulation was discussed earlier in the paper, some types of insulation, like stone wool insulation, provides premium noise reduction and sound absorption. This could also decrease the sound transmission from outdoors to indoors and by that increase the users' comfort within the building.[63]

[63] NCMA TEK 13-2A, Revised 2007

4.4.1 BUILDING ENVELOPE & NET-ZERO ENERGY BUILDINGS

To achieve net zero energy buildings, building energy efficiency is typically optimized by taking into account the several factors, like: lighting, the walls and roof, heating, ventilation, air conditioning, renewables, and building usage and occupant behavior. Each of the variables listed contributes to the ultimate objective of net zero energy. The NZEB approach, on the other hand, includes an airtight, highly insulated building envelope. A well designed, tight building envelope is key to achieve NZB. After all, if conditioned air flows unchecked out of the building, the other efficiency measures may be rendered ineffective.[64]

"Air infiltration can account for 30% or more of a home's heating and cooling costs and contribute to problems with moisture, noise, dust, and entry of pollutants, insects and rodents. Nearly 45% of this uncontrolled air infiltrates through openings in ceilings, walls, and floors, as well as plumbing penetrations." – U.S. Department of Energy.[65]

The table below depicts the effect of airtightness on heating energy demand for an example archetypal six-story, 4,700 m^2, multi-unit residential structure in Climate Zone 4 (southwest British Columbia) with the following energy-efficient design features:

- Effective RSI-4.4 (R-25) walls and USI-1.53 (U-0.27) windows
- Heat recovery ventilation (60% efficient)
- Drain water heat recovery and low-flow fixtures
- LED lighting and occupancy sensors in corridors

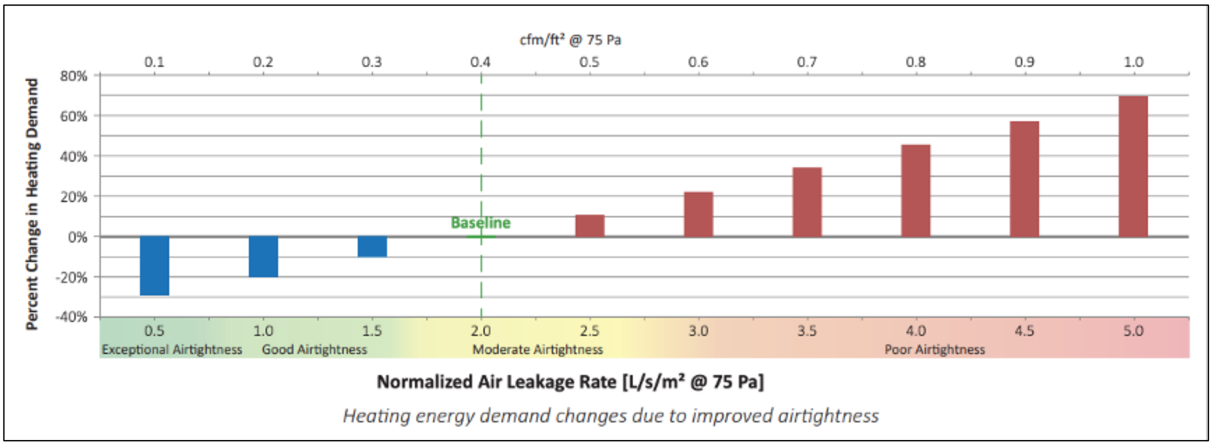

FIGURE 7: Normalized Air Leakage Rate (L/s/m^2 @ 75 Pa)

Figure 7 illustrates that if a baseline Normalized Air Leakage Rate target of 2.0 L/s/m^2 (0.4 cfm/ft^2) is missed and a worse rate of up to 5.0 L/s/m^2 (1.0 cfm/ft^2) is attained, the energy required to heat the building is approximately 70% more. To put this in context, solar panels would need to cover approximately 1,600 m2 (17,200 ft2) of this projected archetypal structure to provide the same amount of electricity. Even when other major energy-efficient design features are in place, this demonstrates the significance of creating an airtight enclosure. By increasing airtightness and reaching a Normalized Air Leakage Rate of 0.5 L/s/m2 (0.1 cfm/ft2), the amount of energy required to heat the building is approximately 30% less than what would be necessary for the baseline construction. The potential energy savings from

64 https://www.rockwool.com/north-america/advice-and-inspiration/blog/net-zero-energy-building-a-quick-reference-guide-to-energy-neutral-sustainable-building/

65 https://www.nervasuiteseal.com/

increased enclosure airtightness can assist in meeting energy efficiency standards and lowering electricity costs.[66]

4.4.2 BUILDING ENVELOPE & PASSIVE HOUSE

It is easy to think that the Passive Houses building envelope is simply the optimization of the thermal insulation layer. It is true that the Passive House Standard delivers such radical energy efficiency, Passive House architecture needs to be optimized just for an efficient thermal envelope. However, air tightness plays a significant role to achieve Passive House certification, user comfort and safety, low-energy and ensure prominent thermal insulation. A Passive House is a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air. (Passive House Institute). To understand the significance of airtightness in terms of thermal insulation, the concept of thermal bypass should be discussed. Thermal bypass is a mode of heat transfer that avoids conductive or conductive-radiative heat transfer between two areas. Convective loops are defined in this way because they contain both air infiltration and windwashing. Air tightness is defined as the property of keeping air from entering through the building's shell, whereas wind tightness is defined as the property of preventing air from penetrating into the shell to avoid the reduction of the insulation material's performance. In general, there are two types of convective loop bypass that occur mostly due to natural convection. Closed loop convection occurs when the air mass remains substantially unaltered but temperature variations persist at the borders, resulting in re-circulatory air flow in which the air flows in a loop. An unventilated cavity wall is a good example of closed loop convection. Open loop convection allows one air mass to be replaced by another, resulting in air gaps that allow air movement and hence heat transfer between two locations. This type of heat loss is caused by air tightness and wind tightness failures.

Closed loop convection can cause major thermal performance problems. In theory, this is caused by the stack effect. A variety of studies have demonstrated that even small air gaps between the (internal) air barrier and the insulation, as well as minor gaps in the joints between the insulation, result in considerable heat loss. As the U-value improves, the proportional influence of convection increases. When there are air spaces beneath the insulation, heat loss might increase by up to 160 percent more than the predicted U-value.

In theory, "open loop" convection is caused by wind entering the thermal envelope. This type of heat loss can be mitigated by improving air tightness and wind tightness. Wind Washing can degrade insulation's thermal performance, short-circuit the performance of the insulating material, and cool an air barrier system placed on the exterior of the wall assembly (potentially below the dew point temperature). Poor wind tightness has been proven to cause catastrophic failures in thermal performance; one research evaluating as-built flaws found that heat loss may be increased by up to 660 % above the U-value. However, this is admittedly an extreme example, an increase of around 40% may be more common where adequate wind tightness is not achieved.[67]

All of these problems could be easily avoided if a building envelope is designed tightly to the Passive House standards. As demonstrated previously, this is achieved successfully by designing a tight, continuous building envelope. The "pen test" is one common method for

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[66] RDH Building Science Inc, (British Columbia, 2017.

[67] https://www.greenspec.co.uk/building-design/thermal-bypass/

determining if the building envelope is continuous. This is when a plan or section drawing is taken and traced in a continuous line around specific features (for example, the weather protection). If the pen is lifted off the paper at any point, then it is a break in the continuity and an indication of a weak spot to be addressed.[68]

For a Passive House project to be certified airtight, rigorous design and construction standards must be met. This implies that when evaluated, the building must have fewer than 0.6 air changes per hour (ACH50) in order to receive Passive House certification. This stringent number is comparable to other high-performance building standards, such as the R2000 program, which allows for up to 1.5 ACH50 of air leakage. To verify that the building satisfies the airtightness criteria, at least one on-site air leakage test must be conducted as extra quality assurance for a Passive House project during construction.[69]

The blower door test is commonly used to help determine a building's airtightness. A blower door is a large fan that is installed in the frame of an external door. The fan draws air out of the home, reducing the internal air pressure. The increased outside air pressure then enters through any unprotected cracks and holes. To discover air leaks, auditors may use a smoke pencil. These tests measure a building's air infiltration rate. Blower doors are made up of a frame and a flexible panel that fit into a doorway, a variable-speed fan, a pressure gauge to detect pressure differences within and outside the residence, and an airflow manometer and hoses to monitor airflow.[70]

5 BUILDING LIFE CYCLE

It is a little-known fact that the demolition and crushing of concrete results in an unexpected quantity of carbon dioxide being absorbed into the freshly formed concrete aggregate owing to carbonation. This naturally occurring process is intentionally restricted throughout the building's in-use period to prevent corrosion of any embedded steel reinforcement. However, there is a significantly higher degree of carbonation towards the end-of-life stage, when crushing greatly increases the surface area of the concrete, allowing for much faster carbon dioxide absorption. Eventually, as described in BS EN 16757:2017, Sustainability of construction works, the combination of carbonation during the building's life cycle and during its secondary life as a recycled aggregate can lower its original carbon footprint by about a third.[71]

Low-energy and sustainable building practices now require the professionals of the building industry to shift the perspective to a broader view. Meaning that the construction and operational phases of a building's lifetime are no longer the main concern. Preliminary phases from the initial extraction of raw material, all the way to the demolition and recycling of the building materials are being considered meticulously, in order to achieve true NetZero and sustainability. As mentioned earlier in the paper this described methodology is called a cradle to grave approach. Meanwhile, a whole-life approach to design may continue to highlight the

68 https://elrondburrell.com/blog/passivhaus-building-envelope/

69 http://passivehousebuildings.com/books/phc-2019/five-principles-of-passive-house-design-and-construction/

70 https://www.energy.gov/energysaver/blower-door-tests

71 The Concrete Centre, Remixed: How Concrete is evolving for net-zero built environment, 2020

contribution concrete block and masonry make throughout its life cycle, including the ambition of making a circular economy a reality.

5.1 TOTAL LIFESPAN

Governed under ISO 14000, the LCA process is a part of the series of international standards addressing environmental management. The International Standard ISO 14040 defines LCA as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." Another thorough definition of LCA provided by The Code of Practice by the Society of Environmental Toxicology and Chemistry (SETAC) is that, it is "a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements." The Environmental Protection Agency (EPA) refers to LCA as "a cradle-to-grave approach for assessing industrial systems that evaluates all stages of a product's life".[72]
A life cycle assessment of a building normally involves evaluating its whole life cycle. This means including all of the stages in the assessment all the way from raw material supply, manufacture of construction products, the construction process stage, operation/use stage, demolition and when the materials are disposed of or sometimes recycled. To simplify, a building's life cycle is typically divided into five stages which need to be addressed: The product stage, construction process stage, use stage, the end-of -life stage and benefits and loads beyond the system boundary.
Most often, the first two stages are the best known and considered. However, due to their wide scope and large number of details in practice, acquiring sufficient data for the calculations can be challenging. The following three stages are scenario-based, which means that the calculations are usually based on assumptions about how the building will be used, maintained, and finally demolished. As per the European standard EN 15978:2011, the final stage, which focuses on the recycling of building waste, must be reported as a separate part of the calculations.

To summarize, an LCA combines all of the interactions with the environment which take place during the course of the total life cycle stages. The interactions may be in the form of transport emissions or resource consumption from the cultivation of trees. The five life cycle stages can be described as follow:

1. Product stage

The product stage concerns the processes that involve the creation of construction products utilized in the construction of the building: raw material supply, transportation to the production site, and final construction product production (manufacturing).

2. Construction process stage

The construction process stage focuses on the construction products' path from production line to the point where they are installed as a part of the finished structure: Installation in the building as well as transportation from the manufacturer to the construction site.

[72] The American Institute of Architects, 2010.

3. Use stage (operational)
The use stage involves the processes related to the construction products' ongoing performance as part of the building, such as maintenance, replacement, repair. There are further processes relating to the building's continuous operational energy and water use. Usually, the procedures will most likely be based on scenarios, or expectations of how the processes will unfold.

4. End-of-life stage
The processes in this stage are also based on assumptions. It concerns what happens when the building reaches the end of its useful life, i.e. the building's demolition and the subsequent procedures involved in reprocessing or handling the construction products/materials before reuse in other product systems.

5. Benefits and loads beyond the system boundary
The fifth and last stage is also a scenario-based one containing the calculated gains and drawbacks from reusing and recycling construction products/materials. In accordance with the European standards, contributions from this stage must be considered outside the system boundary and be reported separately.[73]

5.1.1 EMBODIED ENERGY, OPERATIONAL ENERGY & LCA

The assumptions made for the calculations of stages three, four and five are usually based on accurate energy modeling. Given that the operational use of a building (stage 3) takes up the biggest fraction of its carbon emissions, it cannot simply be dismissed or miscalculated. The estimated energy use within a building as it functions during a typical meteorological year is the output of an energy model and is referred to as operational energy. It is a significant input that is required to complete a building LCA. The embodied energy, which comes from the materials manufacturing and construction phases of the building project, is the second significant component of energy consumed by a building. As actions to reduce operational energy are done, the necessity to understand embodied energy becomes more critical. The majority of the energy implications for net-zero buildings will be embodied, as operational energy needs are increasingly fulfilled by on-site power generation. The straightforward strategy of computing the embodied energy in a building is to use an LCA that incorporates the materials manufacture and construction phases of the project.
LCA provides an overview of the environmental implications of a building's life cycle at different phases. It is feasible to narrow down on the most prominent life cycle stages and aim to reduce the adverse contributions. An LCA enables the prioritization of efforts for optimization based on evidence and evaluates specific activities in the context of the building's overall life cycle. The following are some examples for the broken-down aspects an LCA could accentuate:

- Materials versus energy

  An LCA allows the division of the multiple processes that are linked to energy use and to those related to materials during the building's use stage. Embodied energy can also be highlighted on its own, Energy-related environmental consequences have generally been the most significant component to a building's LCA results. As it is anticipated that future buildings will need less operational energy, and that this energy is expected to come from renewable sources, embodied impacts from construction materials will become proportionally more important in the total LCA for a building.

[73] Birgisdóttir, et al., Introduction to LCA of Buildings, 2016.

- The significance of building parts

LCA provides a summary of how the various components of a building contribute to the overall environmental effect. It can be used to segment the building components separately and determine which building components need to be aware of adjustments. Testing and iterating different building forms to see how the overall results and the distribution of each building part change could also be achieved by an LCA.

- Significance of materials

A comparison between different building materials and/or construction products regarding their environmental profile can be accomplished by an LCA. By that, assessing the environmental impacts of different solutions is facilitated and could help with the best choice of material for building parts.[74]

5.1.2 IMPACT CATEGORIES

LCA techniques have several impact categories depending on the system. LCA entails surveying all inputs and outputs associated with the life cycle of the system under consideration. The possible environmental impacts are calculated using all of the inputs and outputs, such as resource consumption and emissions, that can be linked to the various processes. A life cycle assessment's outcome can be estimated using a set of measurable indicators. The following are the most commonly used indicators for evaluating environmental effect and resource use:

- Global Warming Potential (GWP)

Climate change occurs when the amount of greenhouse gases in the atmosphere rises, warming the atmospheric layers near the ground.

- Depletion Potential of the Stratospheric Ozone Layer (ODP)

Depletion of the stratospheric ozone layer which shields flora and fauna against the sun's harmful UV-A and UV-B radiation.

- Formation Potential of Tropospheric Ozone Photochemical Oxidants (POCP)

Adds to the connection with UV radiation to the formation of ozone in the lower atmosphere (summer smog) which is damaging to the respiratory system, etc.

- Acidification Potential (AP)

When acidifying compounds combine with water and fall as acid rain, it causes root decomposition and nutrient leakage from plants, among other effects.

- Eutrophication Potential (EP)

A surplus of nutrients causes undesirable plant growth in vulnerable ecosystems, such as the growth of algae, which causes fish to die.

- Abiotic Depletion Potential for Non-fossil Resources (ADPe)

A high usage of abiotic resources, such as metals and minerals, can contribute to the depletion of accessible elements.

[74] Birgisdóttir, et al., Introduction to LCA of Buildings, 2016.

o Abiotic Depletion Potential for Fossil Resources (ADPf)
Abiotic resource consumption can lead to the depletion of available fossil energy sources like oil and coal.

o Total Use of Primary Energy (PEtot)
A heavy usage of primary energy resources from fossil and renewable sources can contribute to natural resource depletion.

o Use of Renewable Secondary Fuels (Sec)
Secondary fuels (such as waste) are in general limited, nonrenewable resources; hence their widespread use can indirectly contribute to resource scarcity.[75]

5.1.3 MASS CONCRETE, BLOCK, MASONRY & LCA

The Canadian concrete industry along with experts from MIT, the Athena Sustainable Materials Institute and the International Institute for Sustainable Development have been working to identify and measure concrete's involvement in the sustainability performance of buildings and infrastructure projects. The passive energy efficiency of concrete's thermal mass — gains of 8% over other building materials, according to MIT studies — more than compensates for the embodied impacts of the cement and concrete manufacturing processes. Concrete's thermal mass minimizes the operational energy needs of large commercial buildings when used strategically and in tandem with smart design and technologies. Manitoba Hydro Place (MHP) is one well example, having improved its energy efficiency by 70% over the Model National Energy Code for Buildings[76]. According to the International Institute for Sustainable Development's (IISD) new peer-reviewed study Emission Omissions: Carbon Accounting Gaps in the Built Environment, up to 72 percent of a wood product's carbon emissions may currently be omitted from wood LCAs, and that when these emissions are taken into account, concrete's embodied carbon footprint could be up to 6% less intense than that of wood products. However, there are still gaps to be covered in the industry for a closer stance to sustainability. As per the study, indirect emissions from land-use changes related to clearing land for raw-material mining and quarrying are also poorly documented and should be investigated further. More research into specific carbonation rates might also aid LCA analysis[77].

5.3.1 Concrete and End-Of-Life

Concrete is a 100% recyclable[78]. Recycling concrete has several advantages. Firstly, the reliance on basic raw materials decreases as well as the quantity of trash transported to landfill. There are two primary methods for reusing recycled concrete, as a recycled aggregate in newly made concrete and also as recycled aggregate in road construction and earthworks. The application is usually chosen with the best combination of sustainability, local availability, and long-term technical performance. Another option for recycling concrete that is being developed is the utilization of fine particles from crushed concrete as a supplementary raw material in clinker manufacturing.

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[75] Birgisdóttir, et al., Introduction to LCA of Buildings, 2016.

[76] Rediscover Concrete, 2014.

[77] International Institute for Sustainable Development, 2019.

[78] Humera Ahmed et al, Recycled aggregate concrete from large-scale production to sustainable field application, *Construction and Building Materials* (2020).

A recent study from the European Cement Research Academy (ECRA) titled “Closing the loop: What type of concrete reuse is the most sustainable option?”, was conducted to discover the many possibilities for recycling concrete. The study used LCA (life-cycle analysis) to assess the environmental effect of creating fresh concrete from either primary raw materials or recycled concrete aggregates, as well as employing discarded concrete in road building. The study used different recycled aggregates in a comparison to determine which choice is the most environmentally friendly. According to the study's life-cycle analysis, it is typically better to employ recycled concrete in road building unless there is little or no demand nearby. Because recycled concrete aggregates require additional processing for new concrete, employing primary raw materials is often the most sustainable option. Given the significant impact that transportation distances have on the findings, a case-by-case approach is necessary.[79]

5.4 Building Life Cycle Analysis and Net-Zero

A zero-energy building (ZEB) is a self-contained structure that does not rely on any external energy source to operate. The concept is readily extended to buildings with a net-zero yearly on-site energy balance, which occurs when a facility is linked to the power grid and annual energy usage equals energy exported to the grid. By using the Life Cycle Assessment method, the embodied energy (“cradle to site” or “cradle to grave”) of materials, which is regarded as an extra off-site supply, is incorporated.[80]

Carbon accounting procedures for construction works are primarily defined by EN 15804 and ISO 21930, which are internationally applicable standards for construction life-cycle evaluation.

With modern software that facilitates the process of the LCA, the creation of a full, cohesive assessment that considers intricate details is achievable. To utilize in the project’s carbon foot printing an LCA, allows the selection from a wide range of reused and recycled products. It could also model the preservation of existing building elements, as well as modify the assumptions about material service life and waste. The software also models carbonization for cementitious materials and sequesters biogenic carbon for any products used for the project. Exporting energy from the building model in order to offset other energy flows is also attainable as well as the consideration of in-life carbon sequestration (for example; by having a library of a wide range of trees to choose from). Adjusting end-of-life scenarios from the market standard practice e.g. to model product reuse is also done by an LCA, which is a significant key in the Net Zero Building design.[81]

Since Net Zero standards consider the overall building lifespan, the end-of-life of a project cannot simply be dismissed. By considering the end-of-life and what happens after a building is no longer in use, sustainable measures could be taken to ensure a Net Zero destiny for the building components. At this point, the concept of Circular Economy is highlighted because of how it fits well with Net Zero practices. Net Zero Carbon is widely considered to be the industry's first step toward a circular economy. The circular economy is a solution that is being implemented internationally, to the existing state of affairs, in which demand for scarce resources is growing, many of which are utilized only once before becoming waste. According to a McKinsey study, the price of resources has more than quadrupled in the last 20 years, and

[79] CEMBUREAU, The European Cement Research Academy GmbH, 2015

[80] Patxi, H., and Kenny, P. “Defining Zero Energy Buildings - A Life Cycle Perspective,” 2008.

[81] https://www.oneclicklca.com/designing-net-zero-carbon-buildings-article/

the yearly price volatility of resources has tripled in the last 30 years. The circular economy attempts to extract more value from the resources we consume while maintaining them in circulation for a longer period of time. In contrast to a linear economy in which resources are extracted, used, and then discarded, the circular economy attempts to ‘close the loop' by reusing, repurposing, remanufacturing, or recycling materials. It also entails maximizing the present worth of assets by fully utilizing them.[82]

Although encouraged by Net Zero standards, deconstruction however is not the only option for a building’s end-of-life. Demolition is to this day the most widely made decision when the building is no longer in use. However, with either option, codes and regulations are starting to emerge to regulate such processes and ensure the least damage and harm to the environment and people. The Seattle Land Use Code for Deconstruction and Demolition of buildings is a significant, and relatively new notion, that works towards a safe and regulated end-of-life process with minimal negative impact.[83]

With that in mind, flexible architectural design could also be beneficial in prolonging a building’s lifespan. By designing with that approach, the flexibility will grant the building opportunities to be of mixed/ multi-use. It will also facilitate the adaptability, conversion, or change of building use and typology.

Many architects who have completed large renovations appear to use a flexible, loose-fit strategy in their new-build projects. The architect behind the Bordeaux housing project, Jean-Philippe Vassal, wants for each of the firm's future projects to include an equal proportion of planned space and "undefined space." Similarly, Sarah Featherstone advocates for “baggy space,” stating, “It is about investigating how much we as architects need to accomplish before other people can come in so it can develop and adapt.” You must provide a clear foundation, but you must do as little as possible.” “It's a shared space for two distinct activities, with the community centre as open as possible and this in-between area between the two buildings, which people can pour into and utilise in different ways,” she says of Bay 20, a community centre and boxing club beneath the Westway in London.[84]

The concrete industry is a net consumer of waste, using over 200 times more waste and by-products from other industries than the waste it sends to landfill.[85] If flexible architecture is constructed with durable, resilient building materials such as concrete block and masonry, the goal of a long-life building would be easily and safely achieved, along with low-energy goals.

6 DURABILITY, RESILIENCE AND NET-ZERO BUILDINGS

In addition to the previously discussed topics, that relate to the formulation of concrete block and masonry, and building components and design, concrete itself, as a material, has prominent characteristics that contribute to the aim of this paper (which is designing with Net Zero and Passive House standards). The following discussed features of concrete block and masonry,

[82] https://www.jll.co.uk/en/views/net-zero-carbon-and-the-circular-economy-impact-on-value

[83] www.seattle.gov/sdci

[84] MPA, The Concrete Centre, Remixed: How Concrete is evolving for net-zero built environment, 2020.

[85] MPA UK Concrete, UK Concrete and Cement Industry Roadmap to Beyond Net Zero. 2020.

conclude the hypothesis of the paper, by forming a complete picture in support of the materials' viability and inclusion in sustainable building practices.

The durability and resilience of concrete structures matches the standards of Net Zero Building. These features of concrete as a building material, gives it a strong edge in the Net Zero race. Due to the significance of building durability in the building industry, a minimum amount of years are required for different building uses. This is to ensure that the lifespan of a building will last and that it will not be a short turnover rate that consumes more raw material, energy and resources. Concrete easily surpasses these minimums.

To put it into perspective, if two buildings are in comparison, one with a life span of 50 years and the other of 100 years, there would be nearly twice as many resources and embodied carbon dioxide involved with a structure lasting 50 years, because it would need to be built twice to last the same amount of time. With that in mind, if concrete masonry and block become more famous in the construction of low-energy buildings, much less resources would be consumed, as well as energy and much reductions in carbon emissions and overall GHGs.

"Concrete has an essential role to play in meeting the global challenges posed by population growth, increasing urbanization and resource scarcity," says Patrick Cleary, senior vice president, sales - US Cement, LafargeHolcim. "Concrete is vital to meeting these challenges. It is durable, fire and flood resilient, low carbon across its lifecycle, recyclable, versatile, affordable and available almost everywhere. We believe that sustainability creates value for our business, our shareholders and society. As the global leader in building materials and solutions we are determined to maximize this value and are committed to living up to the responsibilities that come with it." LafargeHolcim, the world's largest cement producer, reaffirmed its commitment to reach its emissions reduction goal by 2030.[86]

Concrete is the dominant material in major infrastructure construction like bridges, tunnels, and dams while masonry has been the dominant material of iconic buildings, monuments for centuries. Both materials are highly durable. Neither concrete nor masonry deteriorate with moisture as they do not mold, rust or rot and are not food for insects. Both material are fireproof and non-combustible. The remarkable durability of concrete and masonry make these two key materials for sustainable, long-lasting construction. Historical evidence proves, concrete and masonry buildings last hundreds of years with very minimal maintenance.

The topic of durability has been addressed in a number of public papers, including the National Building Code of Canada (NBC), materials and installation standards issued by standards-writing groups across the world, and a number of widely disseminated books and good practice manuals. However, consideration of the topic of durability has frequently been restricted to the implications of premature degradation. The Canadian Standards Association contains extra factors (for example, the planned maintenance methods) that designers must take into account in order to address durability and minimize premature degradation over the life of a building. The key concepts to the Canadian Standards Association are:

- The achievement of durability requires the consideration of service life in the design methods for structures and their construction parts;

[86] https://www.forconstructionpros.com/concrete/article/21203676/mission-carbon-zero-the-concrete-industrys-sprint-to-carbon-zero

- Beginning with the basic concept for a building, the design process must include the structural environment and agents to which the building elements will be exposed, as well as the action consequences resulting from environmental action; and

- Decisions made during the design of a building, and even before the production of design papers, have an impact on all subsequent decisions and the performance of the structure.[87]

Since aggregates comprise about 60 to 75 percent of the overall volume of concrete, they have an essential role in the durability of concrete. Many aggregates in Canada might display trouble in the field due to freezing and thawing temperatures, which affects the durability of the material.[88]

Freeze-thaw cycle testing is a type of stability testing that determines if the concrete will remain stable under different circumstances. This sort of test subjects the sample to a series of severe, fast temperature fluctuations to test the effect of extreme temperatures on concrete.[89]

Freeze-thaw testing is required especially for concrete that has recycled aggregates, to determine its safety and performance. Durability can be easily measured using specialized tests, such as the previously described freeze-thaw durability.

The CSA also includes a requirement for the minimum number of years of a building's life that differs according to building type, as shown below;[90]

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[87] CSA Group, "Durability in Buildings," CSA S478:19 Durability in Buildings (2019).

[88] Santosh K. Mummaneni and Kyle A. Riding, "Evaluation of Canadian Unconfined Aggregate Freeze-Thaw Tests for Identifying Nondurable Aggregates" (Kansas Department of Transportation, 2012). http://transport.ksu.edu/files/transport/imported/Reports/KSU-10-9_Final.pdf

[89] https://microchemlab.com/test/freeze-thaw-stability-testing

[90] CSA Group, "Durability in Buildings," CSA S478:19 Durability in Buildings (2019).

Table 1
Categories of design service life for buildings
(See Clauses 6.1.2, 11.2, A.1, and A.2.2.)

Design service life category	Building type	Minimum design service life for building, years	Range of design service life, years
Short life	• Bunkhouses, sales offices • Minor storage buildings	—	Up to 10
Medium life	• Low-hazard industrial • Temporary buildings	10	10 to 25
	• Mercantile • Medium-hazard industrial • Business and personal services occupancies • School portables	25	25 to 50
	• Low-rise commercial and office buildings • Stand-alone parking structures* • High-hazard industrial	25	25 to 99
Long life	• Single-unit residential • Multi-unit residential • Mid- and high-rise commercial and office buildings • Post-disaster buildings (e.g., hospitals, power generating stations, public water treatment facilities, and emergency response facilities) • Performing arts buildings, arenas, schools and colleges, and other assembly occupancies • Detention, care, and treatment occupancy	50	50 to 99
Permanent	• Monumental and heritage buildings	100	100 to 300

** Parking structures shall have a design service life at least equal to the building they serve, except that parking structures serving long-life category buildings may be designed for medium life, provided that*
a) they are not integral to the long-life superstructure; and
b) degradation of the parking structure will not adversely affect the building served.
See CSA S413.

April 2019 *© 2019 Canadian Standards Association* **25**

FIGURE 8: CSA-S478 - Guideline on Durability Categories of services life for buildings

7 CASE STUDY: CONCRETE BLOCK SINGLE FAMILY HOME

The design undertaken in the case study is that of a single-family home located in Toronto, Ontario, Canada. The hypothetical site is situated along the 401/400 highway in Yorkdale Crescent. The following demographic information is based on the dissemination area as defined by Statistics Canada. A dissemination area contains, on average, approximately 200 to 400 households and is often referred to as a small neighborhood. Data was provided by a third-party supplier based on census data from Statistics Canada. The area has 157 households of which 77% are households with children. The area is known for its good school system, crossroads plaza, restaurants, and parks.

The following single family home design explores the viability and inclusivity of using concrete block and brick veneer to meet Passive House requirements and sustainable building practices. The home was drafted using REVIT with the Masonry IQ plug-in. This facilitates accurate 2D and 3D renderings of the concrete block home where the Masonry IQ plug-in captures the modular installation nature of concrete masonry and brick.

7.1 Physical Location of the Home

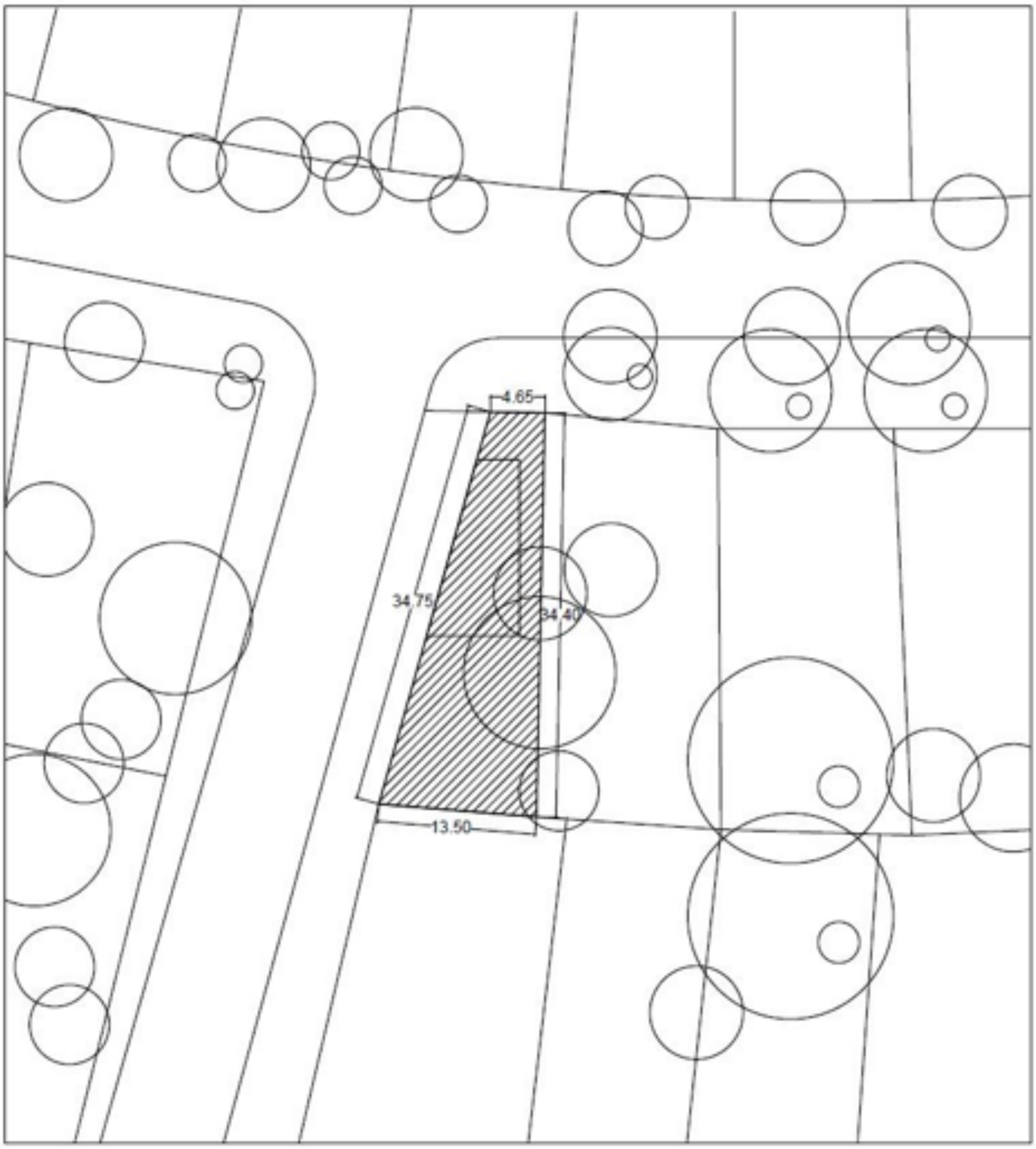

FIGURE 9: Physical dimensions of the Lot.

The site used in the case study is an average-sized, pie-shaped plot,, with a total area of approximately 750 m^2 as can be seen in Figure 9.

The size of the building was based on offsetting from property lines there by imitating the shape of the property. The building also respects zoning requirements, such as the required setback values from neighboring houses and streets.

7.2 Site Plan

The site plan for the proposed single family home is given in Figure 10 below.

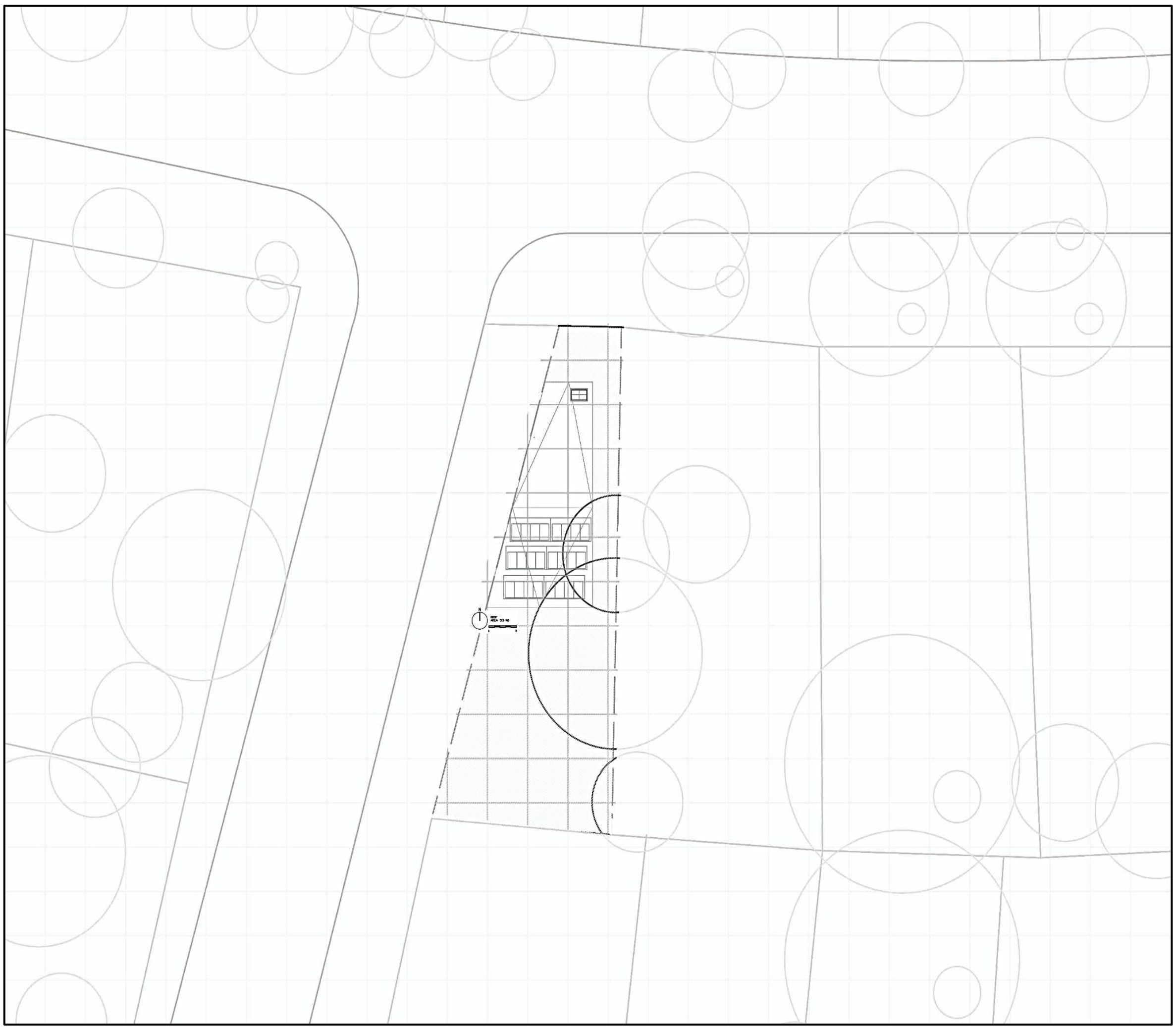

FIGURE 10: Site Plan.

7.4 Isometric Details in 3D

The home was rendered in 3D using REVIT with the Masonry IQ plugin. The front Isometric can be seen in Figure 11 while the rear isometric can be seen in Figure 12. Figure 13 identifies some of the passive features resulting from the design of the home.

FIGURE 11: Front view of the home.

FIGURE 12: Rear view of the home.

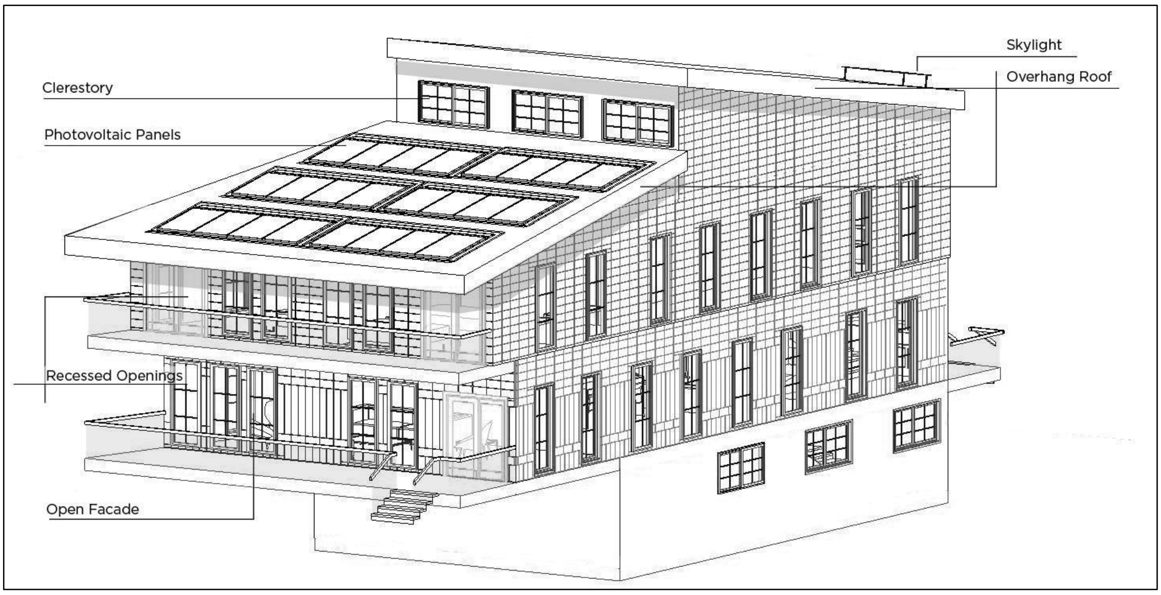

FIGURE 13: Passive house features incorporated into the design of the home.

7.4 Basement

The soil conditions in the geographical area allowed for safe excavation and the inclusion of a basement floor. A simple floor plan with an open space, an office, storage, and mechanical rooms was designed to accommodate any functions the homeowners would require. The plan detail of the basement is found in Figure 14.

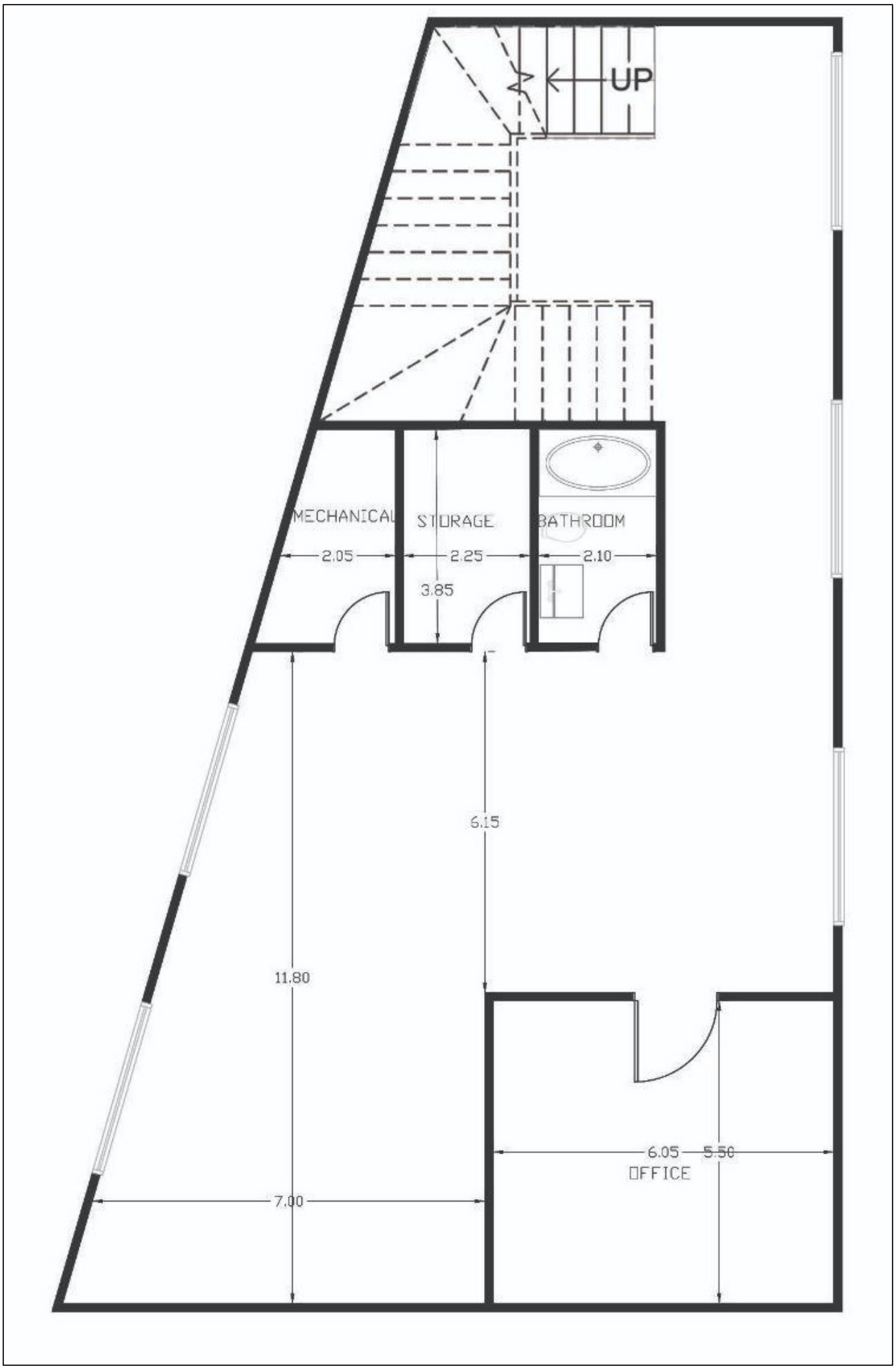

FIGURE 14: Plan Detail of the Basement.

7.5 Main (Ground) Floor

The main floor is located 600 mm above local grade and contains many of the living spaces needed for a single-family home. A primary entrance due north is double-height. The first space encounter from the entrance leads is the foyer, where the occupants can take their time to remove their outer wear before they access the rest of the house. A guest bathroom then follows the foyer, it is in its location to serve the following spaces (kitchen, dining, and living room) as well as the entrance area. Proceeding south, the kitchen area is located on the west side of the building. The intention was to create an open kitchen that directly connects with the dining area facilitating accessibility as well as creating vast spaces and an open concept feel. The living area is the last space on the main (ground) floor. It was designed to be completely open to the south to take advantage of the natural sunlight as well as have an open view and direct access to the home's backyard. Figure 15 below provides the plan detail of the Main (Ground) Floor.

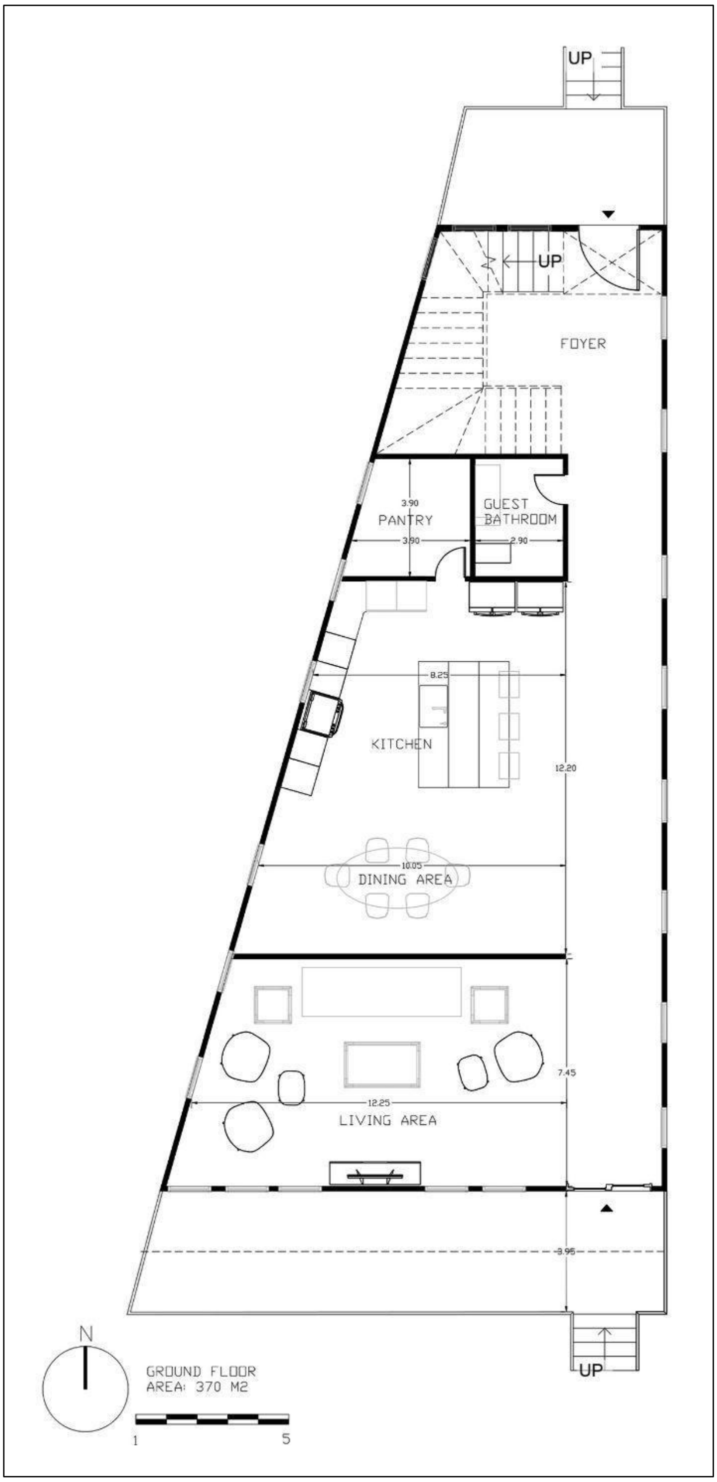

FIGURE 15: Plan Detail of the Main (Ground) Floor.

7.6 Upper (First) Floor

The upper floor is located 3600 mm above local grade and has more private spaces for the homeowners. Traveling up the U-shaped staircase, the first room encountered is the laundry room which is located on the north end of the home. The position of this room is unique because it does not have access to the main facades, so assigning it to the laundry made the most sense. The master bedroom with ensuite and 2 additional bedrooms are also located on this floor.

Through a single ventilated corridor, all three bedrooms can be accessed. There are 2 bedrooms on the south end of the home while the master bedroom and ensuite are located on the west side of the home. A shared bathroom is located directly south of bedroom #1 to facilitate plumbing in both this bathroom and the ensuite. Figure 16 below provides the plan details of the Upper (First) Floor.

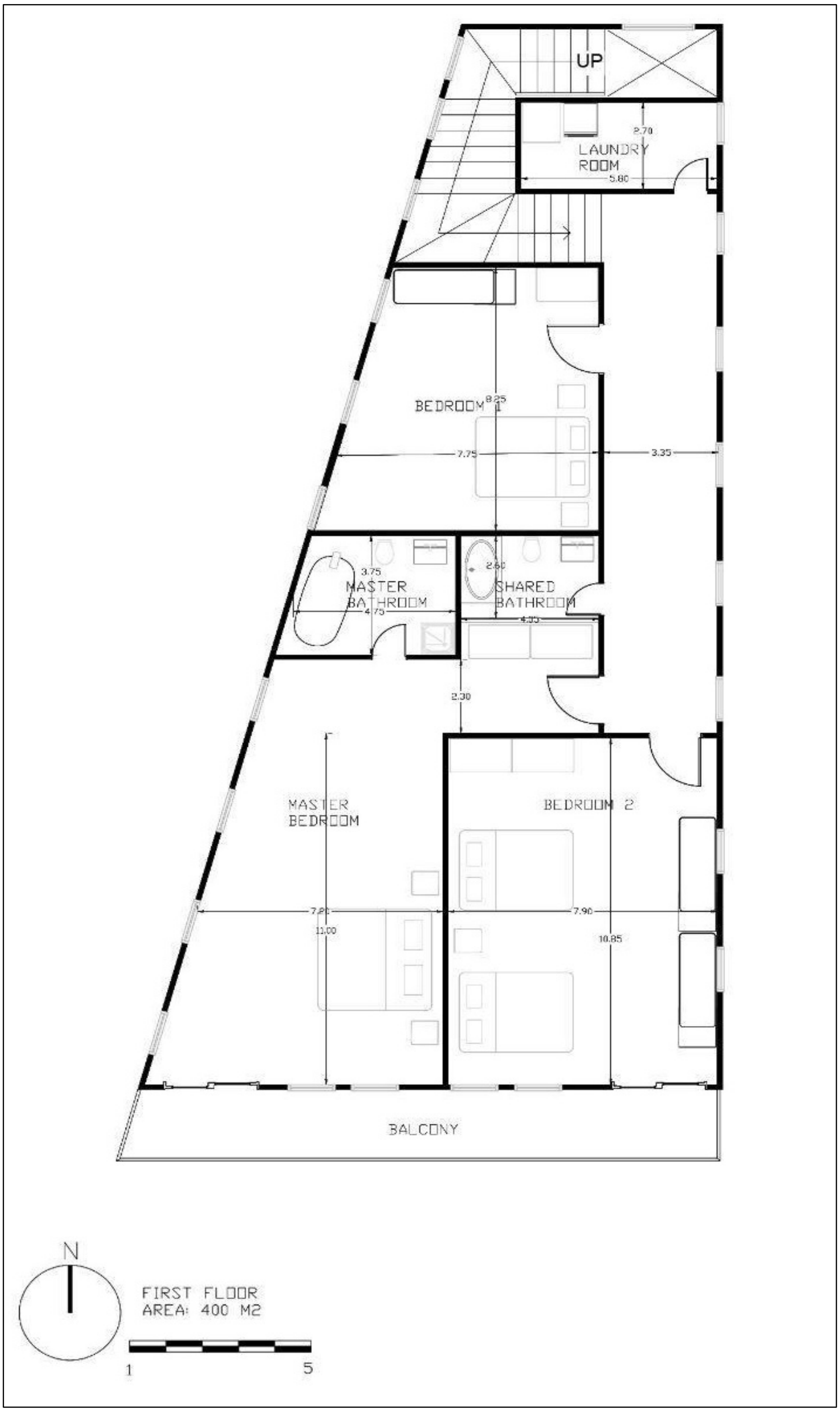

FIGURE 16: Plan Detail of the Upper (First) Floor.

7.7 Attic

The attic could be reached through an attic ladder located near the east side of the home. The floor plan is smaller than those beneath it. The south facing façade is recessed to the back, with above-eye level windows, to maximize the use of usable space while maximizing natural light. This type of roof is referred to as clerestory. The use of clerestories can be traced to ancient Egyptian temples. It has been a popular feature in religious structures for centuries due to its capability to flood vast spaces with natural light, creating interior environments that are so open and bright that they can feel awe inspiring. The attic also acts as a smaller second floor. The space is not defined by walls to allow for maximum flexibility and variety of use. Figure 17 illustrates the plan detail of the attic.

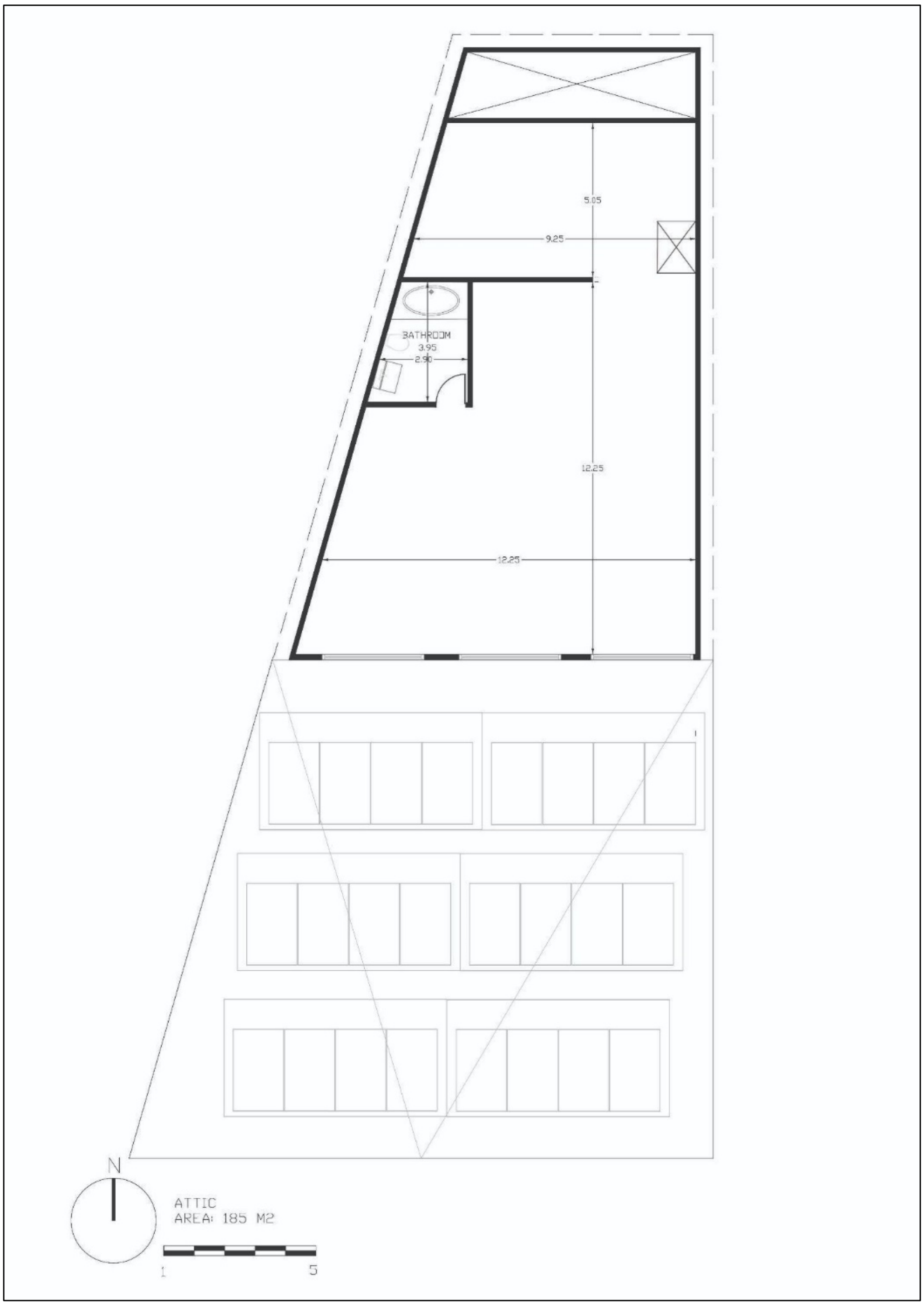

FIGURE 17: Plan Detail of the Upper (First) Floor.

7.8 Roof

The roof is a simple pitched roof with a 10% slope. It has a skylight over the double-height entrance to bring in natural light to the ground floor. Due south, the roof is covered with inclined photovoltaic panels, that are used as the main source of energy of the house, facilitating the Net-Zero Energy goal. Figure 18 illustrates the plan detail of the roof.

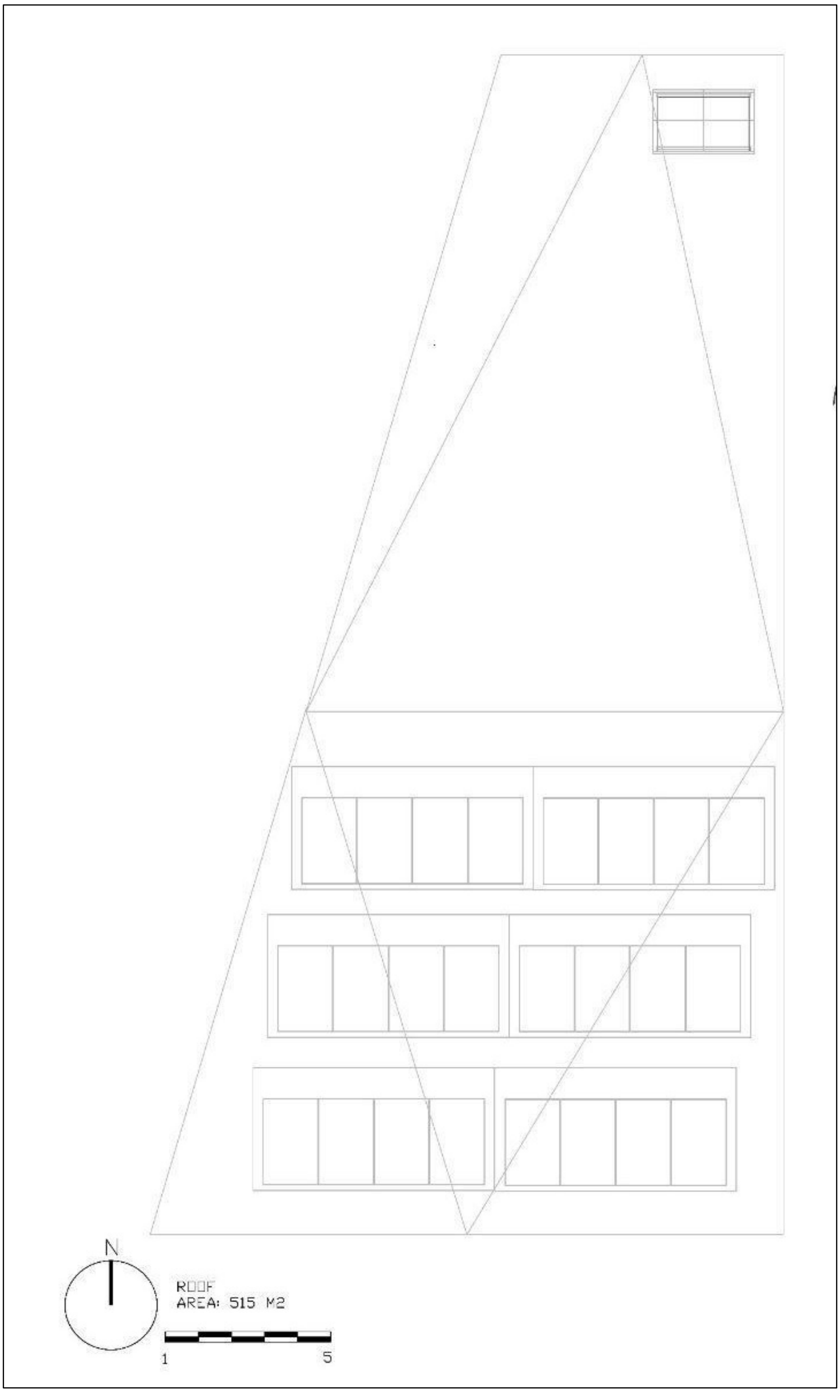

FIGURE 18: Plan Detail of the Roof.

7.9 North South - Section Detail

The detail below illustrates the section detail through the home running north to south.

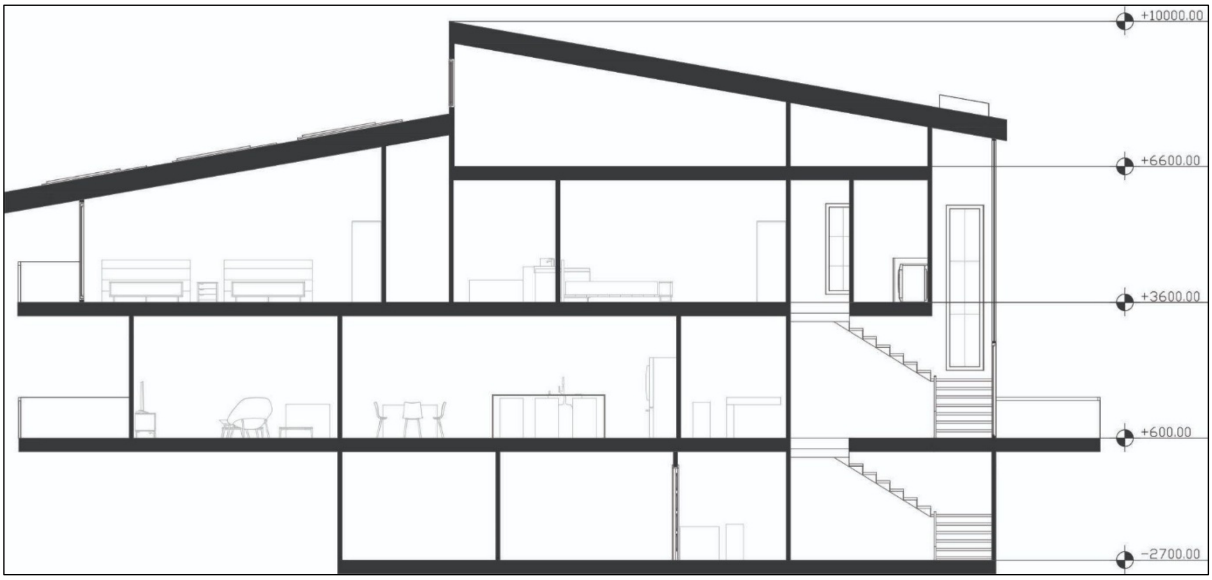

FIGURE 19: North-South Section Detail of the Home.

7.10 Passive Strategies

Through the design process, several design strategies were incorporated for user comfort and a more energy-efficient, and passive design. Some of the energy-aware strategies implemented included solar tempering, highly insulated and sealed building envelope, as well as openings (such as windows and doors), energy-efficient heating and cooling systems such as VRF and Geothermal heating, a fresh supply of air using ERV systems and last but not least, energy-efficient lighting, appliances and electronics.

Overhang Roof:

Having the building's pitched roof extruded by 600 mm is a common design move implemented in modern design. Apart from giving the house a strong aesthetic and signature style, it also has important functions. The pitched roof provides shading for all the facades The Cove.to tool was used to estimate shading provided by the roof. The pitched roof also provides protection of the facades, and thus building envelope, from inclement weather. With the risks of water penetration through the exterior masonry significantly reduced the life expectancy and durability of the envelope is increased.

Clerestory Roof:

Used in modern homes nowadays, increased sunshine isn't the sole advantage. Whereas lower windows can let in direct and occasionally harsh sunlight, a series of windows higher up lets in more ambient light (Architectural Digest,2017).[1] The designed clerestory in this case has operable windows which adds a significant component of passive design, which is the movement and circulation of fresh air.

Skylight:

The skylight due north, over the double-height entrance and staircase, allows natural light to come in from a different direction, reducing the need for artificial lighting and thus supporting lower energy consumption. The Cove.to tool was once again used to estimate the natural light entering the skylight.

Photovoltaic Panels:

Solar photovoltaic (PV) panels are the most cost-effective renewable energy source for most zero energy homes. Because installing a PV system is the costliest element of a zero-energy project the number of solar panels required is to be calculated only after all other energy-saving measures are included.[2] The main sun path is due south of the building; therefore, a logical design of including photovoltaic panels, on an inclined roof, seemed appropriate in designing a passive single-family home. The Cove.to tool was once again used to estimate the amount of sunlight expected to reach the photovoltaic panels.

Open Southern Facade:

As previously mentioned, the main sun direction is due south. The southern façade of the building, all the way from the attic to the ground floor is designed as openly as possible to allow maximum sunlight in. The allocation of balconies and porches was also intended to be due south for the same reason. The Cove.tool was once again used to anticipate the amount of sunlight and shading.

Recessed Openings:

Sunlight, however, could cause discomfort if going directly into a space, as well as cause heat retention in closed spaces. Therefore the openings due south are recessed inwards and shaded horizontally using other structures, such as balconies and roofs, to allow maximum sunlight in but not uncomfortable -or even harmful- sun rays, especially in the summer season where the sun is much lower.

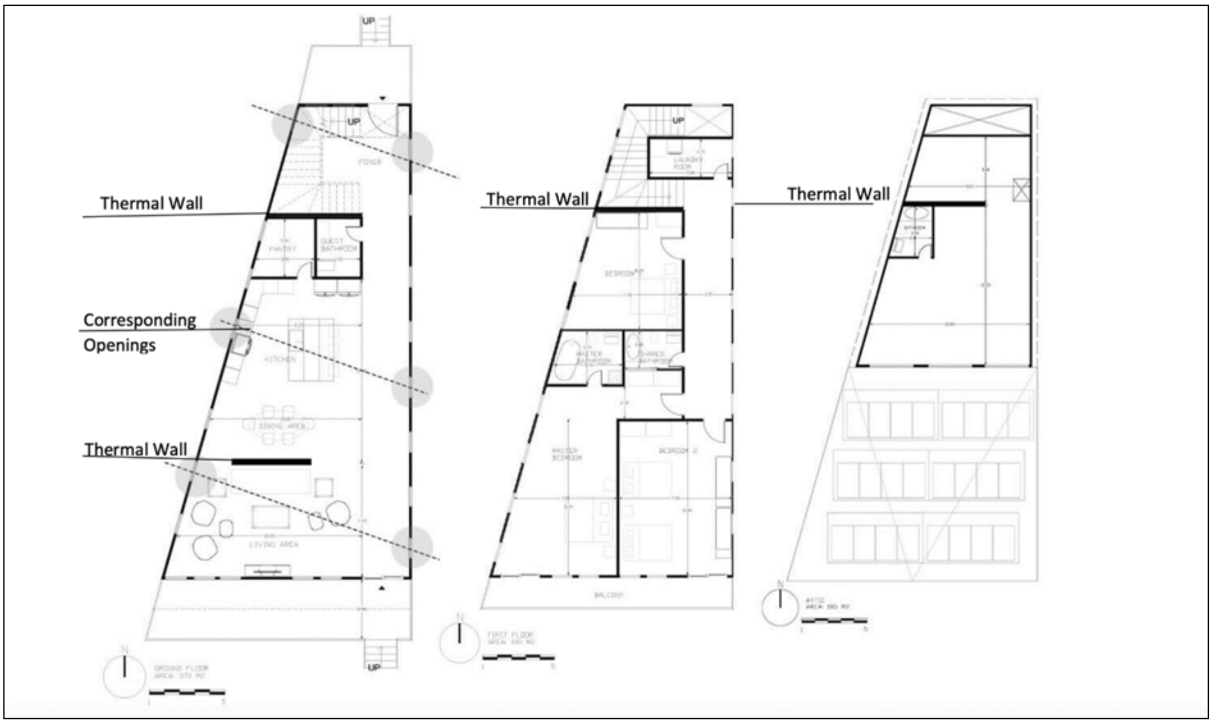

FIGURE 20: Plan Detail of all three floors for sunlight utilization.

Corresponding Openings:

The direction of the prevailing wind in the project's location is west. Tall, floor-to-ceiling windows are designed on both eastern and western facades, correspondingly to allow a continuous current of air inside the house whenever windows are open. This design move helps keep the interior air fresh and circulating, and provides natural ventilation to spaces, which reduces the dependency on energy-consuming systems.

Thermal Walls:

In this proposal, two thermal walls are designed to exploit the potentials of concrete masonry, in terms of thermal mass. Concrete as a material has high thermal mass properties, which gives it a significant edge against other building materials. Thermal mass helps maintain comfortable interior temperatures year-round. Concrete block will absorb heat from the sun during the day and radiate it out as the temperature drops in the afternoon throughout the evening. If implemented correctly, it reduces energy and costs significantly and thus complies with NZEB standards. One thermal wall borders the living area, directly exposed to the southern façade and hence sunlight. Its position heats the spaces around, which are the dining and living areas. The second thermal wall is continuous throughout the floors, from the attic, where it is exposed to sunlight from the clerestory to store heat, and by that goes all the way through its height and radiates heat to the stairway and different rooms throughout the levels.

Building Envelope:

As thoroughly discussed in this paper and Appendix A, the building envelope is the enclosure that includes all the building components, separating the indoors from the outdoors. This includes the exterior walls, foundations, roof, windows, and doors. While designing a Net-Zero

Energy Passive House, the building envelope was given full attention due to the significant impact it has on energy consumption. These components are described in detail below.

Exterior Wall Components:

The material used for the backup wall was concrete block (CMU). Load bearing 15cm (6 inch) CMU full blocks, which have nominal dimensions of 150 mm x 190 mm x 390 mm (6" x 8" x 16") and actual dimensions of 140mm x 90mm x 390mm (5/8" x 7 5/8" x 15 5/8"). Moving from the interior to the exterior of the wall the section is as follow:

- 140mm concrete block
- Self-adhered air/vapour barrier
- 254 mm XPS insulation
- 30 mm airspace
- 76 mm clay brick

The insulation is to be installed as continuous thermal insulation with no interruptions between above and below grade. Continuous insulation is a prominent standard of Passive House. The use of a self-healing, self-adhered membrane was selected because these membranes, when installed correctly, have a proven performance history for ensuring airtight and watertight envelopes. Figure 21 illustrates some of the key features of the building envelope.

Thermal Insulation

Thermal Insulation is one of the most (if not the most) crucial components to be looked out for while designing both a Net Zero Energy and Passive House standards complying building. The significance is thoroughly researched in this paper, as thermal insulation tremendously reduces energy usage and costs, as well as providing residents with a comfortable experience. 254 mm (10 inches) of XPS insulation is included into the wall design, to allow for a nominal R-value of 50. After accounting for effects thermal bridging effects according to NECB 2017, the effective R-value drops to R-41. However, this value exceeds the minimum requirement for Passive House for walls of R-38 (U-value = 0.15 W/m^2 K).

Rainscreen

Also previously discussed in the paper, a rainscreen system was designed to provide protection to the backup wall. If any water manages to penetrate through the exterior brick cladding, there will be sufficient ventilation to prevent moisture accumulation. A 30 mm air cavity was included for this purpose.

Exterior Cladding

Clay brick veneer was used as exterior cladding for this case study. It was selected due to its fire-proof, acoustic, and aesthetic properties. The brick veneer is supported by a thermally broken shelf angle at the bottom of the wall to carry its weight and transfer it to the building's foundation. The bricks are tied to the backup wall with thermally broken surface mounted metal ties that are installed at 400 mm (16") o.c. horizontally and 600 mm (24") o.c. vertically.

Roof

The roof is unventilated, sloped at a 10% value. To meet the Passive House requirements for roof insulation, R-60 roof insulation was used. An SBS modified bitumen self-healing roof membrane was used on top of the insulation while a self-adhered membrane was used beneath the insulation. The double water-proof membranes were used to protect the structure from any water penetration and ensure an airtight and watertight envelope.

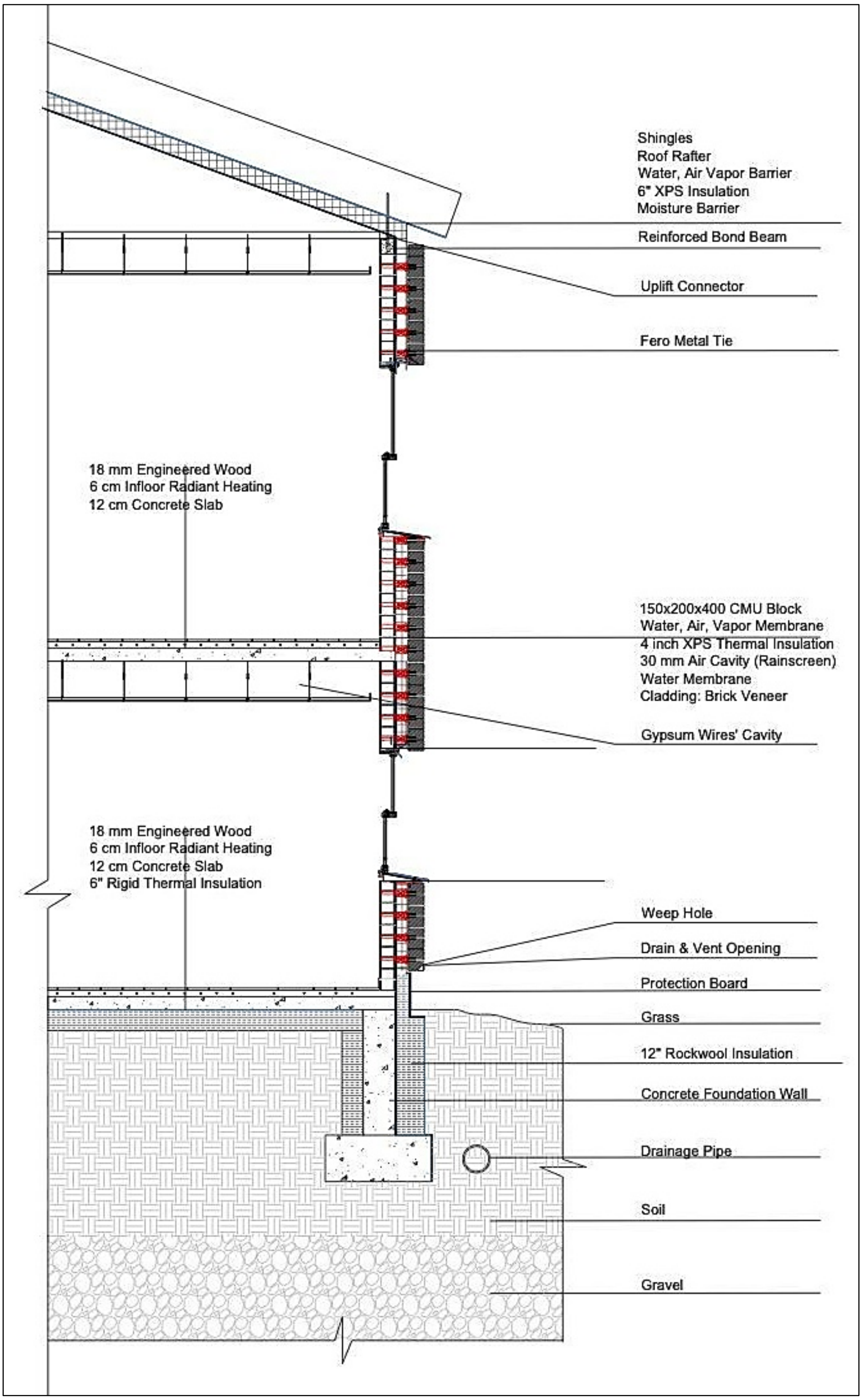

FIGURE 21: Section Detail highlighting features of the building envelope.

7.11 Software Used in the Case Study

The following software programs were used in the design of the single-family home in the case study.

Revit 2021: Drafting and Energy Analysis

The single-family home was drafted using Autodesk REVIT with the following plugins:

Cove.tool

Cove.tool plugin was used to generate a preliminary analysis for the site, as well as for the building. The plugin accounts for sun direction, wall-to-window ratio, and many other factors. It is capable of basic calculations for energy usage as per the simple inputs it requests. However, the software is not able to perform complex calculations in terms of building materials, for any of the materials used in the case study.

MasonryIQ

MasonryIQ is a plugin used in REVIT to give an actual representation of how the exterior masonry veneer assembly would look like.

THERM 7.6: 2D Thermal Analysis

THERM is a 2D finite element software for thermal modeling. It was used to obtain the U-factors and R-values of the walls. As a result, only 2D Thermal calculations were used.

7.13 Energy Analysis Results from Cove.tool

The Cove.tool plugin was used for the energy analysis. Figure 22 to Figure 26 provide the results from the Cove.tool plugin, while Figure 27 provides the national average benchmarks for energy use for single family home.

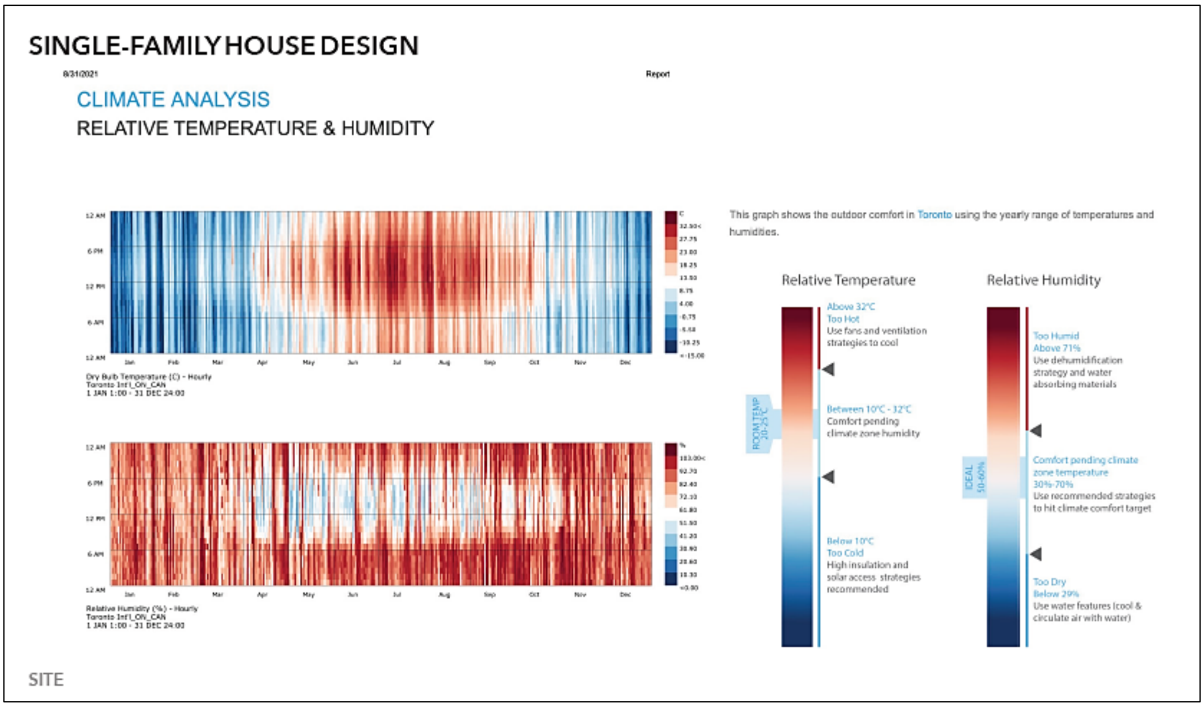

FIGURE 22: Climate Analysis of the Site for Relative Temperature and Relative Humidity

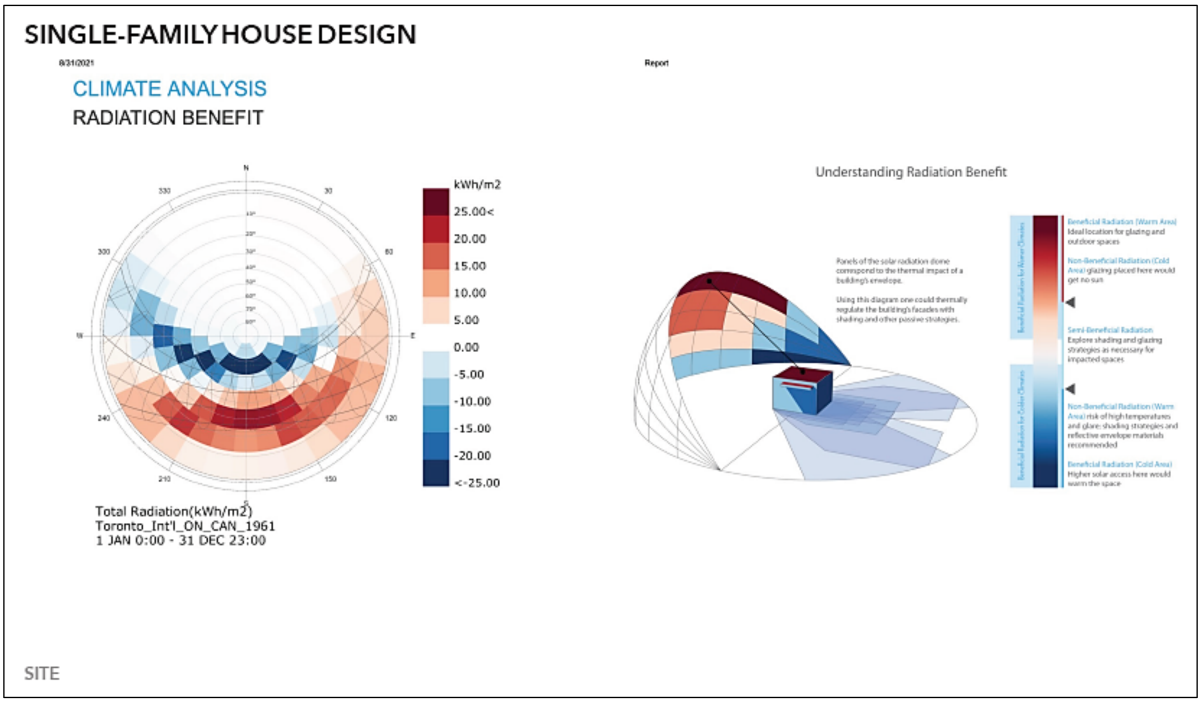

FIGURE 23: Climate Analysis of the Site for Radiation Benefit

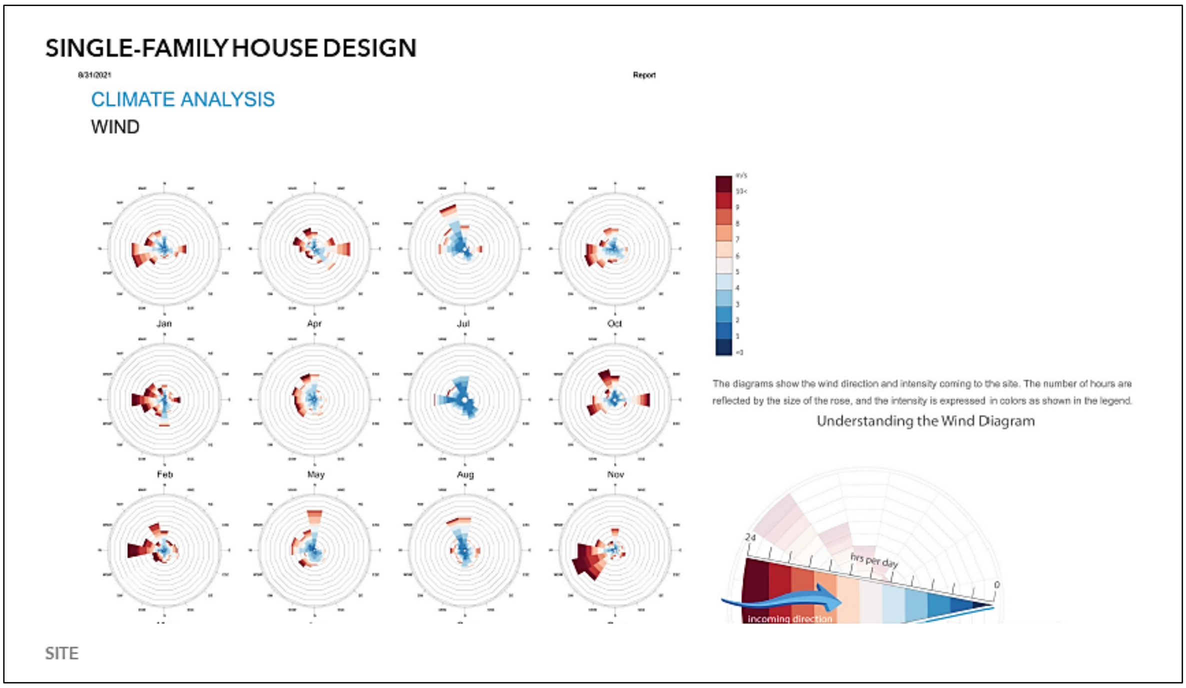

FIGURE 24: Climate Analysis – Wind

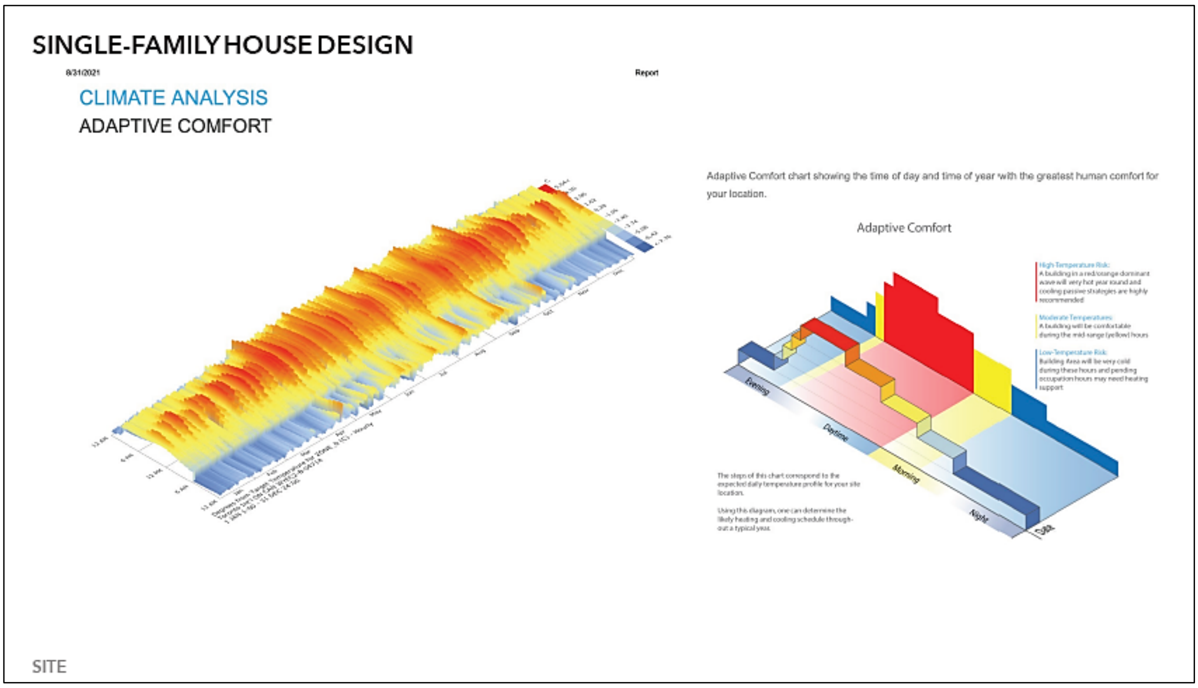

FIGURE 25: Climate Analysis - Adaptive Comfort

FIGURE 26: Energy analysis of the Block brick home

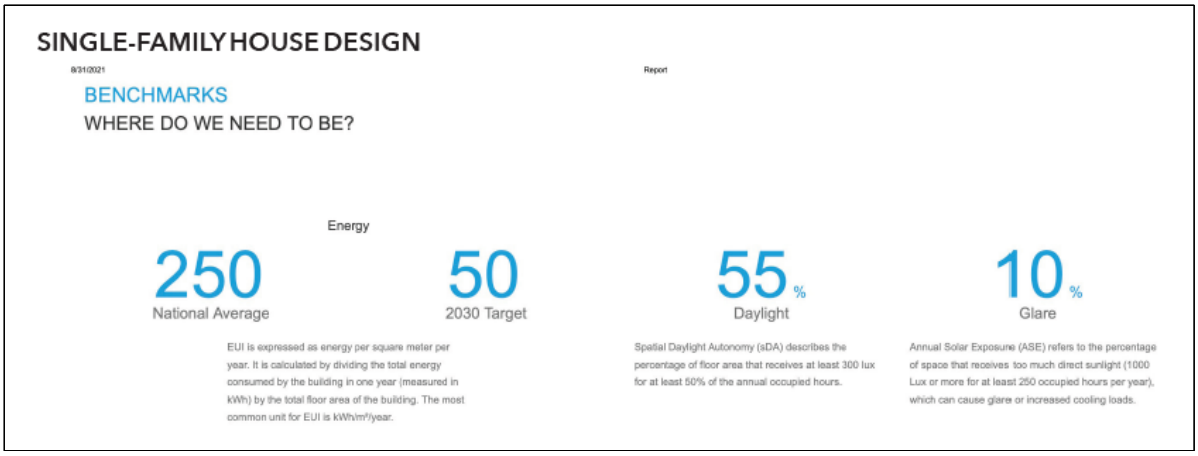

FIGURE 27: National Average - Benchmarks for Single Family Homes

7.14 Discussion of Energy Analysis Results

It can be seen in Figure 26 that the block/brick home in the case study outperforms the current national benchmark Energy Use Intensity (EUI) of 250 kWh/m^2/yr found in Figure 27 with its EUI of 159 kWh/m^2/yr. However, the block/brick home is approximately 3 times the 2030 target found in Figure 27.

In Figure 26 under the "Heating" heading, it can be seen that heating is dominating the energy consumption in the home. One solution would be to reduce the glazing on the party walls (side walls of the home). This would increase the overall thermal performance of the home and reduce the heating demand. Less glazing is often preferable on the party walls for home lots with tight property as privacy is increased with less glazing.

The daylight target of 55% or more was exceeded with lighting in Figure 27 accounting for only 32.5% (Figure 26) of energy consumption due to the home's design to incorporate daylight.

The electrical energy (Figure 26) demand is 18.5% but can be improved as suggested by using LED lighting or other forms of lighting with reduced lighting power density. A more efficient hot water tank was also suggested a solution to reduce the EUI

The use of solar panel on the front elevation roof reduced the EUI by approximately 16 kWh/m^2/yr.

8 CONCLUSIONS

The single-family home in the case study demonstrated that this concrete block brick veneer home out-performs the current national energy targets of 250 kWh/m^2/yr. However for this particular single family home, the EUI will exceed the 2030 target approximately 3-fold. This can be addressed with other strategies such as a more efficient HVAC system, hot water heating system, and lighting. In addition to these measures a reduction in the number or size of windows particularly on the party walls could significantly improve the energy performance of the home. These solutions are independent of the block backup wall and brick veneer.

It remains an undeniable fact that a building envelope using a concrete block backup wall that meets passive house standards would be thicker and have a more expensive initial cost than traditional wood-frame used for single family homes. The average, thermally insulated, highly efficient concrete block wall would be of 20” width (though recent improvements in thermal modeling of concrete block with brick veneer walls suggest this could be reduced to 17”) to achieve passive house thermal requirements, while a timber wall assembly would range from 14”-16” to achieve the same thermal performance. However, given the historically verified long-term benefits of concrete block as a durable, low maintenance building material, concrete block single family homes will outperform wood-frame single family homes in the terms of resilience, cradle to grave, cradle to cradle Net-Zero Building total cost of ownership while still meeting Passive House standards with a marginal increase in wall thickness over wood-frame homes.

8.1 Future Investigation

Thermal mass, which is the most significant property of concrete as a material, was not accounted for in any of the programs used in this project. Incorporation of accurate estimations of thermal mass impacts would be beneficial to the energy analysis of the single-family home in the case study.

In this study, mechanical systems were primarily included using the analysis tool, to be as highly efficient as possible. However, they were not expertly designed. As previously mentioned, optimization of HVAC and lighting systems could significantly improve the EUI of the concrete block brick veneer single family homes.

As more accurate methods of determining the net U-value of the entire walls (after accounting for thermal bridging) are developed for concrete block brick veneer, better thermal performance with the same insulation depth than the current values is likely to result. Therefore, revisiting the single-family home in this case study with more accurate values for clear field, as well as linear transmittance values for the at-grade, floor level, roof, corner, and window/door transitions as they are developed, will likely result in less insulation in the walls and a reduction in wall thickness that still meets or exceeds the passive house standards for performance.

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GLOSSARY

CSA	Canadian Standards Association
Cradle	The cradle is defined as being the earth, i.e., material deposits within the ground.
Carbon sequestration	The extraction of carbon from the atmosphere, for example from trees and plants
Embodied carbon (EC)	Embodied carbon is the sum of fuel related carbon emissions (i.e., embodied energy which is combusted – but not the feedstock energy which is retained within the material) and process related carbon emissions (i.e., non-fuel related emissions which may arise, for example, from chemical reactions). This can be measured from cradle-to-gate, cradle-to- grave, or from cradle-to grave. The ICE data is cradle-to-gate.
Embodied energy (EE)	Is defined here as the total primary energy consumed from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate.
Global warming potential (GWP)	The release of GHGs into the atmosphere gives rise to climate change. There are many GHGs, and each has a different level of potency. Each gas is normalized relative to the impacts of one unit of carbon dioxide. For example, each unit of methane is considered to be 25 times more harmful than a single unit of carbon dioxide (on a 100-year timescale), consequently it has a global warming potential of 25 (kgCO2e).
Global House Gases (GHGs)	Gases that when released into the atmosphere absorb and emit thermal infrared radiation. These gases trap heat within the atmosphere thus contributing to climate change.
ISO	International Organization for Standardization
Life cycle assessment (LCA)	A ‘tool’ where the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life cycle (ideally) from earth-to-grave.
Renewable energy	Energy (including electricity) extracted from renewable resources, such as wind, solar, water.
Low Carbon Fuels (LCF)	In Cement’s case, they are those derived from the waste stream — construction and demolition waste, agricultural waste and non-recyclable plastics.

Environmental Product Declarations (EPD)	The measurement of the wide range of environmental impacts (for example, greenhouse gas emissions, toxic substances, habitat destruction, water impacts, ozone depletion, etc.) at every step of a product's life cycle — from raw material extraction and processing, to manufacturing, to distribution and disposal or recycling at end of life.
Type GUL	General use cement
NECB	National Energy Code for Buildings
NBC	National Building Code
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CMU	Concrete Masonry Unit
EPA	Environmental Protection Agency
EPD	Environmental Product Declarations
EUI	Energy Use Intensity
GWP	Global Warming Potential
ISO	International Organization for Standardization
WWR	WWR is the window-to-wall Ratio
SRI	Solar Reflective index

APPENDIX A:
RAINSCREENS AND THE BUILDING ENVELOPE

Rainscreens are one method to have a ventilated building envelope. A rainscreen relies on the drainage of any water that penetrates through the exterior cladding before reaching other envelope layers (i.e,: thermal insulation, water resistance barriers, etc.). A rainscreen system must have a cavity for water to drain on the backside of the cladding to function properly - a minumum1/8" cavity is required, though ⅜" to 2" are more common. Furthermore, water must be able to exit the wall system, typically through weep holes, perforations, or weep screeds at the bottom of the wall. The importance of drainage cannot be overstated. In cases of using a rainscreen, stucco and EIFS walls usually have a weep screed at the bottom of the cladding while brick walls have a through-wall flashing and weepholes. Figure A illustrates a rainscreen cladding system.

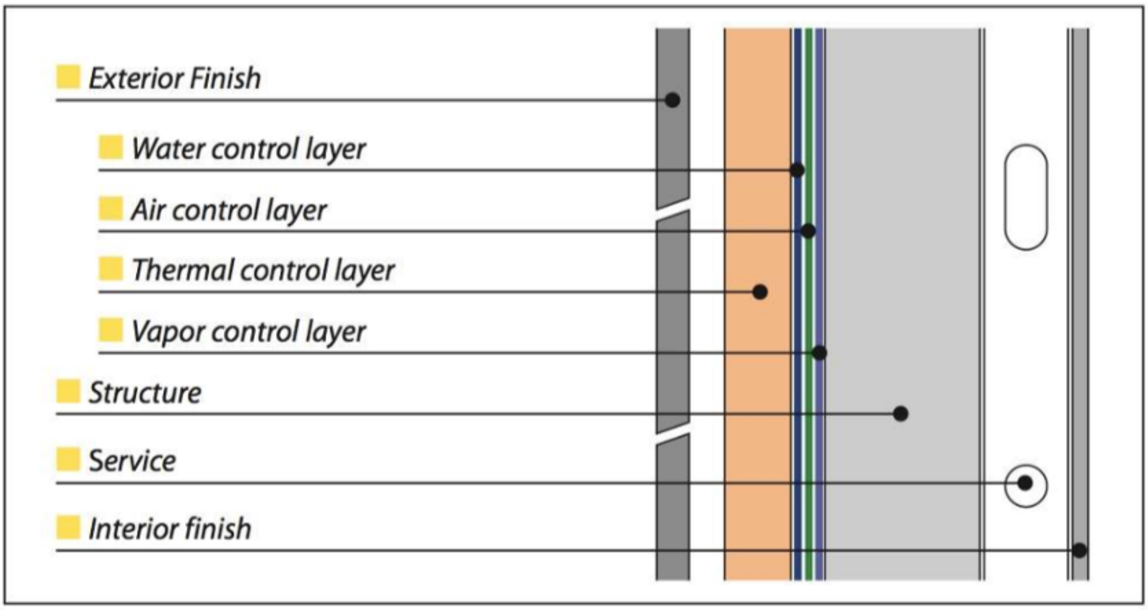

Figure 1: Diagram of the "Perfect" Wall showing ideal sequence of assembly layers
(From John Straube, High Performance Enclosures, Building Science Press)

FIGURE A

Rainscreens operate in the following way: any water that penetrates past the outside cladding layer is no longer being pushed by wind but is instead by diffusion. A tiny gap that separates the cladding material from the remainder of the wall assembly referred to as the cavity provides a capillary break. When the water reaches the cladding's inner surface, gravity forces the water down the inside side of the cladding, and prevents the water from reaching the backup wall. The air that circulates within the cavity between the cladding and the backup wall accelerates the evaporation of any remaining moisture. Where a weather-resistant barrier (WRB) layer is used the WRB provides protection against direct water on to the interior back-up wall sheathing as well as providing a barrier to the movement of air through the back up wall. However, the WRB permits the transmission of water vapour so drying can occur. Because this barrier is protected behind the cladding, it is shielded from the sun's damaging effects and has greater resilience and lifespan. Rainscreens can also help to improve a building's energy efficiency by allowing for more external insulation.. Rainscreens can also help to improve a building's energy efficiency by allowing for external insulation to compliment stud cavity insulation[91].

In summary, a rainscreen cladding is designed as a building envelope support device, not as a barrier against water penetration (such as a weather-resistant barrier). Rather, a rainscreen is designed to restrict the quantity of water that may breach the building's principal envelope defenses, the moisture barrier, thereby limiting the possibility of water entering the wall assembly. It accomplishes this by protecting the wall assembly from the five forces that cause rain to enter buildings: kinetic energy, gravity, capillary action, surface tension, and pressure gradients.[92]

A successful rainscreen relies on cladding and a cavity for drainage and venting. Builders can also significantly minimize energy losses from thermal bridging through external walls by improving the frame design. To accomplish this, using specialized frame schemes to eliminate wasteful framing members is employed. The panelizing of detailed wall sections is also helpful to minimize confusion in the field while construction. Installing both interior and exterior air barriers is also beneficial. While both forms of air barriers perform comparable functions, they complement and improve each other's efficacy. Interior air barriers regulate leakage of a building's interior air into the wall cavity and attic, restrict the ability of wet indoor air to enter the wall cavity during the heating season, and reduce convection losses inside walls. Exterior air barriers reduce the ability of moist outdoor air to enter the wall cavity during the cooling season and prevent wind-washing of wall insulation[93] . For the exterior air barrier (weather resistant barrier), it is often recommended to use spun polyfin commercially known as Housewrap. Housewrap does not degrade with prolonged exposure to moisture like traditional building paper and is often easier to create a tight seal. When applying housewrap, it should be shingle lapped (shingling) and taped on all vertical and horizontal seams and penetrations, and sealed along top and bottom edges to the structure to ensure an air-tight envelope. Shingling also helps to maintain water barrier characteristics. Isolating the attic from exterior walls and conditioned spaces increases the performance of the building envelope. This is usually achieved by installing gaskets and/or sealants for all recessed light fixtures at the attic level and access panels and stairs as well. Sill plate gaskets are also necessary to provide a capillary break as well as an air seal. Vulnerable spots should be also well-cared for throughout the wall sections. These areas include rim joist areas, window and door rough openings, HVAC ductwork and electrical boxes. A minimum ⅜" (10mm) gap is usually recommended for a rainscreen to work optimally. A building should always be designed as a whole continuous structure that takes into account all of the air sealing, insulation, structural, and energy efficiency systems, as well as the specifics of how the components interact. A blower door test is recommended and is an effective method to check for any excessive air leaks in the envelope that can be addressed before occupancy is granted.[94]

ENVELOPE FAILURE

When the building envelope system is correctly designed and constructed, occupants rarely notice.. However, when the building envelope fails (which even the best-built constructions

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[91] https://www.bdcnetwork.com/blog/understanding-rainscreen-wall-systems

[92] https://www.bdcnetwork.com/blog/understanding-rainscreen-wall-systems

[93] https://www.probuilder.com/11-tips-mastering-building-envelope-design

[94] https://www.probuilder.com/choose-right-housewrap

can over time), the failures are often very noticeable. There are many cases where a building envelope could fail to meet its intended goal. This failure could be in the form of water intrusion into the interior space, aesthetic loss of the veneer, deterioration of the structural components from corrosion or rot, poor indoor air quality from mold, energy inefficiency, and, in certain cases, life-threatening structural or indoor air quality conditions. These failures can emerge from incorrect design, installation deficiencies, material failure or acts of nature.

Designers may specify materials or systems that are unsuitable for their intended purpose. such as specifying materials that are incompatible with the other building materials, as well as having insufficient performance requirements for thermal movement, structural capacity, water penetration resistance, fire resistance or durability.

Installers may also create envelope failures through improper execution of a design. Workmanship is likely the most significant factor that affects the quality and performance of a building's envelope. This might result in the materials or systems specified from reaching their intended performance targets or capacities. Poor workmanship by installers during construction booms is common as the labour shortages can result in an increase in the number of unskilled, unsupervised, and untrained workers on projects.

Correctly specified materials can fall short of meeting advertised performance requirements. This might be due to mistakes in the product's production, handling, storage, or installation, or to components within the product. Degrading sealant adhesion, laminated glass delamination, and metal fatigue are all common instances.

Finally, there is always the chance of failure occurring due to unanticipated natural events. Even if the installation is flawless, unexpected failure of good work can occur when environmental circumstances surpass those expected during design. Hurricane-force wind loads, pounding rain, and high temperature changes may overwhelm a correctly planned and constructed building envelope, inflicting damage and leaving the system prone to further degradation or failure. Although the aforementioned type of failure can be difficult to anticipate and prevent, other various problems can be prevented through routine inspection and maintenance to identify small problems before they become big ones.[95]

[95] https://www.echotape.com/blog/contractors-field-guide-building-envelope/

APPENDIX B:
DURABILITY OF CONRCRETE MASONRY

Anecdotally, most contemporary construction may be argued to be durable under certain conditions. It is generally claimed that CMU masonry wall systems are durable for the following reasons:

- Rainscreen cavity wall structure has many layers to prevent moisture infiltration; the failure of one layer (e.g., A/V barrier continuity) can be compensated for by the other levels (brick veneer "screen," cavity, back-up wall, etc.). As a result, the argument for durability is linked to the redundancy inherent in wall systems.

- It is also argued that brick wall systems surpass code minimums due to their design for other uses, such as load bearing. Similar to the usage of precast hollow core floorboards, a fully-grouted 20 cm wall will provide a fire and sound rating considerably above "code minimums." When considering factors like progressive collapse or severe stress, these walled systems also give a lot of structural redundancy.

- It is also claimed that, given the right conditions, concrete masonry exhibits no intrinsic deterioration of their structural characteristics. They do not serve as a food source for molds, they do not typically suffer from creep effects, and they are not typically impacted by the presence of moisture, heat (below fire rating), or incidental contact (bumps, scrapes, etc.), whereas other systems (such as stud-gypsum) function as a structural/fire/sound element based on near perfect in-situ conditions. Technically speaking, hanging a painting on a drywall for instance, will reduce its fire rating since wood deteriorates when exposed to moisture; in fact, all wood characteristics, including fire rating, are linked to moisture.

FIRE RESISTANCE

Concrete is one of the most fire-resistant building materials on the market. It is designated as an A1 material under European Standards (EN 13501-1:2007-A1:2009) — the highest grade of fire resistance. Concrete has been classified as one of the most fire-resistant materials for three major reasons: it is non-combustible, non-toxic, and has low thermal conductivity. This implies it does not quickly transmit heat energy and does not easily react with other chemicals (meaning that in the event of a fire there are no noxious gasses released). This makes concrete one of the safest and most effective materials for structural fire protection.[96]

CONCRETE AS A MATERIAL

Concrete cannot burn — it cannot be ignited, and it emits no harmful gases when ignited. Concrete has been shown to have a high level of fire resistance and may be regarded as essentially fireproof in the majority of situations. This outstanding performance is mostly due to the constituent elements of concrete (cement and aggregates), which when chemically mixed

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[96] https://clmfireproofing.com/understanding-the-fire-resistance-of-concrete/#:~:text=There%20are%20three%20main%20reasons,it%20has%20low%20thermal%20conductivity.&text=This%20makes%20concrete%20one%20of,materials%20for%20structural%20fire%20protection.

within concrete produce a material that is basically inert and, crucially for fire safety design, has relatively low heat conductivity. Because of its slow rate of conductivity (heat transmission), concrete may function as an efficient fire shield not just between neighboring areas, but also to protect itself from fire damage.

Since concrete does not burn and concrete pieces keep their strength at high temperatures, concrete structures can resist the impacts of a fire without the need for additional active or passive protection. This security comes at no extra cost and will always be present, even if the structure changes over time (due to refurbishment or accidents). This implies that when it comes to safety, concrete has a lot more to offer than other construction materials.

Concrete, unlike certain other building materials, cannot be set on fire. It is impervious to smoldering materials, which can reach extremely high temperatures, starting or even re-igniting a fire, while flames from burning contents cannot ignite concrete. As a result, because concrete does not burn, it does not release any smoke, vapors, or harmful chemicals when exposed to fire. Unlike certain polymers and metals, it will not leak molten particles, which might cause fire. Concrete cannot contribute to the outbreak and spread of fires, nor can it increase the fire load.

Concrete constructions hold up well in a fire. This is due to the combination of the intrinsic characteristics of the concrete, as well as the right design of the structural parts to provide the needed fire performance and the overall structure's design to provide robustness.

Fire performance is the capacity of a certain structural element (rather than any particular construction material) to perform its intended function for a specified amount of time in the case of a fire.[97]

Internal zones do not achieve the same high temperatures as a surface exposed to flames due to the slow rate of temperature increase via the cross section of a concrete part. The standard ISO 834 fire test on concrete beams 160 mm wide x 300 mm deep exposed three sides to fire for one hour. While a temperature of 600°C was attained at 16 mm from the surface, this was cut in half at 42 mm from the surface to just 300°C — a temperature differential of 300°C in just 26 mm of concrete.[98]

This clearly demonstrates how concrete's comparatively moderate rate of temperature increase guarantees that its interior zones stay well protected. The interior temperature of concrete remains relatively low even after a lengthy period of time, allowing it to preserve structural capacity and fire shielding qualities as a separating element.[99]

ECONOMIC

Fires may have a severe financial impact on residents and businesses. Because of the strength of concrete, it is not only unaffected by the water used to extinguish a fire, but it is also simple to restore. This reduces the costs of rehabilitation and allows economic activity to recover and resume more quickly, decreasing negative effects on employees and companies. Property

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97 https://www.concretecentre.com/Performance-Sustainability/Fire-Resistance.aspx

98 Kordina, Karl, and Claus Meyer-Ottens. Beton-Brandschutz-Handbuch. Düsseldorf: Beton-Verlag, 1981

99 https://www.theconcreteinitiative.eu/images/ECP_Documents/FireSafety_IE.pdf

insurers respect concrete's outstanding fire safety qualities, and concrete structures benefit from lower fire insurance costs. Because the majority of concrete structures are usually not affected in a fire, one of the primary benefits of concrete is that it can generally be simply restored later, eliminating any difficulty and cost. Because most building fires have light floor loads and low temperatures, the load bearing capability of concrete is preserved both during and after the fire. For these reasons, it is not uncommon for a simple clean-up to be all that is necessary. The speed with which repairs, and rehabilitation are completed is critical in reducing any loss of business following a catastrophic fire; it is plainly preferable to destruction and restoration.[100]

ENVIRONMENTAL

As concrete does not release smoke or harmful gases, the environmental impact of a fire is reduced. Furthermore, the water used to extinguish flames is not polluted.

HUMAN SAFETY

Fire frequently endangers human life. This reality pushes advancements in fire safety and requires us to design structures capable of protecting people and property from fire risks. Concrete buildings and structures provide personal fire protection to safeguard both life and health, in line with Canadian fire safety laws. Concrete's inherent toughness, non-combustibility, and heat shielding characteristics guarantee that buildings stay stable during a fire. This helps people to survive and flee, permits firemen to operate safely, and decreases the environmental effect of combustion products.[101]

Concrete allows for a safe escape and firefighting. The fact that concrete buildings stay solid in fire is especially important for the safe evacuation of building inhabitants and firefighting efforts. Concrete stairwells, floors, ceilings, and walls contain the fire and function as strong compartments, allowing for safe escape and access for rescue personnel. Concrete escape pathways provide a level of resilience and integrity rarely found in other construction materials, whether utilized for residential structures or busy areas such as retail malls, theatres, and office skyscrapers. The use of concrete also ensures that the safety of firemen is not jeopardized. Concrete load bearing and space-enclosing construction components provide good protection to firemen even while they are inside a burning structure. Only under these conditions may such actions be carried out safely. Following the fall of the World Trade Center, the National Institute of Standards and Technology (NIST) released recommendations.[102]

FIRE RESISTANCE & BUILDING CODES

During a fire, concrete buildings stay sturdy. The functions of a structural element in fire-safety design can be designated as load bearing, separating, and/or fire shielding and are typically assigned a numerical value (in minutes, ranging from 15 to 360) that represents the duration for which the element can be expected to perform those functions. In the case of a fire, the building must function at least at the level needed by legislation but preserving the structure's stability for as long as feasible is obviously desired for survival, escape, and firefighting. This is especially essential in multi-story structures and bigger complexes. Furthermore, the inherent

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[100] http://www.theconcreteinitiative.eu/images/Newsroom/Factsheets/TheConcreteInitiative_FacSheet_FireSafety.pdf

[101] https://www.theconcreteinitiative.eu/images/ECP_Documents/FireSafety_EN.pdf

[102] https://www.theconcreteinitiative.eu/images/ECP_Documents/FireSafety_IE.pdf

fire resistance of concrete functions as long-lasting, passive protection — concrete is the only construction material that does not require active firefighting methods like sprinklers to work well in a fire.[103]

The International Building Code (IBC) (ref. 1) specifies three types of fire protection walls: fire wall, fire barrier, and fire partition, depending on the amount of protection required for the type of occupancy and intended use. A fire wall is usually thought to give the highest level of resilience and fire safety of the three designated fire-rated components. As such, it is designed to offer total separation and must be physically stable in the event of a fire.[104]

Both the National Building Code (NBC) and the National Fire Code (NFC) contain rules that address the safety of people in buildings in the event of a fire as well as the protection of buildings from the impacts of fire. (2) These two National Model Codes are being created as complementary and coordinated texts in order to reduce the potential of conflicting provisions. Buildings are expected to conform with both the NBC and the NFC. The NBC typically applies during construction and rebuilding, whereas the NFC relates to the operation and maintenance of fire-related aspects of existing buildings. Concrete structural frames are designed to meet this need for overall stability in the event of a fire, and in many situations, they exceed expectations. Concrete's non-combustibility and modest temperature increase imply that it will not burn, and its strength will not be severely damaged in a normal building fire.

In terms of concrete constructions (block & masonry), the Code dictates the following:

- A firewall permitted to have a fire-resistance rating not more than 2 h need not be constructed of masonry or concrete, provided
  1. the assembly providing the fire-resistance rating is protected against damage that would compromise the integrity of the assembly, and
  2. The design conforms to Article 4.1.5.17.

  (See Note A-3.1.10.2.(4).)

- For Access Route Design:

be designed to support the expected loads imposed by firefighting equipment and be surfaced with concrete, asphalt or other material designed to permit accessibility under all climatic conditions.

- For Fire Escape Construction:

Fire escapes shall be of metal or concrete, of the stair type extending to ground level, constructed throughout in a strong substantial manner and securely fixed to the building, except that wooden fire escapes are permitted to be used on buildings of combustible construction if all posts and brackets are not less than 89 mm in their least dimension and all other woodwork is not less than 38 mm in its least dimension.

- For Electrical Equipment Vaults:

An electrical equipment vault referred to in Sentence (1) shall be separated from the remainder of the building by a fire separation of solid masonry or concrete construction having a fire-resistance rating not less than

a) 3 h if the vault is not protected by an automatic fire extinguishing system, or

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[103] https://www.theconcreteinitiative.eu/images/ECP_Documents/FireSafety_IE.pdf

[104] NCMA TEK 5-8B, Revised 2005.

b) 2 h if the vault is protected by an automatic fire extinguishing system.[105]

In Canadian practice, egress stairs and elevator cores are designed using concrete, even if the main building structure was of another material. By working with concrete masonry and/ or concrete block for safety exits and elevator shafts, the code requirements are usually surpassed, and the safety of building occupants is ensured.

As concrete masonry and block are made of concrete, they have the same durability and resilience features. However, additional features could also be present in a project due to the different geometry and assemblies of the materials. For instance, as previously mentioned, a fully-grouted 20 cm concrete masonry wall will provide an excellent fire and sound rating. While on the other hand, concrete block, has unmatched performance in terms of thermal mass. (refer back to section 3.1).

[105] National Building Code of Canada, 2015. https://nrc-publications.canada.ca/eng/view/ft/?id=c8876272-9028-4358-9b42-6974ba258d99

APPENDIX C: SOUND TRANSMISSION CLASS (STC) FOR CONCRETE MASONRY

Sound transmission class (STC) estimates a wall's acoustic performance in some typical airborne sound insulation applications. A wall's STC is calculated by comparing sound transmission loss (STL) values at different frequencies to a standard contour. STL is the reduction or attenuation of sound energy, measured in decibels (dB), of airborne sound when it travels through a wall. In general, the STL of a concrete masonry wall rises as the frequency of the sound increases. Many sound transmission loss tests on various concrete masonry walls have been conducted. These studies revealed a clear link between wall weight and STC—heavier concrete masonry walls have greater STC ratings. Concrete masonry construction offers a broad range of STC values, depending on wall weight, wall structure, and finish. Standard calculation techniques exist in the absence of test data, and they tend to be cautious. TMS 0302 (ref. 1), Standard Method for Obtaining Sound Transmission Ratings for Masonry Walls, includes techniques for determining STC values of concrete masonry walls. STC can be determined by field or laboratory testing using established test techniques, or by computation, according to the standard. TMS 0302's computation is based on a best-fit connection between concrete masonry wall weight and STC based on a variety of test results. The weight of both wythes is utilized in an Equation to estimate STC for multi-wythe walls where both wythes are concrete masonry. However, because concrete and clay masonry have distinct acoustical characteristics, a separate technique must be utilized for multi-wythe walls with both concrete masonry and clay brick wythes. Another Equation, indicating a best-fit relationship for clay masonry, must be utilised in this situation. To generate a single STC for the wall system, first compute the STC using both Equations, based on the total weight of both wythes, and then linearly interpolate between the two resultant STC ratings based on the relative weights of the wythes.

APPENDIX D: THE CIRCULAR ECONOMY

In compliance with Canada's goal to reach NetZero by 2050, the province of Ontario, Canada, developed a plan where resource recovery and waste reduction are used as economic drivers and environmental protection considerations for Ontario's growth. In other words, in order to establish a circular economy, Ontario's objective is for waste to be viewed as a resource that can be retrieved, repurposed, and reintegrated. Ontario started implementing a detailed approach for achieving its transformation to a circular economy. Three interim goals have been set to track progress and achieve certain milestones; a 30% diversion rate to be accomplished by 2020, 50% by 2030 and 80% by the year 2050. There are four main actions that have already started taking place since 2016 to achieve the province's objectives.

1. Enhancing Provincial Direction and Oversight.
2. Enabling Efficient and Effective Recovery Systems.
3. Increasing Waste Reduction and Resource Productivity.
4. Creating Conditions to Support Sustainable End-Markets.[106]

A circular economy is a method of economic development that benefits businesses, society, and the environment as a whole. In contrast to the linear model of "take-make-waste," a circular economy is designed to gradually detach growth from the consumption of limited resources. It is referred to as circular because it promotes the shift from a linear system to a circular one. The Circular Economy is one that is restorative and regenerative by design. Economic activity in a circular economy builds and rebuilds overall system health. The notion acknowledges the importance of the economy's ability to operate at all scales – for big and small businesses, for organizations and individuals, globally and locally. According to the Ellen McAurthur Foundation, the circular economy is based on 3 main principles, designing out waste and pollution, keeping products and materials in use and regeneration of natural systems. Activities that maintain value in the form of energy, labor, and materials are favored in a circular economy. To keep goods, components, and materials flowing in the economy, durability, reuse, remanufacturing, and recycling must be considered. Circular systems promote efficient use of bio-based resources by fostering a wide range of applications as they cycle between the economy and the natural world. A circular economy works in tandem with NZEB and Passive House Standards by minimizing the use of non-renewable resources while preserving or enhancing renewable ones, such as by returning important nutrients to the soil to aid regeneration or by relying on renewable energy rather than fossil fuels.

[106] Strategy For a Waste-Free Ontario, Building the Circular Economy, 2017.

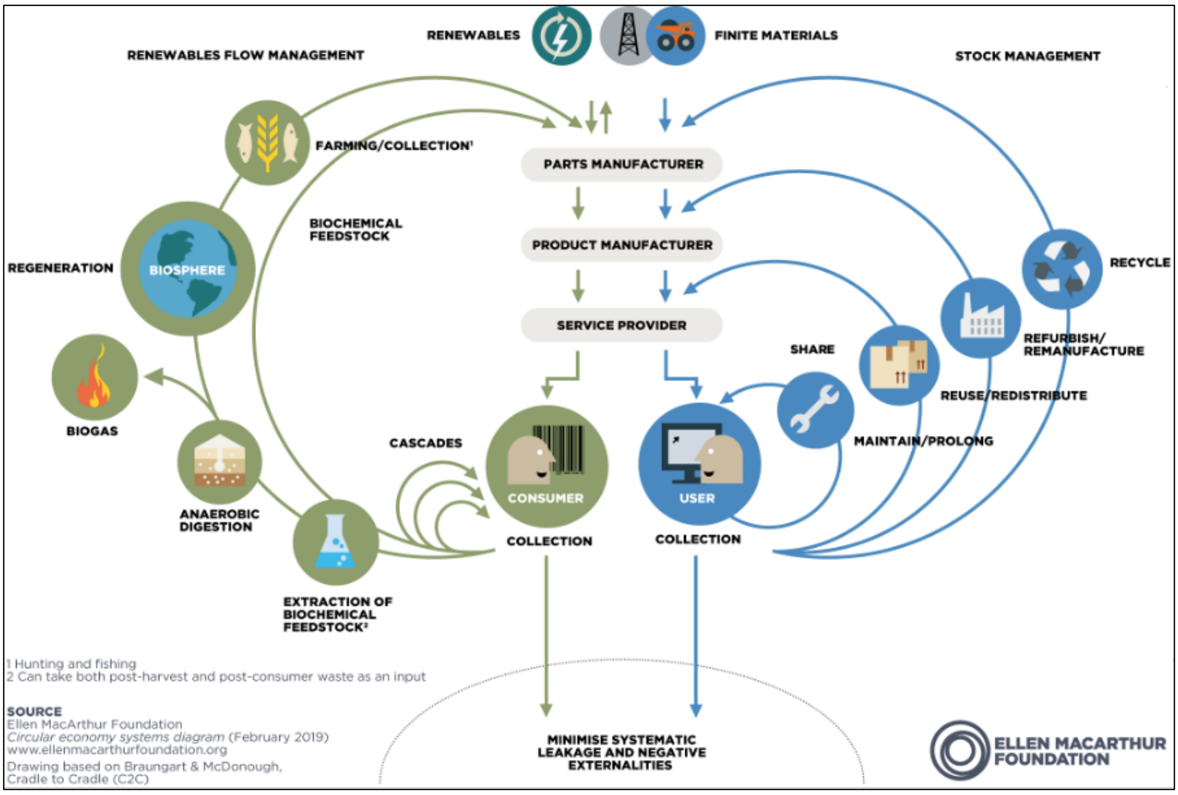

FIGURE B

Figure B, shown above, depicts the flow of resources, nutrients, components, and products while also including a financial value aspect. It is based on numerous schools of thought but is perhaps most recognizably influenced by Cradle to Cradle's two material cycles.

The Ellen McAurthur Foundation divides the flow of materials into two fundamentally separate flows; biological and technical. Biological materials, which are illustrated in green cycles in Figure B, are materials that can be safely reintroduced into the natural world after one or more use cycles, where they will biodegrade over time, returning the embedded nutrients to the environment. Technical materials seen in blue in Figure B cannot be reintroduced into the environment. Concrete, metals, plastics, and synthetic chemicals, for example, must continually cycle through the system so their value to be continuously recaptured. Shifting to a circular economy has potential benefits that reach beyond the economy and into the natural environment. The circular economy makes a significant contribution to meeting global climate targets by eliminating waste and pollution, keeping products and resources in use, and regenerating rather than deteriorating natural systems.[107]

CIRCULAR ECONOMY & CONCRETE

Concrete is created from natural elements that are easily and readily available locally. The use of recycled (un-hardened) concrete in ready-mixed concrete manufacturing is a prominent method for waste reduction in the concrete industry. Upon reaching the end of its useful life, it has been proved that concrete can be 100% recycled completely. Alternative materials such as fly ash, a by-product of coal-fired power plants, and ground granulated blast furnace slag (GGBS) from steel production can also be recycled in the concrete manufacturing process,

107 Strategy For a Waste-Free Ontario, Building the Circular Economy, 2017

depending on the cement type used. Alternative raw materials provide a number of advantages, including less quarrying and consequently lower carbon emissions, if the alternative materials are already decarbonized. Examples of such materials are lignite or coal ashes, blast furnace slag, concrete crusher sand, aerated concrete meal, and demolition waste fractions. It is tough to obtain a uniform response to the question of what type of waste can be utilized in a particular plant. Testing has to occur in order to determine the viability and consequences of using waste. However, as a general guideline, waste considered as an alternative fuel and/or raw material must offer value to the cement kiln in terms of the organic part's calorific value and the mineral part's material value. Usually, a proper sum of alternative materials can meet both of these criteria. Because of the nature of the manufacturing process, the cement industry can co-process the following materials:

- o Alternative fuels, which have a significant calorific value (e.g., waste oils).
- o Materials which have a significant mineral component (e.g., industrial slags).
- o Materials that have both a calorific value and provide mineral components (e.g., used tires and industrial sludges).

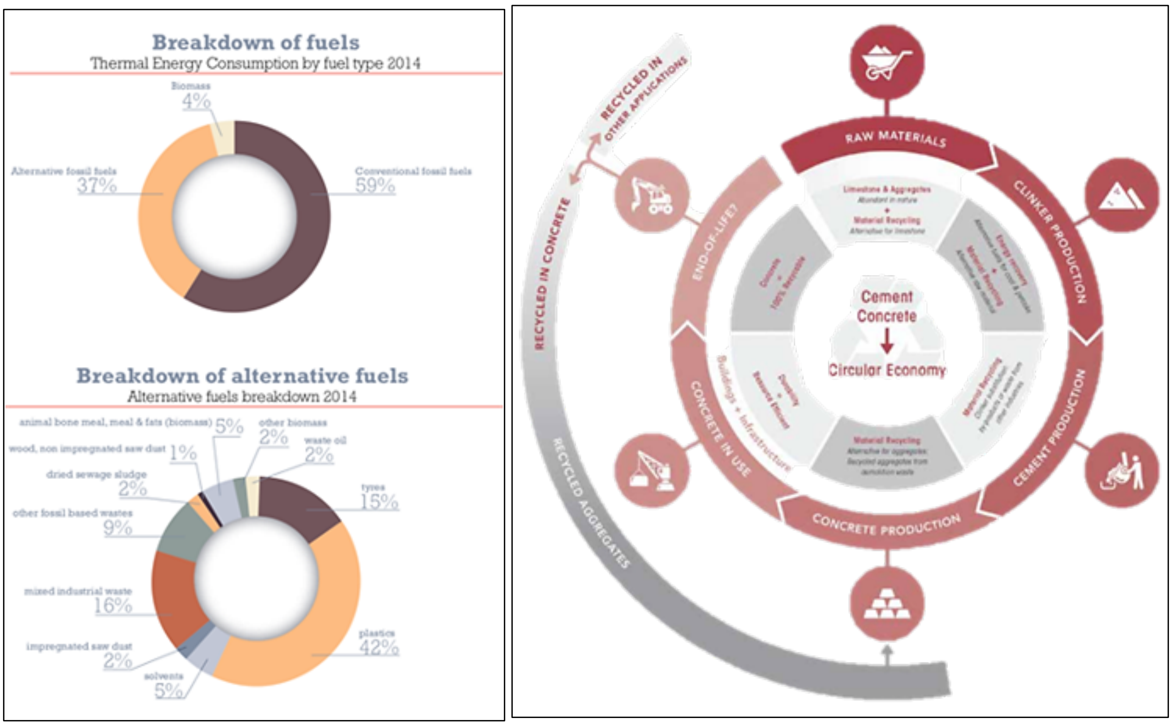

FIGURE C

Co-processing is the combination of energy recovery in tandem. The cement industry specializes in dealing with challenging waste streams and is in favor of prohibiting the landfilling of recyclable and recoverable trash. On one side, the cement industry can use waste as an alternative fuel (Energy Recovery), reducing our reliance on basic fossil fuels while also lowering carbon emissions. On the other hand, the cement industry may use the waste's mineral content as a raw material (Material Recycling), reducing the reliance on virgin raw materials (Figure C).

The uniqueness of co-processing in the cement industry, comes from the dedicated waste pre-treatment facilities that are created to treat waste before it is sent as a fuel to cement plants, besides the combination of both energy recovery and material recycling. The cement industry's alternative materials are sourced solely from specific waste streams. As a result, pre-treatment is an important aspect of the recovery process. Outside suppliers frequently prepare waste for use as an alternate fuel. On the one hand, these facilities provide a steady stream of waste, allowing the cement industry to maintain control over the clinker manufacturing process and ensure clinker quality. At the same time, these pre-treatment facilities sort the garbage and ensure that any recyclable material is transferred to be recycled.

By 2050, it is expected that 40% of kiln energy will come from traditional sources, such as coal (30%) and petcoke (10%), while 60% of kiln energy might potentially come from alternative fuels, with biomass accounting for 40% of that. This fuel blend would result in a 27 percent reduction in fuel CO2 emissions overall.
Nevertheless, in the cement industry, not all waste materials can be co-processed. When determining the viability of the materials, several factors must be considered. These considerations include the chemical composition of the end product (cement) as well as the clinker manufacturing process' environmental impact. Nuclear waste, infectious medical waste, and complete batteries are examples of waste types that are not suited for co-processing in the cement industry. For all of the materials utilized, a robust quality control mechanism is meticulously followed. This ensures that they are co-processed in a safe and environmentally sound manner, protecting the following:

- Health & safety of the workers in the plant and the people living in the neighborhood.
- High quality of the final product.
- Correct and undisturbed functioning of the production process.
- Environmental impact of the production process[108]

DECONSTRUCTION, REASSEMBLY & RE-USE

Canada produces roughly 34 million tons of waste per year and is one of the world's largest per capita producers of waste, with 25 million tons disposed of in landfills. Construction demolition waste accounts for around 4 million tons of solid waste in Canada, with just 16% diverted from landfills in 2016.[109]
Concrete is the world's most consumed material, second only to water. Concrete is utilized in construction twice as much as all other building materials combined. If only road construction is observed, every year, 700,000 km of new roads are created throughout the world. To put it in perspective, a one-kilometer stretch of four-lane roadway necessitates the use of 40 to 50 thousand tons of material. Over 550kg of carbon dioxide are emitted with every ton of cement produced; according to the Cement Association of Canada, 13 million tons of cement were produced in 2014 alone. This amount represents over 7 million tons of carbon dioxide emissions[110]. The CRD (Construction, Renovation, and Demolition) business generates 27 percent of total solid waste in Canada, which is disposed of in a landfill. According to CRD industry experts, about 75% of all waste created by the CRD sector has a residual value by recycling and reuse[111]. The current recycling rate for the CRD industry in Canada is 16%, which is one-fourth of the waste diversion objectives established by the Ministry of

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[108] CEMBUREAU, The European Cement Research Academy GmbH, 2016

[109] ENVI, Evidence, 12 June 2014 (Michael Goeres, Executive Director, Canadian Council of Ministers of the Environment).

[110] The Cement Sustainability Initiative (CSI), www.wbcsdcement.org/recycling

[111] Muluken Yeheyis (2012); An Overview Of Construction And Demolition Waste Management In Canada: A Lifecycle Analysis Approach To Sustainability.

Environment in Ontario[112]. In most situations, new building construction produces higher carbon emissions than repurposing older structures. This is largely due to existing assets carrying lower embodied carbon with them. The inherent carbon disadvantage of most new property construction must be acknowledged. Refurbishment of existing structures should be encouraged by any organization aiming to reach net zero throughout its property assets. The incorporation of a strategy that supports the examination of refurbishment as a preferred choice, should be explored at the beginning of any possible new building construction or investment in newly built assets. According to different studies, waste is planned into building projects even before they begin. On the other hand, the end-of-life fate of waste created, i.e. landfilling or reusing, is determined by costs and monetary advantages rather than policies in existence **(PIC, 2015). Based on a personal interaction of the author with a contractor (I have the paper, let me know if u want me to send it)/ can we include it?**

CASE-STUDY SEATTLE DEMOLITION AND DECONSTRUCTION PERMITS

Demolition is the science and engineering of breaking down buildings and other manmade structures in a safe and effective manner. Demolition, however, contrasts with deconstruction. Deconstruction is the meticulous dismantling of a structure so that the building materials may be reused. There are now growing efforts in North America to regulate the deconstruction and demolition process of buildings. An example is the Seattle Demolition and Deconstruction Permit that was implemented by the city of Seattle in 2019. In this city, a demolition permit is required to remove almost any structure, even accessory structures, with a roof area of more than 120 square feet. However, other solutions other than demolition, such as relocation of the entire structure to a new destination, are now encouraged first.

The Seattle Land Use Code includes rules that protect housing against demolition. In general, Housing demolition is discouraged when the purpose is clearing the site for a small or big institution, a telecommunications utility, or a public school. It is also prohibited to demolish housing for the sake of non-required parking. There are several criteria that have to be met in order for a demolition permit to be granted for housing. The structure must be vacant and unused for rental housing in a previous duration of six months, a permit has been issued by the government to establish or change use of the building and lastly, a permit for the structure's relocation to another lot to be used as residence has to be issued. There are also cases where the demolition of housing is ordered due to health and safety reasons under the housing and building codes. Which is often referred to as an abatement order.

A construction permit must be issued firstly in order for a demolition one could be issued. However, to encourage deconstruction rather than demolition, deconstruction permits could be issued without prior issuance of construction permits. Deconstruction increases the amount of reusable building materials recovered. Dimensional lumber, lower-value doors, siding, and windows are examples of reusable materials. Materials are generally removed in the reverse sequence in which they were installed in order to maximize reuse. This is referred to as the Housing Deconstruction Permit Incentive. This incentive provides applicants additional time to remove the old structure so that construction materials may be salvaged and recycled. Reusing building materials decreases the quantity of construction waste that goes to landfills and the demand on natural resources.

[112] OWMA, 2015, Rethink waste 2015: Evolution towards a circular economy

Prior to the demolishing or deconstructing of a structure several inspections are required to ensure a safe and proper process. These inspections start with ground disturbance inspection which is also known as a Temporary Erosion and Sedimentation Control (TESC) Inspection. Before any ground disturbance related to demolition activities, an inspection must be requested first. Erosion control measures are not necessarily required at the inspection stage but are required prior to any ground disturbing activities. This proactive method of erosion management protects the property from possible harm caused by grading and vegetation clearance.

Sometimes some projects with special inspections require a pre-construction meeting with a site inspector, the structural building inspector, the geotechnical special inspector, the earthwork subcontractor and SDCI structural building inspector. If the project contains ECA issues like wetlands, an ECA special inspector must also attend.

Side sewer capping permits should also be issued before the permanent capping of the project's side sewer. . The side sewer must be capped as close to the property line as possible without interrupting service to any other building. The Seattle Land Use Code also requires the end of the side sewer pipe to be filled completely with concrete for a minimum length of 12 inches. This is done under the supervision of a SDCI.

The Renovation, Repair, and Painting Rule of the Environmental Protection Agency came into force in 2010. The rule requires contractors to be certified if they are executing remodeling, repair, or painting work in houses, child-care facilities, or schools built before 1978 that disturbs lead-based paint. Contractors must adhere to specified work methods in order to avoid lead contamination.

The codes also consider hazardous materials such as Polychlorinated biphenyls, commonly known as PCBs, which are in fact toxic. PCBs can be detected in caulk, paint, sealant, and other construction materials used between 1940 and 1980. Some products made after 1980, such as yellow pigments in paints, include PCBs that were generated unknowingly as a byproduct of the production process. PCBs are a dangerous substance. The best management practices must be implemented so that PCBS do not go airborne or contaminate stormwater. Appropriate disposal of PCB-containing waste should be carefully done for the sake of the health and safety of the workers and the community. The City of Seattle's Stormwater Manual, Volume 2, Best Management Practice C1.25 and C1.30 address demolition, repair, remodeling, and construction procedures. Best Management Practice C1.50 explains how to properly dispose of PCBs.

Salvage and Deconstruction Resources is then supervised by a SDCI but does not need a special permit. Salvage refers to the removal of certain elements from a structure prior to deconstruction or demolition. Salvage typically refers to the recovery of appliances, cabinets, fixtures, flooring, and other items for reuse that involve minimal labor and do not require the building envelope to be disturbed in order to be removed.[113]

The Seattle Land Use Code is mentioned in the paper as a reference to what could be done to ensure an appropriate end-of-life process to buildings. Encouraging deconstruction and the reuse of materials instead of total demolition and waste of resources.

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[113] www.seattle.gov/sdci